AD-A087 828 LOUISVILLE UNIV KY PERFORMANCE RESEARCH LAB F/G 5/10
DEPTH PERCEPTION IN VISUAL SIMULATION.(U)
AUG 80 G S HARKER, P D JONES F33615-78-C-0021
UNCLASSIFIED AFHRL-TR-80-19 NL

1 OF 2
AD A
087826

AFHRL-TR-80-19

AIR FORCE

HUMAN RESOURCES

ADA087828

# DEPTH PERCEPTION IN VISUAL SIMULATION

By

George S. Harker
Paul D. Jones
Performance Research Laboratory
University of Louisville
Louisville, Kentucky 40208

OPERATIONS TRAINING DIVISION
Williams Air Force Base, Arizona 85224

August 1980

Final Report

Approved for public release; distribution unlimited.

LABORATORY



AIR FORCE SYSTEMS COMMAND
BROOKS AIR FORCE BASE, TEXAS 78235

## NOTICE



This final report was submitted by Performance Research Laboratory, University of Louisville, Louisville, Kentucky 40208, under Contract F33615-78-C-0021, Project 6114, with the Operations Training Division, Air Force Human Resources Laboratory (AFSC), Williams Air Force Base, Arizona 85224. Dr. Kenneth R. Boff was the Contract Monitor for the Laboratory.



This technical report has been reviewed and is approved for publication.

DIRK C. PRATHER, Lieutenant Colonel, USAF
Technical Advisor, Operations Training Division

RONALD W. TERRY, Colonel, USAF
Commander

# REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFHRL-TR-80-19
2. GOVT ACCESSION NO.: AD-A087828
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): DEPTH PERCEPTION IN VISUAL SIMULATION
5. TYPE OF REPORT & PERIOD COVERED: Final rept.
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): George S. Harker, Paul D. Jones
8. CONTRACT OR GRANT NUMBER(s): F33615-78-C-0021
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Performance Research Laboratory, University of Louisville, Louisville, Kentucky 40208
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 62205F, 6114[illegible]
11. CONTROLLING OFFICE NAME AND ADDRESS: HQ Air Force Human Resources Laboratory (AFSC), Brooks Air Force Base, Texas 78235
12. REPORT DATE: August 1980
13. NUMBER OF PAGES: 98
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Operations Training Division, Air Force Human Resources Laboratory, Williams Air Force Base, Arizona 85224
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 simulation
   - flying training
   - depth perception
   - task analysis
   - cue requirement
20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

The purpose of the study was to examine human depth perception as it relates to the requirements for visual simulation in Air Force flight simulators. Most, if not all, flying tasks require that depth judgments be made on the basis of extra-cockpit visual information. The bases on which such judgments are made by observers in the real world have been the subject of study for more than a century, and the majority of the cues have been identified. This effort examines the visual displays of a sample of Air Force and commercial flight simulators in order to assess the efficacy with which these cues are presented in visual simulation systems.



397470

Item 20 Continued:

A review of the psychophysical and simulation literature was conducted in order to identify the possible cues to depth and their relative importance at various distances and under various conditions. Each of four flying tasks (approach and landing, formation flying, aerial refueling, and low level flight) was subjected to task analysis/cue requirements determination in order to determine what tasks required depth judgments, whether those judgments were relative or absolute, and to identify the depth cues required for the successful completion of those tasks.

Information gained through the task analysis/cue requirements determination was used to subjectively assess visual simulation systems for the quality of the depth cues presented and to evaluate the need for additional or improved depth cues.

TABLE OF CONTENTS



LIST OF TABLES

## LIST OF FIGURES

# DEPTH PERCEPTION IN VISUAL SIMULATION

## INTRODUCTION

## DEPTH CUES

### PICTORIAL CUES

The set of cues available to the artist in depicting depth in a two-dimensional painting, as distinct from responses of the observer's postural or physiological systems, have been called by Gibson (1950) "stimulus variables." The ability to utilize these cues in the perception of depth is apparently not innate, but requires experience with the environment for "calibration" of the depth perception system.

Linear Perspective. An understanding of perspective requires a knowledge of the concept of visual angle. If one draws projection lines from the top and bottom of a rod of fixed length through the nodal point of the lens, the angle formed by the intersection of those lines is the visual angle. As the rod is moved closer to the eye, the visual angle increases. This is an example of the operation of Euclid's Law, which states that angular size is inversely proportional to the distance from the eye. The angle becomes zero only at an infinite distance from the eye which, in Euclidian space, is at the horizon.

Figure 1 demonstrates the use of linear perspective as a distance cue. The left drawing shows the outline of a runway as viewed from a relatively low altitude; the right drawing illustrates the runway outline, at the same linear distance from the airport, but at a higher altitude. Three points can be made from the illustration. (a) The pilot's estimate of the linear distance from the runway will be affected by the shape of the field, i.e., in order to use the visual information reliably, the pilot must know the length to width ratio of the runway. (b) The pilot's estimate of linear distance and altitude are interactive, i.e., in order to estimate the distance the pilot must know the altitude and vice-versa. (c) The degree of foreshortening of the field will be invariant as long as the viewing angle is invariant, i.e., it will have the same shape when seen from 5 miles away at 3000 feet as it does 1/2 mile away at 300 feet.

Texture Gradient. Gibson (1950) has described what he calls the "gradient of density of texture." We know that ordinary textures may vary from coarse to fine, but if a single surface varies progressively in this way, the gradient of density of texture is an adequate stimulus for the impression of depth. Figure 2, taken from Gibson's (1950) book, shows that a texture gradient does, indeed, result in a compelling impression of distance. Although texture gradient may seem to be merely a special case of linear perspective, the absence of texture cues to provide a surface metric renders the depth judgment task exceedingly difficult.

Apparent/Familiar Size. According to Euclid's Law, if two identical objects are placed such that they subtend different visual angles,

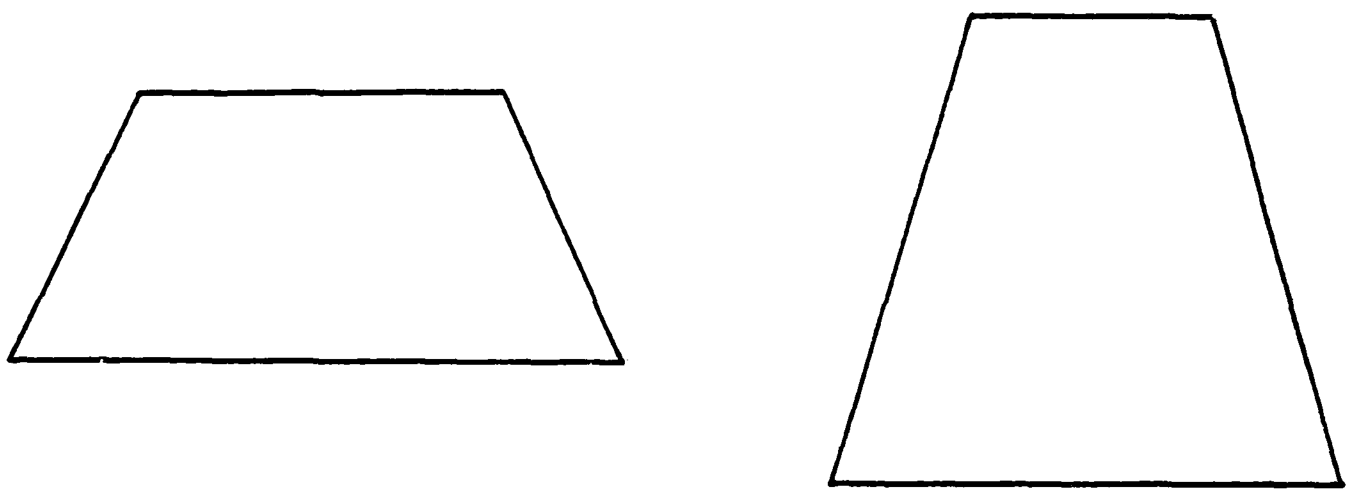


Figure 1. Linear perspectiv⸢ as a cue to distance and altitude (see text for description).

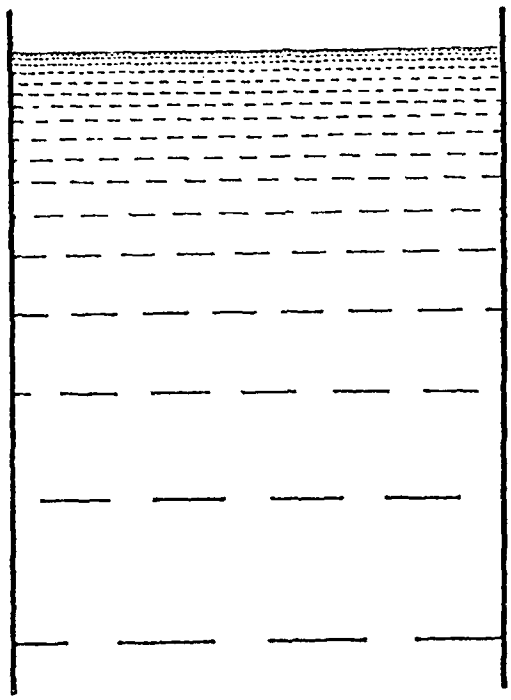


Figure 2. Impression of depth conveyed by texture gradient. From THE PERCEPTION OF THE VISUAL WORLD by James J. Gibson. Copyright c 1950 by James J. Gibson. Reprinted by permission of of Houghton/Mifflin Company and the author.

the smaller of the two angles must represent the object farther from the observer. Clearly, if the smaller of two similar objects is judged to be farther away, then the observer must be aware of the relative image size, as opposed to the relative object size. This notion led Gogel, Hartman, and Harker (1957) to differentiate between relative and absolute distance.

By the term absolute distance, Gogel et al. (1957) meant the distance from the observer to the object, or what is now referred to as "egocentric distance." Relative distance refers to the distance separating two or more objects in space. Gogel et al. (1957) reported that as the image of an object became smaller in successive discrete presentations, the subjects judged the change in distance appropriately. The authors concluded that relative image sizes can be compared even when one of the images exists only in memory. That is, we may speak of observers using learned information about the relative size of retinal images of objects to "calibrate" the depth perception system.

This accords with a result reported by Epstein and Baratz (1964), who found that relative distance could be accurately judged when viewing familiar objects. However, image size was not a reliable cue to relative distance when viewing nonsense figures.

In order for relative size to be an adequate cue to absolute distance, the observer must sense the angular size and have information about the linear size of an object. Then, the observer must integrate this information with knowledge about the appropriate angular size associated with a specific linear size for a variety of distances. Although an observer might commit to memory the angular size of a specific object at a specific distance (e.g., the angular size of an F-4 at the correct fingertip formation distance), the utilization of relative size cues for absolute distance judgments in the general case would be a formidable task. It seems likely that such cues function only in relative distance scaling.

Aerial Perspective. Artists have known, at least since da Vinci, that objects in the distance tend to lose saturation and become blue. Relative brightness of objects is independent of their distance from the observer and depends entirely on their distance from the source of illumination. Since the distance from the sun is very nearly invariant for objects on or near the surface of the earth, illumination in daylight should be uniform. However, at very great distances particles suspended in the air cause an attenuation in both illumination and contrast. Rock (1975) has suggested that aerial perspective alone does not sustain the impression of depth, and is almost certainly not an important variable in the flight tasks discussed in this report. It is worth noting, however, that Ittelson (1960) has reported that, in the absence of other depth cues, the brighter of two objects is reported as nearer.

Light and Shade. Nearly all introductory perception textbooks suggest that depth information can be conveyed by highlight and shading. Certainly, basic art courses emphasize the use of highlights and shading as a means of suggesting depth in two-dimensional representations. The classic demonstration of the effect of shading is a photograph of craters which become blisters when the photograph is inverted.

The general theory to account for this effect was elucidated by Brewster (1847) and is still widely and almost uncritically accepted. However, this theory, which states that the effect is due to the observer's expectation that all illumination comes from above, has not been proved. In fact, all of the textbook demonstrations of this effect incorporate other depth cues, such as perspective. It is unlikely that shading alone can account for the reversal of depth which accompanies the inversion of the stimulus.

Interposition. A further cue to relative distance is provided by the fact that objects located nearer the observer may partially occlude objects located farther away. That this is an extremely powerful cue to distance judgment can be demonstrated by pitting it against other cues, such as relative size. This has been done by Gibson (1950), who arranged two standard playing cards in a row along the mid-saggital plane, with the observer positioned so that the farther card was partially occluded by the nearer card. When Gibson cut away a corner of the nearer card, so that none of the farther card was occluded, observers reported that the farther card was in front of and larger than the objectively nearer card.

Height in Plane. An additional cue to distance is provided by height in plane or relationship to the horizon. The relationship to the horizon provides a good cue to distance regardless of the height from which the objects are viewed. The reason is that for practical purposes the horizon is always at eye level and therefore provides a fixed frame of reference. In general, for objects which are at the same altitude, the closer they are to the horizon line, the farther they are from the observer.

KINETIC CUES

Motion Parallax. Helmholtz (1925) provided the first thorough description of motion parallax as a cue to distance.

> In walking along, the objects that are at rest by the wayside stay behind us; that is, they appear to glide past us in our field of view in the opposite direction to that in which we are advancing. More distant objects do the same way, only more slowly, while very remote bodies like the stars maintain the permanent positions in our field of

> view, provided the direction of the head and body keep in the same directions. Evidently, under these circumstances, the apparent angular velocities of objects in the field of view will be inversely proportional to their real distances away; and, consequently, safe conclusions can be drawn as to the real distance of the body from its apparent angular velocity. p. 295

The minimum threshold for perception of a difference in velocity (which should predict the threshold for motion parallax) has been studied by Graham, Baker, Hecht, and Lloyd (1948) and reported as a few seconds of arc per second. The usefulness of motion parallax as a depth cue has been investigated directly by Gibson, Gibson, Smith, and Flock (1959). These investigators used a shadowgraph technique, in which all the depth cues, except relative motion parallax, were eliminated by presenting the stimuli as moving shadows in a single plane in depth. Gibson et al. (1959) used two transparent sheets of plastic, which were splattered randomly with spots of different sizes and placed at different distances between a point source illuminator and the screen.

Both plastics were moved in the same direction at the same velocity. The shadows cast by the spots on the sheet nearer the screen, therefore, moved more slowly than did the shadows of the other spots. Although observers did report that the two groups of dots moved with different velocities, they were not able to distinguish any differences in apparent depth.

When Gibson et al. (1959) used a single sheet of splattered plastic, which was inclined with respect to the frontal plane, the observers were able to determine correctly the direction of tilt. That is, two (or perhaps a larger number of) discrete velocities will not sustain the impression of depth, but a gradient of motion parallax is capable of doing so. Gibson has described this as motion perspective.

Even before the Gibson et al. (1959) experiment, Wallach and O'Connell (1953) had used the shadowgraph technique with a rod rotating in the coronal plane. They found that if the rod were horizontal, so that the shadow was simply a horizontal line which expanded and contracted, no depth impression was obtained. However, when the rod was tilted off the horizontal, so that its shadow changed in both length and direction, a clear depth perception was the result. Wallach and O'Connell labelled this the Kinetic Depth Effect. Wallach, O'Connell, and Neisser (1953) found that once depth had been established through the kinetic depth effect, the impression of depth was maintained even after the objects became stationary.

Streaming. Gibson, Olum, and Rosenblatt (1955) have noted that relative motion parallax depends on the observer's being displaced laterally from the line between him and the objects in question. That is, motion parallax does not occur for objects directly ahead of the observer during locomotion. Gibson (1950) defined motion parallax as a gradient of deformation of the retinal image. The elements in the visual field move with differential velocities, as a function of their displacement from the direction of locomotion. Figure 3 illustrates the gradients of deformation for the pilot of an aircraft in level flight.

The motion of the objects will, at some point in the periphery, exceed the maximum rate for visual fusion resulting in a blur or streaming effect. For targets which are actively tracked by the observer, the target velocity may reach 100° $sec^{-1}$ without blurring (Whiteside, 1967). If the observer's gaze is fixed in the direction of locomotion, however, blur will occur at target velocities between 15° $sec^{-1}$ and 30° $sec^{-1}$ (Graham, 1951).

PHYSIOLOGICAL CUES

Among the potential physiological cues to depth are accommodation and convergence. However, Ittelson (1960) has suggested that apparent depth is the cue to accommodation and convergence, rather than the reverse. Moreover, Heinemann, Tulving, and Nachmias (1959) have shown that subjects were unable to do better than chance in a depth discrimination experiment, in which accommodation was the only cue. However, Campbell and Westheimer (1959) found that subjects could learn to use astigmatic errors alone for depth judgments. In addition, some subjects were unable to make depth judgments in monochromatic light, suggesting that they had been utilizing chromatic aberration as a source of depth information.

Gogel (1961) reported that some observers were able to give consistent depth estimates to an object for which the eyes were converged (accommodation and image size constant), and adjust their estimates in keeping with changes in vergence. However, the estimated distances did not agree with the distance which the vergence should have provided. On the other hand, the double images, which result from incomplete vergence, are a cue to relative depth (Westheimer & Mitchell, 1956). The cues to distance which are provided by accommodation and vergence can be characterized as weak to nonexistent.

BINOCULAR DEPTH CUES

If an observer fixates an object at a moderate distance in front and in the saggital plane, other objects in that plane located at different distances from the observer fall on non-corresponding points on the retinae. Objects located in front of the point of fixation project to the left of fixation in the right eye and to the right of fixation in the left eye. The converse is true for objects located

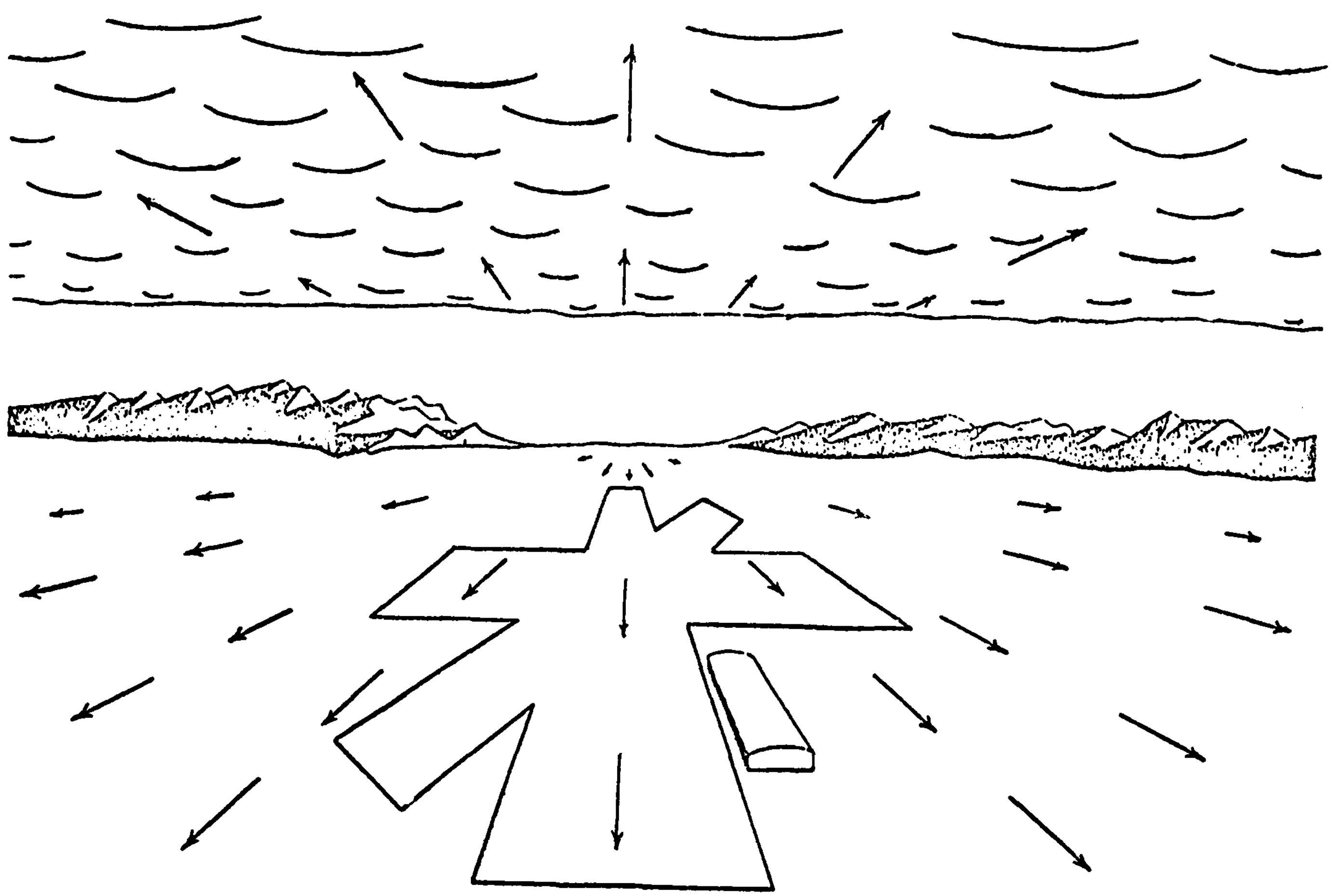


Figure 3. Motion perspective in level flight under an overcast. From THE PERCEPTION OF THE VISUAL WORLD by James J. Gibson. Copyright c 1950 by James J. Gibson. Reprinted by permission of Houghton/Mifflin Company and the author.

behind the point of fixation. Scanning from near to far by verging the eyes, even to the extent of alternately fusing the images of the objects of both near and far, does not alter the inherent disparity of the images established by the position of the objects in the field of view. However, the fact that some objects in the visual field are seen single, while others are projected as double images, provides information as to the relative depths of the objects. The apparent depths between objects is greater when they are alternately fixated, than if the eyes remain passive.

Because the eyes are separated by about 65 mm, the retinal projection of three-dimensional objects located near the observer is not the same in the two eyes. Wheatstone (1852) reasoned that the fusion of these disparate images might provide depth cues. In fact, this retinal disparity is the principal cue in the stereoscope which is used to provide three-dimensional views of common scenes. Several researchers have measured the limits of stereoacuity and have reported results which range from 2 seconds of arc (Berry, 1948) to 24 seconds of arc (Graham, Riggs, Mueller, & Solomon, 1949). If a particular value of stereoacuity is adopted as threshold, it is not difficult to calculate the maximum distance at which retinal disparity might provide a meaningful cue to depth. Using 12 seconds of arc as threshold, for example, the limit of stereoacuity would be approximately 1300 meters. Stratton (1898) empirically determined a limiting distance of 580 meters. In laboratory-type situations then, stereoscopic cues can contribute to the perception of depth at distances up to a few hundred meters. However, in normal viewing, where stereopsis is in competition with other depth cues, the limit may be as little as 20 feet.

## SUMMARY

It is obvious that not all of the depth cues identified in this section are equally important to every flying task. Given the distances and environment of formation flight, few if any of the depth cues can be specifically effective. With experience, apparent/familiar size and linear perspective could become significant as component cues of stadiometry, i.e. the seen size of the companion aircraft judged against canopy and cockpit detail. References to resolution of image detail, letters, insignia, and aircraft detail are used to verbalize this judgment. Aerial refueling provides the closest required approach between aircraft in flight and the distances fall within the range of stereopsis. Thus, stereoscopic cues could play a role in depth judgments during aerial refueling in addition to the cues of stadiometry.

Flight tasks executed in the vicinity of the ground provide the greatest opportunity for the breadth of cues to depth to be operative. The depth cues of linear perspective, texture and parallax gradients, interposition, and height in plane are effective among ground objects. To the degree that the aircraft in flight is among the ground objects, or can be related to them, these cues could serve to locate the aircraft in space. Apparent/familiar size would seem to have a particular significance in landing in that the task is universally discussed in terms of the appearance of the landing strip. However, given the variety of landing strips, particularly in their combinations of width and length, the apparent/familiar size cue could only be specific to each air field.

Streaming also requires the presence of ground detail with the unique feature that, given a threshold characteristic of the observer's vision and knowledge of the aircraft's velocity, absolute judgment of distance would seem to be possible.

The matrix of Table 1 tabulates the depth cues discussed in this section with respect to the four flying tasks examined in this report. Cell entries are the subjective assessments of the utility of each cue for each task. Only limited research has been reported in which the ranges and relative strength of the various depth cues has been the primary focus. Therefore, this assessment is not data-based, but is a subjective analysis based primarily upon pilot interviews (discussed in subsequent sections) and on an actual examination of visual simulation systems. Should the majority of cues be absent, the human observer may still be capable of making accurate depth discriminations by utilizing cues which are not normally of high saliency. However, by the absence of normal redundancy the potential for gross error is also increased.

TABLE I. SUBJECTIVE ASSESSMENT OF THE UTILITY OF VARIOUS DEPTH CUES FOR SELECTED FLYING TASKS. (H=high, M=moderate, L=low)

| Cues | Landing | Formation | Refueling | Low Level |
|---|---|---|---|---|
| LINEAR PERSPECTIVE | H | M | M | H |
| TEXTURE GRADIENT | H | L | L | H |
| APPARENT/FAMILIAR SIZE | H | H | H | L |
| AERIAL PERSPECTIVE | L | L | L | L |
| LIGHT AND SHADE | L | L | L | L |
| INTERPOSITION | M | L | L | M |
| HEIGHT IN PLANE | H | L | L | H |
| MOTION PARALLAX | H | L | L | H |
| STREAMING | H | L | L | H |
| ACCOMMODATION & CONVERGENCE | L | L | L | L |
| STEREOPSIS | L | L | M | L |

## PROCEDURE

The central question addressed by this study was: Are the depth cues which are presently available in visual simulation systems adequate to support the perception of depth? The study was designed to investigate the presentation of depth cues in visual simulation systems to determine whether improved depth cues or alternative methods of presentation of existing depth cues are required for the performance of various training tasks in the simulator.

In order to identify depth cues which might be utilized in the performance of tasks of takeoff and landing, aerial refueling, formation flying, and low-level flying, a search of the relevant psychophysical/perceptual and flight simulation literature was conducted. The purposes of the literature search were to provide a catalog of depth cues available in the real world and to compile information about the ranges over which the various depth cues are effective and the relative importance of the cues at the distances involved in the flight tasks mentioned.

A task analysis/cue requirements determination was conducted to identify which depth cues are required for each flying task, to determine whether the depth judgments are absolute (egocentric) or relative (exocentric), and to assess the relative importance of each depth cue for each task.

The purpose of the visual simulation systems analysis was to determine which depth cues identified in the literature search, task analysis, and cue requirements determination were available in visual simulation systems. In addition, cuing methods presently employed in visual simulation systems were identified and evaluated, and potential sources of non-veridical perception were identified.

### LITERATURE SEARCH

The literature search for both psychophysical and simulation literature was carried out through the DIALOG service (Lockheed Information Systems, a subsidary of Lockheed Missles and Space Co., Inc.) on-line at the University of Louisville Library. In addition to searching subject identifiers and descriptors, DIALOG was also used to search titles and abstracts for the key words and phrases: Flight, flying, simulation, simulator, depth, depth perception, space perception, and stereopsis.

Off-line prints of titles and abstracts were secured for each article identified by one or more of the key words or phrases. Abstracts were then evaluated and full text copies were requested of those articles which appeared to be relevant to the present effort.

