NASA TECHNICAL MEMORANDUM

NASA TM X-3273

NASA TM X-3273

THREE METHODS OF PRESENTING FLIGHT VECTOR INFORMATION IN A HEAD-UP DISPLAY DURING SIMULATED STOL APPROACHES

James H. Dwyer III and Everett A. Palmer III

Ames Research Center

Moffett Field, Calif. 94035

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JULY 1975

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM X-3273		

4. Title and Subtitle	5. Report Date
THREE METHODS OF PRESENTING FLIGHT VECTOR INFORMATION IN A HEAD-UP DISPLAY DURING SIMULATED STOL APPROACHES	July 1975
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
James H. Dwyer III and Everett A. Palmer III	A-5992
9. Performing Organization Name and Address	10. Work Unit No.
Ames Research Center Moffett Field, California 94035	504-09-33
	11. Contract or Grant No.
	NGL 05-046-002
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
National Aeronautics and Space Administration Washington, D. C. 20546	Technical Memorandum
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A simulator study was conducted to determine the usefulness of adding flight path vector symbology to a head-up display designed to improve glide-slope tracking performance during steep 7.5° visual approaches in STOL aircraft. All displays included a fixed attitude symbol, a pitch- and roll-stabilized horizon bar, and a glide-slope reference bar parallel to and 7.5° below the horizon bar. The displays differed with respect to the flight-path marker (FPM) symbol: display I had no FPM symbol; display II had an air-referenced FPM, and display III had a ground-referenced FPM. No differences between displays I and II were found on any of the performance measures. Display III was found to decrease height error in the early part of the approach and to reduce descent rate variation over the entire approach. Two measures of workload did not indicate any differences between the displays.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Simulation Head-up displays STOL Visual approach aid	Unclassified – Unlimited STAR Category – 05

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	16	$3.25

*For sale by the National Technical Information Service, Springfield, Virginia 22151

THREE METHODS OF PRESENTING FLIGHT VECTOR INFORMATION IN A HEAD-UP DISPLAY DURING SIMULATED STOL APPROACHES

James H. Dwyer III* and Everett A. Palmer III

Ames Research Center

SUMMARY

A simulator study was conducted to determine the usefulness of adding flight path vector symbology to a head-up display designed to improve glide-slope tracking performance during steep 7.5° visual approaches in STOL aircraft. All displays included a fixed attitude symbol, a pitch- and roll-stabilized horizon bar, and a glide-slope reference bar parallel to and 7.5° below the horizon bar. The displays differed with respect to the flight-path marker (FPM) symbol: display I had no FPM symbol; display II had an air-referenced FPM, and display III had a ground-referenced FPM. No differences between displays I and II were found on any of the performance measures. Display III was found to decrease height error in the early part of the approach and to reduce descent rate variation over the entire approach. Two measures of workload did not indicate any differences between the displays.

INTRODUCTION

During a visual landing approach, two of the kinds of information a pilot needs are: (1) the present aircraft position relative to the glide-slope approach angle, and (2) flight-path vector information which tells him where he is going. Three variations of a head-up display (HUD) depicting the glide-slope and flight-path angles were evaluated in this study. The objective was to compare different means of displaying flight-path vector symbology during simulated VFR approaches in a short takeoff and landing (STOL) aircraft.

Without electronic guidance, many accidents have occurred during visual approaches. The visual problems associated with present-day aircraft operations are amplified in STOL aircraft operations because of the slower speeds, steeper approach angles, and other factors.

Although the visual problems will be increased in future planned STOL aircraft operations, certain visual cues used today will still remain a basic part of the problem. A visual cue used for determining glide-slope error from a specified glide-slope angle is the visual angle of the runway aim point below the horizon. This perceived distance remains constant throughout the approach when the aircraft is exactly on the glide slope because the angle of elevation from the aim point is constant. The angle of elevation (glide-slope angle) is equivalent to the depression angle of the aim

*James Dwyer was a graduate student in the Department of Psychology, San Jose State University, when this work was done under grant NGL 05-046-002. He is now with the Psychology Board of Studies, Adlai E. Stevenson College, University of California, Santa Cruz.

point below the horizon. If the pilot adjusts his flight path so that the depression angle of the aim point below the horizon remains constant, he will maintain a constant glide-slope angle. That this and other cues to glide-slope angle are not always adequate is attested to by the number of accidents that occur during nonprecision visual approaches.

