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18. Pilot Performance With a Simulated ILS-Independent Pictorial Display

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As part of a general investigation of the effectiveness of pictorial displays for manual control and monitoring of aircraft approaches and landings, a simulator study was conducted in which pilot performance with three pictorial display? was evaluated. These displays differed in the type of guidance symbology added to the basic perspective runway display. The effect of decreased resolution and update rate of the runway image on pilot performance was also determined.

The results indicate that for pictorial displays with added guidance symbology, there was a marked improvement in pilot performance compared to results of a previous study in which the display consisted of only a runway image and aircraft attitude. However, approach precision was inadequate to meet category II tolerances. Landing performance was also improved by providing additional guidance information on the display. The moderate degradation in runway image resolution and update rate had a negligible effect on performance; nevertheless, it was disliked by the pilots.

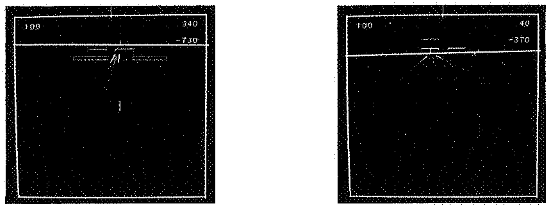
INTRODUCTION

New transport aircraft are being equipped to perform completely automatic approaches and touchdowns in low visibility weather. If the redundancy and reliability provided by the presence of the pilot on board these aircraft is to be effectively utilized, the pilot must remain actively in commandand not become merely a system status monitor. Studies have shown that current displays are inadequate for this task (refs. 1, 2, and 3). Displays should allow the pilot to commit the airplane to a landing if the approach is successful, reject all marginal approaches, and assume manual control to complete the approach or execute a missed approach.

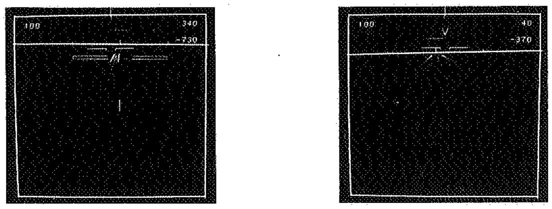
In addition, there is a strong feeling, especially among pilots (ref. 4), that the guidance for such a display must be independent of the guidance for the autoland system. The display should provide a redundant source of information and thereby increase pilot confidence in the use of the automatic system. Such a display is generally referred to as an independent landing monitor (ILM).

One type of ILM generates a perspective image of the terrain and runway ahead of and below the aircraft. This display would be generated by an airborne system such as perspective radar, low light level TV, or a microwave radiometer that could penetrate low visibility atmospheric conditions (ref. 5). This type of imaging pictorial display has several advantages. It provides an integrated and easily interpreted picture of the outside world. The pilot should be able to use many of the same visual cues that he haslearned to use during extensive visual flight. The perspective format should improve the pilot's ability to visualize his position with respect to the real runway and thus facilitate the transition from instrument to visual flight. Finally, symbolic guidance information can be naturally integrated into the display to provide quantitative information and to improve the precision with which the pilot can use the information provided by the perspective image of the runway. However, such display systems usually produce runway images with insufficient content, degraded resolution, and a delay in time.

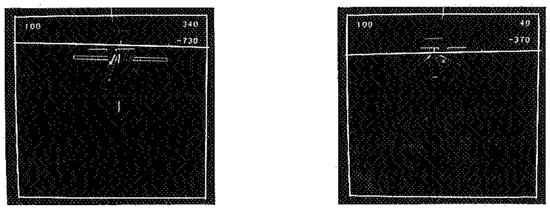
Two simulator studies have been conducted to investigate the attributes and deficiencies of imaging pictorial displays for manual control and monitoring of aircraft approaches and landings. The first study (ref. 6) isolated and studied the basic display element: the perspective runway image. Results of that study indicate that although the display had good pilot acceptance and could be degraded in resolution and update rate with little effect on performance, it was inadequate for making precise approaches and landings. The purpose of the present study was to investigate various methods of adding guidance symbology to augment the information contained in the runway image. Three display configurations and two image resolution and update rates were studied, and the results are compared with those of the first study. Results are also provided on pilot ability to monitor approach performance at a decision altitude of **30** m (100 ft).