## TASK ANALYSIS/CUE REQUIREMENTS DETERMINATION

The task analysis and cue requirements determination were conducted concurrently by means of interviews with pilots either individually or in small groups. Consultation with personnel at Luke AFB and Williams AFB and with the contract monitor at Wright-Patterson AFB indicated that the number of responses which might be expected from a mailed questionnaire was extremely small. It was determined that an on-site interview with instructor pilots (IPs) would prove to be far more fruitful. Therefore, an interview guide (see Appendix A) was constructed with the assistance of IPs from the 4444th Operations Squadron at Luke AFB.

Pilots were interviewed at Davis-Monthan AFB, Arizona; Mountain Home AFB, Idaho; Nellis AFB, Nevada; and Shaw AFB, South Carolina, and included pilots of A-10, F-111, and F-4 aircraft. The purpose of the study was explained to each respondent prior to the interview.

The interviews covered aerial refueling, approach and landing, formation flying, and low level flight. Questions were open ended to allow pilot comment. The questions were designed to assess the visual information required for the successful accomplishment of each task in real aircraft. Many of the pilots interviewed had no experience in a flight simulator, but those who had were asked to compare the visual scene in the simulator with that in the real aircraft by responding to the same or similar questions based on their simulator experience.

## VISUAL SIMULATION SYSTEMS ANALYSIS

The Visual Simulation Systems Analysis was conducted by means of on-site inspections of the ASPT simulator and a Primary Instrument Trainer at Williams AFB; Simulator for Air to Air Combat (SAAC) at Luke AFB; and 737 and 747 commercial aircraft simulators at the Boeing Co., Seattle, Washington. These systems are, respectively, a monochrome Computer Image Generation (CIG) system, a Camera/Modelboard system, a hybrid CIG-Model system, and a color CIG system. In addition, we inspected a variable anamorphic motion picture (VAMP) system at the Boeing Co. and witnessed a portion of the acceptance testing of a CIG system at Luke AFB, which included aerial refueling.

During the analysis of the ASPT system we witnessed a low level weapon delivery training session from the system operator's point of view and were flown on several low-level sorties at altitudes ranging from 0 to approximately 100 feet above ground level (AGL). These low-level sorties were viewed from both the right and left seats of the T-37 cockpit.

In the Camera/Modelboard T-37 simulator we flew two touch-and-go "landings" from the pilot's seat. Because of mechanical constraints, this simulation is not capable of faithfully simulating the landing below approximately 20 feet AGL.

At the Boeing Co., we were flown as co-pilot and over-the-pilot's-shoulder observer on a 2-hour training flight in the 737 simulator. This flight included several landings at each of three simulated airfields in daylight, dusk, and night conditions and in various weather conditions ranging from unlimited visibility to minimum operational visibility. In addition, we flew several low level passes over the simulated airfields at altitudes of 50 to 100 feet AGL.

A second, shorter, series of landings was flown in the 747 simulator. The 747 simulation system has the capability of providing a choice of locations of the four windows in which visual information is presented. That is, the operator can select a wide field which can be viewed by both pilot and co-pilot through the forward windscreen, or a field which fills the pilot's side and forward windows and a portion of the co-pilot's forward view.

Our experience in the VAMP system was a low level flight from the pilot's seat at an altitude of approximately 50 feet AGL. The flightpath was over water and woods typical of the Pacific Northwest.

During each of these simulated flights, we made note of the depth cues present in the visual scene both forward and peripherally. This catalog of depth cues was compared to the list of cues identified in the pilot interviews and literature search to determine whether potentially important cues were absent in the visual simulation. In addition, the quality of the presentation of each depth cue identified was subjectively assessed by each investigator independently.

## FLIGHT TASKS

### FORMATION FLYING AND AERIAL REFUELING

The consensus of pilots interviewed was that aerial refueling is formation flying (see Appendix A). That is, both tasks are alike in that they share the requirement that one maintain a fixed position or series of positions with respect to another aircraft. USAF Phase Manuals describe both tasks in terms of criteria for proper alignment using a system of triangulation, and all pilots interviewed agreed that each task can be accomplished through the use of these alignment criteria. Thus, neither is a primary depth perception task, but rather a triangulation or angle measurement task, i.e. an instance of stadiometric range finding.

Each of the pilots interviewed indicated that after having gained experience in flying fingertip or echelon formation they do not use the triangulation method except as a cross-check to the correct position. Instead, they fly to a position which "looks right." As indicated earlier, Gogel et al. (1957) and Epstein and Baratz (1964) have reported that familiar objects can, through experience, serve as cues to reliable distance judgments. It is significant, however, that the uniform report of pilots was that they continually cross-check this "calibrated distance metric" against the triangulation cues provided for the task.

Although the specific features which are used to accomplish the correct alignment differ on different aircraft, it is instructive to examine the alignment process in the F-4 fingertip formation. Figure 4 illustrates this process as described in the pilot interviews. A line is extended from the star insignia on the fuselage of the lead aircraft through the wingtip light to provide the first alignment projection. The pilot in the wing position flies along this line toward the lead aircraft until reaching a point formed by the intersection of that projection with a line extending across the stabilator assembly of the lead aircraft.

For more extended formations, such as the fluid four or a line-abreast tactical formation, in which aircraft are separated by distances of up to 9000 feet (up to 3000 feet within a single element), pilots reported that they rely on acuity cues for distance judgments. That is, their position is established at the distance at which they can "just barely read" one or another of the markings on the accompanying aircraft. Obviously, the efficacy of acuity as a cue to distance is markedly affected by haze, direction of illumination, etc. In the simulator, acuity is an ineffective cue because the resolution limit of the display makes presentation of the required detail impossible.

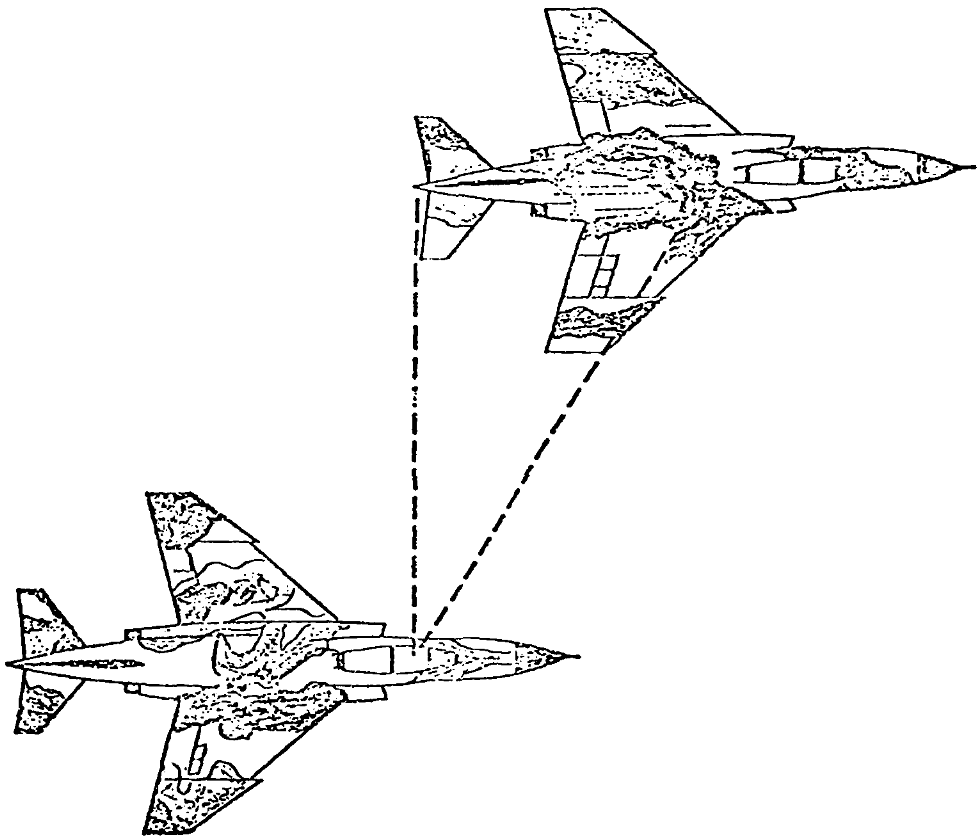


Figure 4. Triangulation alignment used in fingertip formation with the F-4 aircraft.

As indicated earlier, the processes of approach to, and coupling with, a tanker for aerial refueling are essentially the same as those involved in close formation flight. The proper positions for each phase of aerial refueling are described in USAF phase manuals in terms of alignment cues. The holding and ready positions differ from the couple position in that the distances involved are sufficient for the alignments to be achieved between features of the tanker. Information on the correct alignment for couple is described in Phase Manuals as being relayed from the boom operator (boomer) through vocal communication and through the marker lights under the belly of the tanker.

Pilot responses, however, indicate that they can anticipate the boomer's (fuel boom operator) instructions to correct misalignments. Though there are individual differences among pilots with respect to the alignment cues they use, they have in common the element that features of their own aircraft, e.g., portions of the canopy bow, are aligned with features of the tanker's fuselage, e.g., the seam in the sheathing immediately forward of the boom opening. Some pilots report that they adjust their seat height just prior to couple in order that their eye height will be correct to give the desired alignment. Figure 5 illustrates the use of the canopy bow as an alignment reticle in which the engine nacelles provide the external cue.

The critical problem for holding alignment, once couple is achieved, is the separation of up-down from forward-back in the flight adjustments that must be made to hold position. Although the director lights are available for gross information, most pilots indicate that they are not well positioned for use by pilots of tactical aircraft. They report that they use the telescoping of the fuel boom, with its distinctive color coding, to provide the information necessary for maintaining position. Lines of sight to the tanker and the telescoping of the boom give unique combinations of cues when the aircraft being refueled is in the preferred position, such that the boom extends downward at greater than a 45-degree angle (see Table 2).

Of all the flight tasks examined, aerial refueling is the one which might meaningfully utilize stereoscopic vision. The distances involved, particularly those to the boom from the cockpit at the time of couple, are within the range of significant stereoscopic resolution. Also, the mid-line relation of the receptacle and the boom to the cockpit in such aircraft as the F-4 would tend to emphasize stereopsis in the mix of visual cues. In some aircraft, however, the fuel boom does not pass directly over the pilot's head. Therefore, the mix of visual cues would favor the monocular cue of motion parallax. Moreover, the time characteristics of stereoscopic adjustment to changes in distance are easily exceeded by a radially moving object.

LOW LEVEL FLIGHT

Pilot comment. Pilots indicated that the problems of low level

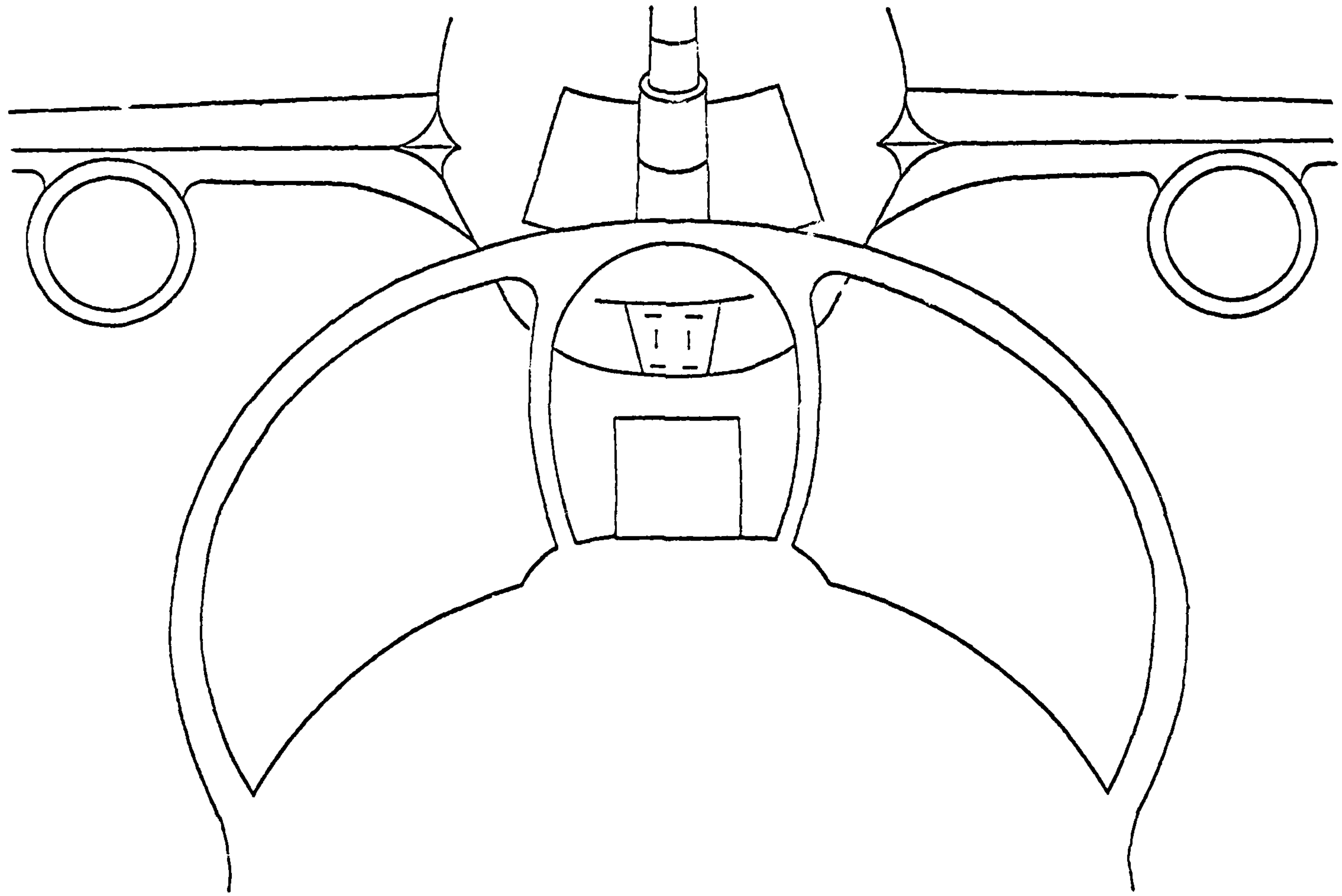


Figure 5. Canopy bow used as a reticle to align on tanker aircraft in aerial refueling.

TABLE 2

POSITION CUE COMBINATIONS IN AERIAL REFUELING

Lines of sight combinations for tanker and boom as a function of direction of motion of the aircraft being refueled.

| Movement of Aircraft Being Refueled | Movement of Lines of Sight to Tanker | Movement of Fuel Boom |
|---|---|---|
| forward | forward or down | in |
| up | back or up | in |
| back | back or up | out |
| down | forward or down | out |

flight are related to the presence (or absence) and type of terrain features in the visual environment. They indicated that direction of illumination and time of day interact with terrain features to make the task more or less difficult. The comment was made that a moderate overcast provides good flying conditions in that shadows do not obstruct the view of the ground while sufficient light is present to illuminate and recognize terrain features.

A pilot who had recently transferred from Europe to Nevada commented that the particular ground detail, e.g., sagebrush and cattle, in Nevada, as compared to church steeples and farm buildings in Europe, required several flights to "recalibrate his eyeballs."

A pilot transferred to South Carolina commented that low-level flight over the wooded ridge lines of the Appalachians was hardly low-level flight at all when compared to flying among the saguaro cacti of Arizona. The flightpaths in South Carolina would not permit entry into the valleys between ridge lines. In Arizona, low-level flightpaths were typically below ground features - buttes and spires - and, in at least one instance, passed through a gap where the view out the side canopy was entirely filled by the rock face of the cut. In this instance, the pilot found that the clarity of detail in the rock face gave a startling sense of closeness.

Comment with respect to navigation and preflight preparation noted that at least one aircraft had been lost because the pilot entered a box canyon which was too short for him to pull up and too narrow for him to turn. Only prior knowledge of the characteristics of the canyon and the ability to recognize it and avoid entering it could have prevented this consequence.

In the Arizona environment, one pilot was concerned that he had not detected rising ground below him until his effective ground clearance had been cut in half. The cue that alerted him was the relative size and height in the field of view of near and far cacti seen out the side canopy.

Similarly, in two instances, pilots reported that they were cued that a maneuver was not progressing as anticipated by the sight, out the side canopy, of terrain features that they felt should have been out of view beneath the aircraft.

All pilots identified low-level flight over desert, dry lake bed, salt flat, and open water (particularly in the absence of waves) as most difficult. One pilot commented that while flying over a salt flat presumably at sufficient altitude, he became aware of what appeared to be a fence post in his flight path. Upon verification that it was indeed a fence post, he pulled up and went on instruments counting himself lucky not to have flown into the ground. Pilot comment uniformly indicated that the presence of vertical features provided knowledge of height above the ground.

Discussion. Low level flight can be viewed as the effort to fly in the vicinity of the ground or water, when the terrain is uniform with no particular protrusions upward into the airspace, or to fly among terrain features when ground features are present and extend upward to or above the height to which low-level flight is proposed. The discussion that follows will assume that the terrains noted represent the limits of a continuum of terrains which vary in the availability of recognizable features. Terrain at the limit most favorable for visual, low-level flight, possibly Central European, presents many cues to depth/distance including the horizon, whereas terrain at the unfavorable limit is devoid of discernible objects and the horizon may be obscured. The Arctic whiteout (Stefansson, 1944) is an extreme example of the latter and requires instrument flight. Flight over a salt flat or water presents many of the same problems as the whiteout.

The flight characteristics of the aircraft differentially interact with the terrains of the continuum in that the distribution and size of terrain features and the speed of the aircraft determine the flight profile that can be achieved within a particular terrain. Pilots flying high performance aircraft will need more air space to accommodate their reaction time. Accordingly, the requirement for visual cues to support depth/distance judgements varies with aircraft performance as a consequence of the potential for low-level flight.

Terrain features which blend together or are subject to confusion, one for another, when viewed from different points of regard, do not provide the necessary depth/distance information for low level flight. However, in a natural environment, a few trees, a stream, and rolling hills can be unique in their distribution such that low level flight is readily achieved. Conversely, wooded, rolling country, even with individual trees in evidence, can require flight above the terrain features when the number and amorphous detail of the trees reduce the aggregate to a surface of tree tops with an occasional clearing. In such a terrain, a transition may occur as a function of light and shade in that shadow can delineate and differentiate, as well as obliterate, the individual terrain features and their perceived spatial relations. When the shadow of an object is clear and sharp, it can enhance the identity of the object and its relation to the ground plane. On the other hand, when the shadow obscures vision of the ground surface between objects, it can cause a false impression of their spacing. This is consistent with the pilot comment that low-level flight in particular terrains was easier at some times of day than at others.

The condition noted as worst (which really has little relation to the terrain) was flight into the sun. The further comment that moderate overcast provides good flying conditions suggests that there must be sufficient light to provide natural contrast, but not so much that shadows obscure the ground position of objects or so little that objects cannot be seen clearly.

Height/distance metrics. Fundamental to visually controlled flight at low level is the pilots' ability to establish their position relative to ground detail both in elevation and distance. Geometrically, given a specific angle of view, height and distance are covariant i.e., determination of one specifies the other. Perceptually, height and distance may be related as with geometry, or each may be independently determined. The geometry of Figure 6 implies that the pilots should be aware of their height above the ground from the detail subtended by the given depression angle. The necessary ingredient is recognizable ground detail. In this minimal form, height would be indefinite in a single view of unfamiliar terrain, and only relative in multiple views. In the presence of familiar objects adequate to a ground metric, a 45-degree depression angle might give a direct measure of height; the ground distance from below the aircraft to the line of sight would be equal to the height of the aircraft.

The manner of determining height and the geometry shown in Figure 6 is suggestive of a perceptual hypothesis which has attracted much research attention - the Size-Distance Invariance Hypothesis (Hochberg, 1971; Epstein, Park, & Casey, 1961; Kilpatrick & Ittelson, 1953). This is portrayed in Figure 7. The portent of this hypothesis is that knowledge of the one dimension (e.g., height or distance) carries knowledge of the other. The implication is that the operation of bringing a depression angle coincident with a measured extent from ground zero is redundant. If the Size-Distance Invariance Hypothesis is true, height should be intuitive as a function of perceived ground distance or vice-versa.

Basic research is equivocal and recent research efforts have been interpreted as denying the hypothesis. The suggestion of Epstein et al. (1961) is that the perceptions of height and distance are individually determined. They comment that, though height and distance are physically related and though an impression of either or both can usually be obtained in most situations, their perceived magnitudes are not necessarily related. For the current discussion, given the pressures of the flight task, particularly at low-level, it is suggested that pilots obtain their information from visual materials as close in visual direction as possible to their task and in the most directly usable form. It is suggested that they use a ground metric to establish distances, and vertical extents either directly or in conjunction with other elements of the terrain to establish their altitude.

In this context, Figure 8 presents the situation for level flight over terrain which provides a number of vertical terrain features. If flight were possible below the tops of these potential obstacles, eye level would give direct information as to the elevation of the aircraft from the perceived height of the terrain features. However, if the spacing of ground features was such that flight must be above the

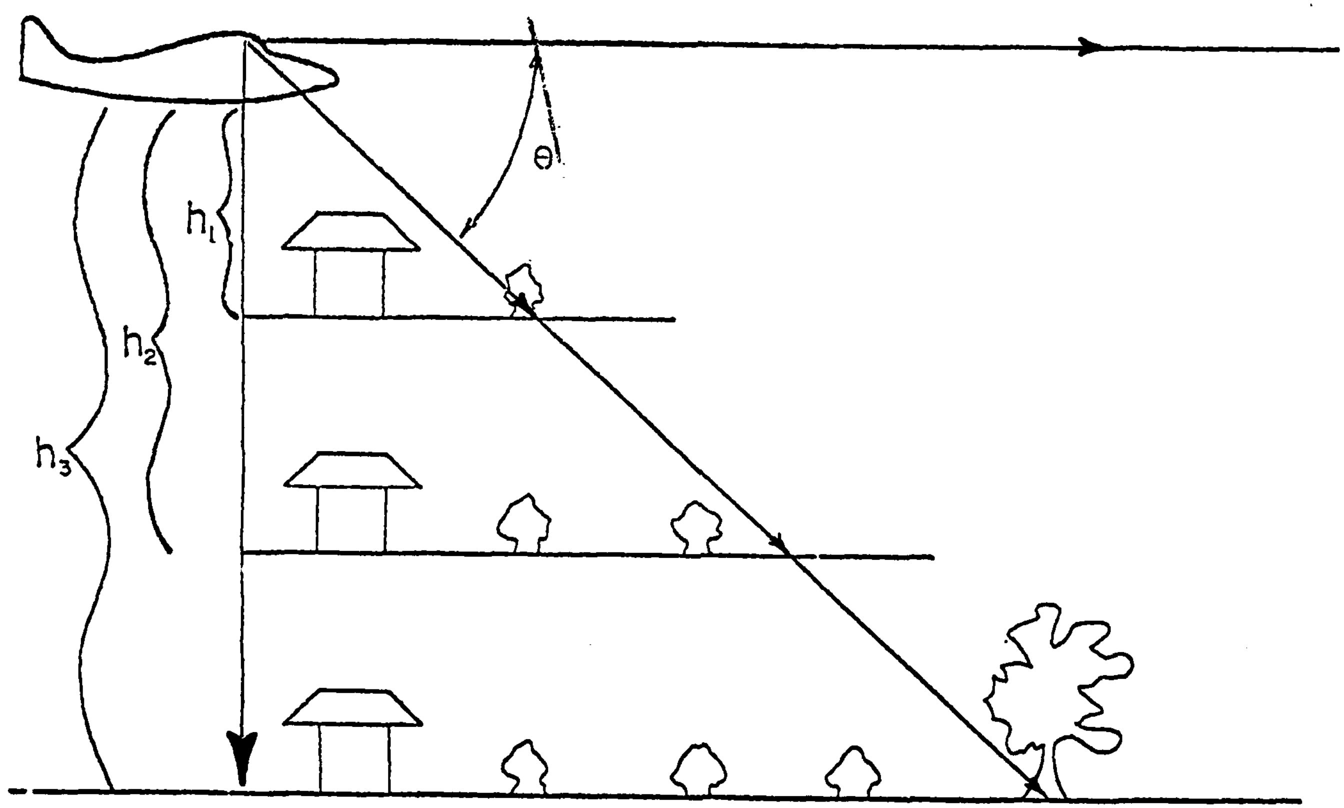



Figure 6. Geometric relation of depression angle and ground intercept as a function of height.

## Size - Distance Invariance Hypothesis

$$\theta = f_h \cdot \frac{1}{d}, \quad \theta_1 > \theta_2, \quad d_1 > d_2$$

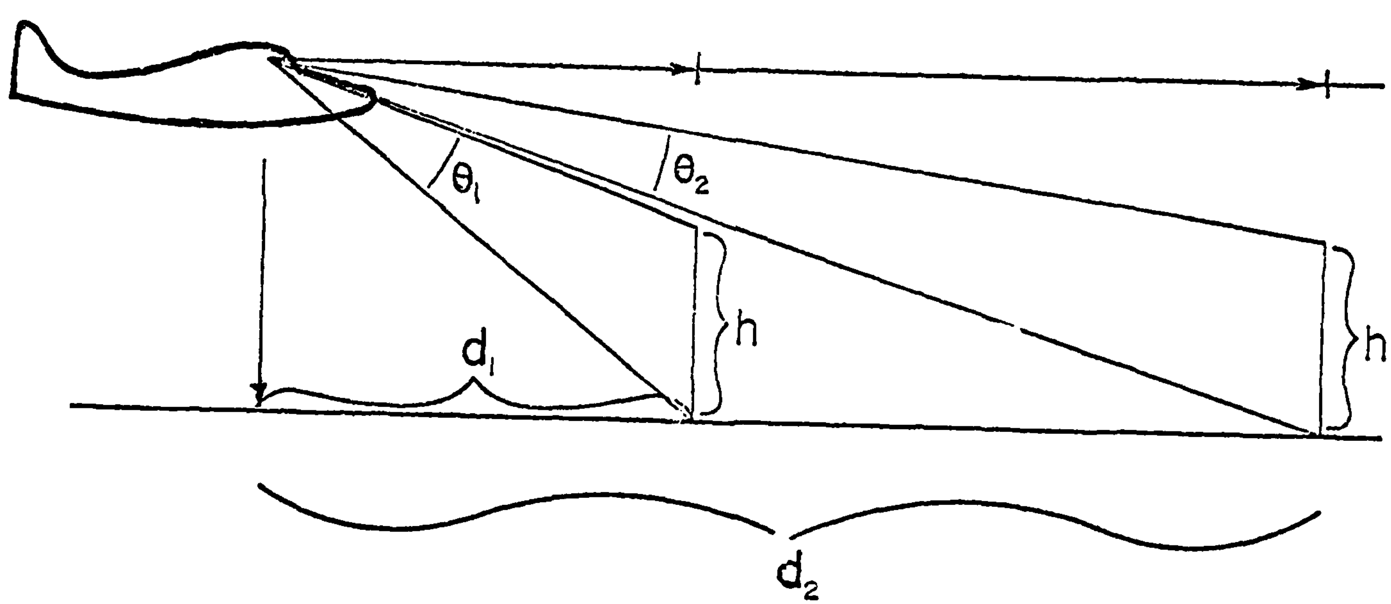
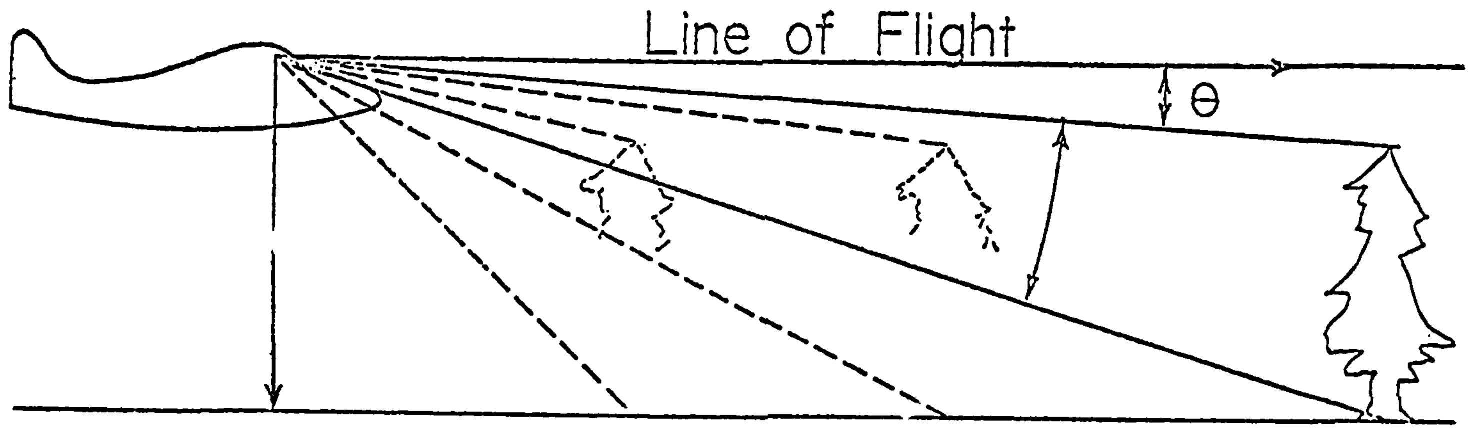



Figure 7. Geometry of the size-distance invariance hypothesis.




