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**ANALYSIS OF VISUAL STIMULUS IN AIRCRAFT
APPROACH TO LANDING OPERATIONS**

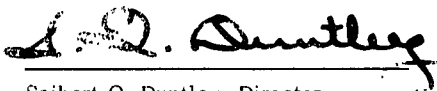
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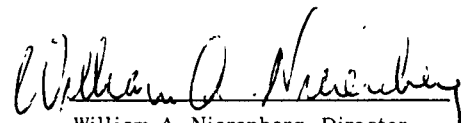
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ABSTRACT

This report analyses the visual cues available to pilots in an aircraft descent down the glide path toward the runway. Computer-generated movies have been used in vision experiments to determine the thresholds of judgment for correct glide path adherence. A computer software program, which accurately duplicates the effects of daytime fog upon a scene, has been developed and gives the capability for study of the visual function during landing operations in bad weather.

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1. INTRODUCTION

Accidents associated with landing operations continue to play a significant role in the overall vital statistics of aircraft operations.¹ Many of these accidents have been related to bad weather conditions in which the instrument landing system (ILS) approach has been used.

The ILS approach offers electronic guidance along the glide slope until visual contact with the runway is made. The final phase of the landing is then made by external visual stimulus. A clear understanding of the relative importance of the various components of the visual stimulus is essential to the determination of the weather conditions under which safe landings can be made and to the design of lighting systems and/or runway marking systems which provide more interpretable visual stimulus.

This report describes studies in which computer generated movies of runways as viewed during landing operations were used to determine thresholds of judgment as to whether the landing would be long or short. The basic data is then examined for its interpretability in terms of the angular rate of change of the desired point of touchdown. The report also describes efforts directed toward the generation of computer software which allows insertion of optically realistic fog into pictures of runways as they would appear from the cockpit.

1.1 VISUAL STIMULUS FOR APPROACH TO LANDING

The studies which have been conducted are directed toward those portions of the final approach which determine whether the landing will be short or long. The visual aspects of the flare – out and touchdown were not included in these studies. The visual cues involved in aircraft landing can be divided into two types depending upon whether the cue is temporally static or temporally dynamic. A static cue is one which exists at an instant of time as for example from a single photograph. A dynamic cue is one which involves a change in the appearance of the scene with time.

1. Nat'l Transportation Safety Board Seminar.

1.2 STATIC VISUAL CUES

If a runway is viewed from a point in space, information can be extracted from this static view. For example, if the true horizon is visible then the angle between the horizontal and the point of touchdown can be estimated, and it is therefore known that the glide slope required to reach the point of touchdown is numerically equal to that angle.

In many cases of interest, the horizon will not be visible, or if visible, will be significantly different than the true horizon. It is a matter of considerable interest to note that the true horizon need not be visible in order to make an estimate of required glide slope from a static view. The knowledge that the runway is rectangular and horizontal is sufficient to allow the mental extrapolation of the sides of the runway to an intersecting point which will fall upon the true horizon. The precision with which this estimate can be made is clearly dependent upon the location of the observer relative to the runway, the runway width and length and the atmospheric viewing conditions.

1.3 DYNAMIC VISUAL CUES

During final approach the runway scene is in a constant state of change. One visual cue which has long been recognized as important to aircraft landing is that when an aircraft is on a constant glide slope, the intersection of the glide slope with the ground plane is the one point in space which does not move in angular position throughout the final approach. All other points in space will move angularly away from this fixed reference point.

Figure 1 shows the basic geometrical relationships. For the purpose of our study, long landings are defined as those where actual touchdown occurs beyond the correct touchdown point. Short landings are defined as those where actual touchdown occurs before the correct touchdown point. To ease the analysis of different situations the derivations will be made with respect to the time remaining until touchdown, (T). All angular measurements are relative to the true horizon and depression is defined as positive.

If the glide slope is assumed constant, the actual touchdown point will be located below the horizon at an angle equal to the glide slope. The altitude of the observer (h) is:

$$h = vT \tan g \quad (1)$$

where v is ground velocity, g is the glide slope, and T is the time remaining until touchdown. The angle from the true horizon to the desired touchdown point is α :

$$\tan \alpha = \frac{h}{vT - m} \quad (2)$$

$$\alpha = \tan^{-1} \left[\frac{vT \tan g}{vT - m} \right] \quad (3)$$

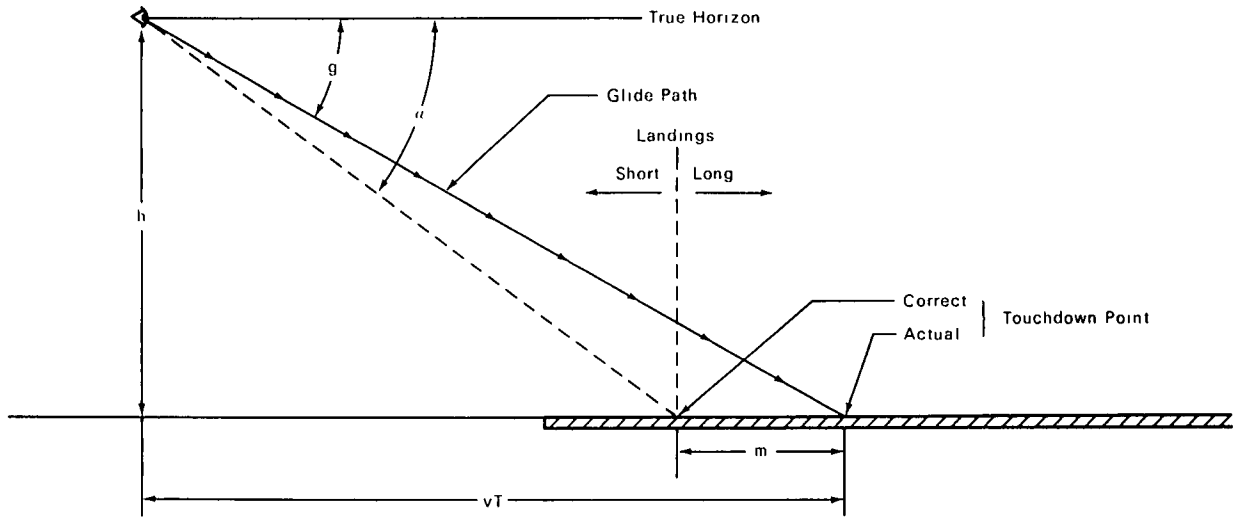


Fig. 1. Glide Path Geometry.

where the miss-distance (m) is positive for long landings and negative for short landings.

The rate of change of α is found by differentiating Eq. (3),

$$\frac{d\alpha}{dT} = \frac{-m v \tan g}{(vT - m)^2 + (vT \tan g)^2} \quad (4)$$

Equation (4) gives the rate of change of α with respect to the time remaining to touchdown (T). We are accustomed to thinking of rates with respect to positive time (t). Since we defined T as seconds until touchdown, the rate of change of T is negative with respect to time:

$$dT = -dt \quad (5)$$

and substituting in Eq. (4)

$$\frac{d\alpha}{dt} = \frac{m v \tan g}{(vT - m)^2 + (vT \tan g)^2} \quad (6)$$

Analysis of Eq. (6) shows that for long landings (positive m), $d\alpha/dt$ is positive and the angle α is increasing (moving down in the pilots visual field). In a short landing situation (negative m), $d\alpha/dt$ is negative and the angle α is decreasing (moving up in the pilots visual field). If the miss distance is zero then $d\alpha/dt$ is zero and $\alpha = g$.

If the glide path is properly oriented with respect to the runway then the actual touchdown point and the desired touchdown point will coincide. Under these conditions the desired touchdown point will have no relative motion within the pilots visual field as referenced from the true horizon. If the pilot senses relative motion of the desired touchdown point, then he knows his glide path will not intercept the desired touchdown point. Correct judgement of the direction of this relative motion indicates to the pilot whether his approach will result in a long or short landing. If the desired touchdown point appears to move up in his visual field, he is making a short approach. If the desired touchdown point appears to move down in his visual field, he is making a long approach.

The size of modern commercial aircraft requires that we consider a further refinement of the mathematics. The pilot is physically located at a significant distance above the landing gear. If we assume that the landing gear is located on the glide path, then the pilot's eyes are travelling parallel to and above the glide path. Figure 2 shows the geometrical relationships with this added complexity. The vertical displacement (h_o) between the landing gear and pilot's eyes is measured with the aircraft in the descent altitude. This vertical displacement would be the altitude of the pilot's eyes above the runway level at the moment the landing gear reached the touchdown point if there were no flare-out maneuver. The visual reference which remains fixed within the pilot's field of view will no longer be the actual touchdown point. The fixed visual reference will be located beyond the actual touchdown point by a distance D_s ,

$$D_s = \frac{h_o}{\tan g} \quad (7)$$

where, as before, g is the angle of the glide slope.

As viewed from the pilot's position, the depression angle from the true horizon to the correct visual reference point is defined to be θ . As before the depression angle from the true horizon to the correct touchdown point is α . The aircraft ground velocity is v and time T is the time remaining until actual touchdown occurs. The altitude of the landing gear is h , measured relative to runway level. The miss distance m is positive when actual touchdown is beyond the correct touchdown point, i.e., long landings. The miss distance is defined as negative for actual touchdowns occurring before the correct touchdown point is reached, i.e., short landings.

For an aircraft with a vertical displacement h_o of 40 feet descending on a 3-degree glide slope the fixed visual reference will be located 763 feet beyond the point of touchdown. Touchdown will occur prior to arrival at the fixed visual reference. The pilot using the rate of change of a point within his visual field to measure his adherence to the proper glide path must be aware that the correct visual reference is located beyond the desired touchdown point by an amount given by equation (7). It is readily apparent that if the pilot uses the desired touchdown point as if it were the correct visual reference and aligns his glide path for no relative motion of this point, then he will land short.

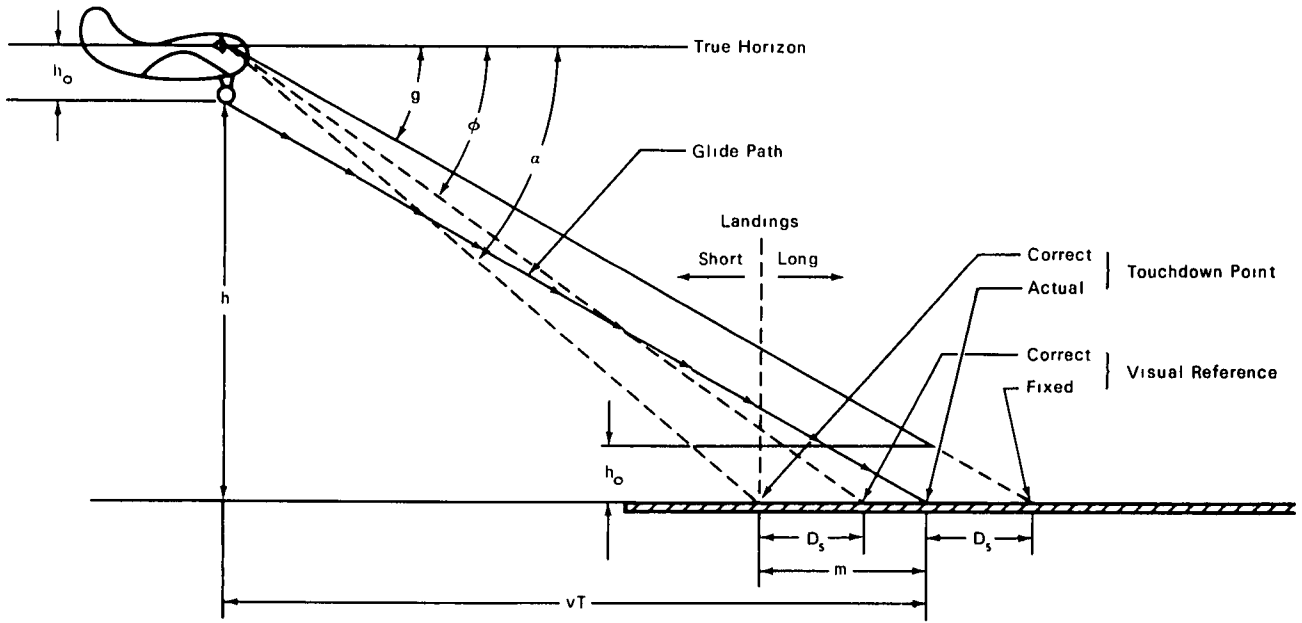


Fig. 2. Glide Path Geometry with Vertical Displacement.

From Fig. 2, the altitude of the pilot h_p is

$$h_p = h + h_o \quad (8)$$

and substituting Eqs. (1) and (7) then

$$h_p = (vT + D_s) \tan g \quad (9)$$

The depression angle to the desired touchdown point α is

$$\alpha = \tan^{-1} \left[\frac{(vT + D_s) \tan g}{vT - m} \right] \quad (10)$$

The rate of change of α is found by differentiating Eq. (10) and substituting Eq. (5),

$$\frac{d\alpha}{dt} = \frac{(m + D_s) v \tan g}{(vT - m)^2 + (vT + D_s)^2 \tan^2 g} \quad (11)$$

The depression angle to the correct visual reference θ is

$$\theta = \tan^{-1} \left[\frac{(vT + D_s) \tan g}{(vT - m + D_s)} \right] \quad (12)$$

The rate of change of θ is found by differentiating Eq. (12) and substituting Eq. (5),

$$\frac{d\theta}{dt} = \frac{m v \tan g}{(vT - m + D_s)^2 + (vT + D_s)^2 \tan^2 g} \quad (13)$$

Since the problem of short landings is of such immediate concern let us examine a case where the glide path is properly aligned with the runway to affect touchdown at the desired point. If the pilot makes no corrections to the glide path his miss distance will be zero. However, let us assume that he is using the desired touchdown point as his visual reference. Using Eq. (11) and $m = 0$ we find that

$$\left. \frac{d\alpha}{dT} \right|_{m=0} = \frac{D_s v \tan g}{(vT)^2 + (vT + D_s)^2 \tan^2 g} \quad (14)$$

and

$$\left. \frac{d\alpha}{dt} \right|_{m=0} = \frac{h_o v}{(vT)^2 + (vT + D_s)^2 \tan^2 g} \quad (15)$$

Examination of Eq. (15) shows that the rate of change of α increases as the time until touchdown T decreases. If at some point this rate of change exceeds the pilot's threshold he will interpret it as signaling a departure from the correct glide path. Since α is increasing with time the touchdown point will be moving down in his visual field and he may well conclude that he is making a long landing. This erroneous

decision caused by using the desired touchdown point as a visual reference would lead to corrective action to avoid the "long landing." The result would be a touchdown short of the desired touchdown point.