(a) DISPLAY I-APPROACH (b) DISPLAY I-TOUCHDOWN



(c) DISPLAY II-APPROACH (d) DISPLAY II-TOUCHDOWN



(e) DISPLAY III-APPROACH (f) DISPLAY III-TOUCHDOWN

FIGURE 1.—Approach and touchdown configurations of the three experimental displays.

TESTS AND PROCEDURES

Display Configurations

Approach and touchdown configurations of the three displays evaluated are shown in figure **1.** Each display comprised basically the same runway image, horizon bar, and airplane reference symbol used in the previous experiment (fig. **2**); and additional symbology (fig. **3**) to aid the pilot in using the natural visual cues provided by the runway image and to provide other guidance information in symbolic form. The central display element was a perspective view of the runway reflectors (fig. **4**). This particular reflector or beacon configuration was designed to improve lateral offset and distance-down-the-runway information when the aircraft was close to the ground. Other configurations with more beacons positioned to simulate actual runway lights were tested, but they added too much clutter for the low-resolution display condition.

Each display configuration contained the following basic information:

(1) Digital readouts of airspeed, altitude, and vertical velocity.

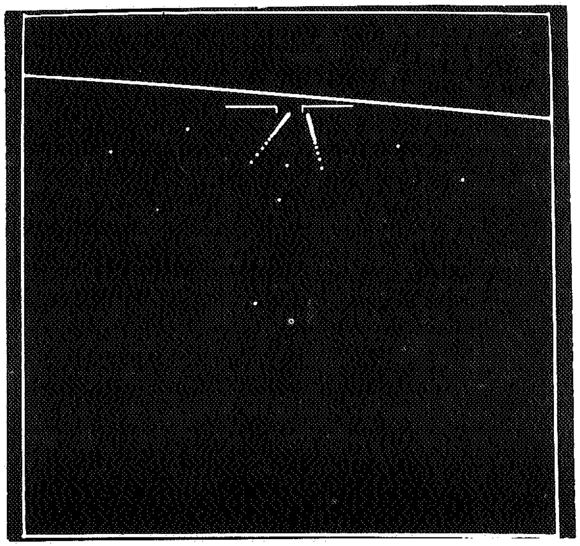


FIGURE 2.—Pictorial display *A* used in prior experiment (ref. *6*).

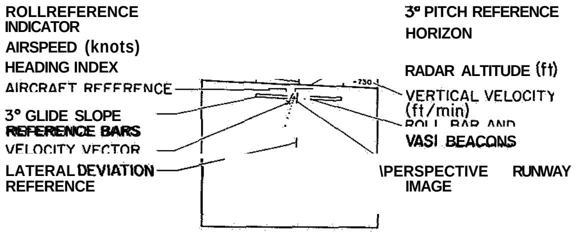


FIGURE 3.—Identification of display elements of display III during the approach.

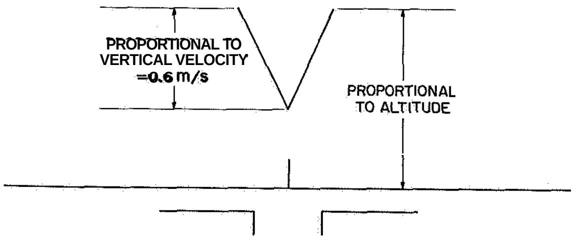


FIGURE 5.—Integrated altitude and vertical velocity symbol during touchdown with display 11.

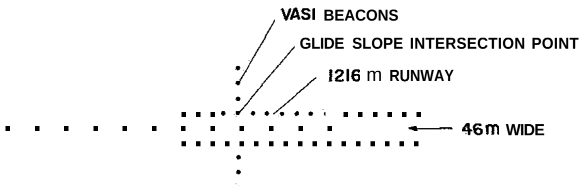


FIGURE 4.—Runway configuration (not to scale).

(2) Pitch, heading, and roll reference marks.