∴ Flight path clearance θ is judged against height of familiar vertical. The ratio $\theta/\alpha$ is monitored. —a ground metric is not necessary.

Figure 8. Height sensed as clearance of potential obstacle.

potential obstacles, the angles indicated in Figure 8 might still provide a cue to elevation of the flightpath. The angles $\theta$ and $\alpha$, as indicated, are the angle of depression to the top of object A and the angle of subtense of object A, respectively. Values of the depression angle $\theta$ and the subtense ratio $\theta/\alpha$ are plotted in Figure 9. (See Appendix B for tabular values of the plotted points.) The fact that the subtense ratio $\theta/\alpha$ remains relatively constant while $\theta$ changes continually is suggestive of its potential utility for visual control of level flight.

The graphed lines of Figure 9 for the depression angle $\theta$ show the angle to increase as the aircraft approaches. This indicates that point A will pass beneath the aircraft, i.e., the aircraft is not on a collision course with this potential obstacle. However, the angle of depression does not indicate by how much the obstacle will be cleared or at what elevation the aircraft is operating. It is hypothesized that tne perceived height of the terrain feature provides a metric to the ratio $\theta/\alpha$, by which pilots can judge their clearance of the obstacle and their height above the ground. Ideally, if the object were of known height, pilots could know their height in linear dimension (see Sedgwick, 1973 for an independent formulation of this relation).

Returning to Figure 6, the situation presented is favorable to a ground metric. The ground surface is populated by a distribution of recognizable, familiar objects extending from directly beneath the observer into the distance. This is the definition of a favorable terrain for low-level flight. With adequate spacing of the terrain features and appropriate height of observation, the ground distances between objects will be visible and by comparison with the vertical height of the objects present will be seen as quantized extents. The resultant metric should be subject to manipulation of height of the point of regard (Gibson, 1950). At low angles, the metric would be sensitive to the perceived height of the verticals present. At high angles, the metric would be a function of known ground demarcations.

Movement parallax as a cue to relative depth/distance would serve to unify the perceived metric in that, the rate and extent of displacement of near and far objects with movement of the point of observation is directly a function of the distance between them. Thus, the inappropriate localization of an object consequent to ground slope, interposition, etc. would be evident from its rate and extent of parallactic motion, and would result in a perceptual adjustment of seen position.

Moment-to-moment localization of an aircraft in relation to its terrain environment would seem to be a complex predictive process. With a favorable terrain, such prediction would be based on the ability to recognize specific objects on the ground and to appreciate the spatial relations between them. For example, a walking individual localizes himself by the flow of objects past and beneath his person.

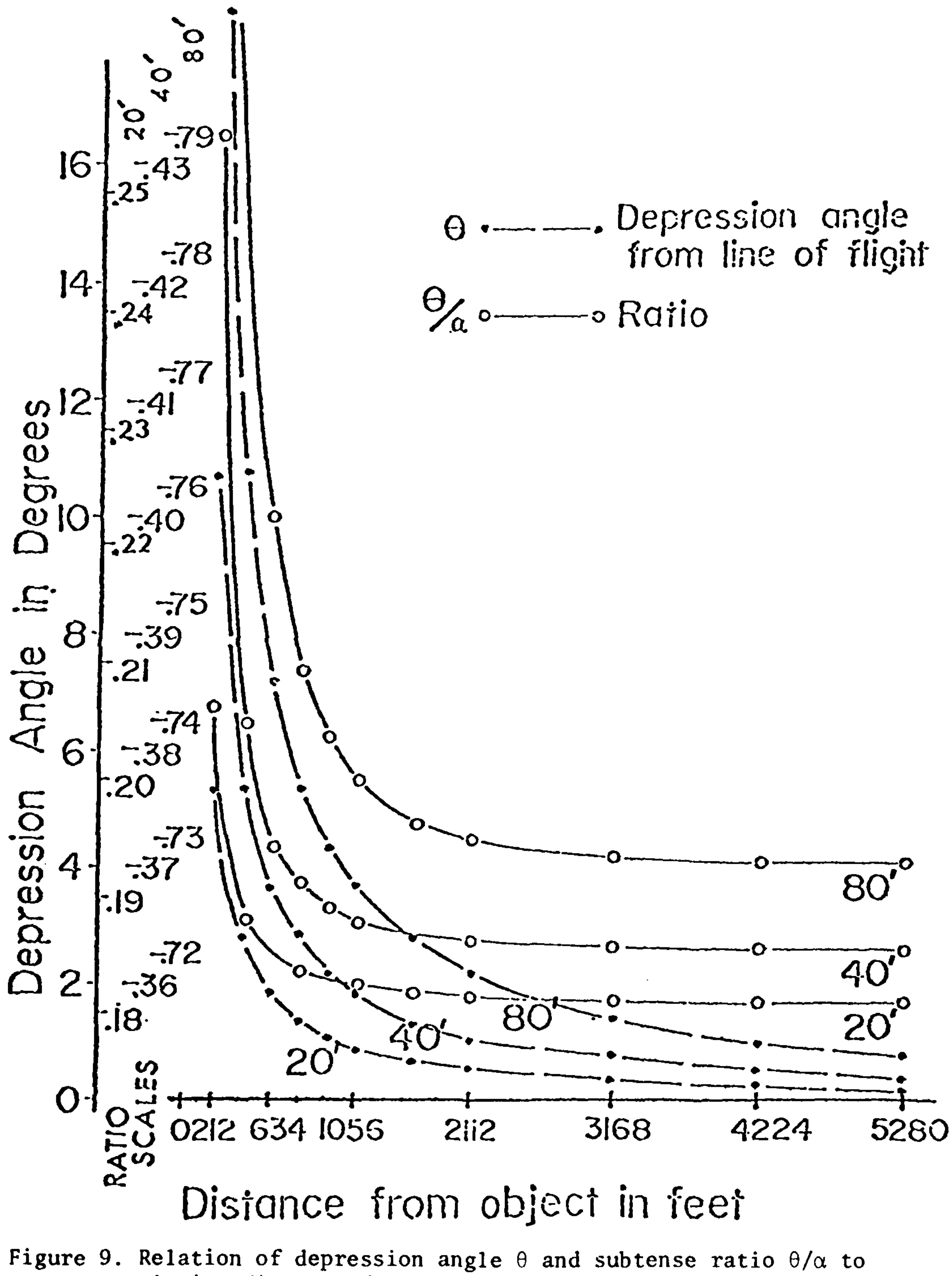



Figure 9. Relation of depression angle θ and subtense ratio θ/α to viewing distance for three flightpath elevations.

The flow is predictable and accounts for the individual's speed and proposed path of movement. In our everyday environment we make these complex predictions easily and with confidence. When approaching a set of stairs, the individual seldom finds the first step other than beneath his foot when and where he expects it.

Similarly, control of an aircraft's flight path requires prediction of where the aircraft will be in subsequent moments of time. Like the step, objects which were originally seen in the field of view ahead are out of sight beneath the aircraft at what might be a critical moment and, unlike a person walking, the pilot generally cannot look down to verify where the object is. (A-10 pilots indicated that they frequently dip a wing in a roll maneuver to check below their aircraft.) Thus the pilot is dependent upon his ability to recognize the spatial relations of objects one to another and to predict the changes in their line-of-sight relations (due to movement parallax) both as to their relative positions and as to the aspect of view of the single object. If it is to provide a pilot the information he needs, a terrain feature must retain its identity over multiple angles of view and be clearly delineated in its relation to objects about it.

The radial distances critical to the pilot's ability to maneuver among potential obstacles extend forward along the projected flight path. For the pilot, these distances project where he must be in space during subsequent moments of time to successfully complete his maneuver. These distances are measured from a point which is continually changing and out of sight beneath the aircraft. Though the visual cues which provide the depth/distance information must occur forward of the aircraft on or near the line of flight, the update of the continuously changing zero referent must be inferred from terrain features in view out the side canopy. Thus, the process of visually controlled low-level flight is a projection/verification system dependent on recognition of terrain features and the presence of a ground metric. Spatial relations among and the distance to terrain features forward of the aircraft are evaluated as a maneuver is initiated. Given the expected response of the aircraft, moment-to-moment changes in the spatial relations of these terrain features, one to another and to the aircraft, are anticipated in keeping with the maneuver and motion parallax. Progress of the maneuver is monitored by moment-to-moment verification of the anticipated spatial relations among the terrain features and their paths below and to either side of the aircraft. The process which initiates in visual depth/distance perceptions of terrain features forward of the aircraft, terminates in confirmatory recognition of the same terrain features in peripheral view in new, predicted, spatial relations as they move past the aircraft.

"New" depth/distance cues. The evident ability of pilots to fly over terrains that approach the unfavorable limit of the continuum for visually controlled, low-level flight suggests that processes other than the classic depth/distance cues may function in these situations.

Since the characteristic of these environments is that they are devoid of identifiable objects, interest has focused on movement per se, supported by texture. Figure 10 illustrates the angular relations which give rise to the expanding flow patterns (see Figure 3) which terrain features appear to follow as an aircraft passes. The ground plane dimension of the figure is given in terms of angle at the eye. In general, the flow pattern will be symmetrical in the field of view, but in the presence of drift, it will be symmetrical about the line of flight and asymmetrical out the wind screen. Discontinuities in the flow pattern of terrain features reflect their relative distance from the observer. Should the terrain offer different ground planes, such as looking over a shallow bank, objects below the bank will be seen to move at a lesser rate than the expansion and flow of the pattern evident above the bank. With rising ground, the flow pattern will diverge more rapidly than over level ground. In this instance (referring to Figure 10), the change in ground elevation beneath the aircraft lengthens the radial viewing distance and decreases $\Delta\tau$. If the ground ahead rises, the decreased elevation shortens the radial viewing distance and increases $\Delta\tau$. A mix of rising and falling ground ahead would result in an irregular and distorted flow pattern.

Harrington and Harrington (1977) have sought to identify the angle of deviation, per se, as a cue to depth/distance. The angle of deviation is a component of the flow pattern, and as such is clearly part of the relative distance cue. There is little question that the human observer in the right situation can be sensitive to this angle.

Whiteside and Samuel (1969; 1970) have responded to the movement aspect of the flow patterns with specification of the Blur Zone. Their formulation lends interest to measures of dynamic visual acuity (DVA). Given the ability of the pilot to follow the object of concern, DVA specifies the limit in the periphery of cockpit view to which verification of the effects of movement parallax can take place.

Given the possibility that the pilots are not free to divert their attention from the flightpath, there is a limit well within that set by Whiteside where objects in the pilot's view will blur. The data of Figure 11 were derived by Snyder's (1964) formulation of the problem. The graphed values are the solution of the first derivative for L (lateral ground distance from the flightpath) where the rate of change of the angle $\theta$ (the angle from the flightpath to the slant range) equalled $15° \sec^{-1}$ and $30° \sec^{-1}$. Snyder took these criteria from Graham (1951) as reasonable limits for the perception of an object in motion with the eyes fixed. The resultant plots, in mirror image to illustrate the full field of view forward of the aircraft, are adjusted in scale for height of the flightpath to permit overlay of the obstructions to clear view present in the A-10 cockpit. These curves identify the ground distance from beneath the aircraft at which objects are no longer clearly discernible when the eyes do not follow the terrain

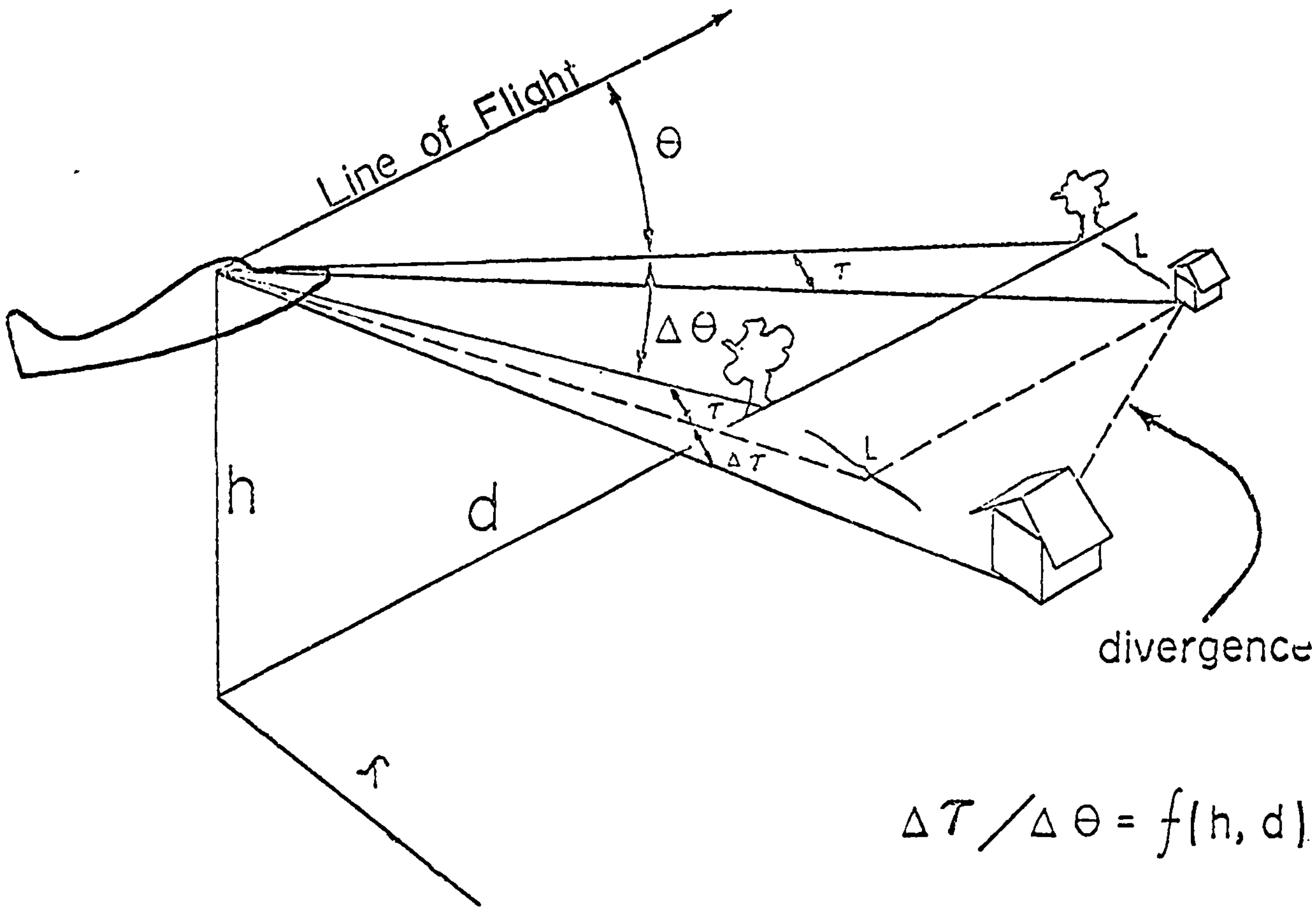



Figure 10. Geometry of the expansion patterns identified by J. J. Gibson.

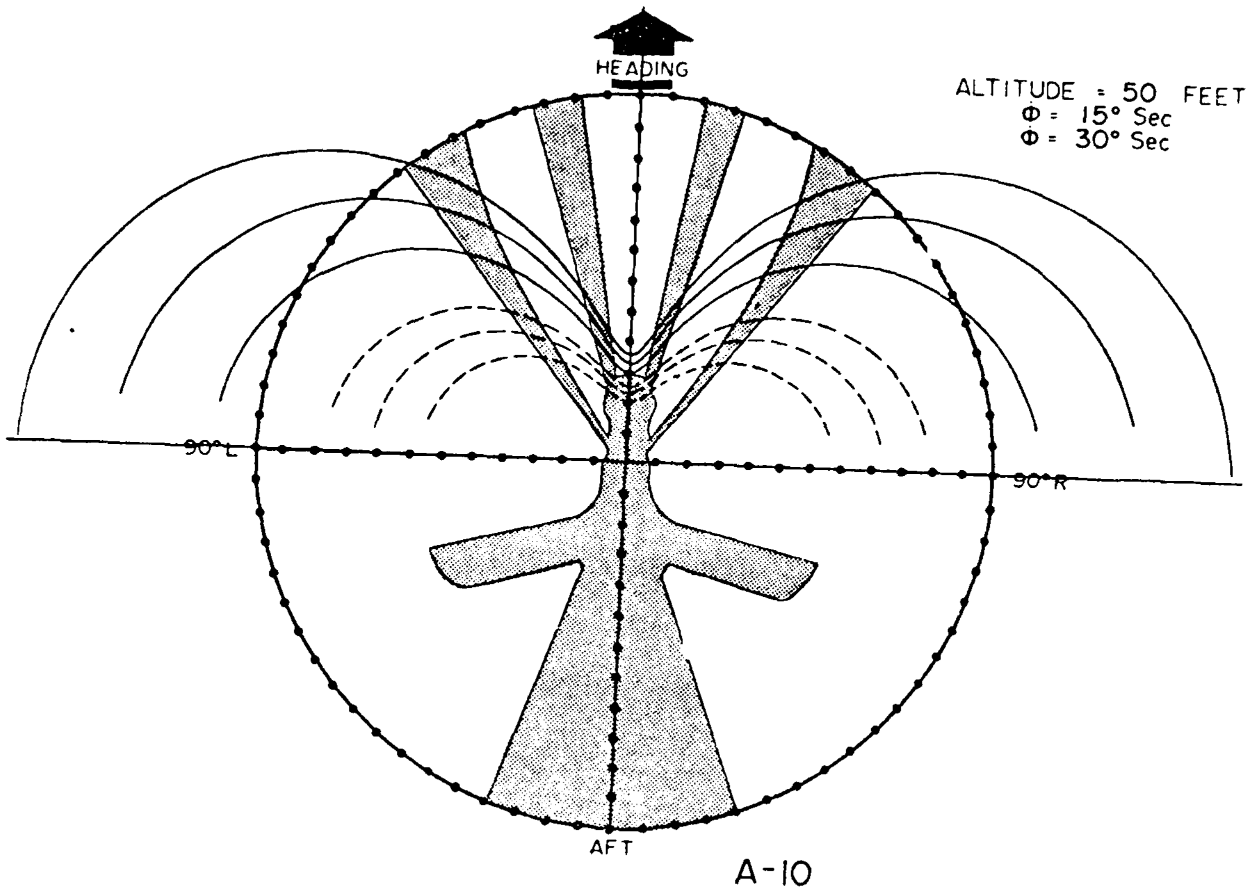


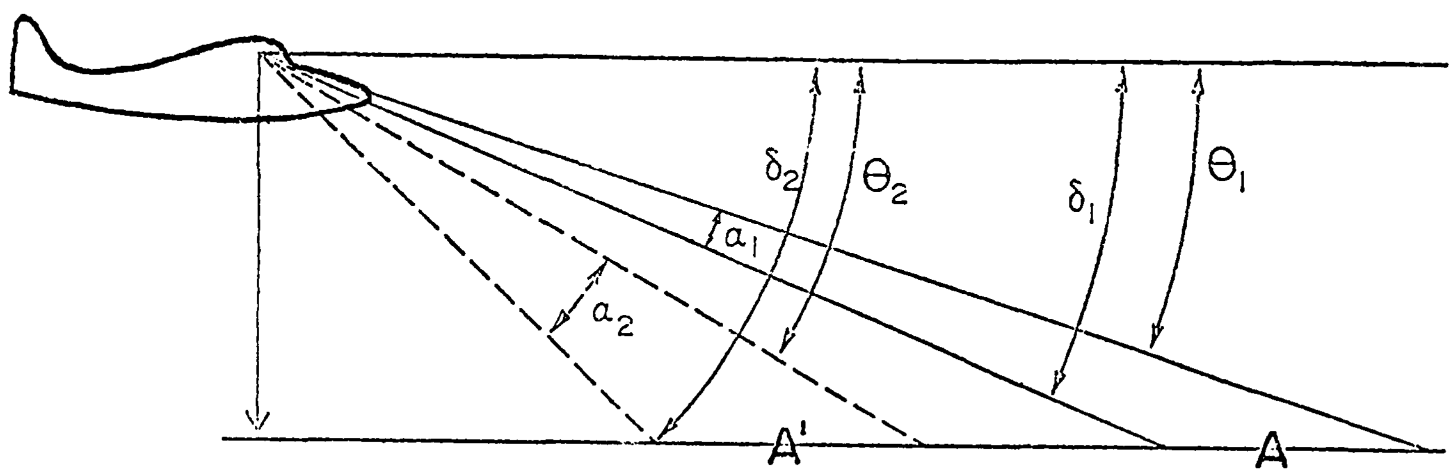

Figure 11. Blur zone envelopes for ground texture from the A-10 cockpit at 50 feet AGL at 450, 550, and 650 knots. Each dot on the vertical and horizontal axes represents 75 feet; each dot on the circumference represents 5°. See text for complete description.

feature. The suggestion is that awareness of the symmetry in peripheral cockpit view of this blur zone as it intrudes forward, read against the canopy, gives information of height and orientation in flight. Curves for other flight conditions as well as ground visibility plots for the A-10, F-4, and F-111 are provided in Appendix C. When compared with the ground visibility plots, these curves reveal that at the lowest elevations and highest speeds, this blur zone intrudes sufficiently forward in the canopy view to be seen (see Figure 11). Few pilots were consciously aware of using the blur pattern prior to our discussion of its presence.

In the absence of texture, unitary contours may be present in an otherwise undifferentiated field of view. Figure 12 presents the angular relations of the lines of sight to a discoloration on a broad expanse of undifferentiated surface (an oil slick on smooth water or a moist area in a dry lake bed). The direction of change of these angles with approach of an aircraft, the angle of depression ($\theta$) to the farther edge of the discoloration, the angle of depression ($\beta$) to the near edge, and the angle of subtense ($\alpha$) of the discoloration is the same. All grow smaller to some limit and then increase as the aircraft approaches and passes overhead. The ratio of the angle of depression, $\theta$, to the angle of subtense, $\alpha$, (the subtense ratio formulated earlier with favorable terrains) grows smaller as the aircraft approaches. To utilize the change in these angles or the subtense ratio to control flightpath elevation on a flyover course would require that the pilot be aware of a multiplicity of specific geometric functions.

The same angles for an object which extends upward from the surface behave somewhat differently. Figure 13 presents the same sequence of angles for such an object (a butte in the desert, a boat on the water, or a cliff face) from a comparable initial distance. The height of the three-dimensional object was chosen such that its initial depression and subtense angles were the same as those for the discoloration. At the initial distance, one could presumably be mistaken for the other. As the object is approached, the top or backside becomes visible and the angle $\beta$ subtracts from the subtense angle $\alpha$. This results in the subtense ratio, $\theta/\alpha$, becoming larger with reduced distance rather than smaller as with the two-dimensional object. Most significantly, the ratio would appear almost constant over a considerable range of distances. Thus, the relative change in these line-of-sight angles is capable of both differentiating between a discoloration and an object that extends upward from an otherwise undifferentiated surface and, as noted earlier, presumably could provide information to the pilot necessary to level flight. The change in depression angle $\theta$, subtense angle $\alpha$, and their ratio $\theta/\alpha$ for the two conditions are summarized as graphed lines in Figure 14. (See Appendix B for tabular values of the plotted points). The data are graphed as though the aircraft were approaching from the right.

The subtense ratio is not the only angular relation present and may

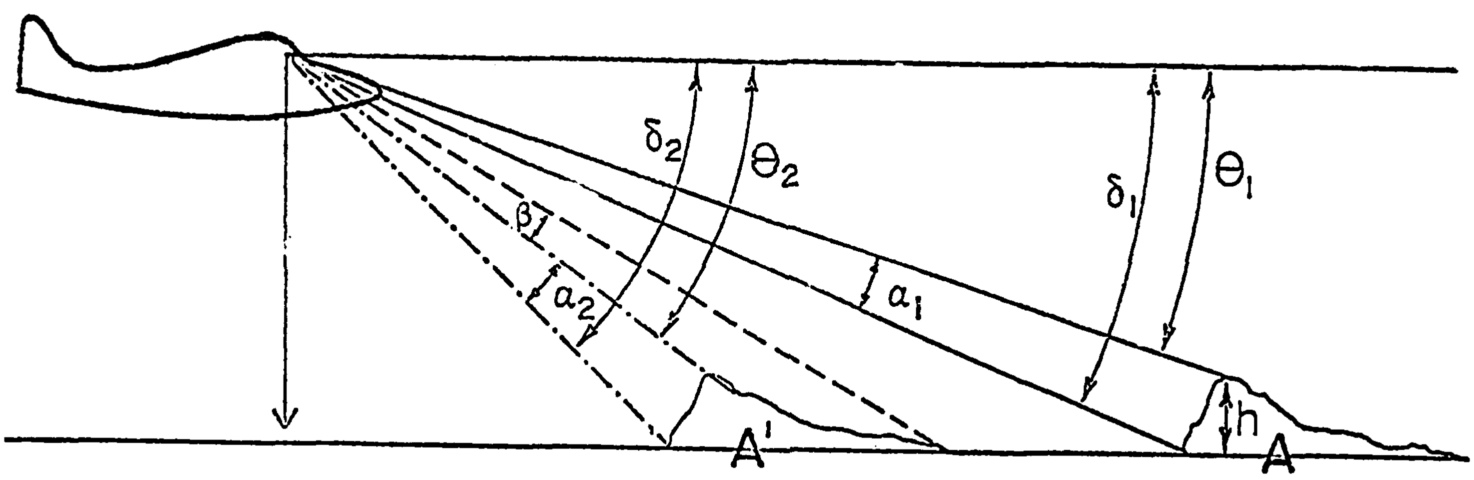



$$\theta_2 > \theta_1, \quad \delta_2 > \delta_1; \quad \alpha_2 = \delta_2 - \theta_2 > \alpha_1 = \delta_1 - \theta_1$$

$$\theta_2 / \alpha_2 < \theta_1 / \alpha_1 \, ^*$$

* See plotted points of Figure 9 & 14

Figure 12. Depression angles to a discoloration on an otherwise undifferentiated surface.




$$\theta_2 > \theta_1 \;,\quad \delta_2 > \delta_1 \;;\; a_2 = \delta_2 - \theta_2 > a = \delta_1 - \theta_2$$

$$\theta_2 / a_2 \quad > \quad \theta_1 / a_1 \;^{*}$$

* See plotted points of Figure 9 & 14

Figure 13. Depression angles to a three dimensional object on an undifferentiated surface.