The rate of change of the depression angle of the desired touchdown point has been plotted in Fig. 3 for the case of a zero miss distance and pilot vertical displacement of 10 and 40 feet. Figure 3(a) is for a 3-degree glide slope at 200 mph while Fig. 3(b) is for the 3-degree glide slope at 135 mph. These rates increase very rapidly as the range closes.

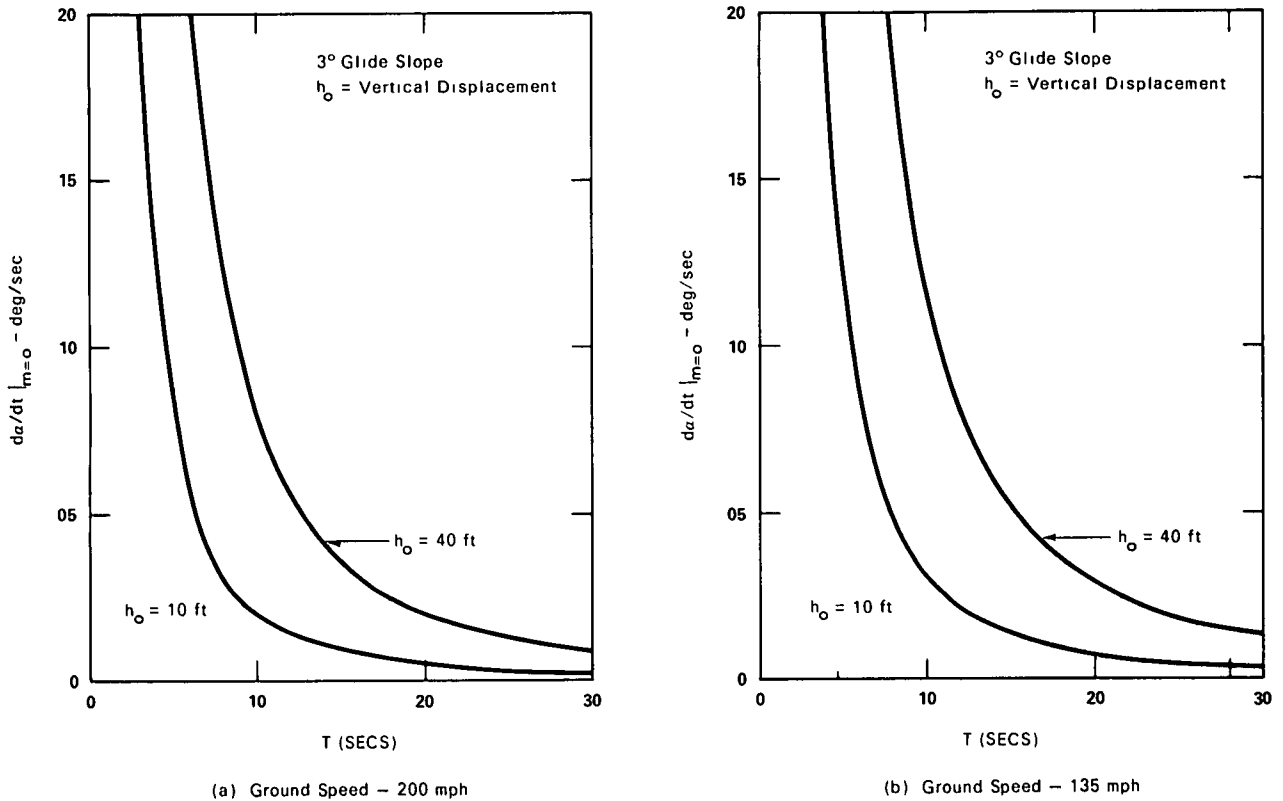


Fig. 3. Rate of Change of Touchdown Point for Correct Glide Path.

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2. COMPUTER GENERATED LANDING FILM EXPERIMENT

An experiment was performed using Visibility Laboratory generated movies as visual stimuli. Its purpose was to document the performance of observers charged with the task of judging adherence to a specified glide path. The data from this experiment was used to determine thresholds of long-short judgments. The information thus obtained is needed to analyze and predict conditions of weather and landing geometries which would or could reduce, destroy, mask or change these visual cues to the extent that a proper landing could not be made or that an improper landing would be made.

The observers were shown a series of computer-generated films depicting the last minute of descent down a glide slope prior to touchdown. His *a priori* knowledge consists of the dimensions of a level runway, the glide slope, the ground speed, the rate of descent, and the location of the optimum touchdown point. His visual task is to make subjective decisions as to whether the glide path in the film will intercept the runway long or short of the desired touchdown point.

The films used as visual stimuli were generated at the Visibility Laboratory's computer image processing facility. The system software and hardware are nonreal time. The stimuli generated are therefore of the "open-loop" type. This means that the observer can make judgments which can be recorded, but he is unable to translate his judgments into actions which will alter the dynamics of the situation.

2.1 RUNWAY BUILD PROGRAM

The runway build software program constructs a two-dimensional perspective view relative to the horizon of a level rectangular runway as seen from an on-runway-axis location at a specific range and altitude. Figure 4 shows pictorially what the software program creates. The scene generated is a stylized runway devoid of any markings, numbers, or structural surroundings. The program requires as inputs:

1. Runway length
2. Runway width
3. Observer's altitude
4. Observer's distance from the end of the runway
5. Relative luminance of the sky
6. Relative luminance of the ground
7. Relative luminance of the runway
8. The location of the horizon in the scene
9. The angular resolution with which the scene is to be generated
10. Meteorological range, a number related to visibility which allows the program to compute the proper contrast reduction for each portion of the field of view.

The images generated are displayed on a cathode ray tube and photographed with a 16mm Bolex single frame movie camera. By starting with an appropriate altitude and distance and then properly incrementing both in accordance with the desired glide slope, the landing sequence film is generated one frame at a time. The landing is made short or long by choosing the starting altitude and range such that the glide slope intercepts the runway long or short by the desired amount.

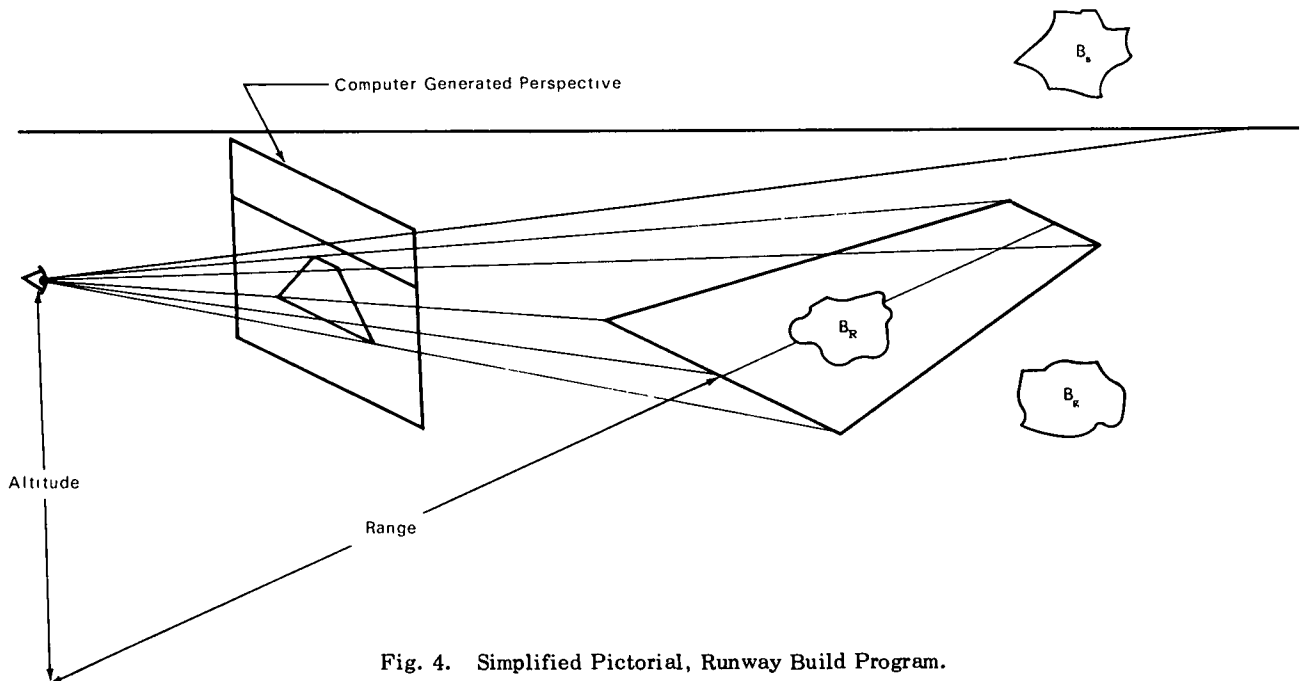


Fig. 4. Simplified Pictorial, Runway Build Program.

2.2 LANDING GEOMETRY

All films used in these tests assume a 3-degree glide slope, a ground speed of 200 mph (293.3 ft/sec) and a descent rate of 15.4 ft/sec (922 ft/min). The vertical displacement of the pilot is 20 feet above the landing gear. The field of view is always $8^\circ \times 8^\circ$. The runway assumed is 9000 feet long and 200 feet wide. The inherent relative luminances are: sky equal to 2, ground equal to .5, and the runway equal to 1.

The desired touchdown point was selected as the leading edge of the runway. Although unrealistic, this was done because the available runway build program did not allow runway markings, and the leading edge of the runway is the only prominent visual reference point. The correct visual reference is thus located 381 feet down the runway from the near end. This would give a pilot altitude of 20 feet when touchdown occurs at the near end of the runway on a correct approach. Sequences were generated with miss distances of ± 250 feet, ± 500 feet, ± 1000 feet, and ± 2000 feet.

The starting ground range is 15 600 feet in all sequences. This was done so that the leading edge of the runway subtends the same angle at the start of all film sequences. This means that the ground distance traveled prior to touchdown will be different in each sequence. Each sequence is terminated at actual touchdown with a pilot altitude of 20 feet. The duration of the sequences thus vary from 46 seconds for the 2000 feet short to 60 seconds for the 2000 feet long.

Figure 5 shows the landing geometries with starting altitudes and ranges. Figure 6(a) and 6(b) are typical single frames that would occur in a sequence generated for the correct glide path.

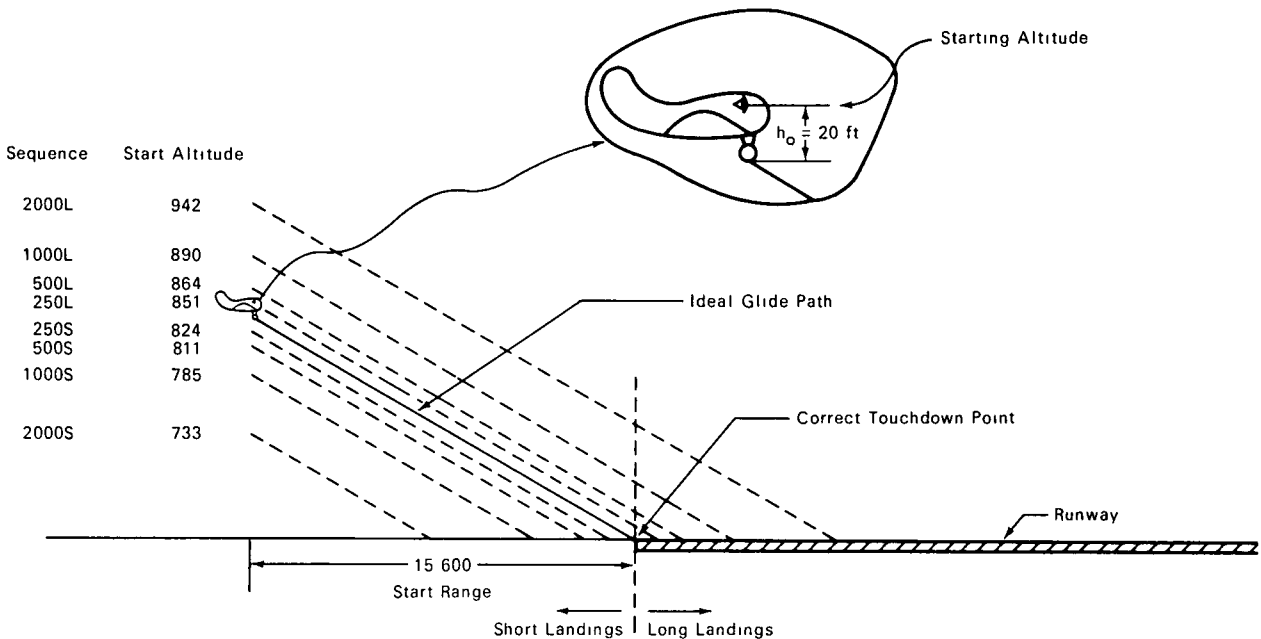
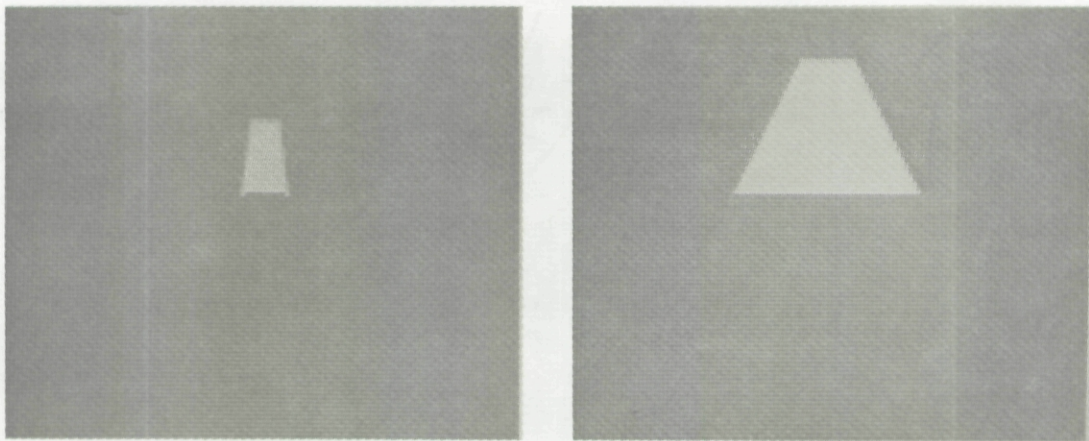


Fig. 5. Landing Film Geometry.