STOL aircraft visual approaches will result in additional visual problems with an increased need for precise glide-slope tracking. The steeper approach angle (7.5° instead of 3°) causes the distance between the horizon and runway aim point to be larger, and hence estimates of small changes in glide-slope angle are more difficult. The visual problem is further aggravated by the planned location of STOLports near or within cities. Substantial blocking of the true horizon reference may occur because of nearby high-rise buildings. Patterns of city lights at night, many of them elevated, also may cause the pilot to make glide-slope corrections in relation to an invalid true horizon reference. This condition has been shown to occur in earlier simulator studies (refs. 1 and 2).

The head-up display evaluated in the present study was designed to portray both a gyro-stabilized true horizon reference and a 7.5° glide-slope reference to counter these visual problems. The glide-slope reference was provided by a pitch- and roll-stabilized glide-slope reference bar (dashed bar in fig. 1) that was parallel to and 7.5° below the true horizon. The display showed the pilot that he was on a 7.5° glide slope to the ground points superimposed by the glide-slope reference bar.

Concurrent with determining the aircraft position relative to the glide-slope angle, the pilot must determine where his flight-path vector is taking him so he can make appropriate flight path corrections to maintain or return to the desired glide-slope angle. Three visual cues used to determine his flight-path vector are (1) expansion cues, (2) aircraft pitch attitude, and (3) the rate of glide-slope angle change. As an aircraft descends on the final approach, all points on the ground appear to expand outward from the one point where the aircraft flight-path vector intersects the ground. Longitudinal changes in the location of this point relative to the runway aim point tell the pilot that his flight-path angle has changed. Experimental studies have shown that it is difficult for pilots to use the expansion cue because of the low angular rates of expansion until the aircraft is close to the runway (ref. 3). The slow approach speeds of STOL aircraft further reduce the usefulness of this cue to flight-path angle, because the expansion rate is even less.

An indirect visual cue to flight-path angle through the air is the pitch attitude of the aircraft. Changes in flight-path angle lag approximately 0.5 sec behind changes in pitch attitude. In the steady state, the two angles differ by the trim angle of attack. Changes in aircraft speed and weight affect the trim angle of attack, so this cue is not always reliable.

The rate of change of glide-slope angle is also a cue to the aircraft flight-path angle relative to the ground. This visual cue suffers from the same inaccuracies as estimating glide slope as discussed above.

THE EXPERIMENT

HUD Symbology

Figure 1 shows the relationship between the symbols of the HUD and the ground. The display symbol labeled "glide-slope reference" (GSR) was parallel to and 7.5° below the horizon symbol. This symbol showed the pilot that he was on a 7.5° glide slope to the ground points superimposed by the GSR bar. If the GSR bar was short of the runway aim point, the aircraft was low; if the GSR bar was beyond the runway aim point, the aircraft was high.

Because of the difficulties in estimating flight-path angle by visual cues, the experiment investigated three methods of displaying flight-path angle information on a HUD. The display symbol labeled ground "flight-path marker" (FPM) (fig. 1) indicates the direction of the aircraft flight vector relative to the ground and marks the point on the ground at which the aircraft would impact if the present direction of motion and wind conditions remained constant. When the GSR bar is superimposed on the runway aim point, the distance between the ground FPM and the GSR bar is proportional to the rate at which the aircraft is deviating from the nominal glide slope.

The onboard instrumentation required to generate a ground FPM is complex and expensive. Such a symbol requires accurate estimates of the motion of the aircraft relative to the ground. The objective of this experiment was to see if simpler but less accurate FPM-like symbology could be used instead of an inertially derived ground FPM symbol. The following three sets of HUD symbology were investigated.

Display I: This display contained no FPM symbol. Flight-path angle had to be estimated from visual cues or by the rate of change of glide-slope angle as indicated by the GSR bar (fig. 2(a)).

Display II: This display added an air FPM that indicated the direction of motion of the aircraft relative to the air mass (fig. 2(b)).

Display III: The most complex of the three, this display had a ground FPM that indicated the direction of motion of the aircraft relative to the ground (fig. 2(c) and 3).

A general-purpose computer graphics system (SEL 816) was programmed to generate the HUD symbology. The output of a closed-circuit TV camera viewing the HUD symbology was mixed with the color TV image of the runway so that the pilot could view the visual scan with superimposed HUD symbology. Special efforts were made to keep the HUD symbology and the runway aligned, but some small alignment errors undoubtedly occurred.

Cockpit

A fixed-base simulator was used for this evaluation. The experimental objective was to evaluate only the information the pilot derived from his view of the runway and the head-up display symbology, and therefore no panel instruments were provided.

Aircraft Dynamics

Simplified linear approximations to the longitudinal dynamics of a jet STOL aircraft were used. These equations included a longitudinal stability augmentation system and an automatic speed control system. The lateral dynamics were made slightly unstable to increase pilot workload and hopefully accentuate display differences in the dependent variables.