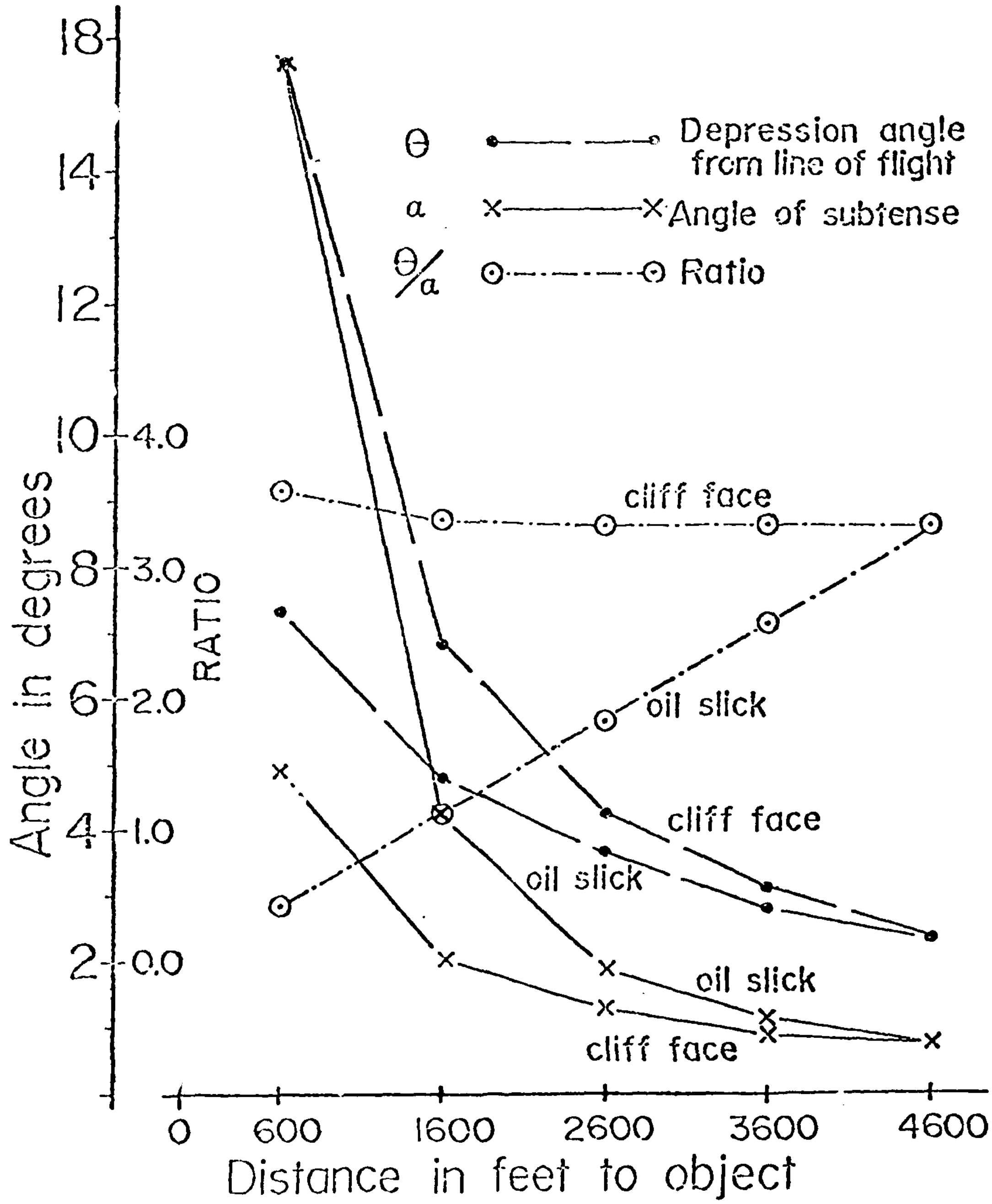



Figure 14. Subtense ratio, and depression and subtense angles for a two and a three dimensional object with overflight at 250 feet.

not be the most significant. The flightpath chosen passed directly over the object or discoloration. A path which passed to either side would reduce the approach aspects of the angular changes of the lines of sight and substitute an azimuth change. In the limit, with the flightpath strongly displaced from the object or discoloration, the approach might never be sufficient for the top of the three-dimensional object to be seen. In this case both the object and the discoloration, if visible, would make an angle of depression from the horizon and would hold that depression angle as the aircraft moved past.

Summary. The need for unique terrain features so the pilots can keep track of their position with a minimum of attention pervades low-level flight. Whiteside comments on this in the AGARD review "Problems of vision in low level flight" (Perdriel & Whiteside, 1967) and presents the blur zone as the limit for recognition of objects moving past the aircraft. Navigation requires the ability to recognize check points from multiple points of regard. A level turn requires the ability to hold in view, or return to a unique terrain feature on the horizon. Formation flight at low-level requires a pilot to mark by a unique terrain feature where the wing man will be at some future time so that when looking back after searching the opposite view, the pilot will be able to see the wing man against the terrain background

It was suggested that height and distance are sensed by the pilot, as needed, and that these perceptions are not necessarily related. The potential for a height metric in the form of the subtense ratio $\theta/\alpha$ was presented in two contexts. Sedgwick (1973) in an independent formulation of this relation suggests that the observer's own height may be the ultimate referent. It was suggested that the ground metric depends on the presence of objects spaced such that the intervening surface can be appreciated. Movement parallax functions to unify the resultant metric in that mis-located terrain features are revealed by inappropriate rates and extents of displacement with movement of the point of observation.

When terrain features can be confused, distances become indefinite and the terrain provides only a texture with patterns of flow and blur. To the degree that the patterns have an integral referent (the center of expansion in the "Gibson curves" or the central cusp of the "Snyder curves"), these patterns have potential utility, as in landing and in low-level flight. Given the continuum of possible terrains and the visual environments they provide, low-level flight is probably accomplished by unique, moment-to-moment combinations of these and the above processes.

The suggestion was present in one pilot's comments that the horizon interacts with terrain features to establish cues for visual control of low-level flight. This pilot was concerned with difficulties experienced when landing at a particular airport where the approach-to-final turn was directly into a mountain. Loss of the visual horizon, as in this instance, probably involved loss of the sense of "level" unless the horizon was replaced by the presence of verticals or other horizontals in the field of view. However, if the horizon is a part of the sense of "height," as with the subtense ratio $\theta / \alpha$, the loss of the far horizon could be replaced only by horizontals present in the near field of view and, accordingly, the change in the subtense ratio with distance would be destabilized and become uncertain as a cue to height.

## APPROACH AND LANDING

The task of landing an aircraft requires control of forward speed, descent rate, and heading. The need for correct speed in landing has been emphasized in a number of pilot interviews, in that changes in airspeed result in changes in lift, groundspeed, vertical speed, flightpath profile and subsequent point of touchdown. Only after proper speed and thrust information is incorporated into normal behavior can the pilot's attention be devoted to the analysis of the visual cues required for a correct approach and landing.

Although verbalization of the visual cues to a correct approach and landing is difficult for most pilots, a number of theoreticians and experimenters have identified various cues which may be used to judge the correctness of an approach.

Perhaps the most commonly identified cue, and certainly the most "intuitively obvious," is the changing perspective of the runway during approach, i.e., the apparent widening and lengthening of the runway trapezoid. The usefulness of this simple perspective cue is open to question, however, when one considers that runways come in a variety of lengths, ranging from under 2000 feet to more than 2 miles, and widths from approximately 50 to 200 feet. Since the possible combinations of runway lengths and widths is nearly infinite, it becomes difficult to sustain the belief that the perspective cue is a reliable cue to a proper landing. Moreover, the use of the perspective cue is further complicated by the fact that many runways are sloped either up or down.

Kraft (1969) has extensively studied simulated approaches to airfields under a variety of conditions of slope and lighting. Under conditions in which the cue set was effectively reduced to the changing perspective of the airfield outline, an up-sloped airfield consistently caused pilots to fly lower flightpaths. This was true even though the pilots were informed of the degree of slope.

An examination of the geometry of the landing situation indicates the types of confusions which arise from the utilization of the perspective cue in landing. The visual projection of a field measuring 100 x 4000 feet, when seen from an altitude of 100 feet at a position 1500 feet from the runway threshold, is identical to a field of twice those dimensions, seen from an altitude of 200 feet when 3000 feet from threshold. Moreover, the same runway, e.g., 100 x 4000 feet, may take on a variety of appearances as a function of runway slope and glide slope. That is, a normal 3° approach to a field sloping downward 2°, results in an effective slope (with respect to the runway) of only 1°, with the resulting impression that the flightpath is too low. In order to establish the "proper" perspective picture, the glide slope would have to be increased to 5°, resulting in an excessively hard landing or an overshoot of the projected landing position. Similarly, a 2° upward sloping runway, combined with a 3° glide slope, would result in the perspective changes normally associated with a 3° glide slope to a level runway, resulting in an excessively low approach. Thus runway configuration has been identified as a causal factor in landing short accidents (Kraft, 1969; Pitts, 1969).

The rate of change of the horizontal and vertical dimension of the runway might provide useful information about the glide slope. If a fixed speed of approach is adopted, the rate of change of the angular and dimensional relationship of the runway will be constant. Variability in thrust, angle of attack, or linearity of the glide slope will alter the rate of change in the runway image characteristics. Whether this information can be utilized by pilots is open to empirical test.

The "streaming" of objects in the periphery of the visual field (Gibson, 1950) has been suggested as a useful cue to estimating change in altitude. As the altitude decreases, the rate at which objects in the peripheral visual field appear to move increases. Obviously, the streaming effect is not independent of ground speed. Thus, an increase in streaming may result in either the impression of increased speed or decreased altitude. If pilots believe their speed to be constant, an increase in the streaming will result in the perception of a decrease in altitude. Therefore, pilots landing into a headwind may be induced to fly below the proper glide slope because of the impression that they are too high. Conversely, an undetected increase in ground speed may cause the pilot to pull up above the proper glide slope.

It was suggested by several IPs that pilots can find their flightpath interception point (FPIP) on the runway by determining the point on the runway which is at the center of the expansion pattern, i.e., the point of no movement. Figure 15, taken from Gibson (1950) shows the velocity flow lines radiating outward from the FPIP during an approach. Gibson et al. (1955) have argued that all objects in the visual field move away from the aim point in a complex pattern of velocities. This pattern is a function of direction of locomotion and of velocity.

Llewellyn (1971) however, has reported that subjects who were asked to locate the center of expansion or point of no movement in a random dot display were unable to do so with useful accuracy. Subjects instead identified the center of expansion at the point on the display

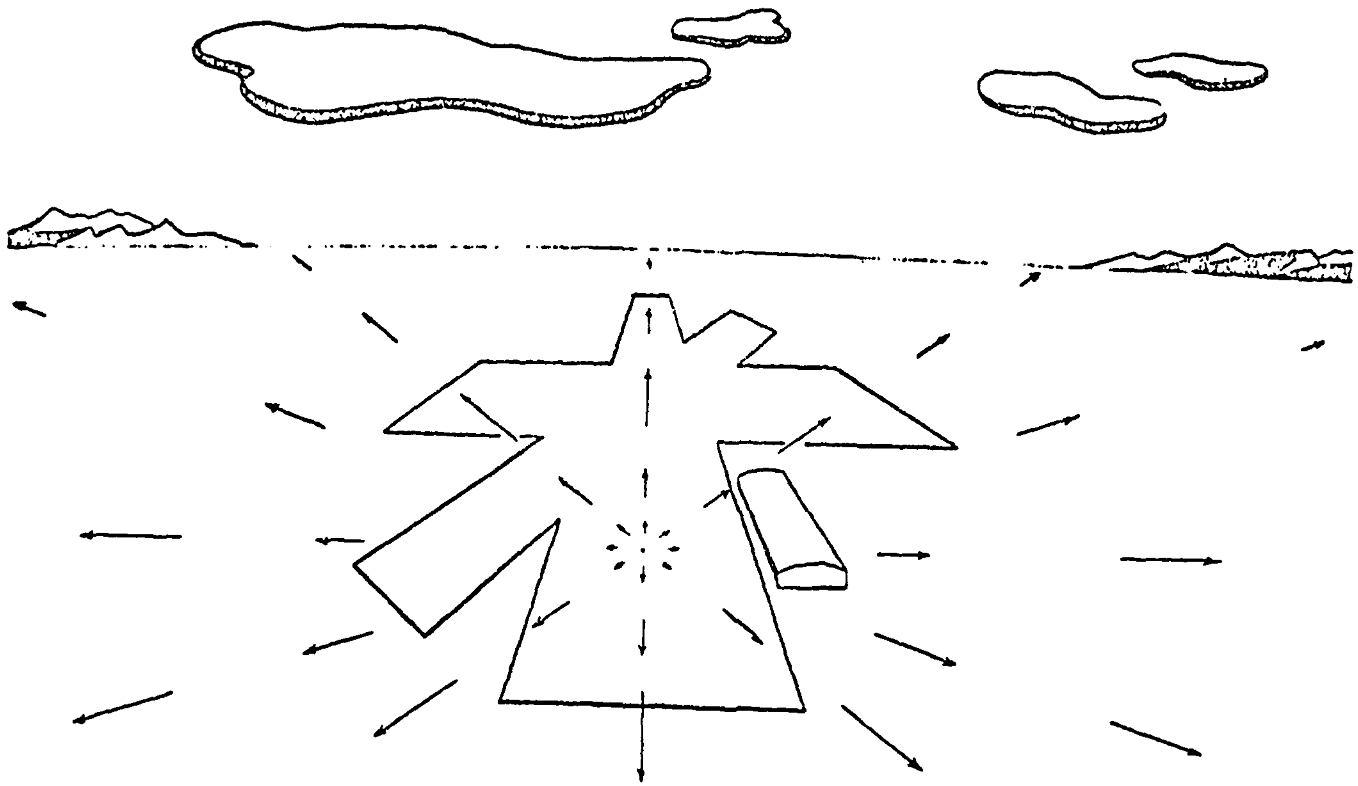


Figure 15. The expansion pattern centered on the touchdown point during an approach to langing. From THE PERCEPTION OF THE VISUAL WORLD by James J. Gibson. Copyright c 1950 by James J. Gibson. Reprinted by permission of Houghton/Mifflin Company and the author.

toward which their gaze was directed. There is, however, a crucial difference in the experiments reported by Llewellyn and the task of landing an aircraft. In the later case, the task is not to identify the point which does not move, but rather to select a point and keep it from moving, that is, eliminate its vertical and horizontal drift.

In addition, the pilot in a landing pattern has an additional aid in stabilizing the FPIP which was not available in Llewellyn's experiment. That is, the spot toward which the pilot is descending remains fixed with respect to its angular distance below the horizon. Figure 16 illustrates this fact with three successive views of a runway as it would appear on a fixed angle of descent. Figure 17 illustrates that the FPIP must remain a fixed angular distance below the horizon because the horizon is always at eye level.

It is also possible that the detection of the center of expansion in a random dot pattern is a much more difficult task than the detection of that spot in an actual or simulated landing. The task of locating the FPIP is the subject of a proposed experiment to be described in a later section of this report.

The traditional belief that binocular vision is required for the operation of an aircraft has been called into serious question. Several studies have been reported (e.g., Cibis, 1952; Roman, Perry, Carpenter, & Awni, 1967; Lewis & Krier, 1969; Lewis, Blakeley, Swaroop, Masters, & McMurty, 1973; Grosslight, Fletcher, Masterton, & Hagen, 1978) in which landing performance has been measured under binocular and monocular conditions. Several studies have suggested that monocular and binocular depth perception are about equally accurate to 20 meters when there are many perspective cues in the field of vision, and Nicholls (1950) has reported that judgement of distances nearer than 12 meters is not required for landing an aircraft.

Although Pfaffman (1948) reported that pilots attempting to land with one eye covered tend to level off too high, Lewis and Krier (1969), compared the accuracy of landing performance of monocular and binocular pilots in a jet trainer and found no significant differences. Speculating that the highly experienced pilots in the study may have affected the outcome, Lewis et al. (1973) performed essentially the same study using low-time general aviation pilots. In that study, the pilots were suddenly deprived of binocular vision by patching either eye on the downwind leg of a closed traffic pattern, thereby allowing little time for adaptation to monocular vision. Although these investigators reported that monocular landing performance was actually superior to binocular performance, Grosslight et al. (1978) suggest that these results were artifactual and that there are no differences in accuracy between monocular and binocular landings. Grosslight et al. did report that there were differences between the two groups in flightpath and impact at touchdown. In view of these differences, and in light of the requirement for monocular flight training for Air

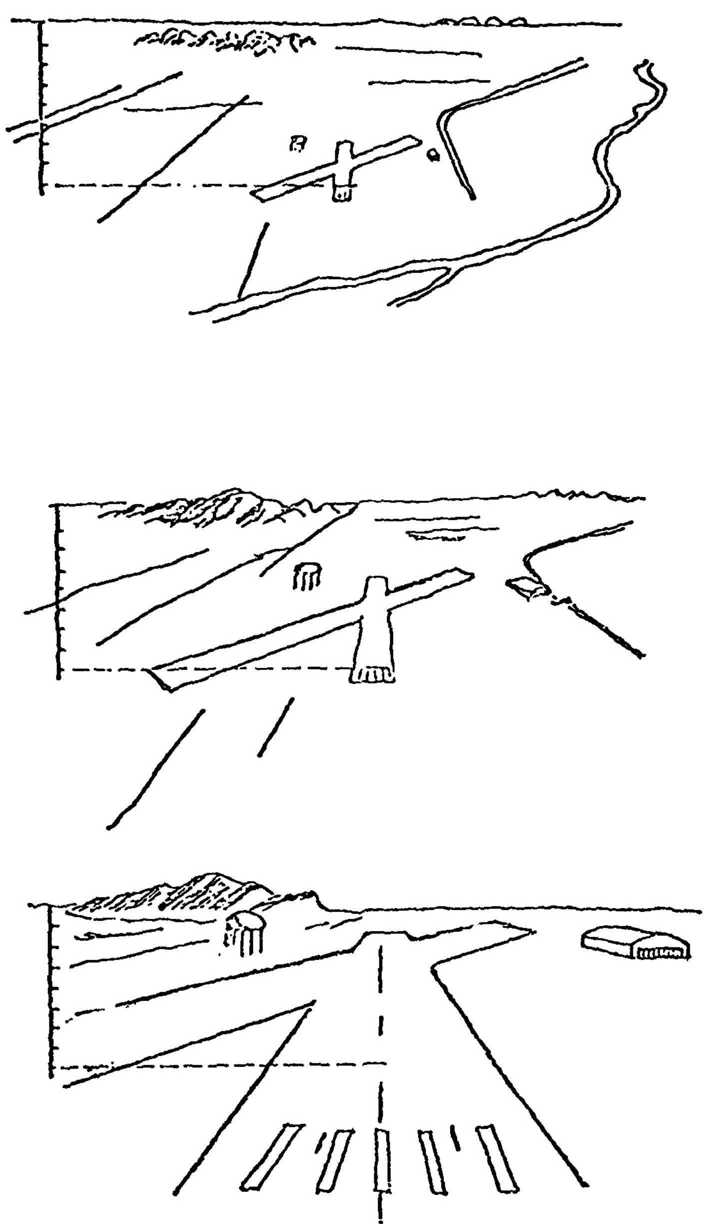


Figure 16. The touchdown point remains at a constant angle below the horizon throughout approach.

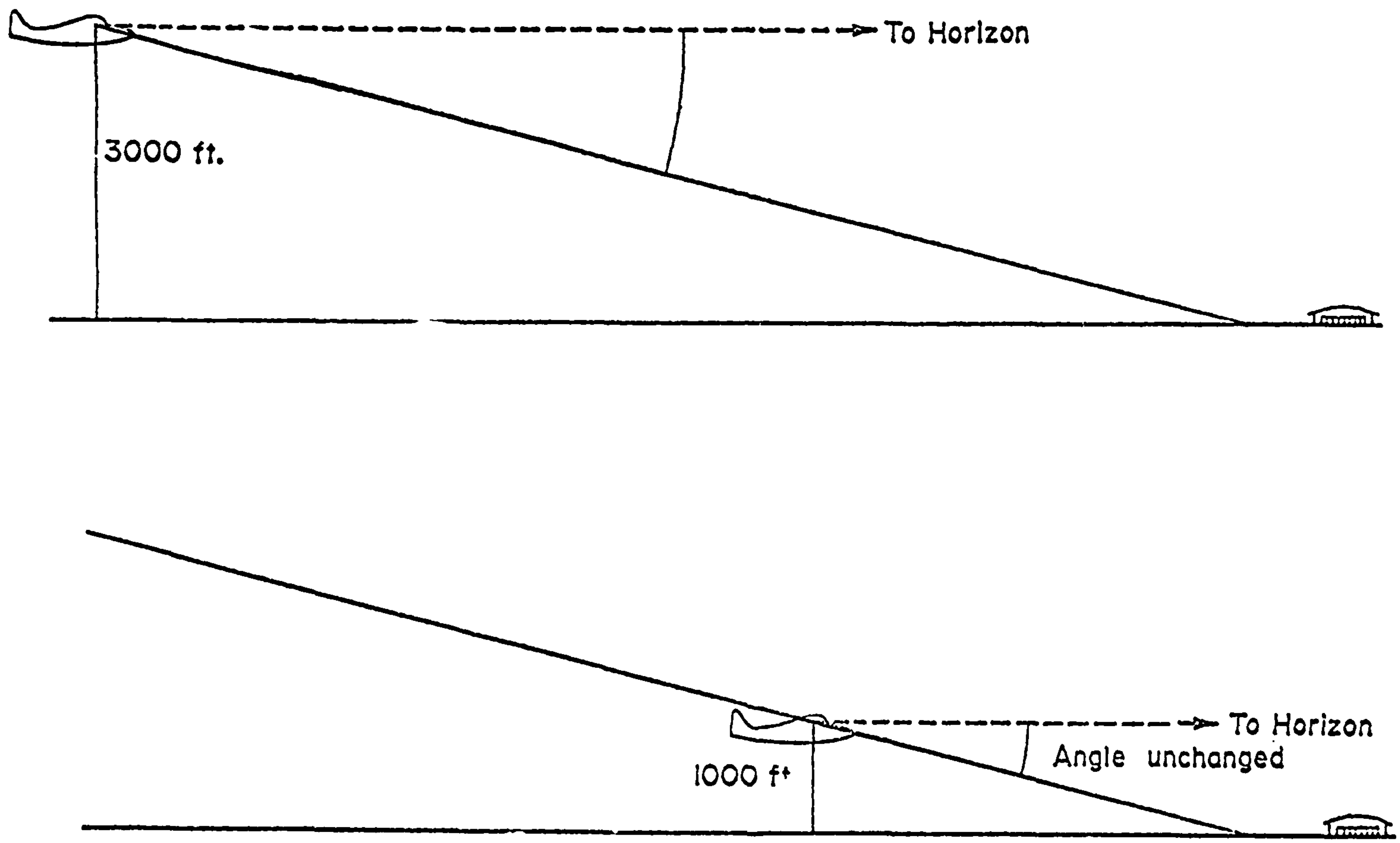



Figure 17. Geometry of the constant angle between the horizon and the touchdown point. Since the horizon is always at eye level, the angle remains constant by the principle of similar triangles.

Force pilots who may be exposed to nuclear flash, it may be worthwhile to investigate the nature of the deficit in monocular flying tasks of various kinds.

## SIMULATION SYSTEMS

An overview of the variety of types of simulators presently in use may be found in Brown (1976). We make no attempt to review the art or science of simulation here, but merely identify some of the shortcomings of the limited number of simulators which we examined.

All visual simulation systems have in common a visual display whose dimensions, point of regard, and perspective change appropriately with each maneuver of the aircraft. The displays are generated on the face of a large CRT with the visual angle increased through the use of an optical system which effectively places the display at infinity (Ganzler, 1971). Generally, simulators share the disadvantages that the perspective of the external environment is optimum from only a single location within the cockpit.

The complexity and fidelity of the information provided by a simulation system vary with the task which is simulated. For example, simulation of air-to-air combat, such as that presented by the Simulator for Air-to-Air Combat (SAAC) at Luke AFB, requires that the target aircraft be rather faithfully portrayed with respect to changes in apparent size, position, and perspective which result from maneuvers of either of the two combatants. This simulator, however, has less stringent requirements for terrain features. On the other hand, primary training simulators must incorporate terrain features which will provide cues necessary to basic flight tasks such as approach and landing.

Since future advances in simulation systems appear likely to come in CIG, rather than Camera/Modelboard, systems, the comments in this section will be restricted to CIG system. Although the displays on CIG system have a cartoon-like appearance, this is not judged to be a serious deficiency inasmuch as the visual elements which are necessary for the perception of movement through space are capable of being presented. Although the ASPT system at Williams AFB provides only a monochrome display, full color CIG systems are in operation at various locations in the aircraft industry and in the Air Force. Including color greatly enhances the realism, and according to many of the pilots who were interviewed, it increases pilot acceptance of the simulation.

The increase of pilot acceptance is not the sole benefit of the color CIG system. Throughout this report we have stressed the importance of object identity in providing confirming information in the periphery. The CIG systems which we examined provided no differences except size among the stylized trees presented in the visual display. Because of the lack of cues which would provide identification of a <u>particular</u> tree (or a particular hill, building, etc.), the necessary confirming information is not available from peripheral vision.

The addition of color provides a cue for discriminability which allows this confirmationto take place. In addition, color potentially adds another dimension of discriminability which allows the addition of elements in the display without an increase in the number of edges.

A problem which appeared in two of the CIG systems which we examined is referred to as a "priority problem" by the system operators. That is, since the CIG system depicts objects in outline form (by defining their edges), the objects appear to be transparent when motion parallax requires that one object appear to pass behind another. This is apparently not a serious problem as it was not noted by any of the pilots until their attention was called to it.

Several pilots reported that the lack of peripheral cues in some of the (Camera/Modelboard) simulators with which they were familiar made landing "impossible." However, as noted earlier, Lewis and Krier (1969) and Lewis et al. (1973) have reported that pilots are able to land successfully with one eye occluded, and Roman et al. (1967) have shown that landings are possible with severely restricted fields of view.