(a) Range 15600 ft

(b) Range 3800 ft

Fig. 6. Computer Generated Runway, Ideal Glide Path.

We are interested in the angle from the horizon to the correct visual reference θ and the rate of change of this angle with respect to the time remaining until touchdown T . These equations were derived earlier as Eqs. (12) and (13) and are plotted in Figs. 7 and 8 for the eight miss distances used in the psychophysics experiment.

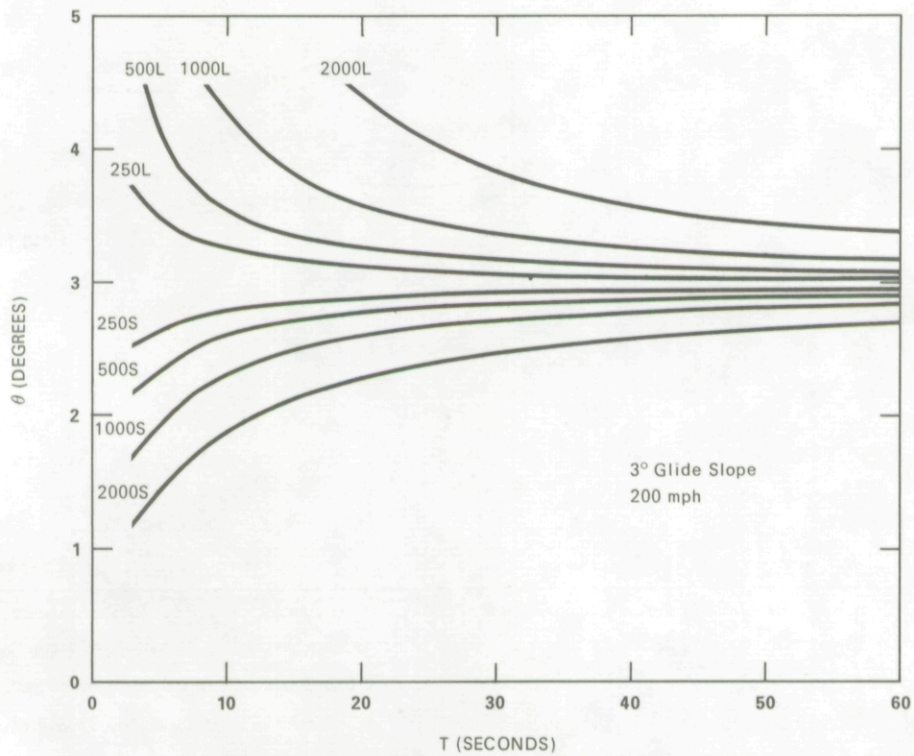


Fig. 7. Angle to Correct Visual Reference.

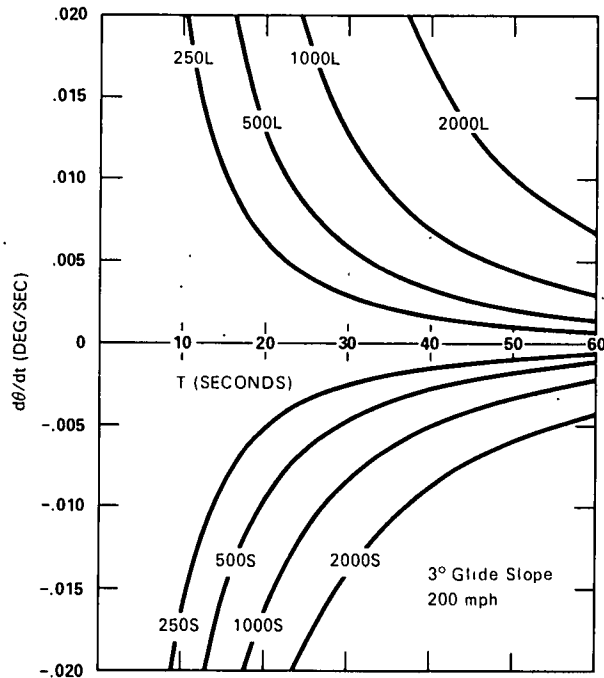


Fig. 8. Rate of Change of Correct Visual Reference.

The leading edge of the runway, the desired touchdown point, is a prominent, easily identified, fixation point. The angle α from the horizon to the leading edge of the runway was derived as Eq. (10), and the rate of change of this angle with the time remaining until touchdown was derived as Eq. (11). Equations (10) and (11) are plotted in Figs. 9 and 10 for the eight miss distances used in the experiment.

2.3 EXPERIMENTAL TECHNIQUE

A free choice technique was used. The observers were requested to make high confidence decisions even though they knew that every approach was either long or short. A complete data run consists of ten random presentations of each landing configuration, a total of 80 landing approaches. The data run was divided into four separate 20-minute sessions.

The observer is located so that the presentation on the screen subtends a field of view that is $8^\circ \times 8^\circ$. The horizon in the film and the eyes of the observer are located in a horizontal plane. Figure 11 shows the facilities used in the experimental setup. The observer operates a three-position toggle switch which is time synchronized with the film presentation. Since the center position indicates no decision, the observer uses the switch to indicate whether he believes the landing will be long or short. The observer operates the switch throughout the complete sequence so that a time record of his responses from start to finish is made.

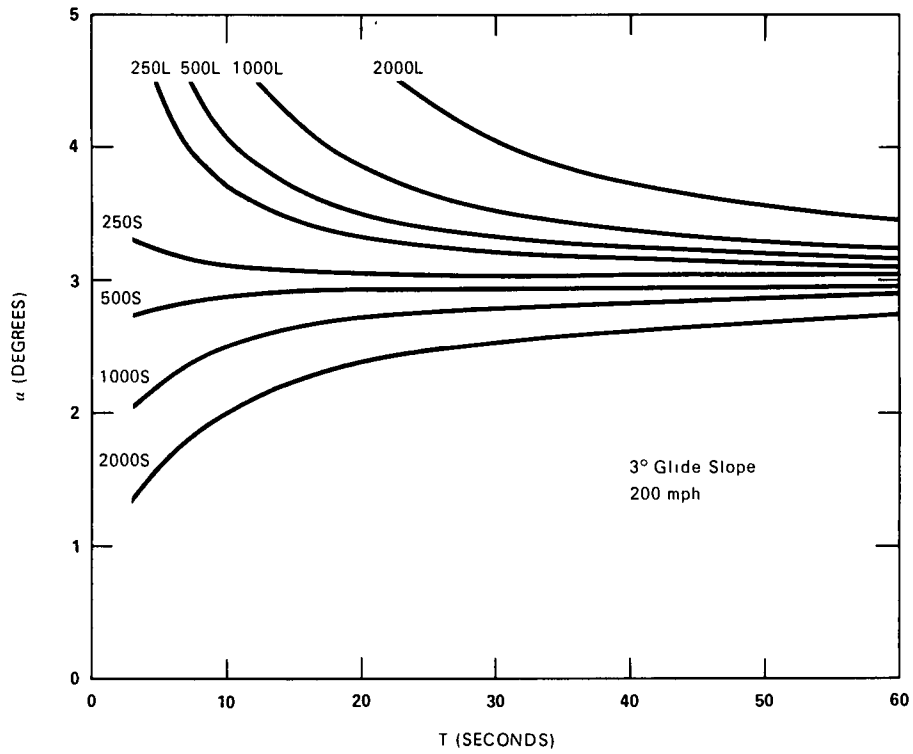


Fig. 9. Angle to Correct Touchdown Point.

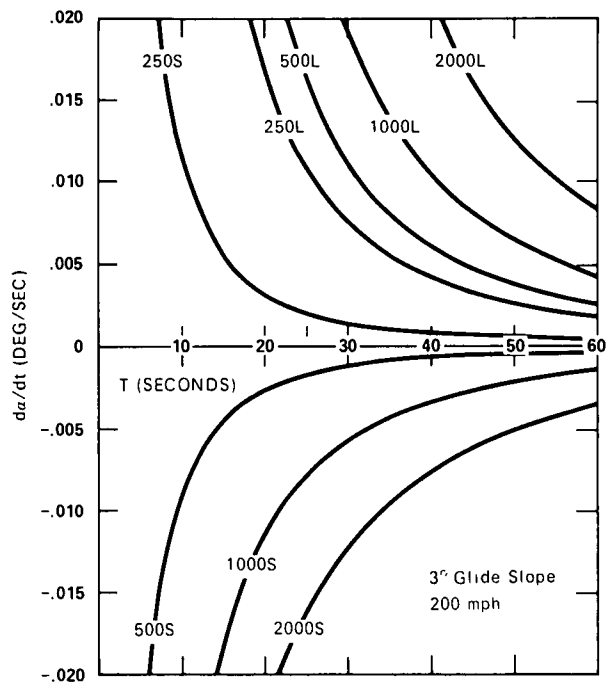


Fig. 10. Rate of Change of Correct Touchdown Point.

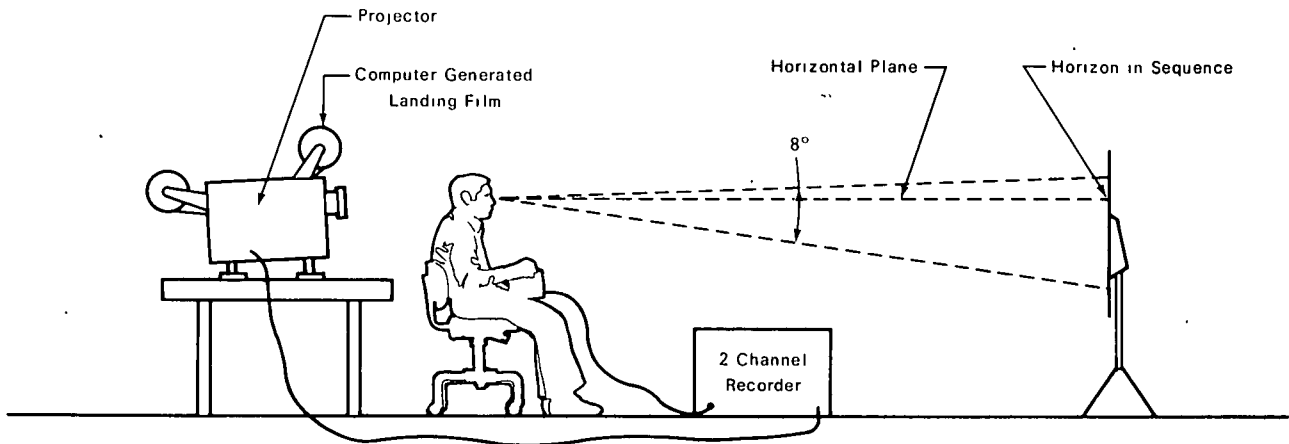


Fig. 11. Facilities, Runway Landing Psychophysics Experiment.

2.4 OBSERVERS

- RLS – This 40 year old male observer has an extensive background in vision experiments both as an observer and as an experiment conductor. His background includes extensive experience as a flight engineer and co-pilot. He currently holds no pilot's license.
- WSF – A 34 year old male commercial pilot with over 6500 hours. He has received Category II landing training, but has never made an actual Category II landing.
- JWS – A 44 year old male commercial pilot with over 9000 hours. He has received Category II landing training and has made two Category II landings in his career.
- AW – A male commercial pilot with 14 000 hours. He has not received Category II, IIIA, or IIIB landing training and has never made a Category II landing.
- EEO – A 50 year old male commercial pilot with over 22 000 hours. He has not received Category II, IIIA, or IIIB landing training but he has made 15 landings in Category II or worse weather.

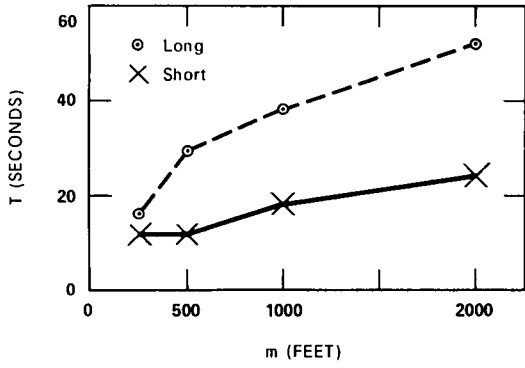
2.5 EXPERIMENTAL DATA

Psychophysics experiments with computer-generated landing films.