Visual Flight Attachment

A visual flight attachment provided the pilot with a color TV display of the airport and surrounding terrain. The pilot viewed the TV monitor through a collimating lens system.

Experimental Design

Independent variables– The independent variables and the four dependent variables are summarized in table 1. Treatments B (displays), C (head winds), D (segments of the approach), and R (A) (pilots) were completely crossed. Each pilot received every display, headwind, and approach segment combination. In order to control for sequential effects, pilots were nested in treatment A: half the pilots received one sequence of displays (II, I, III), and the rest received a second sequence (III, I, II). Kirk (ref. 4) refers to this design as a "Split Plot Factorial Anova: SPF p. gru". It allows for point estimation of five main effects, nine second-order interactions, seven third-order interactions, and one four-order interaction. Estimates if the proportion of experimental variance associated with each of the terms of the linear analysis of variance model were computed.

Each pilot participated in the experiment on four different days. The first day consisted of practice on display I. The second day included 12 practice flights with a second display (II for four pilots; III for the other four pilots), followed by 16 data flights with that same display. The following two days consisted of similar series of 12 practice and 16 data flights on the two remaining displays.

The variation of headwind was accomplished by presenting in random order constant headwinds of various velocities in blocks of four approaches. Each block of headwinds consisted of four headwinds with velocities of 0, 5, 10 and 15 m/sec.

Performance measures– The dependent variables (table 1) were: (1) rms height error from the 7.5° glide slope, (2) standard deviation (SD) of sink rate, (3) SD of control movement, and (4) the number of secondary task responses (see below). Data on these variables were gathered during three segments of the approach as measured from the touchdown point (fig. 4): 1500-1250 m, 1000-750 m, and 500-250 m. A total of 896 flights were made – 512 practice and 384 data. Each datum used in the statistical analysis was the mean of four flights under identical conditions.

Secondary workload task– The addition of a secondary loading task has been useful in display evaluation experiments where tracking performance measures have not distinguished between displays (ref. 5). Visual workload is of particular importance in the evaluation of a display used during the landing approach because of the pilot's need for time to cross check head-down instruments and scan for other air traffic.

The secondary loading task in the present experiment consisted of an "X" in the upper left-hand corner of the display (figs. 2 and 3), which defined four quadrants. As each flight commenced, a dot appeared randomly in one of the four quadrants and remained in that position until a four-way button (located near the pilot's left thumb on the control wheel) was pushed in the direction of that quadrant. This task was "secondary" because each pilot was instructed to perform the task only when he felt that he was adequately tracking the glide slope. The number of times the button was pushed during each segment of the approach was the measure of secondary task performance.

Pilots– Eight airline pilots with current FAA flying status served as subjects. The pilots were volunteers and were paid for their time.

RESULTS AND DISCUSSION

Height Error

This dependent variable was a measure of how well the pilots tracked the 7.5° glide slope. The results of the analysis of variance on this variable are presented in table 2. As expected, the height error was greater in the more distant segments of the approach. Furthermore, it was found that the standard deviation of the more distant measurements was proportional to the magnitude of the height error. Therefore, the height error data was logarithmically transformed to equalize the variance before the analysis of variance was performed.

Table 2 shows that only 0.7 percent of the total experimental variance was associated with the two sequences of displays. This indicates that there was almost no sequential effect on height error during the course of the experiment. The effect of the headwinds on height error was significant at the 0.001 level and accounted for 5.0 percent of the total variance. However, there was not a significant interaction between displays and winds. This indicates that no one display was more effective than the others in helping the pilot correct for the different headwinds.

It is clear that the pilots and their interaction with the displays (29.9 and 11.1 percent of the total variation) account for the largest portion of the variability in height error. This serves as a reminder of the importance of individual differences. The following discussion of the significant display effect within the 1500-1250 m interval should be understood in the context of that reminder.

The three displays were not significantly different ($F = 3.85$; $df = 2, 18$; $p < 0.10$) when height error was averaged over segments, winds, sequences, and pilots. There was, however, a significant interaction between displays and segments. Figure 5 shows this interaction, and the analysis-of-variance test for the difference between displays at each segment is presented in table 3.

Figure 5 shows that the 4.27 m height error for display III was 45 percent less than the height error for display I (6.69 m) and 40 percent less than the height error for display II (7.07 m) during the 1500-1250 m segment of the approach. Table 4 shows that in this segment the displays account for more variance than the headwinds and over a fourth as much as the pilots. A Tukey test (ref. 5) of the difference between the three means confirms the statistical significance of the difference between display III and the other two displays (I, II: $q = 0.77$, n.s.) I, II: $q = 5.70, p < 0.01$; II, III: $q = 4.93, p = 0.01$; $df = 3, 14$). These results are included in table 5.