(3) Glide slope reference (GSR) bars, which were depressed 3° below the horizon. If the glide slope intersection point on the runway was held 3° below the horizon, the aircraft would remain on a 3" glide slope. The gap between the glide slope reference bars indicated a ±0.3° glide slope tolerance.

(4) A lateral deviation reference (LDR) bar, which was a short line perpendicular to the horizon on the same heading as the runway. If the airplane was over the extended runway centerline, the runway lead-in beacons were perpendicular to the horizon. The LDR bar helped the pilot maintain this relationship.

(5) At an altitude of 36 m (120 ft) above the runway, a minimum decision height (MDH) marker flashed on the display to indicate to the pilot that he was approaching the MDH. At an altitude of 30 m (100 ft) the MDH marker was removed, and an integrated display of radar altitude above the runway appeared. At an altitude of 15 m (50 ft) the GSR bars and LDR bar were removed to reduce clutter and to cue the pilot that he was 15 m above the runway.

The experimental displays contained the following additional symbology:

Display I.—The approach symbology was the same as described above. At an altitude of 30 m, the short bar shown above the horizon in figure 1(b) appeared. Its distance above the horizon was proportional to wheel height above the runway. The scaling was 6 m per degree.

Display II.—During the approach, the roll bar lights at the glide slope intersection point formed a visual approach slope indicator (VASI). If the aircraft was at a glide slope angle of between 2.85" and 3.15°, two roll bar lights were visible. Below 2.85" only one light was visible, and above 3.15" three lights were visible. At an altitude of 30 m the chevron shown in figure 1(d) appeared. It provided an integrated measure of both wheel height above the runway and vertical velocity (fig. 5). The display gains were set so that the chevron could be used as a flare command. If the pilot began his flare when the point of the chevron touched the horizon and then continued to pitch up just enough to hold the point of the chevron on the horizon, he would execute an exponential flare and touchdown with a vertical velocity of 0.6 m/sec (2 ft/sec). The display gains on altitude and vertical velocity were 6 m/deg and 1 m/sec/deg, respectively.

Display III.—In addition to the VASI lights, this display included a velocity vector symbol (the *X* in fig. 1(e)), which indicated the point on the ground toward which the aircraft was aiming at any instant. Vertically, it provided flight-path angle; laterally, it provided track information. At 30 m, the radar altitude bar shown in figure 1(f) appeared. It was scaled the same as the bar in display 11. If the velocity vector was held on the runway aim point until the radar altitude bar passed through the velocity vector and then the flare was initiated, holding the velocity vector just below the altitude bar, an exponential flare would be executed.

Display Quality

Two runway image qualities were tested for each of the three display conditions. These were “good display quality” (horizontal resolution, **0.05”;**vertical resolution, **0.05”;**and update interval, 0.1 sec), and “poor display quality” (horizontal resolution, 0.4°; vertical resolution, 0.4°; and update interval, 0.3 aec). The resolution of the displayed runway image was degraded by reducing the effective digital resolution of the computer display. The update interval, the time between new frames of information, was simulated by adjusting the updating in the digital program. The horizon and other display symbols were updated every **0.05** sec and always had a resolution of **0.05”** relative to the “real world.” All display elements were refreshed at the rate of 60 frames/sec to prevent flicker.

The field of view of the perspective display was 40” by 40° in the “real world.” The display was generated on a cathode ray tube and transmitted by a 946-line closed-circuit TV system to a monitor in the pilot’s cab. The pilots viewed the TV monitor from a distance of about 45 cm. The display was thus compressed to a scaling of approximately **1**:2 as compared to a “real world” view of the runway.

Test Setup

The piloting tasks were performed by pilot-subjects seated inside a small portable cab. The pilot had three controls: a side-arm controller with a flexible plastic fiber control stick, a combination recycle and start switch, and a decision switch. Figure **6** shows the interconnection between the cab and the simulation equipment.