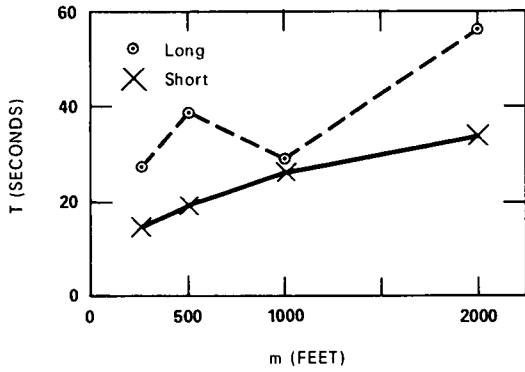
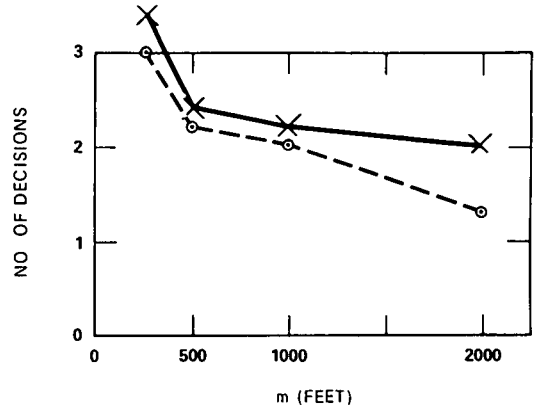
TYPE I EXPERIMENT

Computer-generated films made with a meteorological range of infinity, i.e., there are no effects upon the runway images due to the intervening atmosphere. The miss distances are ± 250 , ± 500 , ± 1000 , and ± 2000 feet.

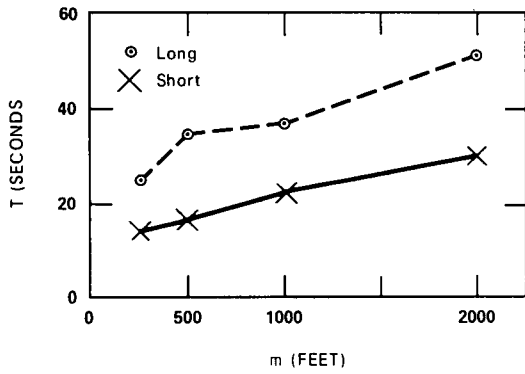
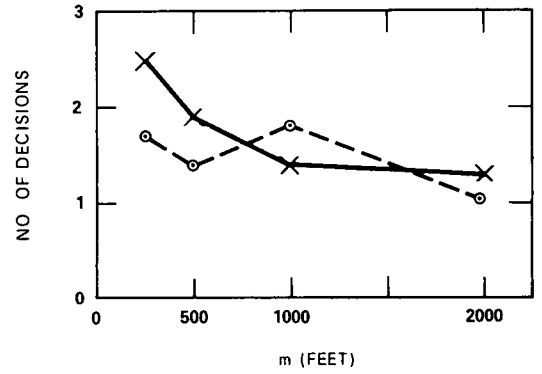
Figure 12 gives the performance of observer RLS in four runs through the experiment. It gives the time remaining until touchdown versus the miss distance. The time is measured from the instant of his last decision. Also given is the average number of decisions that were made in each case. Figure 13 is the average response of RLS for all four data runs. Therefore each point is the result of 40 viewings of each landing configuration. This observer's last decision was correct more than 95% of the time.



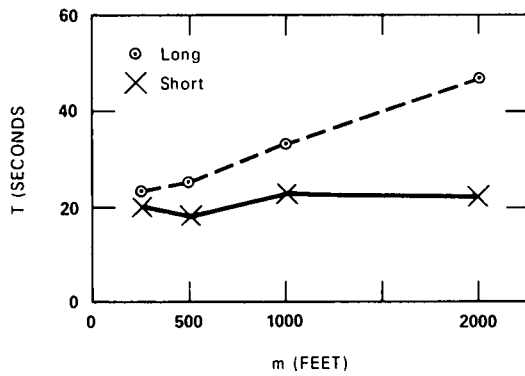
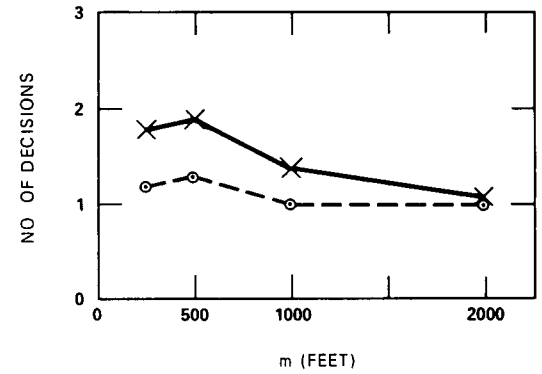
(a) Run 1



(b) Run 2



(c) Run 3



(d) Run 4

Fig. 12. Observer RLS, 4 Runs, T at Time of Last Decision and Number of Decisions, Variable Miss Distance, $R_{MET} = \infty$.

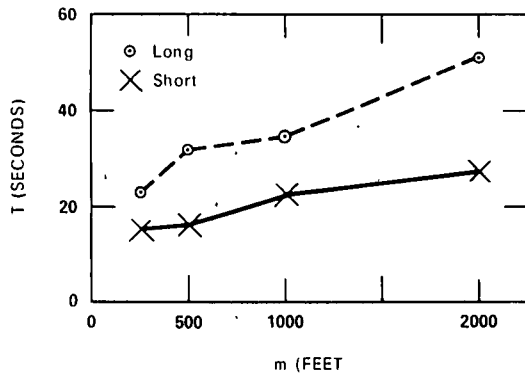


Fig. 13. Average Response of RLS, Runs 1-4, T at Time of Last Decision, Variable Miss Distance, $R_{MET} = \infty$.

The four commercial airline pilots' results are shown in Fig. 14. Figure 15 is the average response of these four observers. Again their last response was correct 95% of the time. Observer EEO had the tendency to call the 250 long landings as short, a bias that he demonstrated in 7 of the 10 times.

The average response of the five different observers is given in Fig. 16. This data from the average response will be used in the analysis.

TYPE II EXPERIMENT

Same as Type I but with an external reference added to the scene by the use of a secondary projector. The external reference is a straight line parallel to the horizon and located a fixed number of degrees below the horizon in the scene.

Figure 17 gives the performance of RLS for the short landing configurations from three complete data runs with fixed horizontal references of 3, 4, and 5 degrees below the horizon.

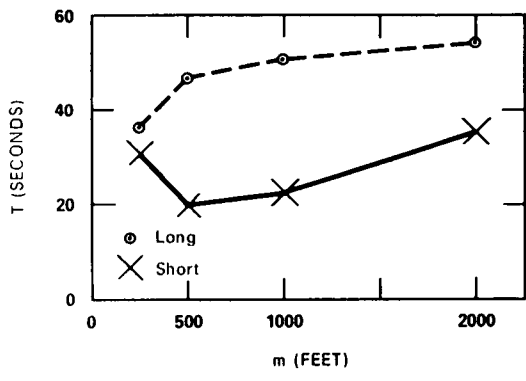
Figure 18 gives the performance of RLS for the long landing configurations from three complete data runs with fixed horizontal references of 3, 4, and 5 degrees below the horizon.

Figure 19 shows the average performance of the five observers for a data run with a fixed horizontal reference at 4 degrees.

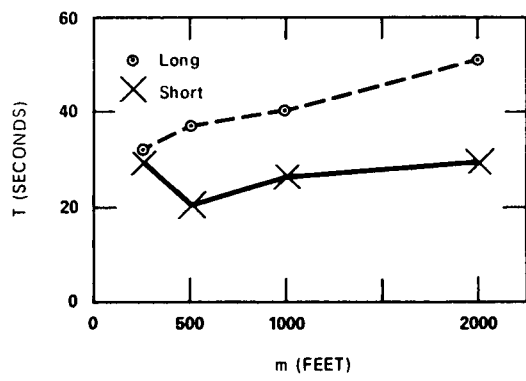
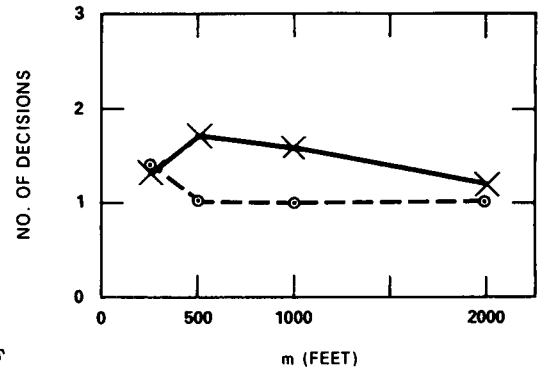
TYPE III EXPERIMENT

A test using landing sequences with a fixed miss distance of ± 2000 feet but with a meteorological range of either 7.5, 10, 15, or 20 miles. This is ten random presentations of each of the eight combinations of miss distance and meteorological range.

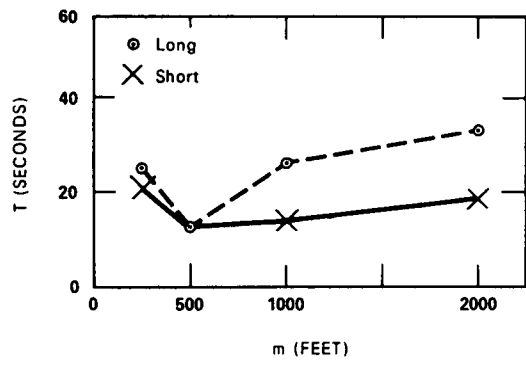
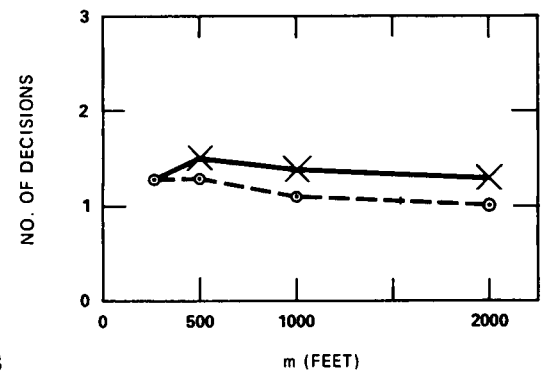
Figure 20 shows the performance of observer RLS, for the ± 2000 feet miss distance experiment with variable meteorological range.



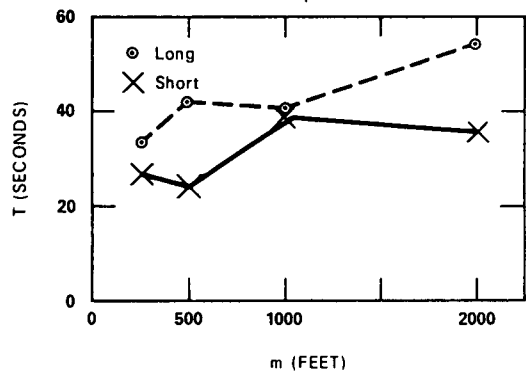
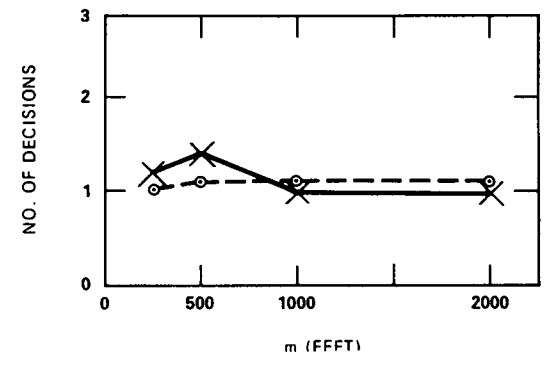
(a) Observer WSF



(b) Observer JWS



(c) Observer AW



(d) Observer EEO

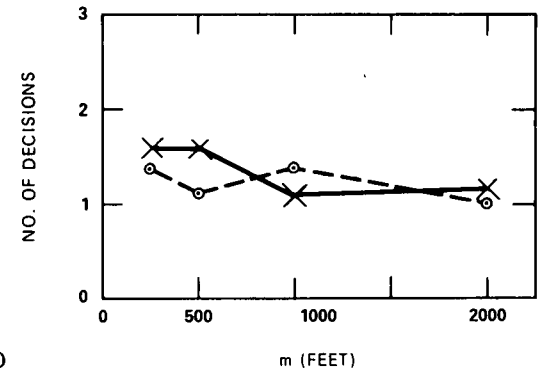


Fig. 14. Pilot Observers, T at Time of Last Decision and Number of Decisions, Variable Miss Distance, $R_{MET} = \infty$.

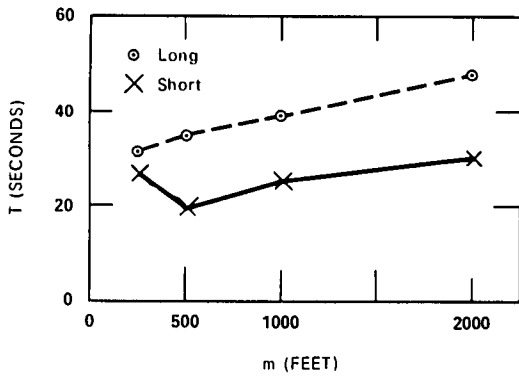


Fig. 15. Average Response of Four Pilot Observers, T at Time of Last Decision, Variable Miss Distance, $R_{MET} = \infty$.

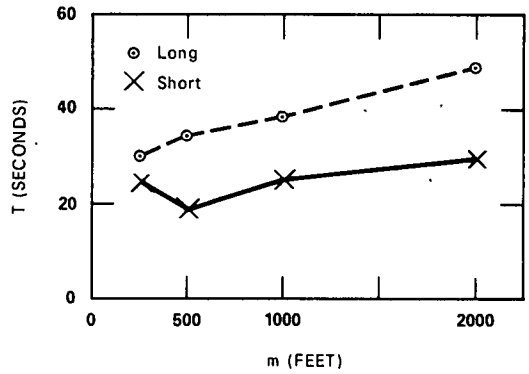


Fig. 16. Average Response of Five Observers, T at Time of Last Decision, Variable Miss Distance, $R_{MET} = \infty$.