Rosinski (1979) has reported that in graphic displays of space, perceived orientation does not correspond to physical orientation. Magnification or minification results when a graphic display is viewed from other than the geometrically correct viewing point and results in a distortion of the visual space. With magnification, perceived orientation of slanted planes is shifted towards the frontal. Rosinski suggests that this is the result of a conflict between the cues provided by the texture gradient of the virtual surface and the binocular and accommodative cues provided by the display plane itself. It is possible that this distortion of visual space is responsible for the well-established discrepancy in such variables as descent rate between simulation and actual flight.

On the other hand, the reported distortion may be due to the use of a Euclidian metric to describe visual space. Luneberg (1947, 1950) has suggested that a hyperbolic space such as that described by Lobachevski (1826) and, independently by Bolyai (1832), more properly describes binocular visual space. Foley (1968) has also reported data which are consistent with the hypothesis that the intrinsic geometry of visual space is non-Euclidian. The incorporation of a hyperbolic metric might eliminate distortions of space such as those reported by Rosinski (1979). It is also possible that the use of the Euclidian metric might be res sible for the report (by some of the pilots interviewed) that p pheral streaming was not "realistic" in the simulators they had flown.

The most serious limitation in CIG systems is that imposed by the number of edges which can be displayed. The operation of an aircraft at low levels and in landing requires a firmly established ground surface. The limited number of edges available for display requires that ground texture cues be limited. The ASPT simulation deals with this problem by displaying a limited ground plane of about 1 mile in the direction of flight. The introduction of a mountain at that distance eliminates the need for an extended ground plane by occluding the surface of the earth beyond the mountain. In addition to the fact that one appears to be continually flying over the same mountain, this solution is not workable at high altitude.

The number of edges required for the establishment of a ground metric has not been determined. It was suggested by one of the pilots interviewed that a minimum of 2500 edges per mile of simulated space is required; a figure which far exceeds the capacity of any existing system. A potential solution to the problem is the texture generator, which is a hard-wired adjunct to the computer which controls the visual display. The texture generator provides ground plane textures independent of other textures in the visual environment. A similar development, the circle generator, will lend more realism to the visual scene and eliminate many of the confusions among computer-generated figures.

## SUGGESTED RESEARCH

Simulation of the visual world in flight simulators is generally quite effective. In the simulators which we examined, the classical cues to depth are represented extremely well. The only cue which appears to be wholly lacking is that provided by stereopsis. In the following section we suggest five experiments which examine the locus of attention during flight, the presence of symmetrical stereopsis in aerial refueling, and basic questions on the establishment of height and distance metrics and the localization of direction of locomotion. We conclude with additional suggestions for potentially fruitful areas of research which are relevant to some of the problems which were identified in our analysis of flight simulation systems.

### POINT OF REGARD ASSESSMENT

Since the conclusions reached in this report were formed on the basis of subjective responses of pilots to questions posed by the authors (see Appendix A for Interview Guide), any assessment of the relative importance of information presented in various parts of the visual field is subject to uncontrolled bias. That is, it may be the case that during the course of a maneuver, pilots believe they attend to a particular location in the visual scene (e.g., the landing spot) in order to gain the maximum information when, in fact, they are scanning or attending to a different locus. Inasmuch as the analysis of depth cues required for a given task was based primarily on information about where the pilot's gaze was directed during various flight maneuvers, an objective measure of point of regard should be provided.

Subjects. Air Force instructor pilots (IPs), familiar with the T-37 trainer and the ASPT system, will be employed in these studies.

Apparatus. An SRI Eye-Tracker (developed by Stanford Research Institute), or similar device, will be incorporated into the ASPT.

Procedure. Each of the IPs will fly a series of simulated approaches and landings (touch-and-go) from a fixed altitude and distance from the anticipated touchdown point, and a series of sorties through a prescribed low-level flight course in the simulator. (Similar studies of aerial refueling and/or formation flying require the use of simulation systems equipped for those tasks).

During each maneuver, the Eye-Tracker will provide a continuous record of direction of gaze. Dependent variables will include the percentage of time spent looking at gauges versus looking outside the cockpit, as well as identification of specific gauges and extra-cockpit terrain features towards which gaze is directed.

Implications. The data collected in this study will provide a basis for objective assessment of the importance of specific features of the terrain and the cockpit in the successful accomplishment of each flight task. In this context, "importance" is assumed to be a direct function of time spent in looking at any given feature.

In addition, the study will provide a firmer basis for conclusions about the efficacy with which depth cues are presented in visual simulation systems. Finally, these data, collected from experienced pilots, may provide a set of baseline measures against which student pilots can be assessed. That is, it is likely that there are differences in the "looking behavior" of IPs and student pilots. Diminution of these differences might prove to be a useful objective measure of student progress.

STEREOVISION IN AERIAL REFUELING

In the text of the report, it has been suggested that (1) the pilots can control the mix of stereoscopic and parallax cues present as they close to couple with the tanker boom, and (2) they may use parallax cues in preference to stereoscopic cues. Resolution of the second assertion by use of the first could provide information meaningful to the potential utility of 3-D simulation for aerial refueling. The mechanism by which the pilots might control the mix of stereoscopic and parallax cues, assertion 1, would be the natural response of stepping out of line with an approaching object. If such behavior is present, it would be evident in the path of the boom as it passes over the pilot's head to engage the fuel receptacle behind the cockpit.

Consistent displacement relative to the boom, of the pilot in the cockpit or of the aircraft, would be interpreted as increasing the availability of parallax cues. The object of the proposed research would be to determine the possible presence of a displacement, left or right, of the pilot of the pursuit craft (an F-4) relative to the boom on approach to couple.

Subjects. Data from as many as 12 pilots would be desirable, but meaningful information could be gained from as few as one to three although this lesser number would not provide a basis for generalization.

Procedure. The proposed research would measure the relative position of the pilot and boom from in-flight film sequences taken by movie camera as the aircraft is moved forward to couple. A rigidly mounted camera faced forward from the rear cockpit would be focused to record the back of the pilot's helmet and to pick up detail of the tanker to serve as referent for reading displacement of the aircraft as a whole as well as the trailing angle of the boom. The Weapons

Systems Officer would be responsible to trigger the "on" and "off" of the camera to record the passage of the boom overhead.

Reference for quantitative data would be the midline of the back of the pilot's helmet. Displacement of the boom, left or right, with sign notation would be read in a convenient unit from stop frame projection of the filmed sequences. A simple t-test of the mean absolute displacement (with pilots as a random variable) would test the assertion. A sign test for the presence or absence of a displacement across pilots without regard to sign would also be meaningful in that consistency of the sign and t-test would indicate the outcome to be robust.

Implication. A significant "t" could be interpreted as confirming the assertion that pilots approach the tanker off center to utilize parallax of the boom against detail of the tanker. This positive outcome would place the limitation on the optical designers of 3-D systems that, to meet the real world behavior of pilots, they would need to choose eye points to provide for asymmetrical stereopsis. A negative outcome would deny the assertion only to the degree of the precision of measurement and the evident randomness of the measured displacements both within repeated sequences for the same pilot and between sequences by different pilots.

THE SUBTENSE RATIO AND A HEIGHT METRIC

The subtense ratio has been offered in the text as a possible cue to height of flightpath. The suggestion was made that flight over a familiar object of known height could give pilots knowledge of their elevation in linear dimension. As a cue to height of the flightpath above the ground the subtense ratio would be most significant to low-level flight. Sedgwick (1973) suggests that the subtense ratio is fundamental to the matrix of classic cues to depth in that it incorporates a base referent, the individual's height. The object of the research would be to demonstrate an influence of the horizon and vertical extents on the judgment of height.

Subjects. A minimum of six pilots in advanced training will be necessary to give a statistical base. Twelve would be desirable.

Procedure. To check the efficacy of the subtense ratio as a cue to flightpath elevation, a situation is necessary in which the point of regard can be manipulated as well as the presence of the horizon. This could be done with photographs or slides. However, to be assured of veridicality with low-level flight, it would be desirable to do the work from an airplane in flight. Working in the real world would avoid the problems of pictorial representation (Rosinski & Farber, 1979; Sedgwick, 1973) and the possibility that the obtained results would be specific to the pictorial technique used.

The pilot's task would be consistent with training flight activities. The pilot would be asked to fly over designated ground features at specific heights (subtense ratios), on specific headings without the benefit of an altimeter or artificial horizon.

A selection of ground features of known height, both man-made and natural, would be required. It would be desirable to have a building, a water tower, a radio or power tower, the edge of a woods or a cliff face, and two different lone trees. These six objects would be overflown at each of three heights on headings to present their vertical extent without obstruction with clear view of the horizon and on a second pass against a near bluff or hill to occlude the far horizon. (A bluff without horizontal characteristics close to the terrain features would maximize the "no horizon" variable).

Half of the pilots would be given the height of the terrain feature in feet. The data, the altitude held at the moment of overflight, would be recorded and identified by the instructions given. No practice flights or repeats should be necessary or allowed. The data would be analyzed both as elevations, as the data were taken, and as absolute deviations from the specified altitude for each pass.

Implications. In keeping with the subtense ratio as a cue to height, the analysis of elevations would be expected to produce significant F-ratios in an Analysis of Variance for terrain feature and subtense ratio. Failure of these F-ratios would indicate that there were no cues to height in the situation, or more likely that the data were improperly taken. F-ratios for the presence versus the absence of horizon and for with versus without knowledge of height would be expected to be non-significant. The variances for no horizon, natural features, and no knowledge might be large consequent to the uncertainty these categories of the variables would impart to the components of the ratio . Presumably, within the precision of measurement, there would be no inversions in the order of the obtained mean elevations relative to the specified flightpaths.

The expected outcomes for the analysis of absolute deviations would be essentially opposite to that with elevations. The mean deviation would be expected to be larger for natural than for man-made objects, for without knowledge than for with, and for without horizon than for with. This follows from the expectation that the detail of the man-made objects and the knowledge of actual height would specify the denominator of the subtense ratio while the presence of the far horizon would specify the numerator to permit more precise estimates of height. Interaction of horizon and type and/or knowledge would be strong indication of the efficacy of the subtense ratio as a cue to height.

A GROUND METRIC

This research would study utilization of the performance capability of an aircraft by the pilot in executing low-level maneuvers. It is possible for a pilot's distance estimates to be so conservative as to effectively negate the performance capability of the aircraft. For example, faced with the requirement to make a level turn among terrain features or abort the mission and pull up, the pilot may abort unnecessarily due to lack of confidence when estimating the distances available.

In the text we have suggested that distance estimates over terrain favorable to low-level flight are subject to the presence of a ground metric generated and supported by the features present. This formulation should be challenged and replaced with hard data documenting the relation of terrain to distance estimation in low-level flight. To this end, standardized demanding maneuvers might be flown at low level in the presence of a variety of terrain features in the simulator.

Subjects. Both highly trained pilots and pilots in training should be used. Multiple sorties might be flown by the same pilot, but these should be limited to prevent the individual becoming "simulator wise."

Procedure. The pilot would be asked to fly, for example, a dog leg, either left or right, to parallel a ridge line and to pull up preparatory to making a level crossing. The clear path approach to the ridge would be populated by selected terrain features to provide the ground metric. The one constant would be that terrain features below the ridge would be masked by those along the clear path such that the air space adjacent to the ridge would become evident only after the pilot was committed to a level turn.

The experimenter would manipulate the number and assortment of the features present in the terrain extending to the ridge and the presence and location of possible obstacles in the air space immediately adjacent to the ridge. Sorties flown at selected elevations would provide a means of assessing the relation of eye height to the achieved metric.

Performance measures should be taken at two levels -- instrumental and physiological. The instrumental measures would be cockpit control movements reduced to radial distances to the potential obstacles present at the initiation of the level turn and pull up maneuvers. The physiological measure could be an electromyogram (EMG) from the arm or leg. If an unpleasant physical consequent could be provided to coincide with simulated collision, a conditioned anxiety might substitute for the extreme apprehension that accompanies the possibility of such an experience in real life. Should the pilots intellectually withhold an avoidance maneuver, knowing they were in a simulator, the anticipation of an electric shock, hopefully, would cause them to tense and provide a "true" measure of their distance estimate.

Interpretation. Systematic manipulation of the number, type, and distribution of terrain features tested against the pilot's ability to initiate a turn to parallel the ridge at a distance to provide minimal clearance would demonstrate the adequacy of the ground metric. Also, the point of initiation of an avoidance maneuver in response to the presence of a hidden obstacle would provide a second measure of the ground metric present. The use of a surprise obstacle, visible only after the turn was partially completed, would keep the situation honest as would the use of conditioned anxiety. Executed in the simulator, with a CIG system, the data obtained would be a direct measure of the adequacy of simulation as well as being interpretable in terms of basic cues to depth.

EXPANSION POINT IN LANDING

It has been reported earlier that pilots generally report that they locate their touchdown point by finding the point on the runway which is motionless. Regan, Beverley and Cynader (1979) have studied visual guidance of locomotion and have confirmed Gibson's report (Gibson, 1950; Gibson et al., 1955) that the center of expansion provides information about the direction of locomotion. Llewellyn (1971) and Gregory (1976), on the other hand, have reported that subjects who are instructed to do so cannot accurately locate the center of expansion in a random dot display. There are, of course, many differences between the task of locating the center of expansion in a random dot display and the task of locating the spot toward which locomotion is proceeding. The purpose of this proposed research is to examine the differences in the two situations to determine whether it is possible to use the center of expansion to locate the landing spot. While not specifically a "depth cue," in that it does not directly convey information about absolute or relative depth, the center of expansion has been studied as a referent for visual guidance of locomotion in three dimensions (Gibson, 1950; Gibson et al., 1955; Regan et al., 1979). Moreover, responses from pilots indicate that they feel it is a useful cue to a safe approach and landing.

Subjects. Each of the following experiments would incorporate two groups of subjects: pilots and non-pilots.

Procedure. The experiments will be conducted using the CRT display of a laboratory computer or the visual display system of a flight simulator. A light pen, incorporated into the computer system, would be used to indicate the locus of the center of expansion. In the first experiment, we would attempt to replicate Llewellyn's finding. The random dot pattern displayed on the CRT face would expand radially around one of several randomly chosen points. The task of the observer would be to locate the center of expansion and to indicate its locus by pointing a light pen to the correct spot on the CRT. Integrated distance error (Pythagorean distance) from the correct center of expansion would be the dependent measure.

In the second experiment, the pointing task would be repeated using a display in which the random dots were replaced by a computer-generated scene depicting a real-world environment. This would allow the assessment of whether Llewellyn's finding is an artifact of the stimulus situation. In this display, no horizon line or fixed referent would be provided.

Both the random dot display and the simulated scene would be used in another experiment in which a fixed referent was provided. Sedgwick (1973) has demonstrated the importance of the horizon in establishing distance and height. This, rather than the center of expansion, may be the best indicator of the landing spot. This experiment will allow us to assess the importance of such a fixed referent in assessing direction of locomotion.

Finally, the same displays will be employed in a second series of experiments in which the observer's task is to direct the apparent locomotion toward a specific spot in the display rather than to select the spot toward which the observer is apparently moving. These experiments will make it possible to assess the differences in active versus passive task in the determination of direction of locomotion. In these experiments, the dependent variable will be the distance between the point toward which the observer has been instructed to "move" and the center of expansion, which is under subject control.

Implications. These experiments will allow the examination of the effects of training, stimulus type, external referent, and active versus passive task on the observer's ability to determine the direction of locomotion. In addition to providing data of interest to basic visual science, the experiments have implications for primary flight training. IPs indicated to us that they used the "point of no movement" (center of expansion) as a visual referent for landing. If it is demonstrated that subjects are not able to locate such a spot, then changes in basic flight instruction may be necessary.

## POTENTIAL AREAS OF RESEARCH

The following suggested experiments are presented without elaboration. It is not clear that the state-of-the-art in simulation software/hardware has advanced to the point necessary to support the first two studies. The first experiment suggests an examination of an alternative visual space which would require a major programming effort and which would, perhaps, require the use of far more "edges" than are now utilized in CIG displays. The second proposal, a suggestion which might result in a considerable saving of edges displayed, addresses the development of a sensor system which (to our knowledge) is not yet operational.

### NON-EUCLIDIAN GEOMETRY

Two reports which are prevalent in the literature on flight simulation and in pilot reports are the differences in the landing of simulators and real aircraft, and the difficulty in utilizing peripheral streaming as a cue to flaring in the simulator. It is conceivable that these differences are the result of the use of a Euclidian metric to describe visual space in the simulator. The assessment of this would require that a computer program be prepared, using the hyperbolic space suggested by Luneberg (1947, 1950) and Blank (1959), in which a runway and a limited number of ground plane cues were presented. Comparison of landing performance in the Euclidian space and the hyperbolic space would provide a basis for determining the benefit of reprogramming the visual scene.

### PIXEL GRADIENT

It might be possible, through software modifications, to design simulator displays in which the number of picture elements (pixels) is a decreasing function of displacement from the point of regard. Such systems would provide a way of increasing pixel density in the regions of the display in which information was critical; utilizing fewer lines in less critical areas. Such systems would require continuous monitoring of the direction of gaze and the ability to shift pixel density as a function of direction of gaze.

Since there would be a finite delay in the [illegible] of the pixel density spectrum after the observers' direction [illegible] shifted, preliminary data are needed to assess the threshold for detection of display lag and the minimum "acceptable" lag in the display.

### SIZE DISTANCE INVARIANCE HYPOTHESIS

Data for the evaluation of the size-distance invariance hypothesis would properly be a by-product of the ground metric study. It would be necessary to execute both a pull-up and a level turn to the same obstacle in the same visual scene. The choice of terrain features would need to balance off the clarity of the vertical metric and the ground metric, so that their presence ranged from one or the other, but not both, to both in approximately equal strength. The radial distance estimates, functionally evidenced by the maneuvers as executed, should remain constant for any one altitude, if the hypothesis is correct. Departures from the hypothesis should yield an assortment of functions consistent with the geometry of separate vertical and horizontal metric and the angle of regard.

## SUMMARY AND CONCLUSIONS

In this study, we examined human depth perception as it relates to the requirements for visual simulation. We reviewed the literature in visual psychophysics and in flight simulation in order to provide a list of the cues which are available for the representation of depth on two dimensional surfaces. We also interviewed experienced Air Force pilots to determine the visual information required for various flying tasks. An examination of a small sample of Air Force and commercial flight simulation systems was conducted to assess the quality and variety of depth cues in visual simulation systems.

In general, the visual simulation systems we examined (CIG, Camera/Modelboard, and VAMP) made available all of the pictorial cues described in the first section of this report as well as the dynamic visual cues to distance. The impression of depth in the forward view of the simulators was quite realistic consistent with the limitations of the particular system used. Departure from reality was greatest with the CIG displays in which stylized features were used. However, adherence to the rules of perspective and visual direction, particularly with motion, maintained a strong sense of reality.

Major shortcomings of the systems reviewed have been well documented in the literature. The limitation of flightpath with the VAMP is such that it is generally not pursued as a viable system for today's problems. Camera/Modelboard systems are capable of presenting realistic displays. The limitation in detail of such systems is imposed, not by the skill of the model builder, but by the resolution capacity of the associated video system. Unfortunately, the restrictions of the flightpath which are imposed by the finite limits of the modelboard limit the usefulness of such systems for extended and/or varied terrain simulation. In CIG systems, abstraction and stylizing of the visual scene results in displays which are cartoon-like, but which are clearly capable of supporting the perception of depth.

The tasks chosen for this study are differentially affected in simulation by the resolution limits noted. In tactical formation flight, the resolution limits of the visual simulation system are insufficient to allow the pilots to utilize acuity as a cue to distance. Pilot responses indicated that fine details of the tanker are used for alignment cues in aerial refueling. However, such detail is entirely absent in both CIG and Camera/Modelboard systems. The simulated tanker in the CIG system which we examined lacked all fine detail and often broke up during changes in perspective consequent to maneuvers of the refueling aircraft. Given the optical and mechanical problems inherent to providing a binocular display, it appears to us unlikely that the addition of stereopsis to the simulation would provide a cost-effective increment in depth perception.

Both landing and low-level flight can be accomplished on a Camera/Modelboard system. However, mechanical constraints imposed by the camera system limit the simulated speed, and the finite limits of the modelboard impose rather severe restrictions on the flightpath. The flexibility of the CIG system is preferable to the limitations of the Camera/Modelboard systems for these tasks. However, in CIG systems the limitation on the number of edges and the processing priority impose constraints on the detail which can be displayed. Stylizing of features to ease these constraints results in uniformity among objects of the same class (trees, buildings, etc.). We have suggested that the ability to identify specific objects in the terrain is crucial to depth/distance estimation. The uniformity of objects in CIG systems makes such identification difficult.

Review of the angular relations among objects which are available to the pilot in low-level flight over favorable terrain and those available over unfavorable terrain suggested the possibility for height judgments in the form of the "subtense ratio." We suggest that judgment is referenced to the horizon and uses the assumed height of ground features to assess altitude and flight path clearance. Similarly, the constant visual angle between the horizon and the touchdown point during approach may be the critical visual cue of the landing task. The runway ultimately fills this angle at the moment of flare when the pilot transitions from descending flight to roll-out and taxi. This may be the constant against which the variable lengths and widths of runways are tested to develop the cue systems particular to each airfield.

The fact that pilots learn to fly over unfavorable terrains prompted a review of the specifics of the blur patterns available. When the terrain features can be confused, distances become indefinite, and the terrain provides only a texture with patterns of flow and blur. To the degree that these patterns have an internal referent, they have potential for utility in landing and low-level flight. An internal referent is evident in the symmetry of such patterns about the line of flight. Thus, the availability of the patterns at tactical elevations and speeds is the concern. This was reviewed in the form of ground visibility plots. Only at the lowest altitude and highest velocities did the blur patterns extend forward sufficiently to enter the pilot's field of vision.

Several experiments, which are based on issues raised during the conduct of this effort, have been suggested. These include efforts in both basic and applied research.

## REFERENCES


Berry, R. N. Qualitative relations among vernier, real depth and stereoscopic depth acuity. Journal of Experimental Psychology, 1948, 38, 708-721

Blank, A. A. The Luneberg theory of binocular space perception. In S. Koch (Ed.), Psychology: A study of a science, New York: McGraw-Hill, 1959, 395-426.

Bolyai, Janos. Scientem spatii absolute veram exhibens. Appendix to Farkas Bolyai, Tentamen juventutem studiosum in elementa mathesos purae, elementaris ac sublimioris, methodo intuitiva, evidentiaque huic propria introducendi. Maros Vasarhelyini, 1832-33.

Brewster, D. On the conversion of relief by inverted vision. Edinburgh Philosophical Transactions, 1847, 15, 657.

Brown, J. L. Visual elements in flight simulation. Aviation, Space and Environmental Medicine, 1976, 47, 913-924.

Campbell, F. W., & Westheimer, G. Factors involving accommodation responses of the human eye. Journal of the Optical Society of America, 1959, 49, 568-571.

Cibis, P. A. Problems of depth perception in monocular and binocular flying. Journal of Aviation Medicine, 1952, 23, 612-631.

Epstein, W., & Baratz, S. S. Relative size in isolation as a stimulus for relative perceived distance. Journal of Experimental Psychology, 1964, 67, 507-513.

Epstein, W., Park, J., & Casey, A. The current status of the size-distance hypothesis. Psychological Bulletin, 1961, 58, 491-514.

Foley, J. M. Depth, size and distance in stereoscopic vision. Perception and Psychophysics, 1968, 3, 265-274.

Ganzler, B. C. Virtual image display for flight simulation. NASA Technical Memorandum No. NASA-TM X-2327, 1971.

Gibson, E. J., Gibson, J. J., Smith, O. W., & Flock, H. Motion parallax as a determinant of perceived distance. Journal of Experimental Psychology, 1959, 58, 40-51.

Gibson, J. J. The perception of the visual world. Boston: Houghton Mifflin, 1950.

Gibson, J. J., Olum, P., & Rosenblatt, F. Parallax and perspective during aircraft landings. American Journal of Psychology, 1955, 68, 372-385.

Gogel, W. C. Convergence as a cue to absolute distance. Journal of Psychology, 1961, 52, 287-301.

Gogel, W. C., Hartman, B. O., & Harker, G. S. The retinal size of a familiar object as a determiner of apparent distance. Psychological Monographs, 1957, 71, 1-16.

Graham, C. H. Visual perception. In S. S. Stevens (Ed.), Handbook of Experimental Psychology. New York: Wiley, 1951.

Graham, C. H., Baker, K. F., Hecht, M., & Lloyd, V. V. Factors influencing thresholds for monocular movement parallax. Journal of Experimental Psychology, 1948, 38, 205-223.

Graham, C. H., Riggs, L. A., Mueller, C. G., & Solomon, R. L. Precision of stereoscopic settings as influenced by distance of target from a fiducial line. Journal of Psychology, 1949, 27, 203-207.

Gregory, R. L. The display problem in flight simulation. Royal Aeronautical Society Symposium on Theory and Practice in Flight Simulation, April, 1976.

Grosslight, J. H., Fletcher, H. J., Masterton, R. B., & Hagen, R. Monocular vision and landing performance in general aviation pilots: Cyclops revisited. Human Factors, 1978, 20, 27-33.

Harrington, T. L., & Harrington, M. K. Spatial orientation from high-velocity blur patterns: Perception of divergence. Technical Report No. 1977-1. Fast Motion Perception Laboratory, University of Nevada at Reno, 1977.

Heinemann, E. G., Tulving, E., & Nachmias, J. The effect of oculomotor adjustment on apparent size. American Journal of Psychology, 1959, 72, 32-45.

Helmholtz, H. von (Treatise on physiological optics, v. III) J.P.C. Southall (Ed. and trans.) New York; Optical Society of America, 1925. (Originally published, 1910).

Hochberg, J. Perception II: Space and movement. In J. W. Kling & L. A. Riggs (Eds.), Woodworth and Schlosberg's Experimental Psychology, (3rd ed.), New York: Holt, Rinehart and Winston, 1971.

Ittelson, W. H. Visual space perception. New York: Springer, 1960.

Kennedy, K. W., & McKechnie, D. Visibility toward the ground from selected tactical aircraft. AMRL Technical Memorandum No. AMRL-TR-69-123, 1970.

Kilpatrick, F. P., & Ittelson, W. H. The size-distance invariance hypothesis. Psychological Review, 1953, 60, 223-231.

Kraft, C. L. Measurement of height and distance information provided pilots by the extra-cockpit scene. In Visual Factors in Transportation Systems, Washington, D.C.: National Academy of Sciences, 1969.

Lewis, C. E., Jr., Blakeley, W. R., Swaroop, R., Masters, R. L., & McMurty, T. C. Landing performance by low time private pilots after sudden loss of binocular vision--Cyclops II. Aerospace Medicine, 1973, 44, 1241-1245.

Lewis, C. E., Jr., & Krier, G. E. Flight research program XIV: Landing performance in jet aircraft after the loss of binocular vision. Aerospace Medicine, 1969, 40, 957-963.

Llewellyn, K. R. Visual guidance of locomotion. Journal of Experimental Psychology, 1971, 91, 245-261.