Rate of Descent

An ideal landing approach would have consisted of zero height errors: perfect tracking of a 7.5° glide slope. If such a path had been followed, a constant sink rate would also have been characteristic. Since such an ideal was unlikely to occur, variation in the sink rate was expected. Less variation in sink rate, however, would indicate "smoother" adjustments to tracking errors. Thus, the standard deviation of the sink rate was computed for each of the 250 m data segments of the approach.

Although the same statistical analyses were used for each dependent variable, the following tables are abbreviated by the omission of interaction terms that accounted for less than one percent of the variance. The analysis of variance of sink rate variability is presented in table 6.

The effect of the displays provides the only significant F ratio and is estimated to account for approximately one-fourth as much variation as the pilots and almost four times that of the head-winds. A Tukey test between the three pairs of displays indicates that there is no significant difference between displays I and II ($q = 0.75$; $df = 3, 12$). The sink rate variation with display III was significantly less 33 percent than display I ($q = 4.18, p < 0.05$; $df = 3,12$) and almost significantly less (29 percent) than display II ($q = 3.44, p < 0.10$; $df = 3, 12$).

These findings (table 5) lend further support to the superiority of the HUD with a ground-referenced FPM. Although the significance levels of these sink rate differences were not as great as those for height error, it should be remembered that the height error differences were restricted to one segment of the approach. In contrast, the reduction in sink rate variation by about one-third with display III prevailed across all segments of the approach and all headwind conditions.

Control Column Movement

The physical workload of the system operator was inferred from the standard deviation of the position of the control column. The analysis of variance revealed that the slight reduction in control column movement shown in table 5 (approximately 5 percent) associated with display III was insignificant ($F = 0.04$, $df = 2, 12$). Likewise, the various interactions between displays and the other independent variables were not statistically significant.

There were two significant main effects with this variable: headwinds ($F = 3.77$, $p < 0.05$; $df = 3, 18$) and segments of the approach ($F = 33.65$, $p < 0.001$; $df = 2, 12$). The main effect of the headwinds is a reduction in stick movement with higher velocity headwinds (see table 5). This result may be explained by the greater amount of time available to the pilots for control inputs. The headwinds essentially serve to "slow down" the motion of the A/C relative to the ground. The effect of this slowdown was also seen in reduced height error.

The main effect of the segments simply confirms the expected increase in the pilot's physical workload as he progressed in the approach. This finding tends to support the validity of employing the standard deviation of the control stick position as a measure of physical workload. However, there are differences between displays with respect to physical workload. This particular measure was not sufficiently sensitive to detect them.

Secondary Loading Task

This task was included in the investigation to accentuate display differences in visual and overall workload. None of the F ratios approached significance, however, except for the headwinds ($F = 14.48$, $p < 0.001$; $df = 3, 18$). The main effect due to headwinds was clearly a result of the slowdown phenomenon previously discussed. As the headwind velocity increased (table 5), the amount of time that the A/C was within the ground-referenced data segments also increased, and more responses to the secondary task were possible.

CONCLUSIONS

Some of the problems associated with projected STOL operations were noted in the introduction: steep-angled approaches, unusual airport locations, and slow approach speeds. The results of this simulator experiment indicate that the use of a ground-referenced flight-path marker (FPM) symbol in the head-up display (HUD) significantly improves the ability of pilots to track a steep-angled glide slope. Compared to the other two displays, the display with the FPM allowed a 40 percent reduction in height error in the first part of the approach. The superiority of this display was also strongly evidenced by a one-third reduction in the variation of descent rate over the other two displays during the entire approach. Both of these improvements in tracking performance were achieved without a measurable increase in physical and visual scanning workload.

The reason display III was associated with improved performance is open to conjecture. However, it is clear that information presented by the ground FPM was crucial. It seems particularly likely that the reduced height error at the earlier stage of the approach was due to the GSR, ground FPM, and runway aim point coincidence. The superimposition of these symbols over the touchdown point ensures glide-path accuracy. In contrast, display II requires a displacement of the air FPM from the GSR that is proportional to the headwind or tailwind.

The overall reduction in the variability of descent rate is probably due to reduced searching for a stable display/ground configuration. The ground FPM provides lead information about vertical displacement from the ILS glide slope that minimizes the pilot's uncertainty about the direction and impact of control inputs.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, California, 94035, April 2, 1975

REFERENCES

1. Kraft, Conrad L.; and Elworth, Charles L.: Flight Deck Workload and Night Visual Approach Performance. AGARD-CP-56, Dec. 1969, pp. 11-1, 11-14.