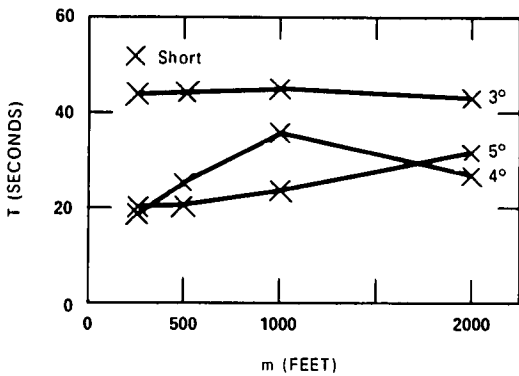


Fig. 17. Observer RLS, with External Reference, T at Time of Last Decision, Variable Short Miss Distance, $R_{MET} = \infty$.

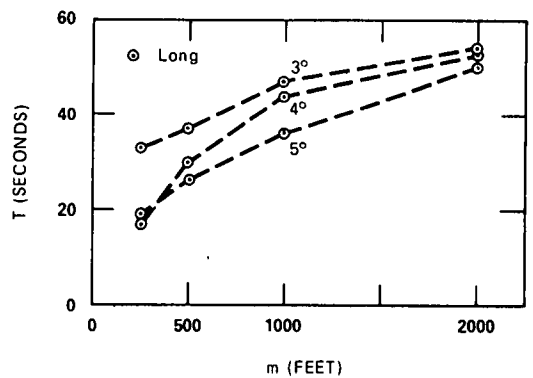


Fig. 18. Observer RLS, with External Reference, T at Time of Last Decision, Variable Long Miss Distance, $R_{MET} = \infty$.

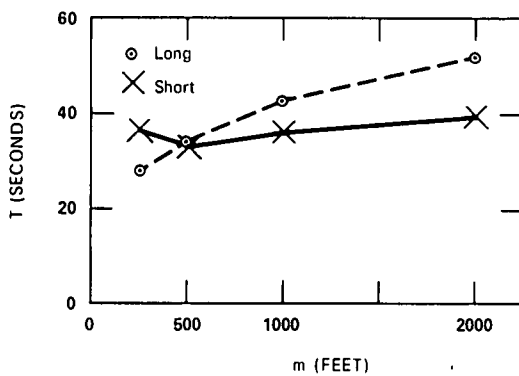


Fig. 19. Average Response of Four Pilots, External 4° Reference, T at Time of Last Decision, Variable Miss Distance, $R_{MET} = \infty$, 1 Run.

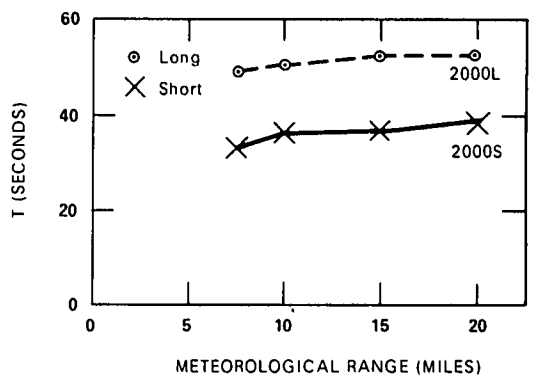


Fig. 20. Observer RLS, T at Time of Last Decision, Variable Meteorological Range, 2000-Foot Miss Distance.

2.6 ANALYSIS

If the observer was utilizing the displacement of either the correct visual reference or the leading edge of the runway as a primary visual cue his subjective decisions should all occur when his fixation point has changed by some finite amount. In Figs. 21 and 22 the five observers average data from Fig. 16 has been indicated on the curves of Figs. 7 and 9 which show the angles to the correct visual reference and the end of the runway.

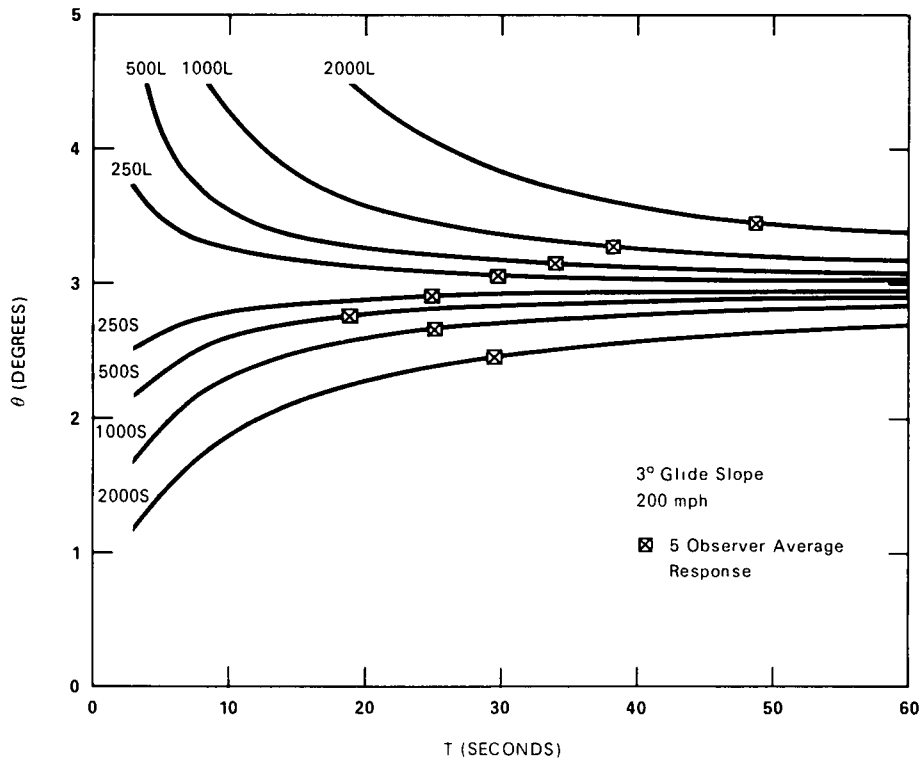


Fig. 21. Angle to Correct Visual Reference.

Each of the computer-generated movies started at a time before touchdown which is a function of the magnitude of the touchdown error. For this reason Figs. 21 and 22 do not clearly indicate the change in angular location which has taken place between the start of the film and the time of final decision. Fig. 23 is a plot of the absolute magnitude of this angular change as a function of the miss distance. It is of considerable interest to note that 6 of the 8 averaged data points fall within the relatively narrow range between 0.095 and 0.14 degrees.

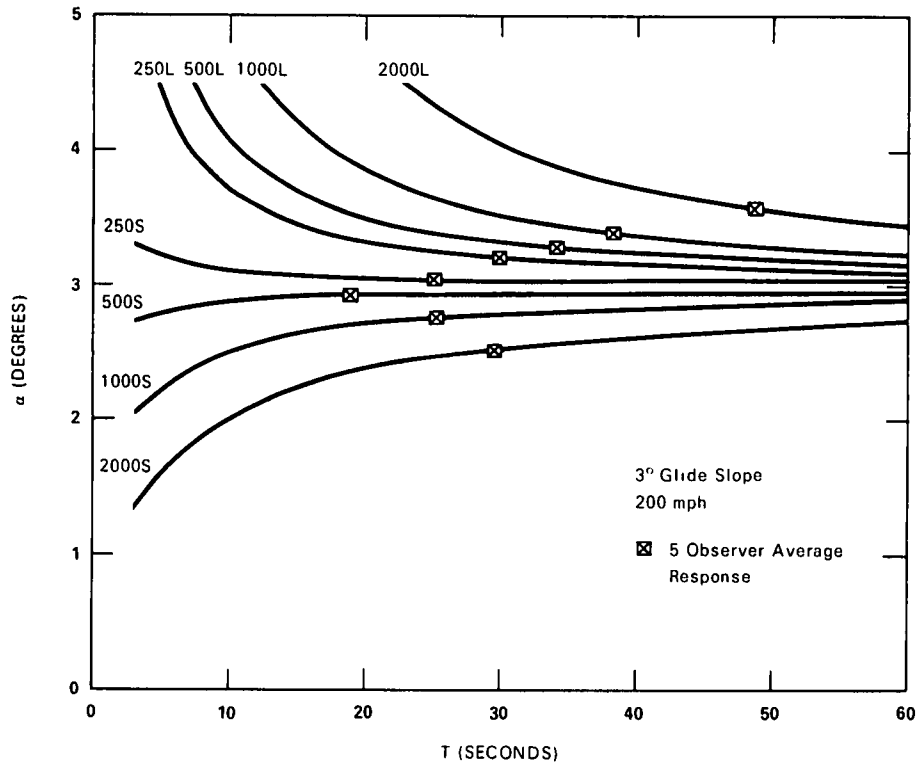


Fig. 22. Angle to Correct Touchdown Point.

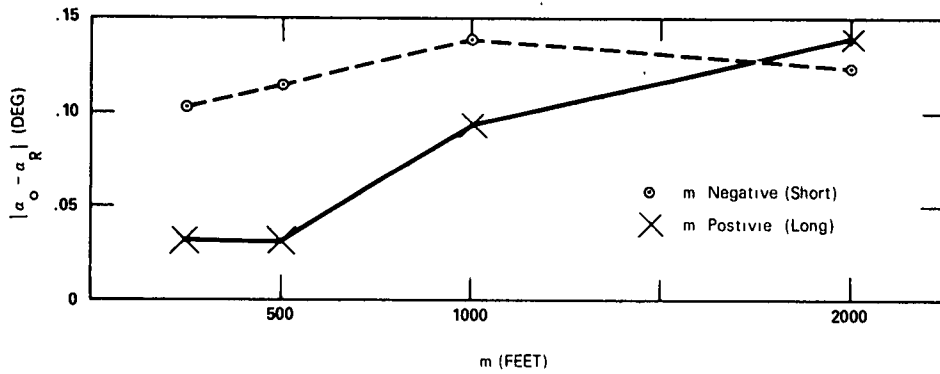


Fig. 23. Absolute Displacement of Correct Touchdown Point From Start of Film Sequence to Time of Observer Average Response.

The dynamic visual cue was investigated by indicating the average observer from Fig. 16 on the curves of Figs. 8 and 10 which show the rate of change of the angles to the correct visual reference and the end of the runway. These are shown in Figs. 24 and 25.

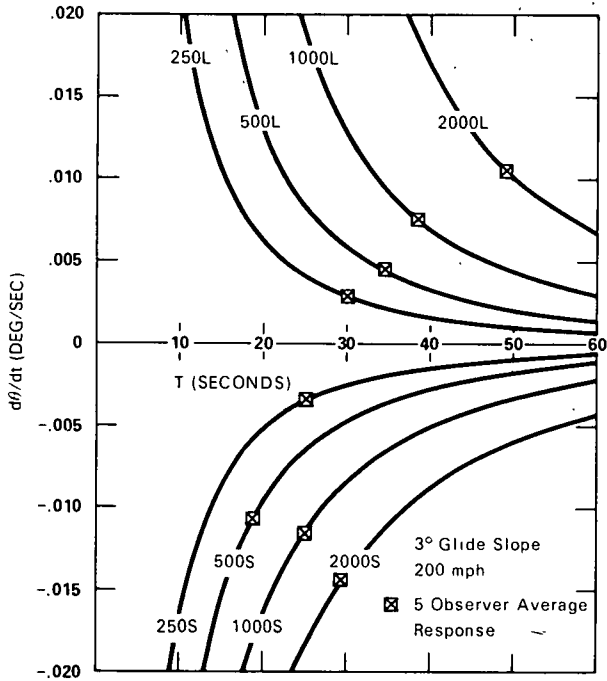


Fig. 24. Rate of Change of Correct Visual Reference.

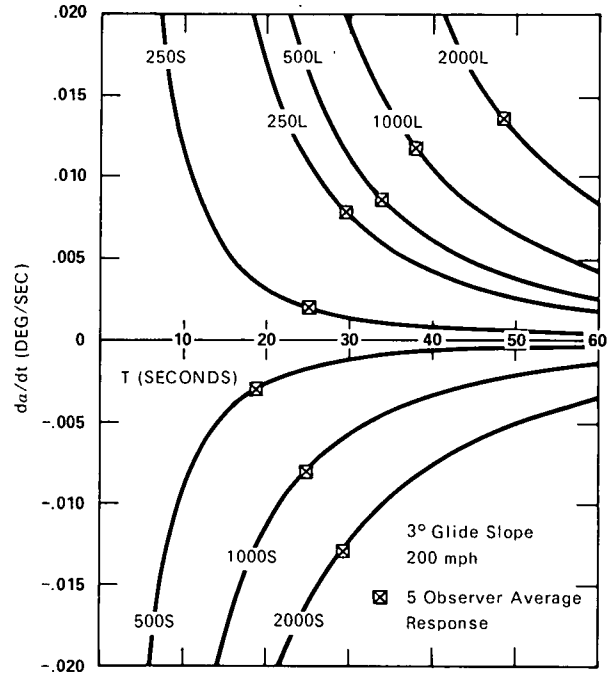


Fig. 25. Rate of Change of Correct Touchdown Point.

It should be remembered that the stylized runway in the experiments had no physical identification of the correct visual reference that the observers could use for visual fixation. The closest identifiable fixation point would be the leading edge of the runway which was designated as the correct touchdown point. If the subjective decisions were based solely on the observers ability to sense a rate of change in the correct touchdown point then the experimental data points would all fall on the appropriate curve at the same absolute rate of change. Examination of Fig. 25 shows that the last decision took place at times where the rate of change of the correct touchdown varied from .0030 to .0135 degrees per second.

An interesting check on the data can be obtained by assuming a fixed threshold for rate of change of the leading edge of the runway and calculating expected performance. The curve shown in Fig. 26 was made by calculating the time T at which the absolute rate of change would be .01 degrees per second. This theoretical curve is a reasonable match to the average observer curve in Fig. 16. Since the geometry dictates that the 250-foot short case will reach the .01 degrees per second rate before the 500-foot short case, because of the offset of the visual axis from the wheels, there is a rational reason for the observer to show earlier detection of the 250-foot short landing than the 500-foot short landing.