Lobachevski, N. I. (Geometrical research on the theory of parallels) original in Russian. Kazan Messenger, February 12, 1826. Published in German as: Geometrische untersuchungen zue theorie der parallellinien. Scientiae Baccalaureus, 1887, 1.

Luneberg, R. K. Mathematical analysis of binocular vision. Princeton, N.J.: Princeton University Press, 1947.

Luneberg, R. K. The metric of binocular visual space. Journal of the Optical Society of America, 1950, 40, 627-642.

Nicholls, J. V. V. The relationship of heterophoria to depth perception in aviation - Part I. American Journal of Ophthalmology, 1950, 33, 1497-1515.

Pfaffman, C. Aircraft landings without binocular cues: A study based upon observations made in flight. American Journal of Psychology, 1948, 61, 323-334.

Perdriel, A. M. G., & Whiteside, T. C. D. Problems of vision in low level flight. North Atlantic Treaty Organization, Advisory Group for Aerospace Research and Development, AGARDograph 107, 1967 (DDC - AD 661164).

Pitts, D. G. Visual illusions in aircraft accidents. In Visual Factors in Transportation Systems, Washington, D. C.: National Academy of Sciences, 1969.

Regan, D., Beverley, K., & Cynader, M. The visual perception of motion in depth. Scientific American, 1979, 241, 136-151.

Rock, I. Introduction to perception. New York: MacMillan, 1975.

Roman, J., Perry, J. J., Carpenter, L. R., & Awni, S. Flight research program VI: Heart rate and landing error in restricted field of view landings. Aerospace Medicine, 1967, 38, 128-132.

Rosinski, R. R. Effect of optical magnification of the perception of displayed orientation. Technical Report No. 79-1, Office of Naval Research, 1979.

Rosinski, R. R. & Farber, J. Compensation for viewing point in the perception of pictured space. Technical Report No. 79-2, Office of Naval Research, 1979.

Sedgwick, H. A. The visible horizon: A potential source of visual information for the perception of size and distance. Ann Arbor, MI: University Microfilms, 1973.

Snyder, H. L. Visual aspects of low-level flight. In J. W. Miller (Ed.), ONR Symposium Proceedings Anaheim, California, March 1964.

Stratton, G. M. A mirror pseudoscope and the limit of visible depth. Psychological Review, 1898, 5, 632-638.

Stefansson, V. Arctic Manual. New York: Macmillan, 1944.

Wallach, H. & O'Connell, D. N. The kinetic depth effect. Journal of Experimental Psychology, 1953, 45, 205-217.

Wallach, H., O'Connell, D. N., & Neisser, U. The memory effect of visual perception of three-dimensional form. Journal of Experimental Psychology, 1953, 45, 360-368.

Westheimer, G. H., & Mitchell, A. M. Eye movement responses to convergence stimuli. A.M.A. Archives of Ophthalmology, 1956, 55, 848-856.

Wheatstone, C. On some remarkable and hitherto unobserved phenomena of binocular vision: Part 2. Philosophical Magazine, 1852, Series 4, 504-523.

Whiteside, T. C. D. The blur zone. Royal Institute of Aviation Medicine Report No. 354 April 1967.

Whiteside, T. C. D., & Samuel, G. D. The blur zone. Flying Personnel Research Committee Report No. FPRC/1293, 1969. Exchange Document No. 4-34MOT, DDC No. N70-33480.

Whiteside, T. C. D., & Samuel, G. D. Blur zone. Nature, 1970, 225, 94-95.

## APPENDIX A

## INTERVIEW GUIDE

Interviews were conducted at four locations: Davis-Monthan AFB, Arizona; Mountain Home AFB, Idaho; Nellis AFB, Nevada; and Shaw AFB, South Carolina. The total number of pilots interviewed was 32. In three of the above locations, the pilots agreed to be interviewed only in groups, and the composition of the group was somewhat flexible; that is, pilots entered and left the interview room during the course of the interview. Because it was not feasible to begin the interview anew each time the personnel changed, the number of respondents is not the same for every section of the interview.

The interview guide questions presented in this appendix are those which elicited meaningful responses. Many questions proved to be redundant or pointless as the processes of flight were understood. For instance, questions designed to probe the depth/distance cues used in Formation Flying only caused the pilots to repeat the traingulation procedures. Since triangulation responses were uniformly obtained at all bases visited, it was concluded that Formation Flying and Aerial Refueling were reasonably well understood tasks and that this was the source of the consistency. The responses to questions on Approach and Landing and Low-Level Flight suggested that these tasks are less well understood and that responses to our questions were subject to selective perceptions. In particular, descriptions of critical instances of near misses did not reasonably square with the critical cues presented in response to previously asked direct questions. With the recognition that the primary information content was in the critical instances, the direct questions were abbreviated in favor of probing a critical instance when given. The answers provided are typical in information content.

The answers provided are typical in information content. The informal nature of the interviews generally resulted in group discussion and forestalled independent responses to individual questions. Consequently, data such as frequency of response are not meaningful. In the one instance where one-on-one interviews were organized, it became apparent that the pilots were giving canned answers. Questions directed to this problem revealed that the commend had recently evaluated a new training series for use by instructor pilots.

Responses noted in this appendix in all capital letters represent typical (modal) responses on a sample of the range of responses.

Interview Guide

Our purpose is to obtain an accurate and complete description of the visual cues employed by a cross section of Air Force pilots in Formation Flying, Aerial Refueling, Approach and Landing, and Low Level Flight. Your comments will be analyzed to identify the significant visual cues.

What type of plane to you presently fly? A-10 (F-4, F-111)

How many total air hours do you have? 4000

How many hours in your present aircraft? 425

Aerial Refueling

Final Approach Maneuver

1. Approximately how many times have you accomplished aerial refueling?

   RANGE FROM 3 TO 75 COUPLINGS

2. What instruments do you use to match your airspeed and elevation to that of the tanker?

   AIRSPEED INDICATOR IS CRITICAL TO AVOID OVER-SHOOTING.

3. How does your view of the tanker change as you approach the contact position?

   STABILATOR ASSEMBLY MOVES OVERHEAD AND DETAIL OF THE TANKER SKIN BECOMES CLEAR. IT BECOMES BIGGER, MORE DETAIL IS VISIBLE. GENERAL RESPONSE WAS MORE DETAIL.

   a. Can you see the tanker's ailerons, outboard-inboard engine nacelles? What is their final position in your field of view?

      THE BOOMER'S (fuel boom operator) OPENING IS CENTERED ABOVE THE HUD (head-up display). INBOARD ENGINE NACELLES ARE JUST ABOVE AND OUTSIDE THE CANOPY BOW.

   b. Can you see the tanker's stabilator assembly? What is the final position in your field of view?

      NO. IT IS OVERHEAD.

4. Do you align near and far features of the tanker -- for instance, inboard engine nacelles with wing detail to the position of your aircraft?

   NO.

   a. Do you align canopy features -- the canopy bow for instance -- with features of the tanker to sense the relation of your aircraft to the tanker?

      YES. (There were a variety of responses, about what features were used, but all respondents used some feature of their own aircraft to align with some feature of the tanker.)

   b. Do you place markers on your canopy for this purpose?

      NO.

5. When you are in position and ready for boom and fuel line deployment, to what portions of the tanker do you attend to hold your position?

   (Variable response) THE WING AND ENGINE NACELLES, UHF ANTENNA, LOWER EDGE OF BOOMER OPENING, SEAM IN TANKER FUSELAGE.

6. Comments.

   I USE THE COLORED SEGMENTS OF THE BOOM AGAINST THE EXTENSION COLLAR TO MAINTAIN POSITION. I USE THE WSO (weapons system officer) TO CALL CUT POSITION.

Fuel Line Deployment and Coupling

1. Can you anticipate the lights and the boom operator's instruction to correct your position?

   MOST OF THE TIME. THE LIGHTS ARE IN POOR POSITION FOR USE BY TACTICAL AIRCRAFT AND GENERALLY GIVE ONLY GROSS INFORMATION.

   a. How do you know to expect an instruction to correct elevation with reference to the tanker?

      BY WATCHING THE CLEARANCE OF THE BOOMER'S OPENING ABOVE THE HUD, BY WATCHING MOVEMENT OF TANKER FEATURES RELATIVE TO AIRCRAFT FEATURES.

b. How do you know to expect an instruction to correct your fore and aft distance from the tanker?

IF THE BOOM IS TOO FAR OUT I MUST MOVE FORWARD, IF IT IS TOO FAR IN, I MUST FALL BACK.

2. Comment.

WITH THE BOOMER'S OPENING SITTING JUST ABOVE THE HUD, THE BOOM EXTENSION GIVES ME FORE AND AFT. I DO NOT USE THE LIGHTS EXCEPT FOR GROSS ALIGNMENT.

Simulation

1. Have you ever flown a simulated aerial refueling mission?

VERY FEW POSITIVE RESPONSES.

a. What type of presentation was used?

CIG, MODEL BOARD.

b. If you have flown more than one type of simulation system, which was superior?

(None of the respondents had flown more than a single type of simulation system.)

c. Briefly give your opinion of simulation for aerial refueling.

EXCEPT FOR THE FACT THAT IT REQUIRES A GREAT DEAL OF ADMINISTRATIVE COORDINATION, AERIAL REFUELING IS MOST EASILY DONE IN THE AIR. I HAVE NOT SEEN A SIMULATOR THAT PROVIDES ENOUGH DETAIL TO TRAIN A NEW PILOT, AND I HAVE NEVER HAD A NEW PILOT FAIL TO COUPLE ON HIS FIRST TRY IN THE REAL SITUATION.

Formation Flying

1. Assume you are flying the wing position in a finger tip formation. What cues do you use to hold position?

a. fore and aft -- I ALIGN ON THE STABILIZER ASSEMBLY OF THE LEAD PLANE BY LOOKING OVER MY SHOULDER. (A-10) I ALIGN WITH THE JET EXHAUST OPENING.

b. in elevation -- I PREFER TO JUST BARELY SEE THE UNDERSIDE OF MY LEAD MAN'S WING

c. wing tip distance -- I SIGHT THE WING TIP LIGHT ON THE STAR JUST BELOW THE COCKPIT ON THE FUSELAGE OF MY LEAD MAN.

2. Are you aware of some feature in your cockpit or canopy that you use to facilitate this alignment?

NO

3. Are you more comfortable flying slightly above, on the same elevation, or slightly below the lead aircraft? Why?

SLIGHTLY BELOW. I GET A BETTER PICTURE OF THE PLACE AND CAN SENSE WHAT MY LEAD MAN IS DOING MORE EASILY.

4. How do you hold your distance in line abreast - tactical formation?

BY EYEBALL -- COLORS FADE AND LETTERS CAN'T BE READ.

5. Have you flown formation in a simulator?

NO

a. What type of presentation was used?

b. If you have flown more than one type of simulation system, which was superior?

c. Briefly state your opinion of the usefulness of simulation for formation flying.

THE SIMULATOR WITH WHICH MOST PILOTS WERE FAMILIAR DID NOT PROVIDE A PERIPHERAL VIEW WHICH WOULD BE ADEQUATE TO SUPPORT FORMATION FLYING.

Low Level Flight

1. At what altitude do you customarily fly in low-level flight?

WE USED TO GO TO 100 FEET, NOW WE ONLY GO TO 300 FEET.

2. Have you had experience flying at low level over salt flats, dry lake bed, or open water? How did you maintain your altitude?

YES. I MAINTAIN ALTITUDE BY SCANNING OUT THE SIDE CANOPY TO THE HORIZON. IT'S VERY DANGEROUS AND DIFFICULT.

3. Of what significance to low-level flight is vertical detail in ground features, when visible out the side of your aircraft?

VERY IMPORTANT.

Out the front of your aircraft?

VERY IMPORTANT. AT THE LOWEST ALTITUDES, VERTICAL DETAIL AT EYE LEVEL IS YOUR BEST INDICATOR OF HEIGHT.

4. In shifting from an altitude where you feel comfortable to your minimum altitude capability, do you lose detail in the terrain beneath you?

YES, I THINK SO.

a. At your comfortable altitude does the terrain stream beneath you with noticeable velocity?

I NEVER NOTICED.

b. At your minimum altitude does the terrain stream with noticeable velocity?

YES, NOW THAT YOU MENTION IT, BUT I DON'T THINK I USE THE INFORMATION.

5. Over which terrain is your minimum altitude capability the lowest and why?

a. Sparsely wooded with individual tall trees, ridge line, etc.?

TO OBVIATE NECESSITY OF OBJECT AVOIDANCE YOU STAY ABOVE THE HIGHEST TREE.

b. Open country with stunted trees and bushes?

THE TREES AND BUSHES GIVE ME A FEEL FOR MY HEIGHT ABOVE THE GROUND.

c. Open ground with only grass, sand or fine gravel?

TOO DANGEROUS TO FLY LOW OVER GROUND WITHOUT DETAIL.

6. Have you experienced a "near miss" in low-level flight -- an experience in which you felt an impending crash or loss of control of your aircraft?

YES.

a. What corrective action did you take?

PULLED UP AND LEVELED OFF, ADDED THRUST.

b. Reconstruct the situation just prior to your taking corrective action.

A LARGE DEAD TREE I HAD EXPECTED TO SEE BELOW ME APPEARED HIGH IN THE SIDE CANOPY. GENERALLY THE AVOIDANCE MANEUVER WAS INITIATED IN RESPONSE TO AN UNEXPECTED OBJECT IN THE FIELD OF VIEW OR AN OBJECT IN AN UNEXPECTED PLACE.

7. Have you flown a low altitude simulator?

YES.

a. What type of presentation was used?

MODEL BOARD (in England) - (only positive response.)

b. If you have flown more than one type of simulation system, which was superior?

c. Briefly state your opinion of the usefulness of simulation for low level flight.

THE BOARD WAS LIMITED IN THE RANGE OF TERRAIN IT COULD PRESENT. IT WAS GOOD AS FAR AS IT WENT. ONE COULD TOO EASILY FLY OFF THE BOARD.

Visual Approach and Landing

1. Do you use different procedures when landing at an airport from which you have never flown before?

YES

a. Comment

I MAY FLY THE PATTERN A TIME OR TWO TO GET THE LAY OF THE LAND. I RELY MORE HEAVILY ON INSTRUMENTS.

2. Do you use different procedures in visual approach to an airport that is snow-covered in the sense that, the runways may be clear, but the surrounding areas are snow-blanketed?

   a. When there is good visibility, a bright sky, and sharp horizon?

   NO.

   b. When there is good visibility, an overcast sky, and blurred, or uncertain horizon?

   NO

   c. Comment.

   VASI (Visual Approach Slope Indicator) LIGHTS ARE MY PRIMARY GLIDE ANGLE INDICATOR. WITH THE VASI LIGHTS I CAN LAND IF I CAN SEE THE RUNWAY. VASI LIGHTS, WHICH ARE UNIFORM ON MILITARY AIRSTRIPS MAKE MOST LANDINGS COMPARABLE REGARDLESS OF THE TERRAIN.

3. What can you see forward when you initiate your descent?

   Out the side? NOTHING BUT SKY.

   Out the front? RUNWAY AND TOUCHDOWN POINT.

   a. If you can see forward, do you look forward?

   YES.

   b. What do you look for?

   HORIZON AND TOUCHDOWN POINT.

4. How do you align on the runway when you initiate your descent?

   a. Comment.

   I PICK UP THE EDGE OF THE RUNWAY AND ADJUST MY LINE OF FLIGHT SO THAT I STAY THE SAME DISTANCE AWAY FROM THE EDGE.

5. Is there change in motion of ground detail, as you drop below trees or buildings, in your approach to touchdown?

YES, PROBABLY, BUT IT'S NOT IMPORTANT. I DON'T KNOW, I NEVER LOOKED.

Point of Touchdown

6. Do you lose vision of your point of touchdown at any time?

   a. Just prior to touchdown? YES.

   b. Midway of descent?

   c. When you initiate your descent?

7. If the point of touchdown is not visible in forward vision, how do you know where it is?

   IT MUST BE BENEATH ME. I AM COMMITTED AND AM FLARING THE AIRCRAFT. MY EYES ARE DOWN THE RUNWAY TO PICK UP MY GUIDE FOR ROLL OUT, BRAKING, ETC.

   a. Are there things in view on the ground to the left and right of the point of touchdown?

      YES.

   b. Are they put there intentionally for your use?

      I DON'T THINK SO. WE ARE CERTAINLY NOT TRAINED TO USE THEM.

Taxiing and Takeoff

1. What do you use as guide as you taxi?

   TAXIING IS LIKE DRIVING. I LOOK OUT THE SIDE WIND SCREEN, BECAUSE THE NOSE BLOCKS CLOSE IN FORWARD VIEW.

2. Do you use out-the-canopy detail to decide when your speed is sufficient for takeoff?

   NO.

   What gives you the information?

   THE FEEL OF THE STICK. THE AIRSPEED INDICATOR.

3. On an airstrip without markers, what would be the cue for a decision to abort, rather than take off?

THE DECISION TO ABORT USUALLY INVOLVES THE STATE OF THE AIRCRAFT-- IT IS NOT READY FOR FLIGHT -- AND IS NOT RELATED TO GROUND SPEED.

Simulation

1. Have you flown take-off, approach and landing in a simulator?

YES.

a. What type of presentation was used?

MODEL BOARD.

2. If you have flown more than one type of simulation system, which was superior?

MODEL BOARD -- IT PROVIDES THE MOST DETAIL. I DID NOT ACTUALLY LAND IN THE MODEL BOARD SIMULATOR. IT WAS NECESSARY TO PULL UP ABOUT 20 FEET FROM THE GROUND TO AVOID DAMAGING THE MODEL BOARD.

3. Briefly give your opinion of simulation.

## APPENDIX B

### FORMULATION OF SUBTENSE RATIO

Tables B-1 and B-2 give the distances in feet and the associated angles in degrees for the plotted points of Figures 9 and 14. The ratio $\theta/\delta$ is obtained by division of the appropriate degree values. Other details follow from the geometry of Figures 6, 12, and 13 or are self-explanatory within the tables.

Table B-1

Data for Figure 9

Flightpath at 190 feet: clearance 80 feet, object 110 feet tall.

Angular relations: $\alpha = \delta - \theta$

| Distance Feet | $\theta$ | $\delta$ | $\alpha$ | Ratio $\theta/\alpha$ |
|---|---|---|---|---|
| 5,280 | .868 | 2.060 | 1.192 | .727 |
| 4,224 | 1.085 | 2.575 | 1.490 | .727 |
| 3,168 | 1.446 | 3.432 | 1.985 | .728 |
| 2,112 | 2.169 | 5.140 | 2.971 | .730 |
| 1,690 | 2.710 | 6.414 | 3.704 | .731 |
| 1,268 | 3.610 | 8.521 | 4.911 | .735 |
| 1,056 | 4.332 | 10.199 | 5.867 | .738 |
| 845 | 5.408 | 12.672 | 7.264 | .744 |
| 634 | 7.191 | 16.682 | 9.491 | .757 |
| 423 | 10.709 | 24.188 | 13.478 | .794 |
| 212 | 20.674 | 41.867 | 21.193 | .975 |

Flightpath at 150 feet, clearance 40 feet.

| | | | | |
|---|---|---|---|---|
| 5,280 | .434 | 1.627 | 1.193 | .363 |
| 4,224 | .542 | 2.033 | 1.491 | .363 |
| 3,168 | .723 | 2.710 | 1.987 | .364 |
| 2,112 | 1.085 | 4.062 | 2.977 | .364 |
| 1,690 | 1.355 | 5.072 | 3.716 | .364 |
| 1,268 | 1.806 | 6.746 | 4.939 | .365 |
| 1,056 | 2.169 | 8.084 | 5.915 | .366 |

Table B-1 Continued

| Distance Feet | Angles in Degrees θ | δ | α | Ratio θ/α |
|---|---|---|---|---|
| 845 | 2.710 | 10.066 | 7.355 | .368 |
| 634 | 3.610 | 13.311 | 9.700 | .372 |
| 423 | 5.402 | 19.525 | 14.123 | .382 |
| 212 | 10.684 | 35.291 | 29.596 | .434 |
| Flightpath at 130 feet, clearance 20 feet. | | | | |
| 5,280 | .217 | 1.410 | 1.193 | .181 |
| 4,224 | .271 | 1.762 | 1.491 | .181 |
| 3,168 | .361 | 2.349 | 1.988 | .181 |
| 2,112 | .542 | 3.522 | 2.979 | .182 |
| 1,690 | .678 | 4.398 | 3.720 | .182 |
| 1,268 | .903 | 5.853 | 4.950 | .182 |
| 1,056 | 1.085 | 7.018 | 5.933 | .182 |
| 845 | 1.355 | 8.746 | 7.390 | .183 |
| 634 | 1.806 | 11.587 | 9.780 | .184 |
| 423 | 2.707 | 17.083 | 14.376 | .188 |
| 212 | 5.389 | 31.516 | 27.127 | .206 |

Table B-2

Data for Figure 14

Flightpath at 250 feet elevation: clearance of 3D object - 191.8 feet.

Initial and equivalent distances: near - 4600 feet, far - 4602.8/6000 feet.

3D object: peak 2.8 feet beyond near edge, height 58.2 feet.

Angular relations: $\alpha = \delta - \theta$

<u>OIL SLICK</u>

| Distances Feet | Angles in Degrees $\theta$ | $\delta$ | $\alpha$ | Ratio $\theta/\alpha$ |
|---|---|---|---|---|
| 4600/6000 | 2.385 | 3.110 | .724 | 3.291 |
| 3600/5000 | 2.862 | 3.972 | 1.110 | 2.578 |
| 2600/4000 | 3.576 | 5.492 | 1.916 | 1.186 |
| 1600/3000 | 4.763 | 8.880 | 4.117 | 1.157 |
| 600/2000 | 7.125 | 22.619 | 15.494 | .459 |

<u>Cliff Face</u>

| Distances Feet | $\theta$ | $\delta$ | $\alpha$ | $\theta/\alpha$ |
|---|---|---|---|---|
| 4600/4602.8 | 2.385 | 3.110 | .724 | 3.291 |
| 3600/3602.8 | 3.047 | 3.972 | .925 | 3.292 |
| 2600/2602.8 | 4.214 | 5.492 | 1.278 | 3.296 |
| 1600/1602.8 | 6.823 | 8.880 | 2.057 | 3.316 |
| 600/602.8 | 17.649 | 22.619 | 4.970 | 3.550 |

## APPENDIX C

## GROUND VISIBILITY PLOTS AND BLUR ZONES

This appendix includes ground visibility plots for the RF-4C and F-111 (Figures C-1 and C-2), taken from Kennedy and McKechnie (1970), and for the A-10 (Figure C-3), drawn by one of the authors (PDJ) in the manner described by Kennedy and McKechnie. The cockpit visibility record from which the A-10 ground visibility plot was drawn was supplied by the Air Force Human Resources Laboratory.

Each dot on the vertical and horizontal axes of the ground visibility plots is equal to 1.5 x the altitude of the aircraft. In the RF-4C and F-111 plots, the small solid circle is coincident with the second dot, i.e. 3 x the altitude, and the dashed lines are slant ranges with the multiplier labelled. That is, at an altitude of 50 feet AGL, the first dot represents a point on the ground which is 75 feet from the point directly below the aircraft. At an altitude of 500 feet AGL, the same dot represents a point on the ground which is 750 feet from the point which is directly below the aircraft.

Each dot on the circumference of the circle represents 5°. These dots are useful in determining the direction in which vision is occluded by features of the aircraft. Shaded areas in the ground visibility plots indicate areas in which visibility of objects on the ground are occluded.

Blur zones were computed in the manner described by Snyder (1964). The computer plots in this appendix are the locus of points on the ground for which the value of the first derivative of Ø was equal to 15° $sec^{-1}$ and 30° $sec^{-1}$, the approximate lows of "fusion" reported by Graham (1951). Because of limitations inherent in the microprocessor software, both curves are plotted as solid lines. In each plot, the larger curve represents the lows of points associated with the 15° $sec^{-1}$ criterion.

In order to compare the blur zone plots with ground visibility from the three aircraft, the blur zone plots for speeds of 450, 550, and 650 knots were merged, drawn in mirror image, and photographically scaled for equivalence with the blur zone plots. Overlays of the re-scaled blur zone plots and the ground visibility plots were prepared and examined visually in order to determine whether the blur zones intruded into the pilots' visual field at altitudes of 50, 100, 300, and 500 feet AGL at airspeeds of 450, 550, and 650 knots.

Blur zone plots contained in this appendix have not been [illegible]ically re-scaled. An example of the result of this proce[illegible] contained in the text of this report at Figure 11.

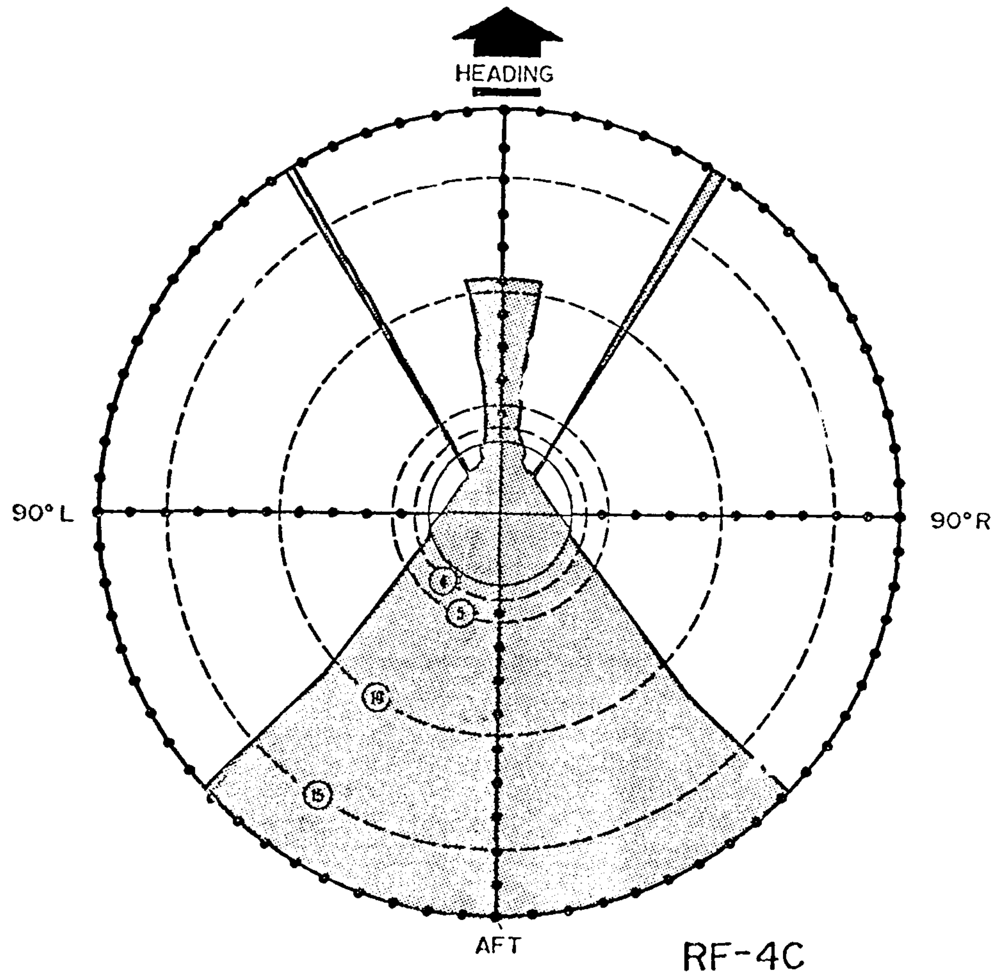



Figure C1. Ground visibility from RF-4C cockpit.