2. Palmer, Everett A.: Night Visual Approaches – Pilot Performance With and Without a Head-Up Display. NASA TMX-62,188, 1972.

3. Palmer, Everett A.: Experimental Determination of Human Ability to Perceive Aircraft Aim Point From Expanding Gradient Cues. Paper presented at the 40th Annual Scientific Meeting, AMA, May 1969.

4. Kirk, R. E.: Experimental Design: Procedures for the Behavioral Sciences. Belmont, California: Brooks/Cole, 1968.

5. Knowles, W. B.: Operator Loading Tasks. Human Factors, vol. 5, 1963, pp. 155-161.

TABLE 1.–INDEPENDENT AND DEPENDENT VARIABLES

Independent variables	A: two sequences of display presentation (II, I, III or III, I, II) B: three experimental displays C: four headwind conditions (0, 5, 10, 15 m/sec) D: three segments of the approach (1500-1250, 1000-750, and 500-250 m from the nominal touchdown point) R(A): eight pilots (nested in A)
Dependent variables	Height error (m): root mean square of an altitude error over three 250 m segments of the approach. Variation in rate of descent (m/s): standard deviation of the sink rate during the data intervals. Control stick movement (deg): standard deviation of the control stick position during the data-gathering segments. Secondary loading task performance: the number of times the S correctly pushed the trim button during the data segments of each approach.

TABLE 2.– ANALYSIS OF VARIANCE OF LOGARITHMIC TRANSFORMATION OF HEIGHT ERROR

Source	*df*	*F*	Variance component estimates (percent)
A (sequence)	1	3.85 ($p < 0.10$)	0.7
B (sequence)	2	12.95 ($p < 0.001$)	2.6
C (winds)	3	73.06 ($p < 0.001$)	5.0
D (segments)	2		23.2
R(A) (pilots)	6		22.9
A X B	2		0.0
A X C	3		0.8
B X C	6		0.2
A X D	2		0.2
B X D	4	5.30 ($p < 0.005$)	2.5
C X D	6		0.0
B X R(A)	12		11.1
C X R(A)	18		3.4
D X R(A)	12		2.6
A X B X C	6		0.0
A X B X D	4		0.0
A X C X D	6		0.0
B X C X D	12		0.3
B X C X R(A)	36		8.6
B X D X R(A)	24		4.6
C X D X R(A)	36		2.7
A X B X C X D	12		0.3
Error	72		5.9

TABLE 3.– SIMPLE MAIN EFFECT OF DISPLAYS ON HEIGHT ERROR WITHIN THE THREE SEGMENTS OF THE APPROACH

Source	*SS*	*df*	*F*
Displays at 1500-1250 m	1.45	2	9.56 ($p < 0.001$)
Displays at 1000-750 m	.16	2	1.05 (n.s.)
Displays at 500-250 m	.02	2	.13 (n.s.)
Pooled error	2.73	36	

TABLE 4.– PROPORTION OF HEIGHT ERROR VARIANCE ASSOCIATED WITH TREATMENTS WITHIN THE 1500-1250 m SEGMENT OF THE APPROACH

Source	Estimates of variance components (percent)
A (sequence)	0.9
B (displays)	9.0
C (winds)	6.8
R(A) (Ss)	31.3
A X B	0.0
A X C	1.1
B X C	0.2
B X R(A)	22.7
C X R(A)	6.1
A X B X C	0.0
Error	21.9
Total	100.0

TABLE 5.– THE MEANS OF THE DEPENDENT VARIABLES WITHIN SELECTED TREATMENT LEVELS

Selected treatment levels	Number of flights	Dependent variables			
		Height error (m)	Sink rate standard deviation (m/s)	Control stick position standard deviation (deg)	Secondary task performance (responses)
Display I	128	5.23	0.388	1.51	4.07
Display II	128	4.93	.365	1.50	3.86
Display III	128	4.06	.260	1.46	3.83
1500-1250 m					
Display I	128	7.69	.382	1.28	4.08
Display II	128	7.07	.393	1.38	3.73
Display III	128	4.27	.247	1.20	4.08
Headwind:					
0 m/sec	96	5.78	.360	1.62	3.23
5 m/sec	96	4.76	.341	1.49	3.66
10 m/sec	96	4.20	.330	1.43	3.95
15 m/sec	96	4.23	.319	1.43	4.83
Segments:					
1500-1250 m	384	6.34	.341	1.29	3.92
1000-750 m	384	5.02	.322	1.44	3.96
500-250 m	384	2.86	.349	1.75	3.87

Note: The brackets between pairs of means indicate significant differences by the Tukey test. Left brackets, $p < 0.05$; right brackets, $p < 0.01$.