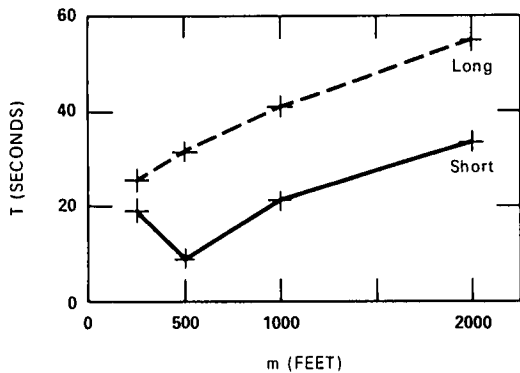


Fig. 26. Theoretical Response Time for $d\alpha/dt = .01$ Deg/Sec, $R_{MET} = \infty$.

Analysis of Figs. 17, 18, and 19 confirms that the addition of a stable horizontal reference to the scene improves the ability of the observer to make correct subjective decisions about the glide path. It is apparent that the closer this external reference is to the place where the observer is fixating, the easier the visual task.

The purpose of the Type III experiment was to determine the ability of the observer to perform his visual task in a situation where the intervening atmosphere obscured the horizon and the far end of the runway. Figure 27 is a family of curves showing the contrast reduction for the four meteorological ranges used in the experiment as a function of the time until touchdown T for the 2000-foot short configuration. The four data points are the RLS response from Fig. 20 superimposed to show the contrast attenuation of the far end of the runway at the time of observer decision. Figure 28 shows the contrast attenuation of the far end of runway at the moment of decision for the 2000-foot long landing configuration.

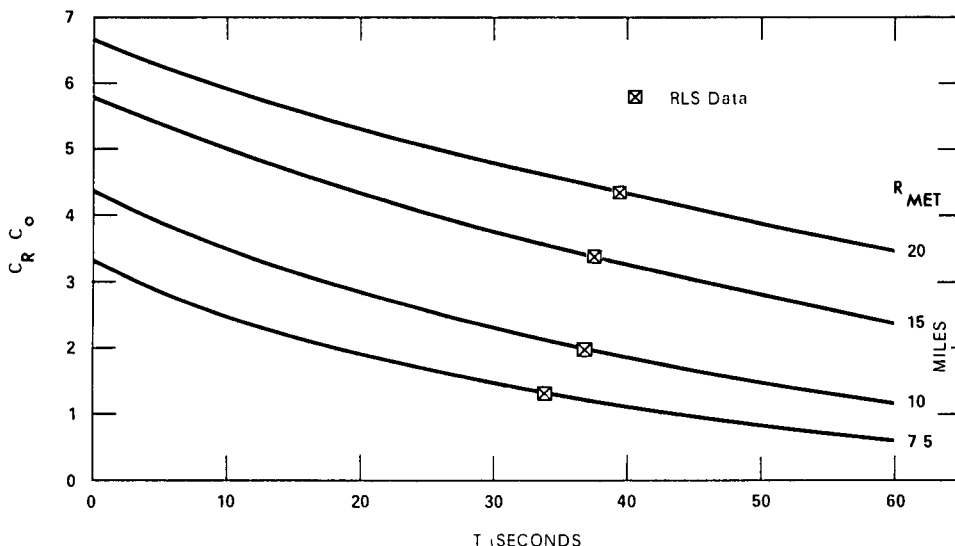


Fig. 27. Contrast Reduction Far End of Runway Versus T For Four Meteorological Ranges and a 2000-Foot Short Miss Distance.

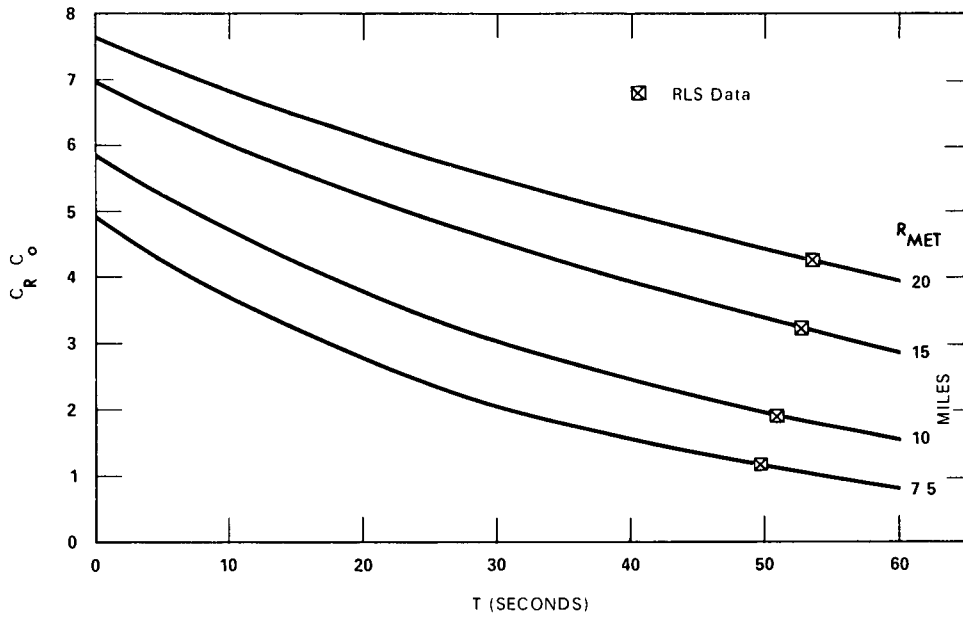


Fig. 28. Contrast Reduction Far End of Runway Versus T For Four Meteorological Ranges and a 2000-Foot Long Miss Distance.

Examination of Figs. 27 and 28 does not show a marked dependence of decision time upon contrast reduction of the far end of the runway, however, it should be noted that the contrast transmittance values were not low enough to badly obscure the far end of the runway.

3. INTRODUCTION TO MOTION DETECTION THRESHOLD EXPERIMENT

The results of the experiments performed with the computer-generated movies seem to suggest that the observer is able to sense that he is long or short in his landing when the leading edge of the runway has moved in angular space by an amount equal to something on the order of 0.1 degrees. In an effort to provide additional independent testing of this hypothesis, an experiment was performed using a horizontal line displayed on a cathode-ray-tube to measure the angular thresholds for detection of motion.

3.1 EXPERIMENTAL TECHNIQUE

The visual stimuli was presented to the observer in a uniform field of view of $8^\circ \times 8^\circ$. This size display is identical to the field of view used in the landing film experiments. The $8^\circ \times 8^\circ$ field was centered in another uniform field of view of 30° to insure that no bias is introduced by extraneous visual references such as the control knobs on the display scope.

Each data run consists of a series of presentations where the line moves away from a starting position θ_0 with a constant velocity. After each presentation the display is returned to the starting position and after a five second pause the next presentation occurs. Both starting position and the horizontal width of the line are a constant for a complete data run.

The observer's task is to make a judgment as to the direction of travel of the horizontal line. He is instructed to make high confidence decisions but to respond as soon as he has consciously made a choice. It is a free choice experiment and he can change his decision at any time in the presentation. The start of a presentation is indicated by the cessation of an audio signal.

The observer responses are made with a three position toggle switch spring loaded to the no decision position. His decisions and the rate of motion in the display are recorded on a two-channel time synchronized recorder in a manner similar to that used for the computer-generated landing sequences.

The data desired is the average time from the start of the presentation to the instant when the observer makes the correct decision as to the direction of travel.

Figure 29 is a block diagram of the equipment used in the experiment. Figure 30 shows the arrangement of the facilities.

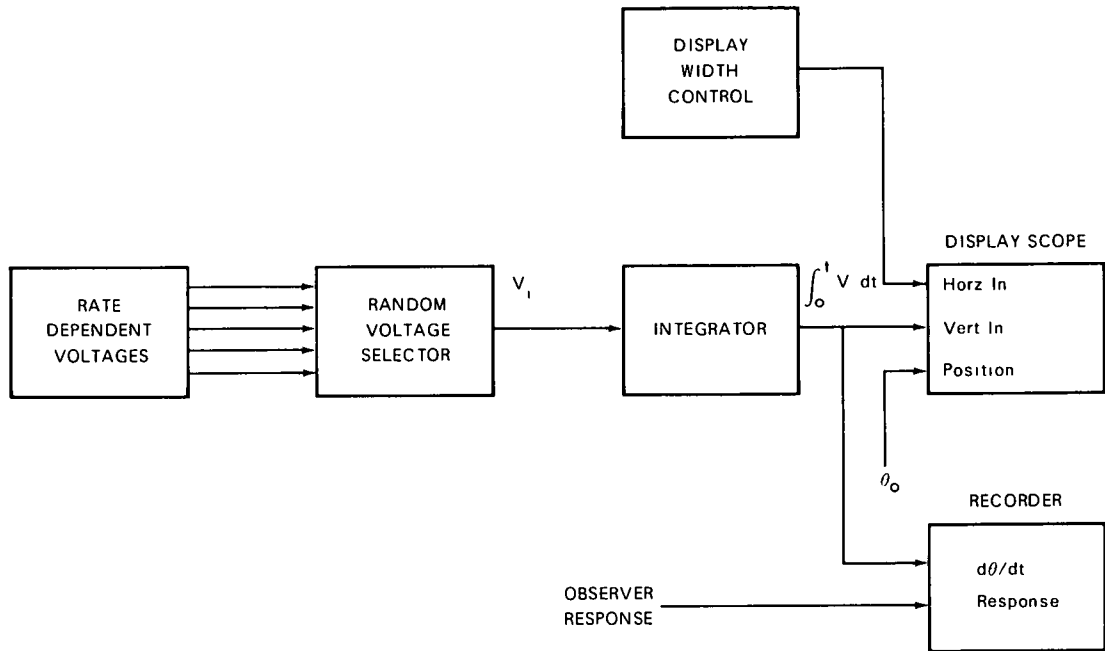


Fig. 29. Block Diagram, Motion Threshold Experiment.

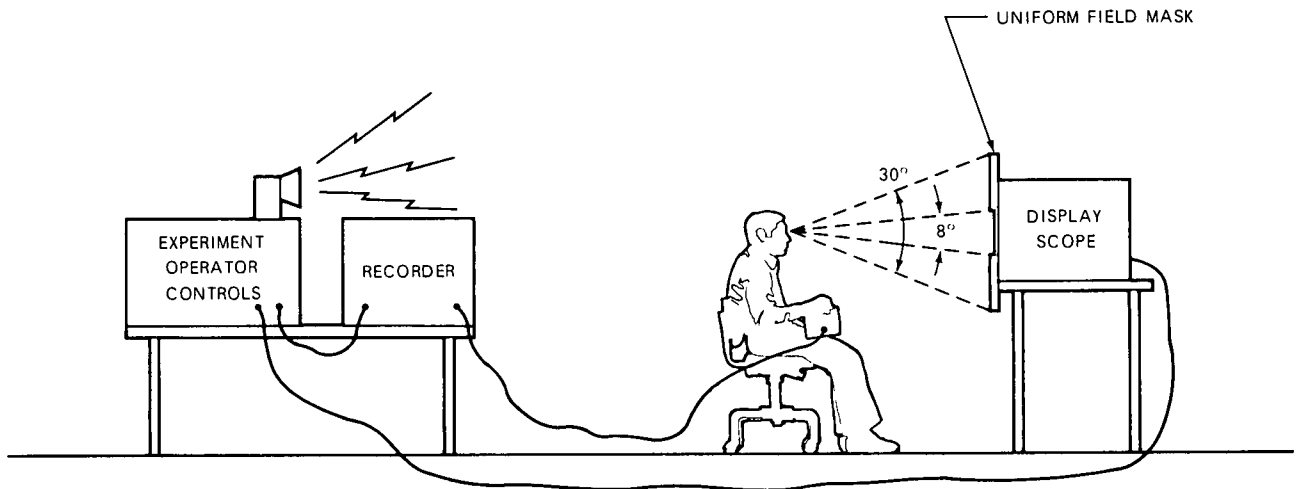
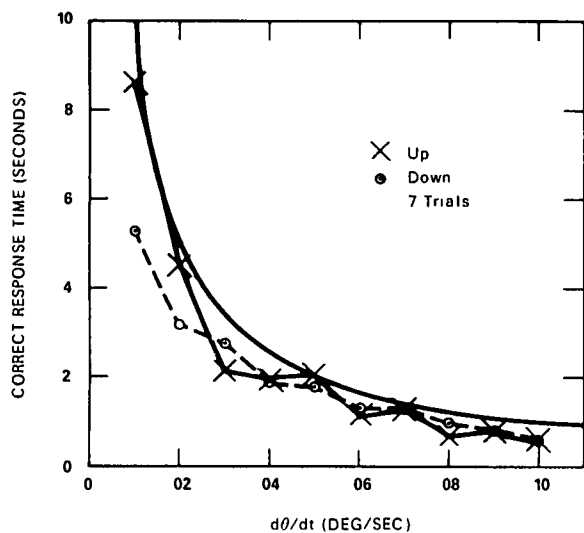


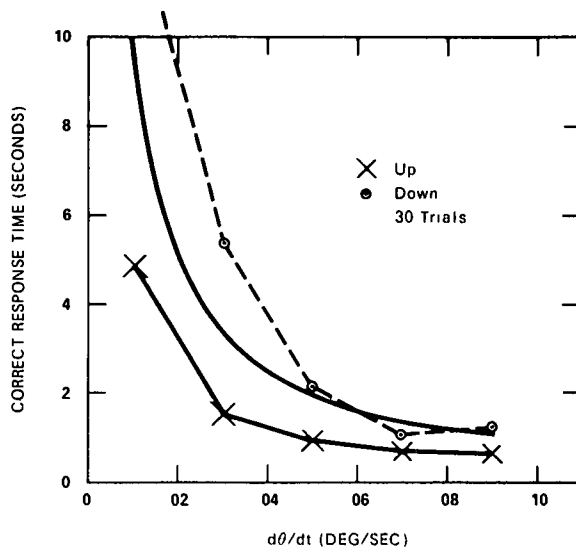
Fig. 30. Facilities, Motion Threshold Experiment.