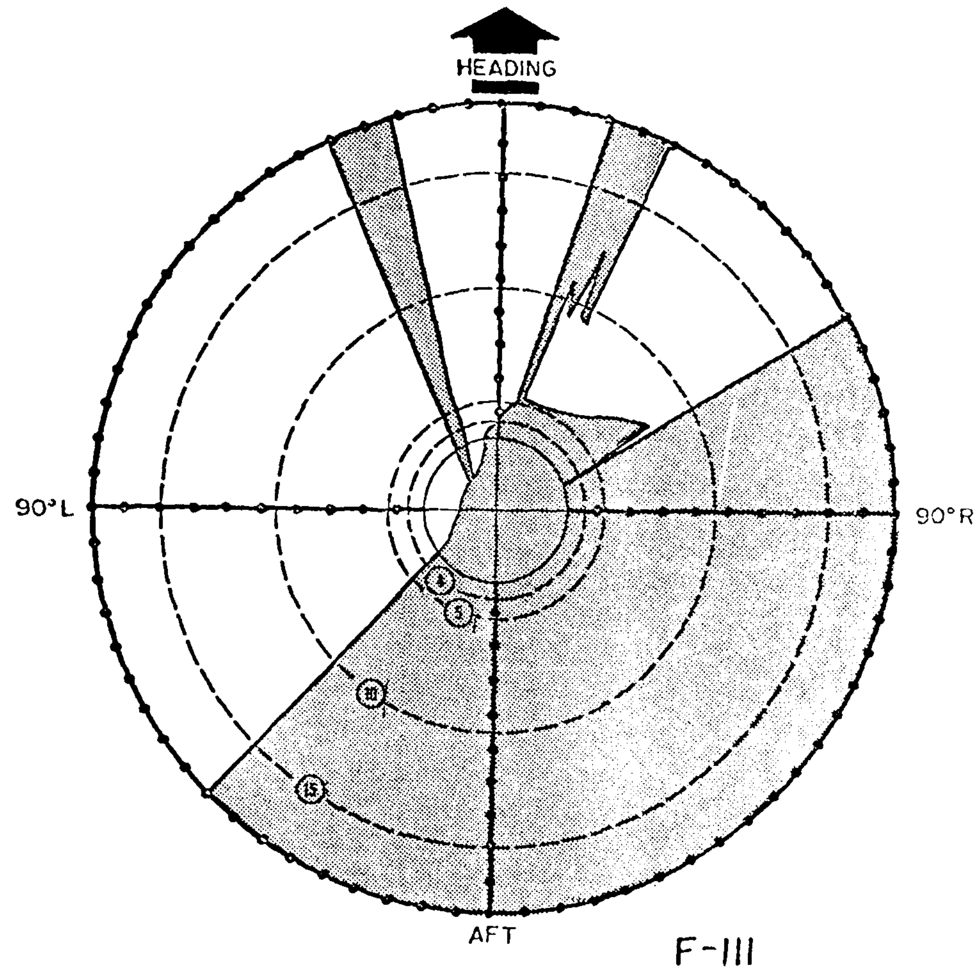



Figure C2. Ground visibility from F-111 cockpit.

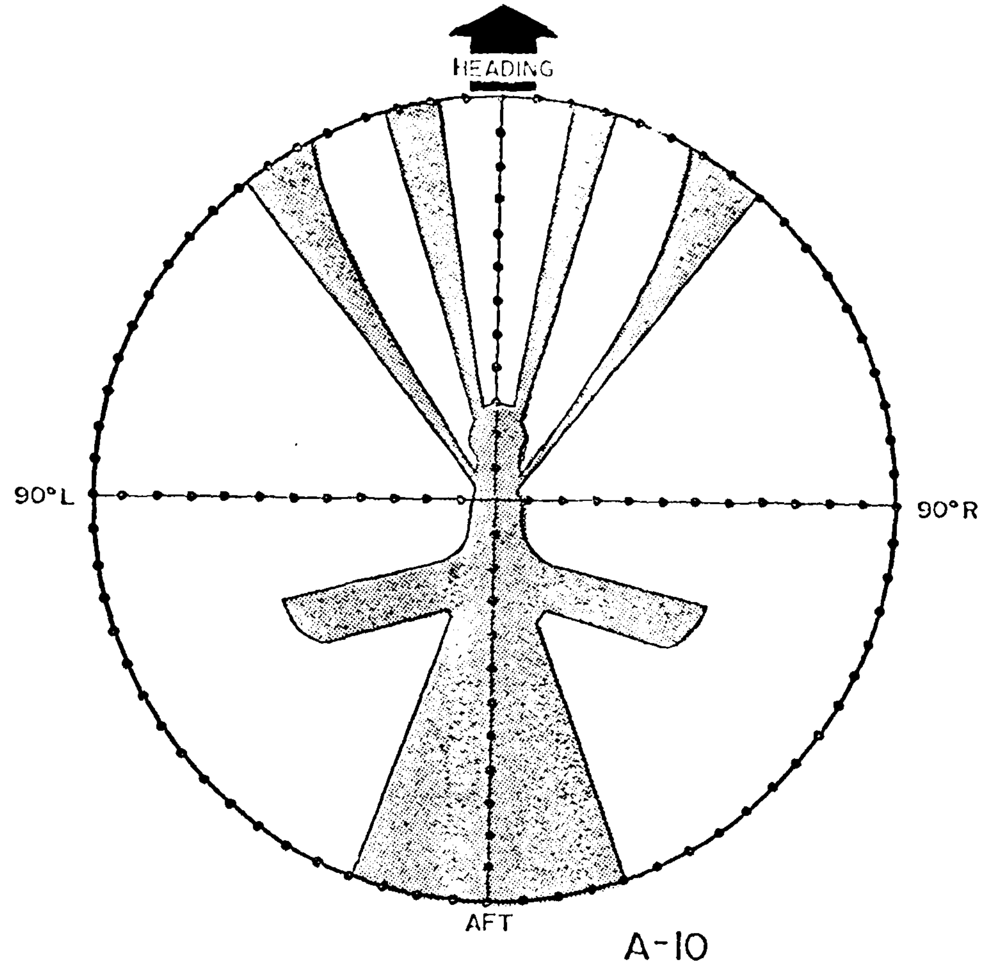



Figure C5. Ground visibility from A-10 cockpit.

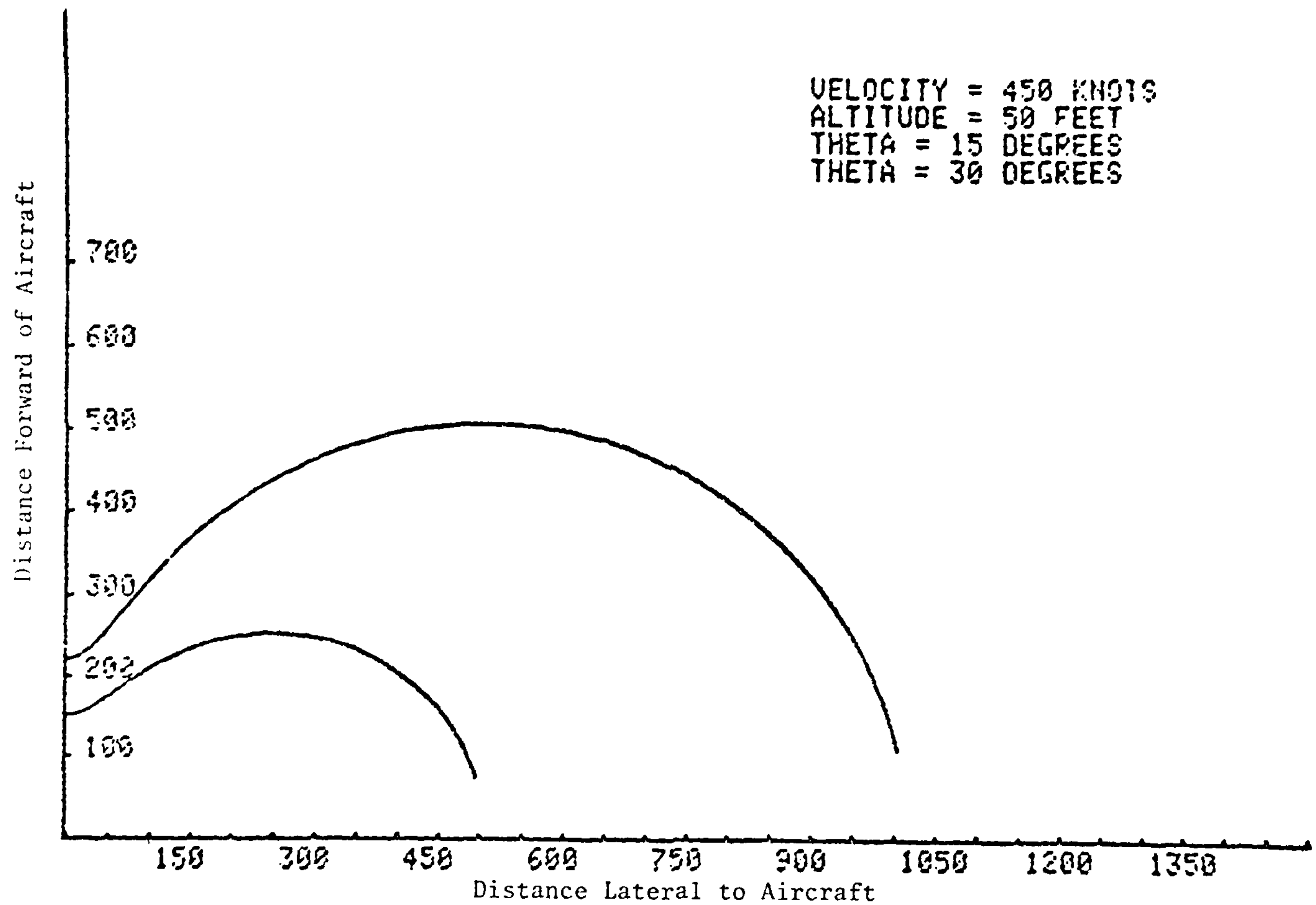



Figure C4. Blur zone as a function of altitude and velocity for fusion thresholds of $15^{o}$ $sec^{-1}$ and $30^{o}$ $sec^{-1}$ (velocity 450 knots, altitude 50 feet).

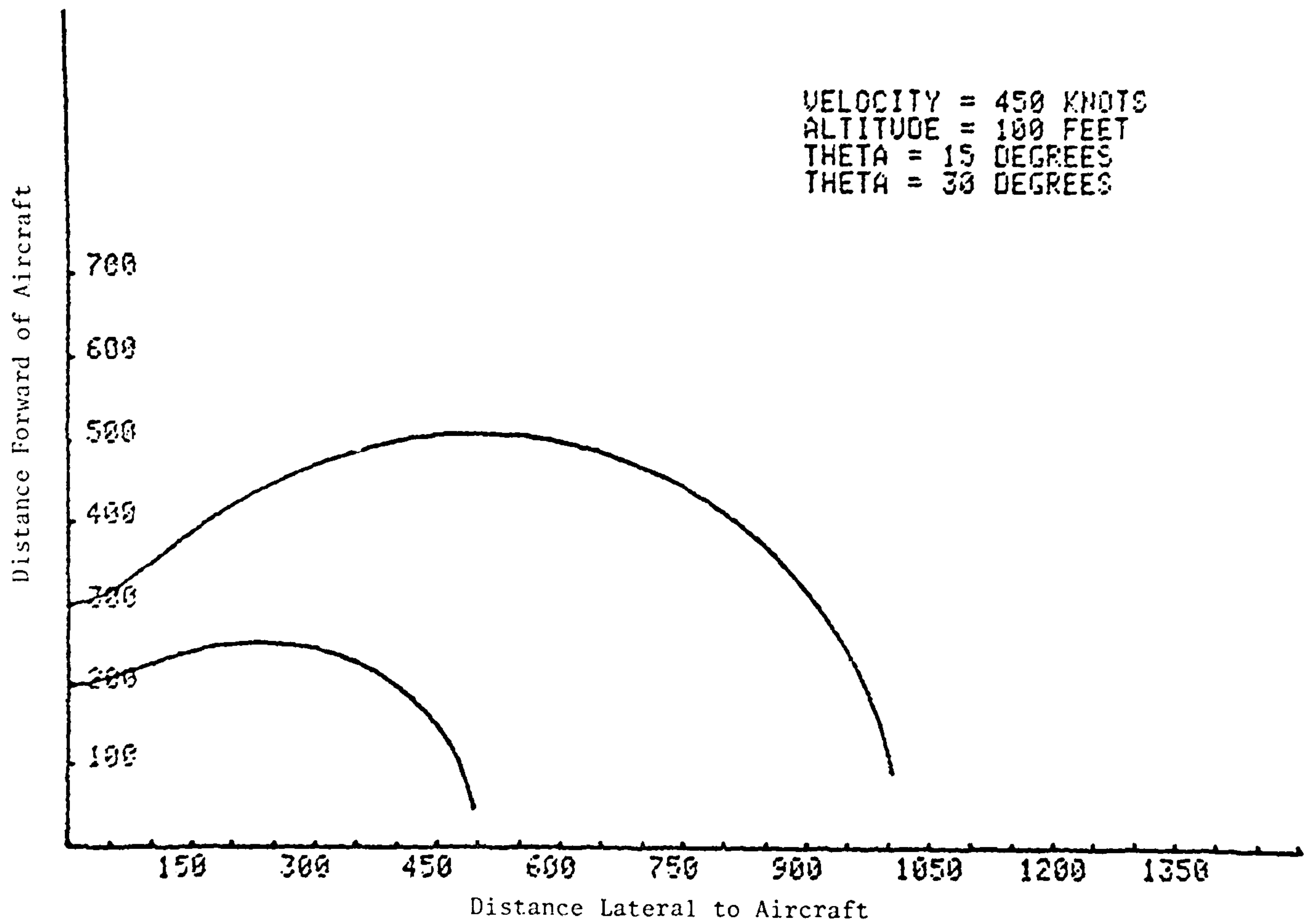



Figure C5. Blur zone as a function of altitude and velocity for fusion thresholds of $15^{o}$ $sec^{-1}$ and $30^{o}$ $sec^{-1}$ (velocity 450 knots, altitude 100 feet).

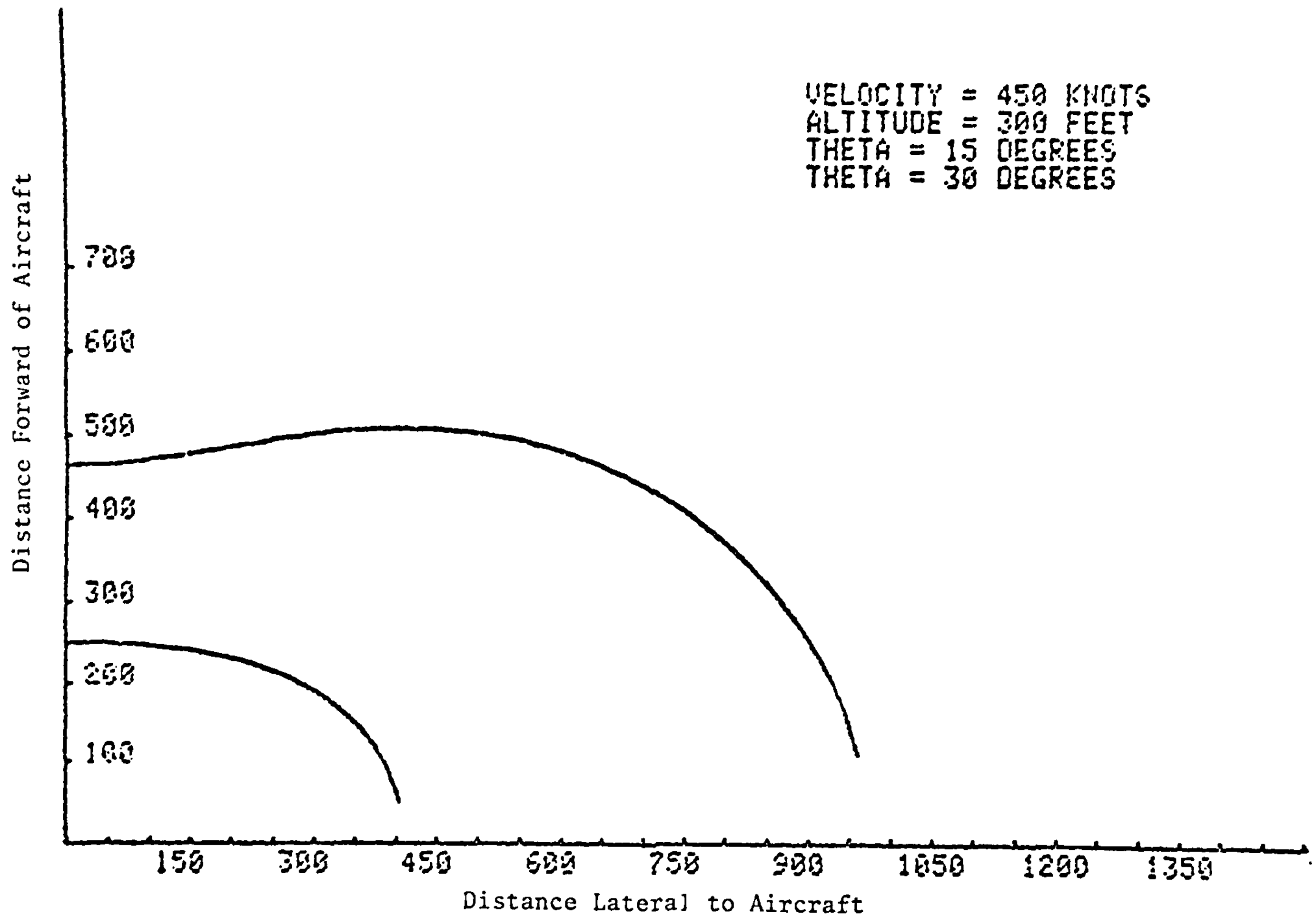



Figure C6. Blur zone as a function of altitude and velocity for fusion thresholds of $15^{o}$ $sec^{-1}$ and $30^{o}$ $sec^{-1}$ (velocity 450 knots, altitude 300 feet).

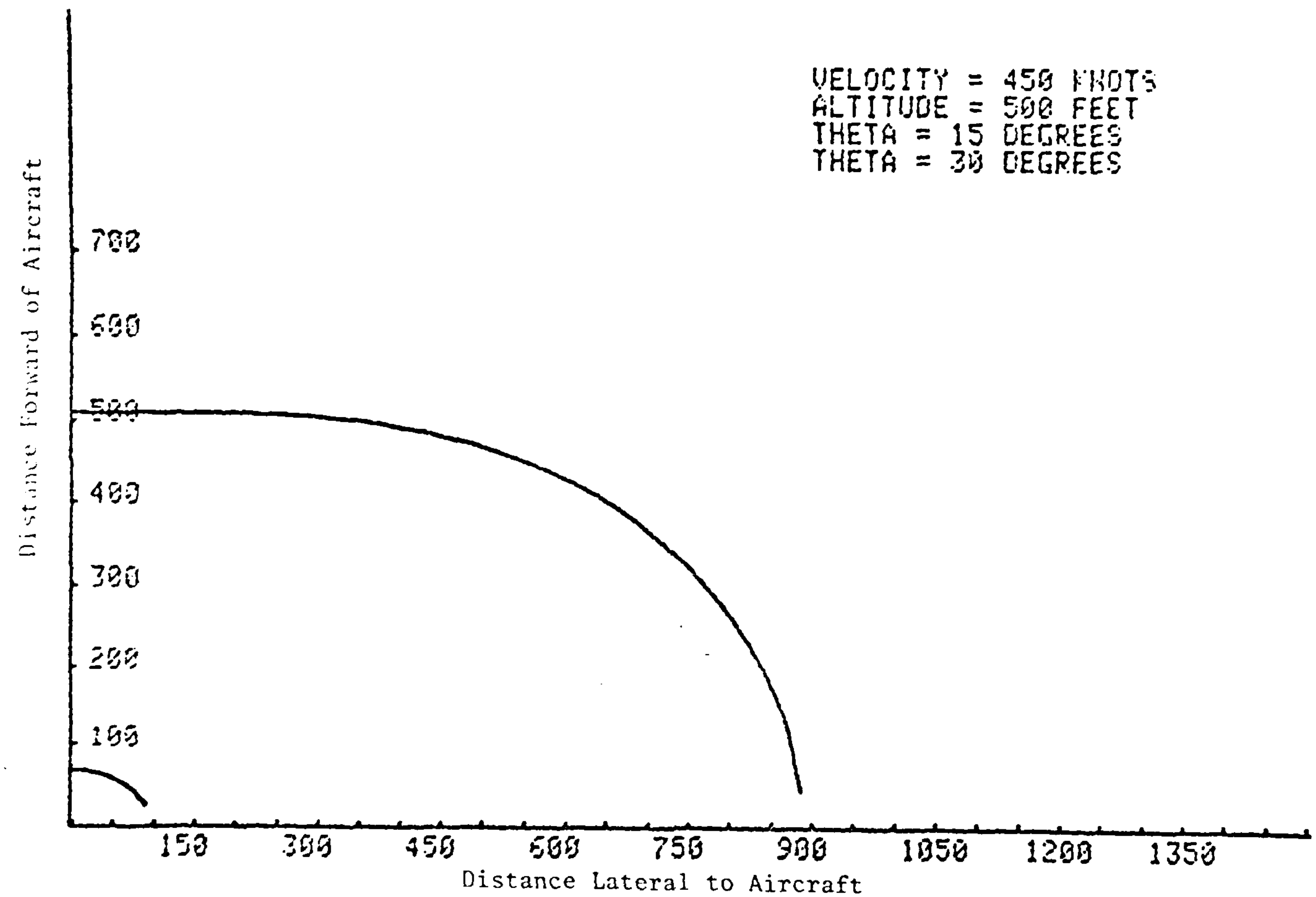



Figure C7. Blur zone as a function of altitude and velocity for fusion thresholds of $15^{\circ}\ sec^{-1}$ and $30^{\circ}\ sec^{-1}$ (velocity 450 knots, altitude 500 feet).

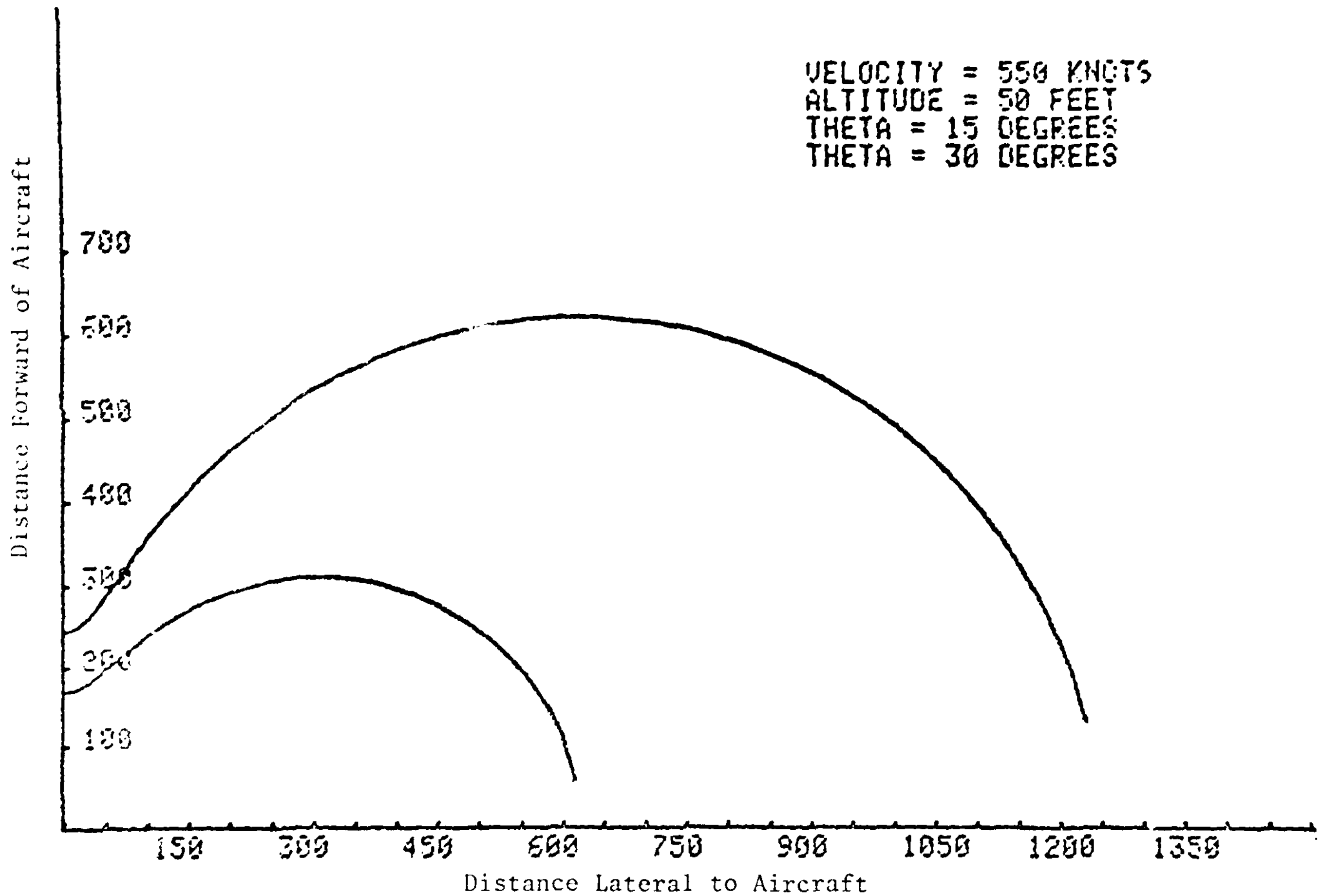



Figure C8. Blur zone as a function of altitude and velocity for fusion thresholds of $15^{0}\ sec^{-1}$ and $30^{0}\ sec^{-1}$ (velocity 550 knots, altitude 50 feet).