TABLE 6.– ABBREVIATED SUMMARY OF SINK RATE VARIATION ANALYSIS OF VARIANCE

Source	F	Estimates of variance components (percent)
A (sequence)	4.99 ($p < 0.025$)	0.0
B (displays)		7.1
C (winds)		2.0
D (segments)		.1
R(A) (pilots)		31.0
B × R(A)		18.8
B × C × R(A)		4.9
C × D × R(A)		2.9
Error		31.2

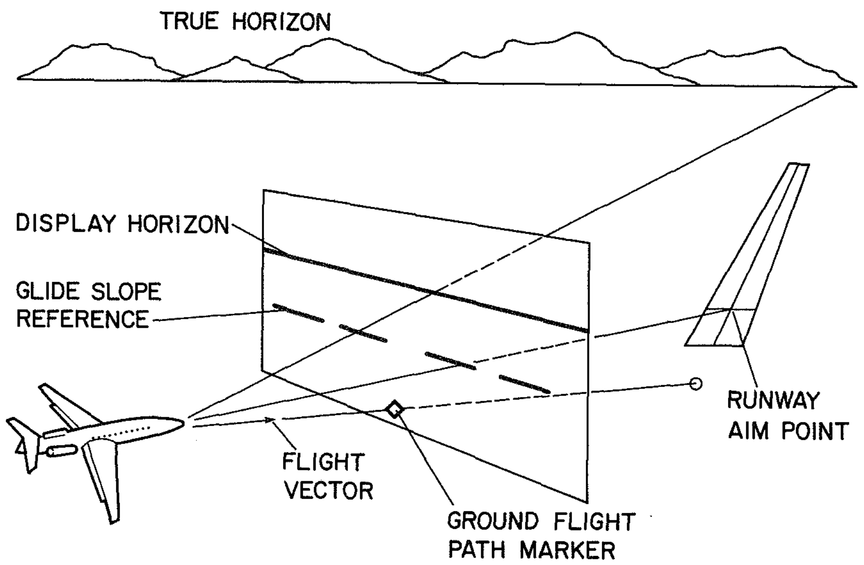
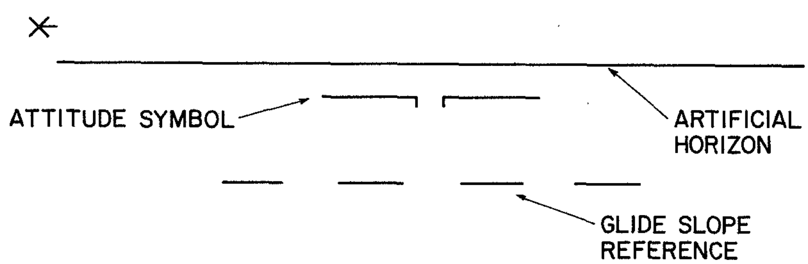
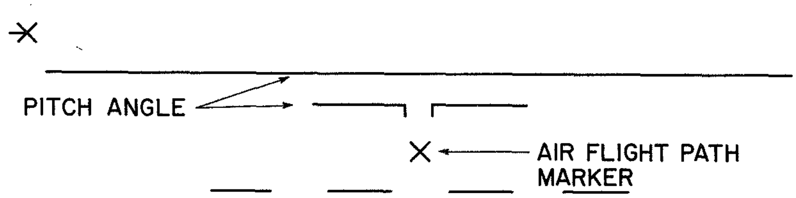


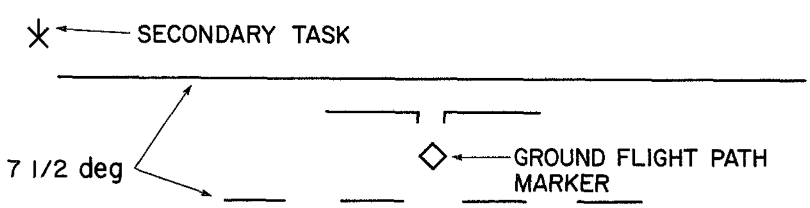
Figure 1.– Relationship between the HUD symbols and the ground.



(a) Display I



(b) Display II



(c) Display III

Figure 2.– Three experimental head-up displays.