3.2 DATA AND ANALYSIS

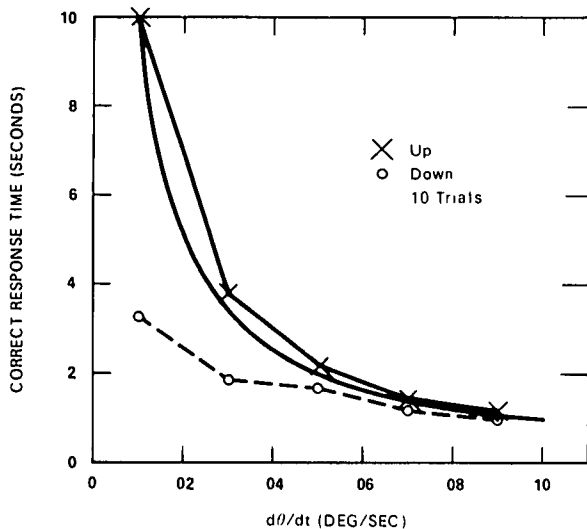
The first run was conducted with observer RLS and the line equal to the width of the display 8° and always starting in the middle $\theta_o = 4^\circ$. The results are shown in Fig 31(a). A theoretical curve has been added to all four graphs in this figure which indicated the performance which would correspond to detection of an angular change of 0.1 degrees



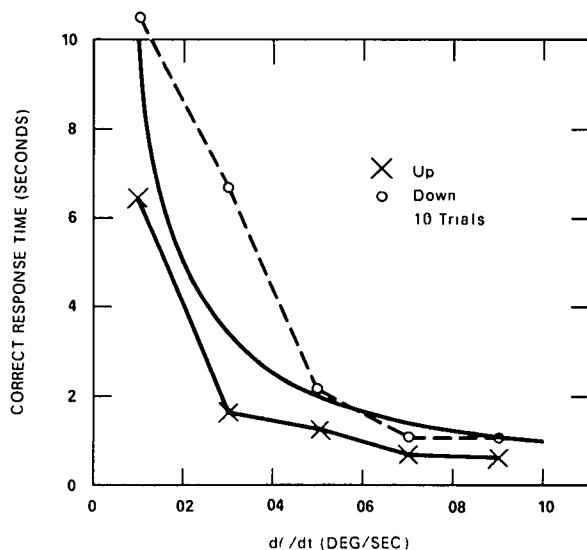
(a) OBSERVER RLS $\theta_o = 4^\circ$ WIDTH 8°



(b) OBSERVER RLS $\theta_o = 4^\circ$ WIDTH 2°



(c) OBSERVER GDE $\theta_o = 4^\circ$ WIDTH 2°



(d) OBSERVER RLS $\theta_o = 6^\circ$ WIDTH 2°

Fig 31. Data, Motion Threshold Experiment.

It was then decided to reduce the width of the horizontal display line to more closely match the angular subtense of the stylized runway used in the runway landing experiment. Two degrees were chosen as the angle the 200-foot wide runway would subtend at a ground range of 11 457 feet. Three sessions of 100 presentations each were then conducted with observer RLS, thus giving us 30 trials for each of the ten data points (5 rates and 2 directions). This data is shown in Fig. 31(b). Observer GDE participated in one session of 100 presentations and the results are shown in Fig. 31(c).

It was then decided to move the starting point of the line closer to the lower edge of the display. This was done in an attempt to check the dependency of the response upon the angular distance to the closest fixed visual reference. The data for observer RLS with a starting point 6° from the top of the display is given in Fig. 31(d).

Figures 31(a), (b), (c), and (d) generally support the hypothesis that detection will occur when the line has moved by an amount on the order of 0.1 degrees which is in turn consistent with the hypothesis that the judgments of long and short landings in the computer-generated movies were made based upon angular movement of the leading edge of the runway.

Although the number of observations is relatively small, it is interesting to note that the two observers had opposite preferential capability with reference to the direction of motion of the line.

4. INTRODUCTION TO DAYTIME FOG PROGRAM

Bad weather is a contributing factor in many aircraft landing accidents. Continued study of the visual function during landing requires that computer software programs be developed which allow the effects of bad weather to be added to a scene. These programs can then be used both in analytic studies and in generation of visual stimuli for psychophysics experiments.

Fog is one of the most severe and important conditions related to aircraft landings and bad weather. Therefore, a software program has been developed to duplicate the effects of fog upon any scene, the scene being stored in the computer as a two-dimensional array of relative luminance values.

4.1 THEORY FOR DAYTIME FOG PROGRAM

There are a number of factors involved in the reduction of image quality imposed by transmission of the light through fog. The purpose of this section is to discuss very briefly the nature of these processes and to indicate the equations which are the basis of the computer program for insertion of fog in daytime scenes.

Light is emitted or reflected from a point on the object of interest in such a way that it travels toward the observer. Some of this light encounters the water droplets of the fog and is scattered. If we assume that light which is scattered is no longer useful for image formation, then the image is determined by knowing what portion of the light is transmitted without undergoing scatter. If the inherent luminance of the scene is B_o , then the unscattered component at a distance R will be

$$B_R = B_o e^{-\alpha R} , \quad (16)$$

where α is the attenuation coefficient. The constant α is the sum of both scattering and absorption coefficients, although the literature seems to indicate that the absorption of most fogs is small.

Some of the light which is scattered by only a small angle will still reach the observer. This is apparent in the nighttime viewing of a small light source where one can see the glow surrounding the light. During the daytime this glow component will not be apparent, and will generally be numerically negligible and is therefore neglected. This simplification does restrict this computer program to daytime use. A nighttime program can and probably will be written, but will be more complex and will require more computer time for execution.

The other important factor in the deterioration of image quality by fog is the addition of path luminance. Path luminance is ambient light which has been scattered by the fog in a direction toward the observer such that it appears to be coming from the object. For a viewing situation which is homogeneous both with respect to transmission properties and lighting geometry, the path luminance also obeys the exponential and asymptotically approaches a value called equilibrium luminance B_Q when the range is large. Mathematically,

$$B^* = B_Q(1 - e^{-\alpha R}) . \quad (17)$$

The total luminance of the path of sight is the sum of Eqs. (16) and (17), or

$$B = B_o e^{-\alpha R} + B_Q(1 - e^{-\alpha R}) . \quad (18)$$

Equation (18) is the basis of the Daytime Fog Computer Program.

4.2 COMPUTER PROGRAM

Assume that a clear weather photograph is taken of a runway scene as viewed from some point along the approach path. This photograph is then scanned and digitized for entry into the computer. The job of the computer program is to operate upon this numerical image in such a way as to produce a new computer image appropriate to viewing through a specified fog condition.

Figure 32 will be used in the derivation for the range at a point in the array. The origin is defined in the upper left-hand corner of the array. The optical axis OH of the camera system is parallel to the horizontal plane at an altitude h and is perpendicular to the film plane. The infinity point in the array H' is located at point I,J. Let us define a point P somewhere on the horizontal plane which maps onto point P' in the array. P' is located at point i,j.

If the film were taken with a focal length of F and if the scanning aperture used to generate the array is the same in both directions, i.e., $\Delta x = \Delta y = \Delta$, then each element in the array subtends an angle of θ where

$$\theta = 2 \tan^{-1} \frac{\Delta}{2F} . \quad (19)$$

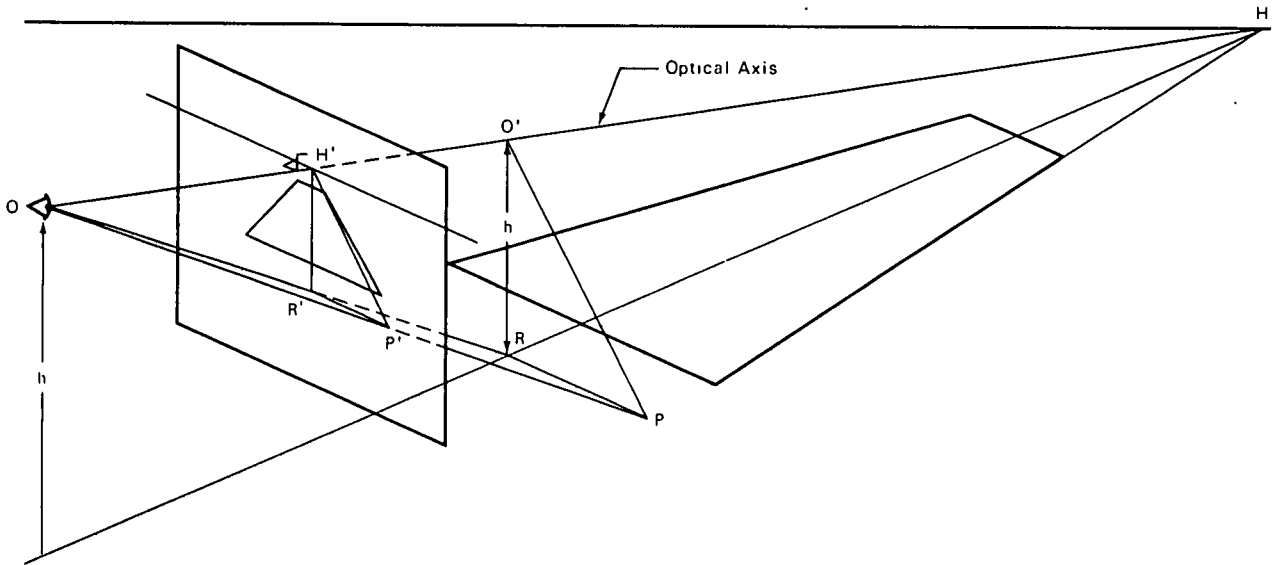


Fig. 32. Range for Runway Build Program

The unmagnified film should be viewed from a distance OH' equal to the focal length

$$OH' = F \quad (20)$$

The distance between any two points, i_2, j_2 and i_1, j_1 , in the array is

$$\text{length}_{21} = \left[\Delta^2(i_2 - i_1)^2 + \Delta^2(j_2 - j_1)^2 \right]^{1/2} \quad (21)$$

Therefore, the length of $H'P'$ in the array is

$$H'P' = \left[\Delta^2(i - I)^2 + \Delta^2(j - J)^2 \right]^{1/2} \quad (22)$$

and the length of OP' can be found as

$$OP' = \left[(OH')^2 + (H'P')^2 \right]^{1/2} \quad (23)$$

Substituting Eqs. (20 and (22) into Eq. (23)

$$OP' = \left[F^2 + \Delta^2(i - I)^2 + \Delta^2(j - J)^2 \right]^{1/2} . \quad (24)$$

The range to the point P is OP. Using the geometry of similar triangles and knowing the altitude h at which the film was taken, thus

$$\frac{OP}{OP'} = \frac{h}{H'R'} , \quad (25)$$

but

$$H'R' = \Delta(j - J) , \quad (26)$$

and therefore the range to point P is

$$OP = \frac{h}{\Delta(j - J)} \left[F^2 + \Delta^2(i - I)^2 + \Delta^2(j - J)^2 \right]^{1/2} . \quad (27)$$

At each point in the array there will be a luminance $B_o(i,j)$. The program will replace this luminance with $B_R(i,j)$, when $j > J$

$$B_R(i,j) = B_o(i,j) e^{-\alpha R_{ij}} + B_Q(1 - e^{-\alpha R_{ij}}) , \quad (28)$$

and

$$R_{ij} = \frac{h}{\Delta(j - J)} \left[F^2 + \Delta^2(i - I)^2 + \Delta^2(j - J)^2 \right]^{1/2} , \quad (29)$$

and when $j \leq J$

$$B_R(i,j) = B_Q \quad (30)$$

since

$$R = \infty$$

4.3 RUNWAY VISIBILITY RANGE (RVR) AND ALPHA (α)

The RVR is defined as the distance at which a standard observer can detect runway lights of a given intensity I . The limit of detection is set by the illumination threshold of the eye according to the relationship by Allard

$$E_t = \frac{I}{R^2} e^{-\alpha R} \quad (31)$$

where

- E_t = Illuminance threshold cd/m^2
- I = Intensity of lights (cd)
- R = Distance (m)
- α = Attenuation coefficient (m^{-1}) .

However, the illumination threshold E_t is related to the background luminance. As reported by D. C. Thomas,² the Blind Landing Experiment Unit, a part of the Royal Aircraft Establishment, has postulated the relationship as

$$\log E_t = -5.7 + .64 \log B \quad (32)$$

where B = background luminance cd/m^2 .

Equations 31 and 32 can be combined to solve for the attenuation coefficient α ,

$$\alpha = \frac{\log I + 5.7 - .64 \log B - 2 \log R}{R \log e} \quad (33)$$

2. J. Sci. & Technology, Vol. 37, No. 2, 1970.

The high intensity runway edge lights used today have an intensity of 20 000 candles. Therefore, to select the proper attenuation coefficient α to use in the daytime fog program, the background illuminance and the RVR of the scene must be known.

4.4 REAL FOG AND COMPUTER-GENERATED FOG

On 26 April 1973 Visibility Laboratory personnel made photographs and measured background luminance in the FAA/NASA Low Visibility Research Facility at the Richmond Field Station in Richmond, California. This occurred during a test being conducted by NASA-Ames personnel. A Gamma Scientific photometer with a two-degree field of view was used to measure the background luminance looking down the runway at various elevation angles. Measurements were made in the clear and with fogs having RVR's of 2400, 1200, 700, and 300 feet. This data is plotted in Fig. 33. Photographs were made at the same time looking down the runway from the aircraft cockpit. The photographs were returned to the Visibility Laboratory and scanned with the Optronics Scanner to get the two-dimensional arrays.