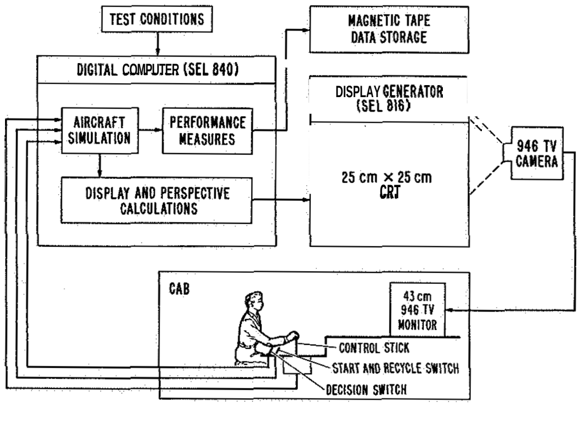


FIGURE 6.—Cab and simulation equipment.

An aircraft with good handling qualities was selected so that the effects of the flight display variables considered in this study on pilot performance could be more easily determined. The dynamics of a Navion low-wing, four-passenger, light plane were simulated on a digital computer using the linear equations described in appendix A. To reduce the effects of differences in piloting techniques, pilot options such as power adjustments and flap settings were not included in the simulation. The power and trim were set to maintain an airspeed of **53** m/sec (104 knots) on a **3”** glide slope. The yaw rate was computed so that the aircraft always made coordinated turns; hence, rudder control was not required or provided. At the beginning of each flight the simulated aircraft was positioned 3040 m **(10** 000 ft**)** from the threshold on a 3” glide slope to a point 304 m **(1000** ft) down the 1216-m (4000 ft) long runway.

Test Subjects and Procedure

Six airline pilots with extensive backgrounds in instrument flying were selected to participate in these experiments. They had very little prior experience with pictorial displays or laboratory simulation experiments. Their flight experience is summarized in table **1.**

The experiment was divided into two phases. Phase **1** provided the pilots with initial practice on the displays and included a test to identify pilots with a tendency to make control reversals on an inside-out display in a fixed-base simulator. Phase 2 was designed to measure the overall performance levels of the different displays, the relative differences between the displays, and the effect of poor display image quality on pilot performance.

Phase 1.—Each pilot was informed of the background and objectives of the experiment. He then was given a detailed description of the particular display he would fly, the aircraft dynamics, the environmental disturbance, and the task to be performed.

The pilot was seated in the cab and allowed to fly the simulated aircraft. The display provided only numeric readouts of airspeed, altitude and

TABLE 1.—*Pilot Experience*

Pilot	Position	Aircraft	Flight time Total	Night	Instrument
1	2nd officer	707	3,000	700	1,000
2	Captain	720	14,500	.....	.....
3	1st officer	707	2,700	1,200	500
4	2nd officer	DC-8	4,000	1,500	500
5	1st officer	707	5,000	1,800	700
6	2nd officer	DC-8	5,000	500	500

vertical velocity, and aircraft attitude information. The runway image, glide slope reference bars, and lateral reference bar were removed. After about 10 min of flying, a series of 36 random disturbances in bank, pitch, and yaw angle were introduced and the pilot was instructed to correct for them. The pilot was subjectively scored by the experimenter on the number of control reversals he made.

If a pilot made any control reversals during the the last 18 disturbances he was not asked to participate in phase 2. Six pilots were eliminated in this way. There was no apparent difference in experience or position between these pilots and those selected to participate in phase 2 of the experiment. All pilots then made 32 approaches and landings for practice with one of the three displays with the runway image quality degraded.

Phase 2.—Six pilot-subjects who passed the control reversal test spent 2 hr on three different days on phase 2. Each pilot was briefed on the display he would fly that day and then made 32 flights. The first 16 flights were made with one runway image quality and the second 16 flights with the other; the first 8 flights of each group of 16 were for practice. The flights were made in sets of four. In each set of four flights, initial crosswinds were drawn randomly without replacement from the set (−2.7, −1.35, +1.35, and +2.7 m/sec). Vertical drafts were drawn in the same manner from the set (−0.9, −0.45, +0.45, and +0.9 m/sec). At a range of 1520 m (5000 ft) from the threshold, the constant vertical drafts were reduced to zero. The crosswinds for the remainder of the flight were drawn randomly without replacement from the set (0, 0, 0.6, and 1.2 m/sec). The sign of these winds was the same as the initial crosswind. A moderate level (0.9 m/sec rms) of vertical and horizontal turbulence was also included on every other flight. This turbulence faded out below an altitude of 30 m (100 ft). On all flights the pilots were instructed to land. At an altitude of 30 m (100 ft), when the MDH light went off, they were instructed to judge whether or not they were within 0.3° of a 3° glide slope and within the extended runway confines, and to indicate their decision by pushing the decision switch in the appropriate direction.