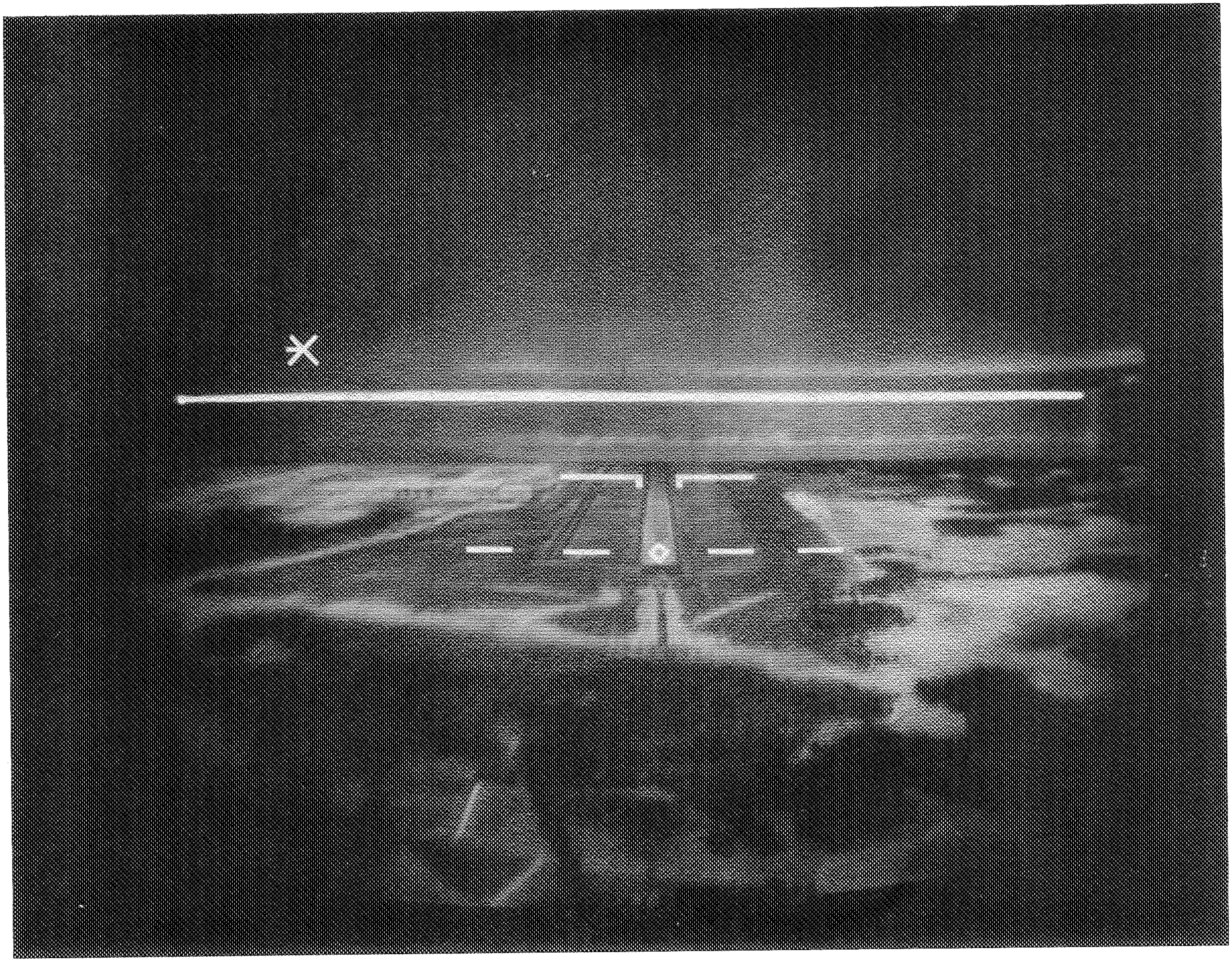


Figure 3.– Experimental display III.