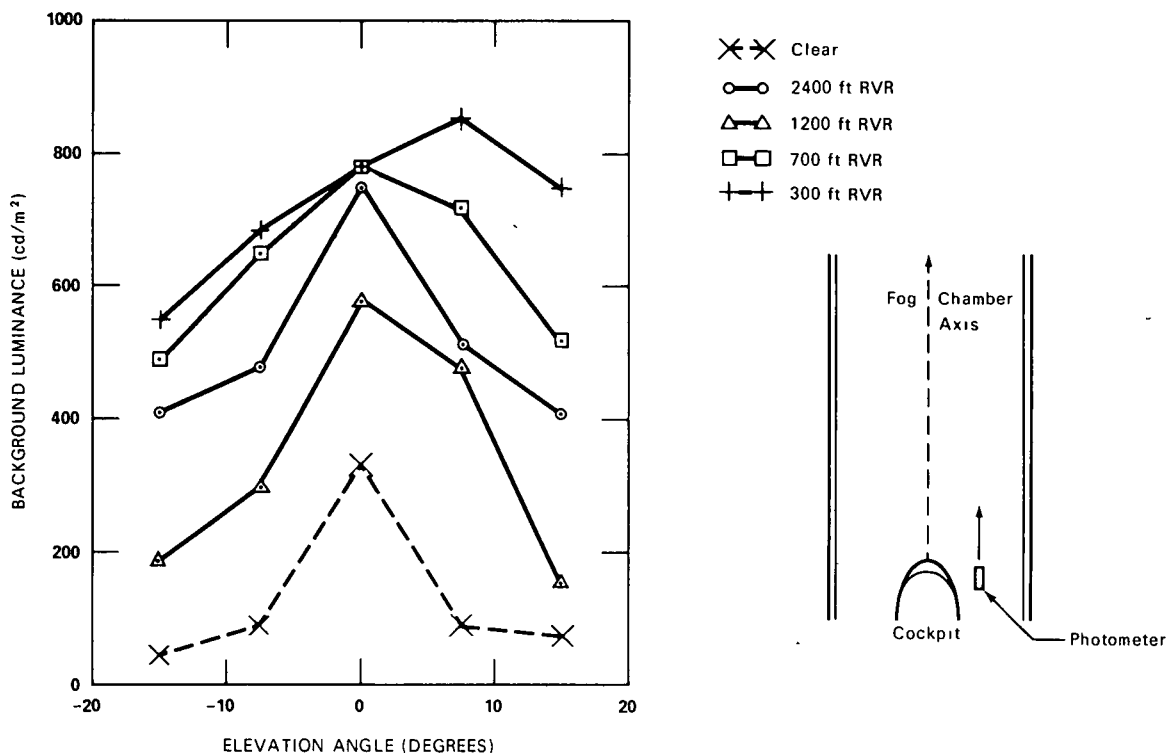


Fig. 33. Background Luminance, Richmond Field Station Fog Chamber, HIRL Step 5, 26 April 1973, 1700 Hours.

Figure 34 is the original photograph taken without fog. Selecting a background luminance value of 684 cd/m^2 from Fig. 32, the attenuation coefficients α were calculated corresponding to RVR's of

$$2400 \text{ feet RVR, } \alpha = .00774 \text{ M}^{-1}$$

$$1200 \text{ feet RVR, } \alpha = .01925 \text{ M}^{-1}$$

$$700 \text{ feet RVR, } \alpha = .03805 \text{ M}^{-1}$$

$$300 \text{ feet RVR, } \alpha = .10925 \text{ M}^{-1} .$$

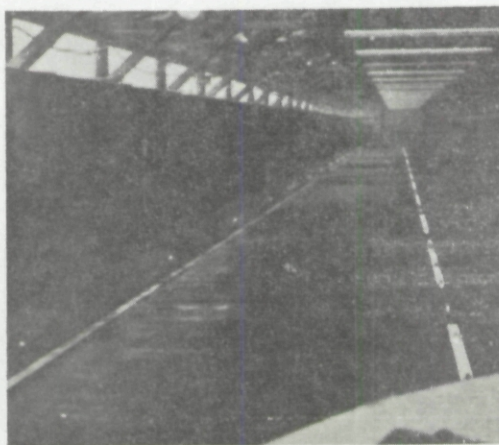


Fig. 34. FAA/NASA Low Visibility Research Facility Runway, Clear Atmosphere.

The original runway scene was then processed using the daytime fog program to add fog to the array.

The pictures taken in the fog chamber are shown for comparison to the results of the daytime fog program,



Figure 35 RVR of 2400 feet



Figure 36 RVR of 1200 feet

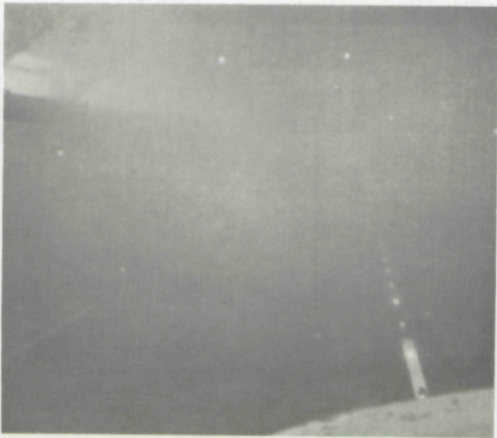


Figure 37 RVR of 700 feet

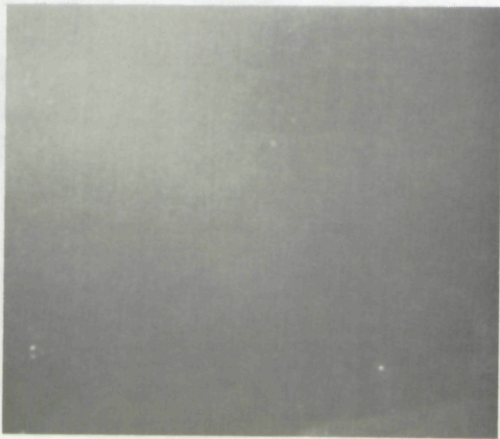


Figure 38 RVR of 300 feet

It is believed that the ability to generate computer pictures which accurately portray viewing situations through fog can be an important tool in the quantitative evaluation of the visual stimulus involved in bad weather landings.

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5. SUMMARY AND CONCLUSIONS

The intent of the landing studies was to attempt to determine the nature of the visual stimulus of importance to the pilot and to quantitatively define his threshold judgments of long and short landings. The experiments performed in connection with these studies tend to suggest that long and short judgments are based upon an angular change of the leading edge of the runway with the threshold of this change being on the order of 0.1 degrees. The data for the 250 and 500 foot short landing cases did not fit this pattern and as of the time of writing this report no explanation of these deviations has been discovered.

The independent experiment using a moving line on a cathode-ray-tube served two useful purposes. First of all it tended to confirm a visual threshold corresponding to a total angular movement on the order of 0.1 degrees. This tends to substantiate the idea that the long-short judgments are based upon motion of the leading edge of the runway and are independent of the presence of the horizon and/or the changing geometric pattern formed by the runway. The experiment was also useful in that it did not involve either the discrete resolution of the computer pictures nor the discrete frame-by-frame presentation of the movie camera. This suggests that neither the discrete resolution nor the discrete frame-by-frame presentation adversely affected this experimental determination of the motion thresholds.

The computer program which was written to insert fog into photographs of runway scenes has been shown to be capable of generating very realistic fog viewing. It is believed that this program will be of great value in studying the problems of visual stimulus during low-ceiling, - low visibility landing situations.

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APPENDIX

COMPUTER FACILITY

The Visibility Laboratory computer installation, shown in Fig. 39 and 40, is an IBM System 360/44. The physical characteristics of the IBM 360/44 are listed below.

UNIT	DESCRIPTION
2044	Central Processing Unit with 1 microsecond, 32K 32-bit word core and disk storage of 1×10^6 bytes.
1442	Card Read-Punch, 400 cards/minute.
1443	Line Printer, 240 lines/minute.
2415	Magnetic Tape Unit, two drives, nine track, 15 000 bytes/second.
2841	Disk Storage Control.
2311	Disk Drive with 1316 cartridge, 7×10^6 bytes.
2701	Data Adapter Unit.
2741	Communication Terminal: One 16-bit A/D converter Two 16-bit contact operate banks Three 16-bit digital input groups Two 13-bit D/A converters

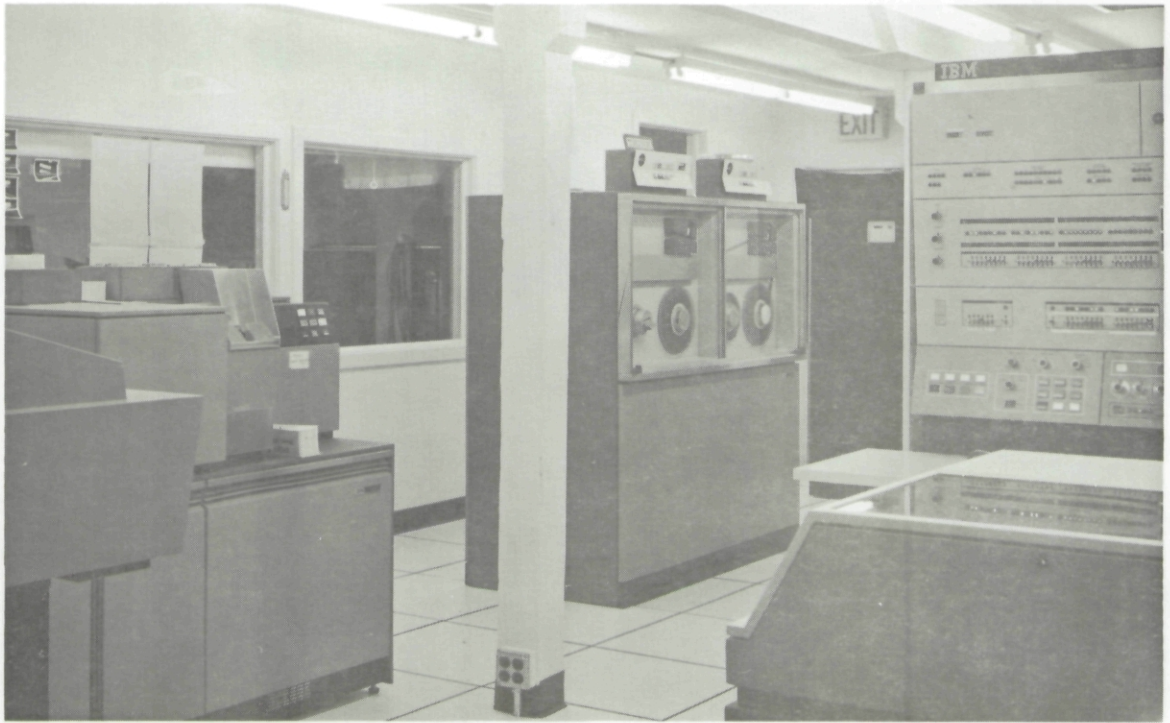


Fig. 39. The IBM System 360/44 Computer.

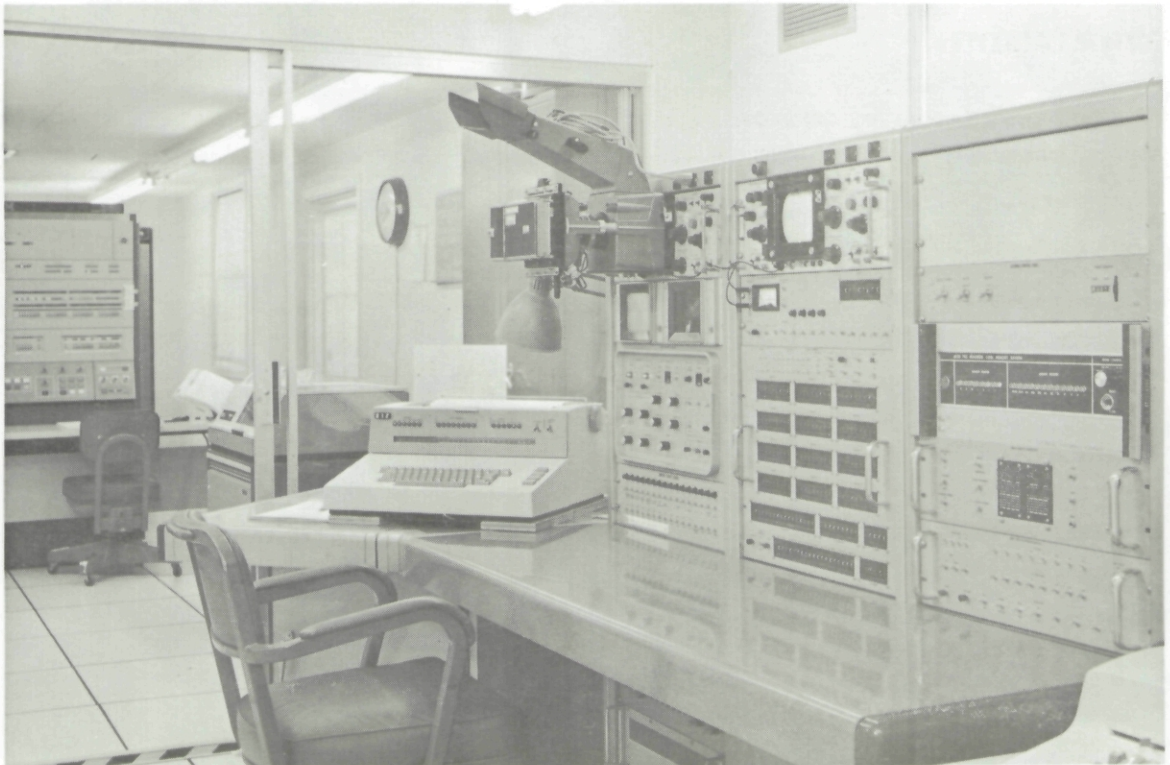


Fig. 40. The IBM System 360/44 Computer and the Refresh Display Console.