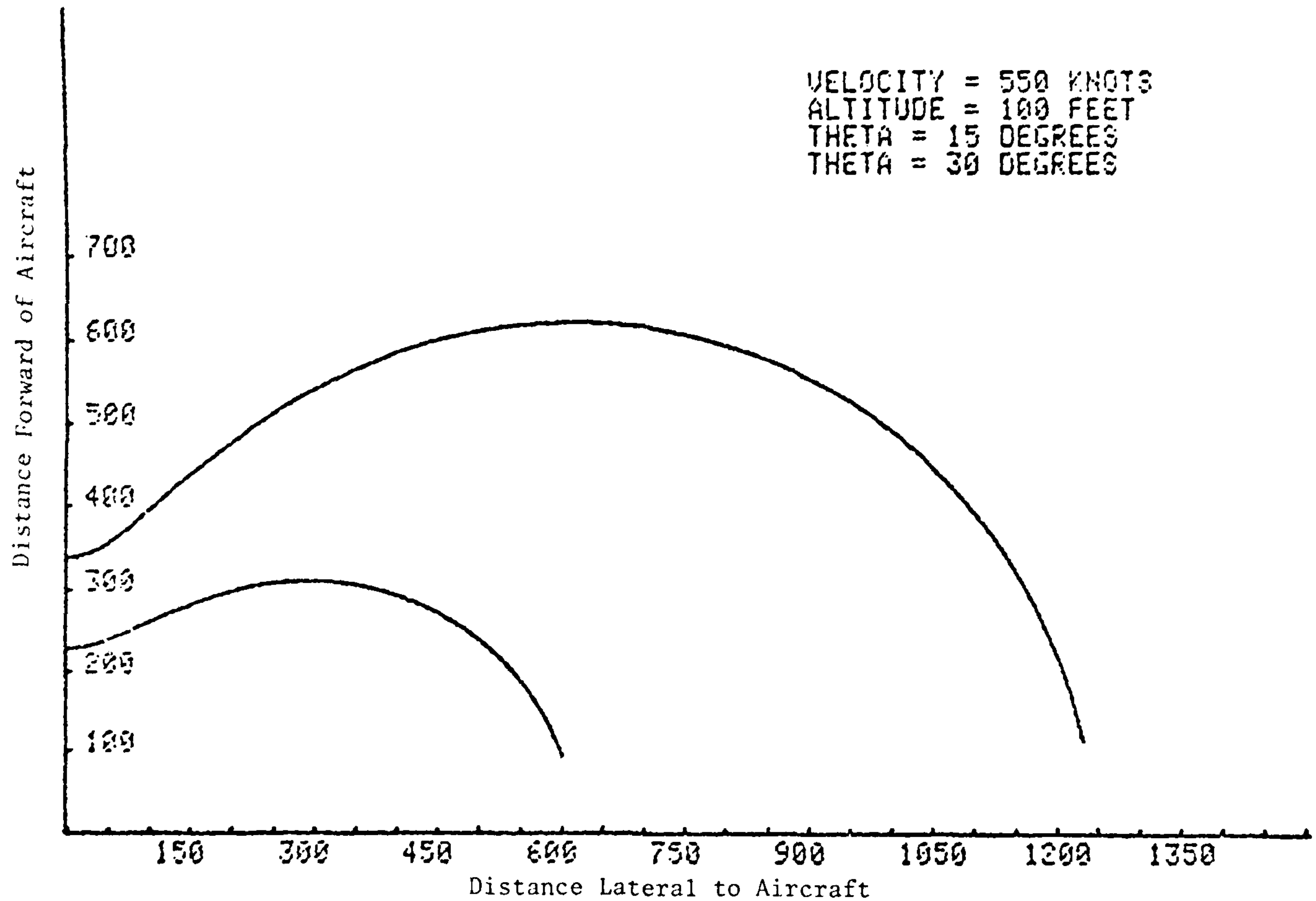



Figure C9. Blur zone as a function of altitude and velocity for fusion thresholds of $15^{o}$ $sec^{-1}$ and $30^{o}$ $sec^{-1}$ (velocity 550 knots, altitude 100 feet).

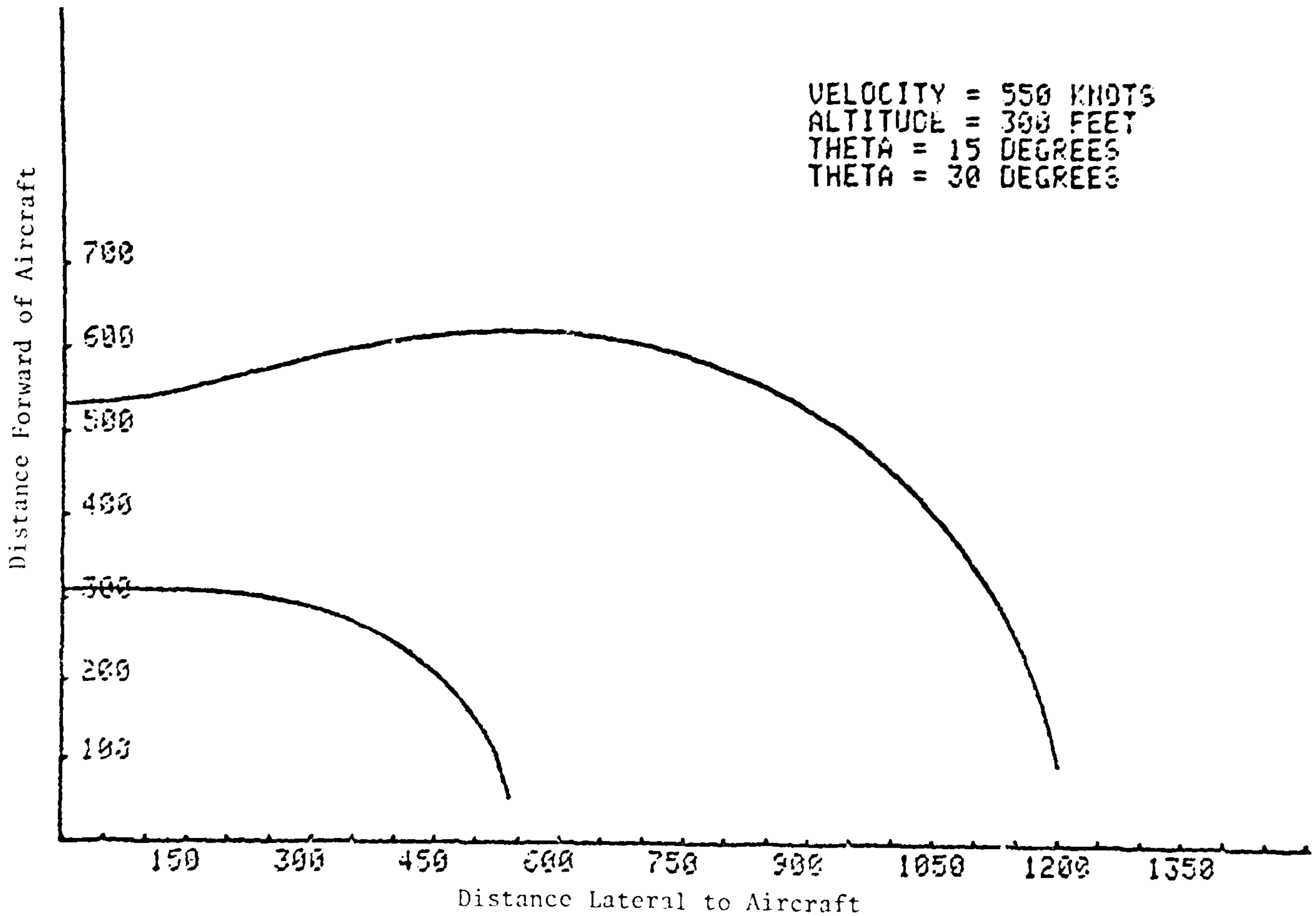



Figure C10. Blur zone as a function of altitude and velocity for fusion thresholds of $15^{\circ}$ $sec^{-1}$ and $30^{\circ}$ $sec^{-1}$ (velocity 550 knots, altitude 300 feet).

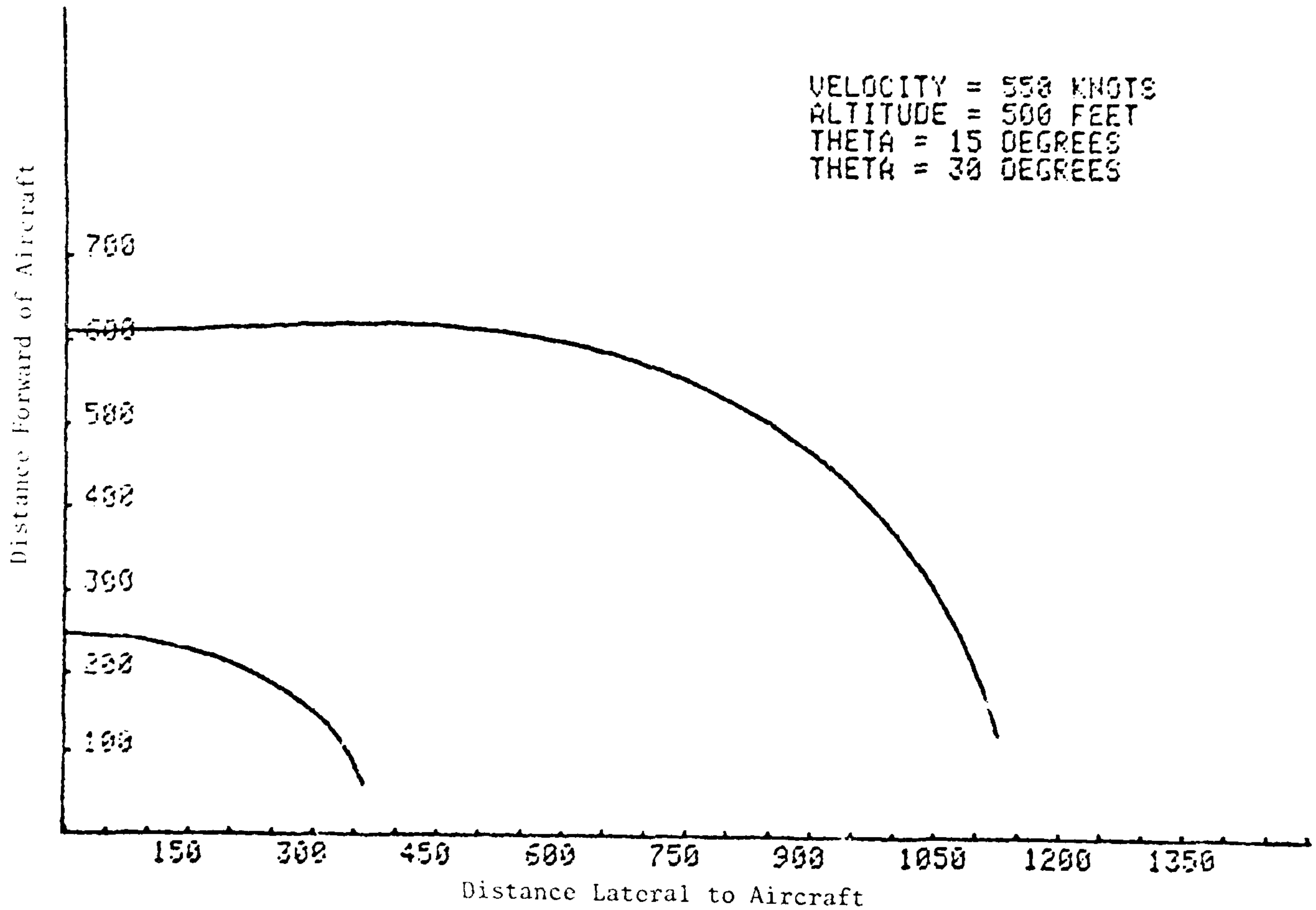



Figure C11. Blur zone as a function of altitude and velocity for fusion thresholds of $15^{0}$ $sec^{-1}$ and $30^{0}$ $sec^{-1}$ (velocity 550 knots, altitude 500 feet).

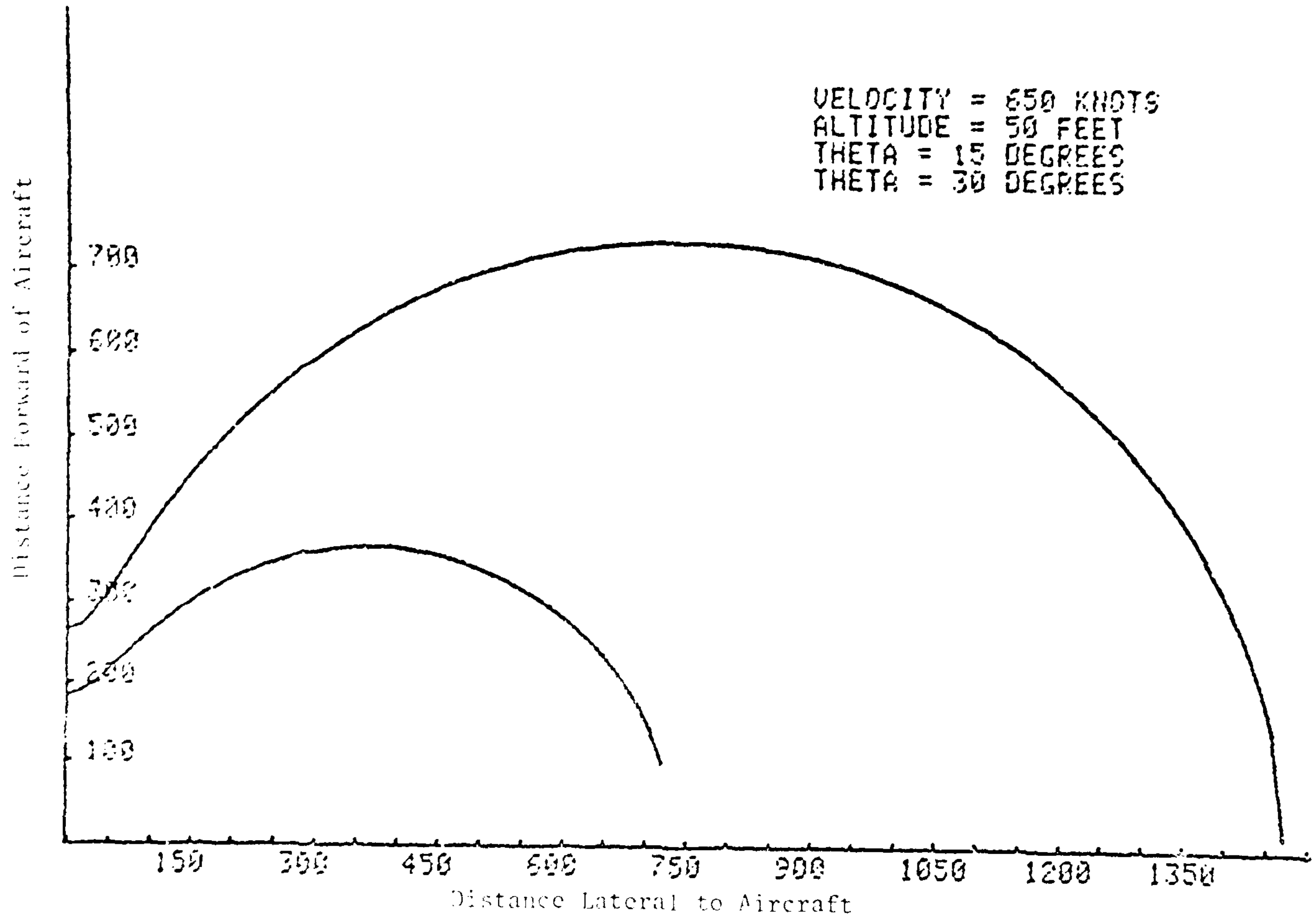



Figure [illegible]. Blur zone [illegible] function of altitude and velocity for fusion thresholds of $15^{0}$ sec$^{-1}$ and $30^{0}$ sec$^{-1}$ (velocity 650 knots, altitude 50 feet).

AD-A087 828 LOUISVILLE UNIV KY PERFORMANCE RESEARCH LAB F/G 5/10
DEPTH PERCEPTION IN VISUAL SIMULATION.(U)
AUG 80 G S HARKER, P D JONES F33615-78-C-0021
UNCLASSIFIED AFHRL-TR-80-19 NL

2 OF 2
AD A
087828

END
DATE
FILMED
9-80
DTIC

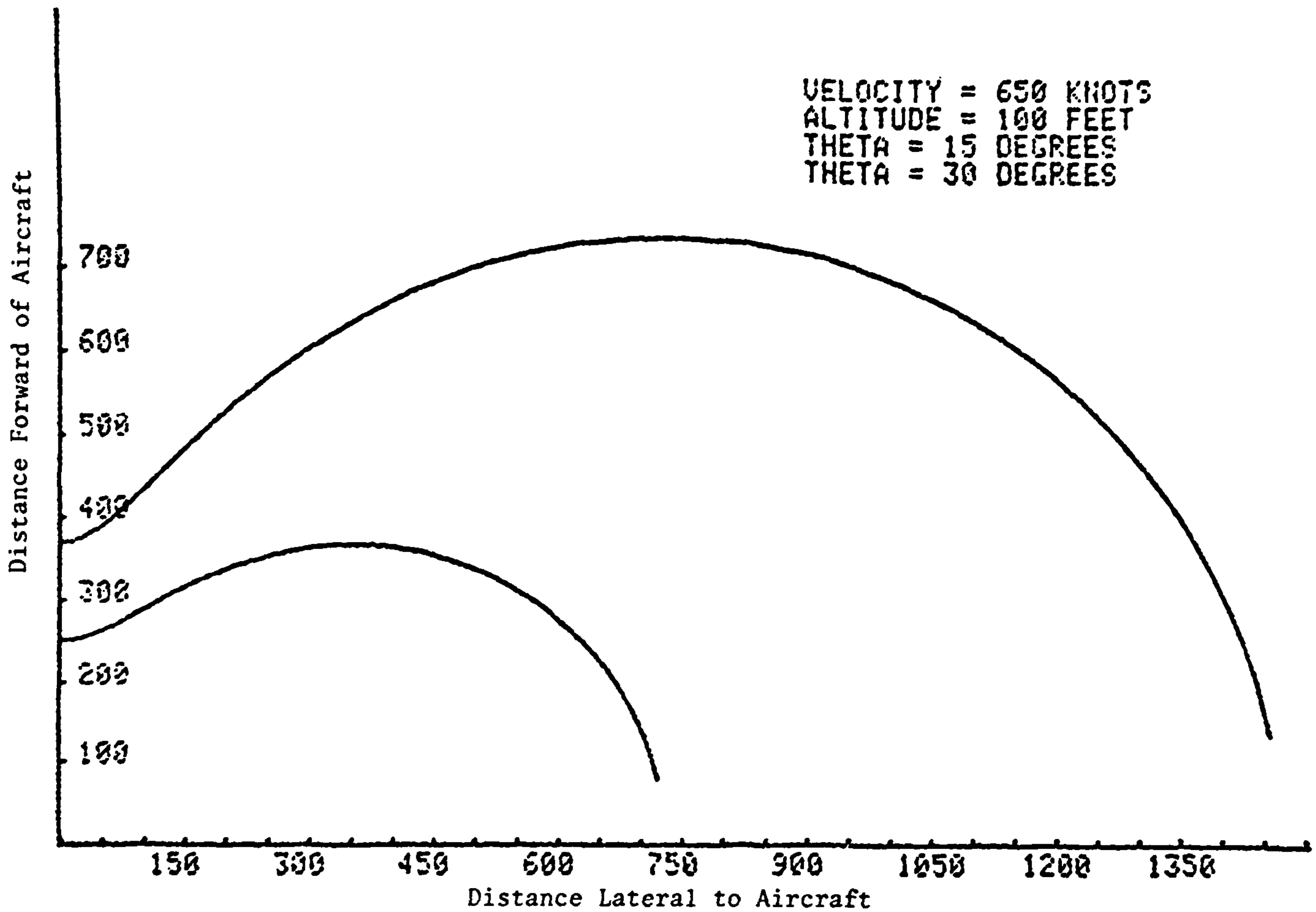



Figure C13. Blur zone as a function of altitude and velocity for fusion thresholds of $15^{\circ}$ $sec^{-1}$ and $30^{\circ}$ $sec^{-1}$ (velocity 650 knots, altitude 100 feet).

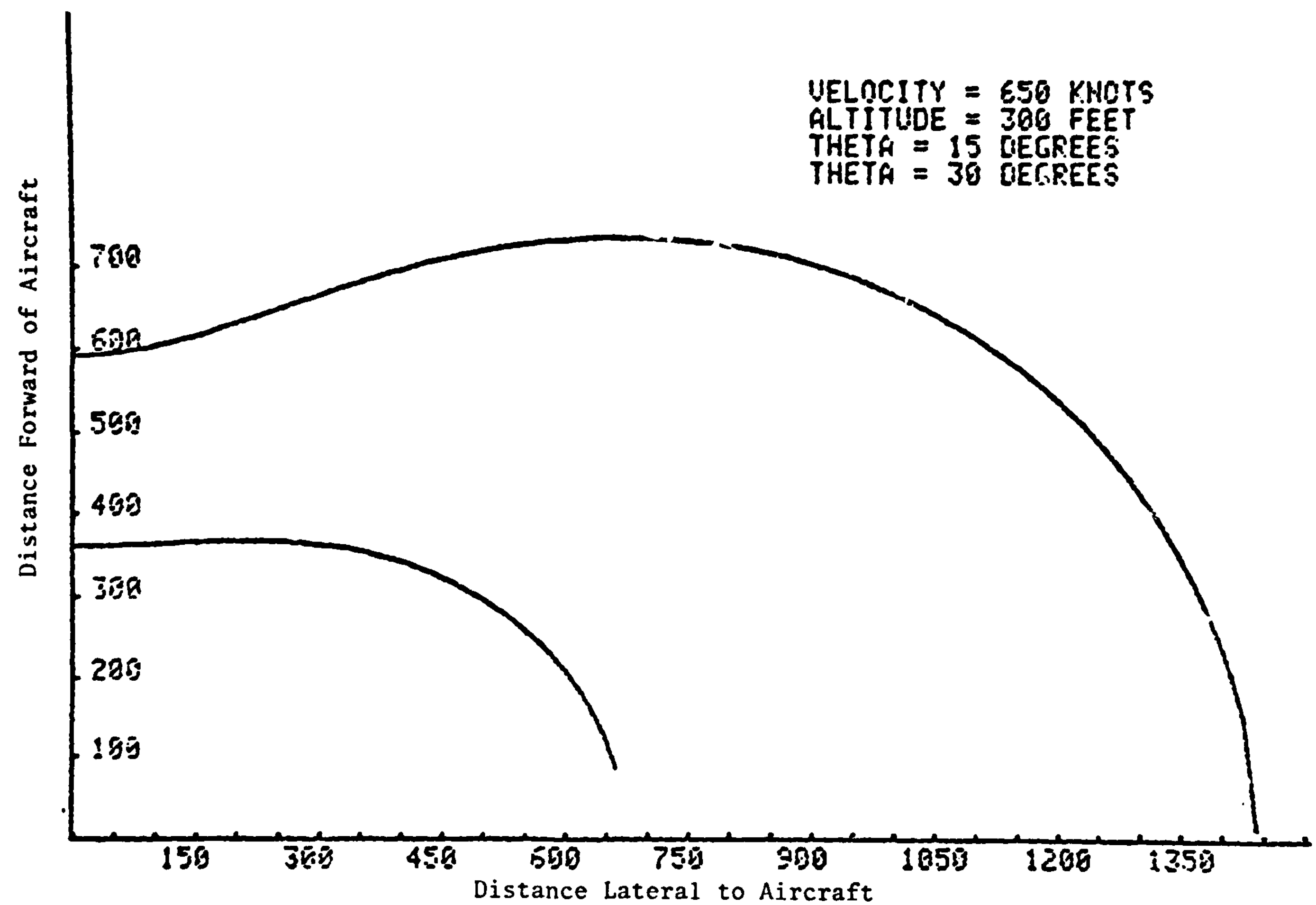



Figure C14. Blur zone as a function of altitude and velocity for fusion thresholds of $15^{o}$ $sec^{-1}$ and $30^{o}$ $sec^{-1}$ (velocity 650 knots, altitude 300 feet).

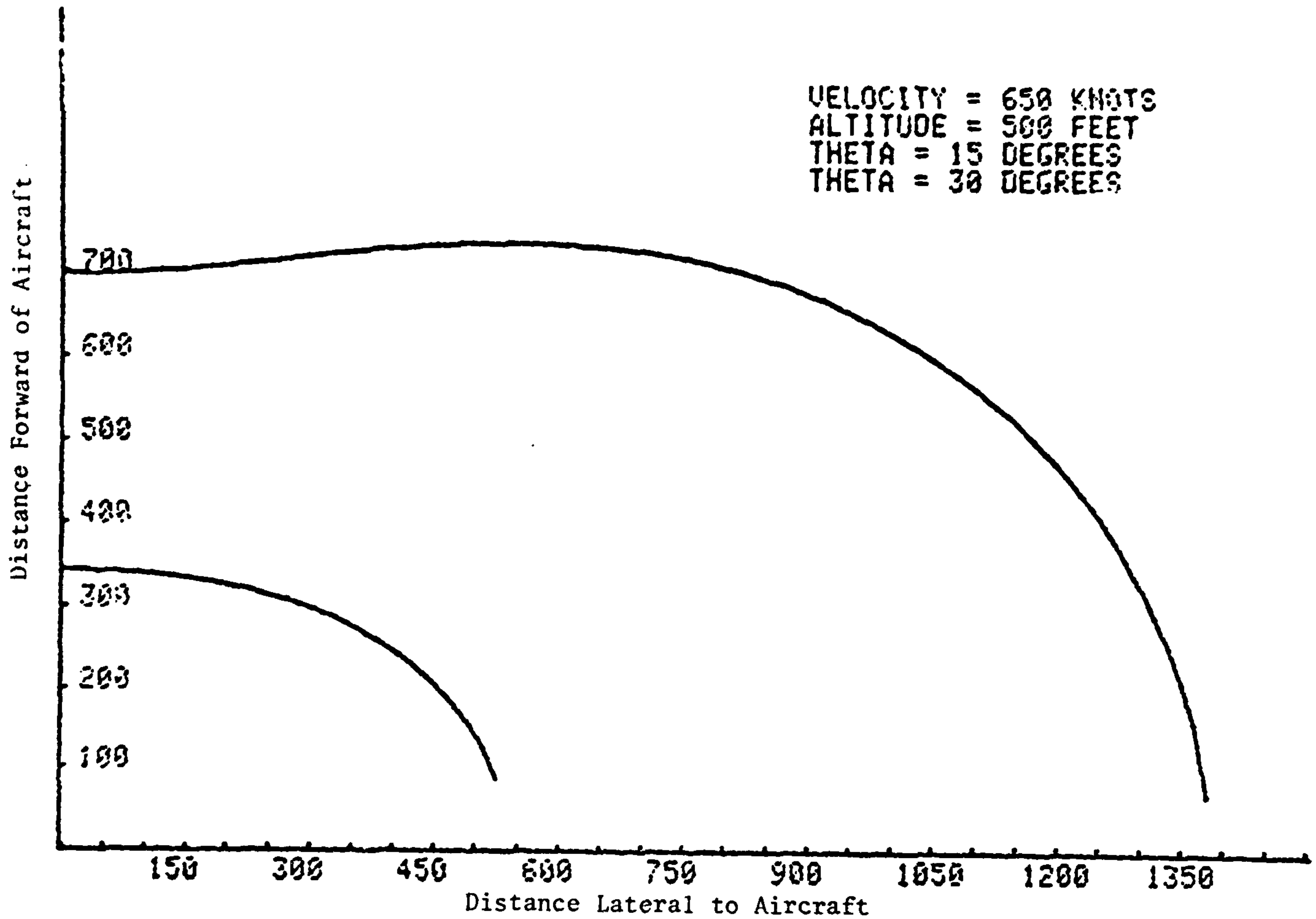



Figure C15. Blur zone as a function of altitude and velocity for fusion thresholds of $15^{\circ}$ $sec^{-1}$ and $30^{\circ}$ $sec^{-1}$ (velocity 650 knots, altitude 500 feet).