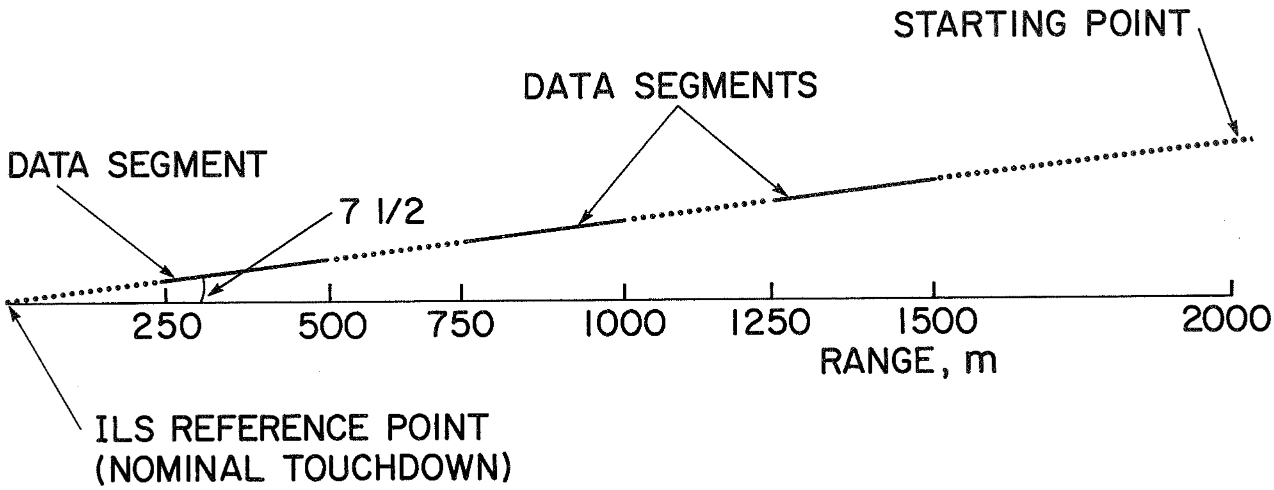


Figure 4.– Segments of each approach (flight) in which data were collected.

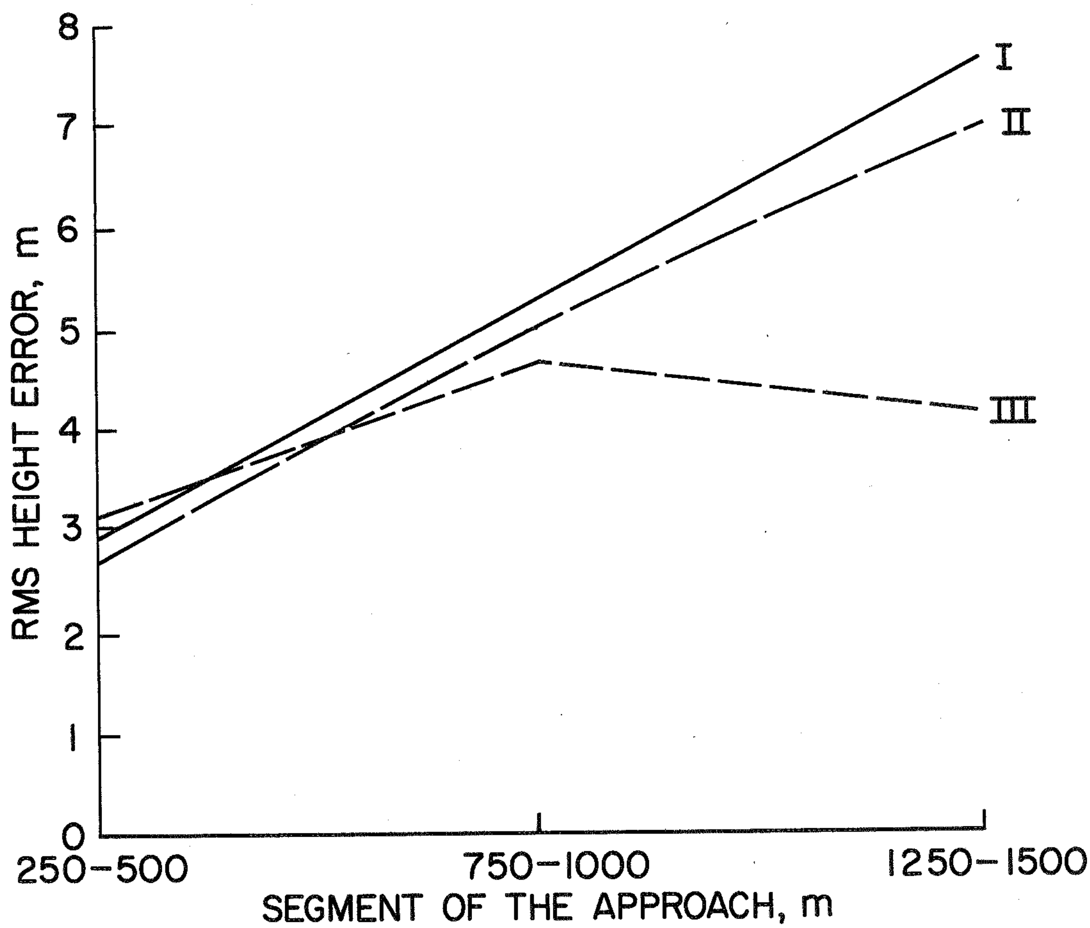


Figure 5.– RMS height error at three segments of the approach for three displays: B X D interaction.