The pilot-subjects were arbitrarily divided into two groups and the order of display conditions was balanced in a Latin square for each group. The order in which the display qualities were presented was also balanced between the two groups of three subjects.

Performance Measures and Pilot Opinion

Altitude, lateral displacement from an extension of the runway centerline, and sink rate were recorded at distances of 1520 and 304 m from the threshold for each simulated flight. These same measures and the distance down the runway from the threshold were also recorded at touchdown. When the pilot pushed the decision height switch, his decision as well as the aircraft range, altitude, and offset at that instant were recorded. At the end of the 16 flights for a given display condition, each pilot rated the usefulness of the display for both the approach and landing according to the Cooper-Harper rating scale (ref. 7). At the end of the experiment, each pilot was interviewed.

RESULTS AND DISCUSSION

Means and variances of the data taken at ranges of 1520 and 304 m from threshold and at touchdown were computed for the 288 data flights. In addition, the data for each flight at 304 m (1000 ft) and at touchdown was converted to a qualitative performance description. The altitude and lateral position at 304 m were converted into one of three qualitative performance descriptions according to the definitions provided in table 2. The touchdown data were categorized in a similar way (table 3). The resulting performance data for the 288 flights were subjected to chi-square tests; results for 304 m and touchdown are summarized in tables 4 and 5, respectively.

TABLE 2.—*Qualitative Definition of 304-m Approach Window Performance* *

Approach window performance	Lateral displacement from centerline L, m	Altitude error from glide slope Ae, m
Excellent	$\|L\|<11.2$	$\|Ae\|<1.8$
Successful	$11.2<\|L\|<22.8$	$1.8<\|Ae\|<3.6$
Unsuccessful	$22.8<\|L\|$	$3.6<\|Ae\|$

* The rating for each flight was the worst of the two variables, L or Ae.

Display Symbology Effects

Approach performance: 1520-m range.—The mean and standard deviation of altitude error and the rms lateral offset at the 1520-m window are shown in table 6; rms lateral offset was used to include the effect of crosswind biases to obtain the worst case dispersion. A Cochran's test for homogeneity of altitude variances of the three displays indicated that the displays were significantly different at the 0.05 level. Table 6 indicates a progressive reduction in altitude variability from display I to display III. This was as expected since the VASI beacons in display II should improve the pilot's ability to see glide slope errors, and the velocity vector symbol in display III allowed the pilot to immediately estimate and correct for the constant vertical drafts, thereby reducing his overall altitude variability. There was a similar trend in the lateral offset data, but the differences were not statistically significant. The addition of turbulence did not cause any significant difference in performance.

TABLE 3.—*Qualitative Definition of Touchdown Performance* *

Touchdown performance	Lateral displacement from centerline L, m	Distance down the runway D, m	Sink rate S, m/sec
Excellent	$\|L\|<3.0$	$365<D<547$	$S<0.9$
Successful	$3.0<\|L\|<12.1$	$182<D<365$ or $547<D<730$	$0.9<S<1.5$
Marginal	$12.1<\|L\|<21.9$	$0<D<182$ or $730<D<1034$	$1.5<S<2.4$
Unsuccessful	$21.9<\|L\|$	$D<0$ or $3400<D$	$2.4<S$

* The rating for each flight was the worst of any of three variable, L, D, or S.

TABLE 4.—*Chi-Square Analysis of 304-m Approach Window Data*

Controlled variable	Degrees of freedom	Chi square	Level of significance
Display I vs II vs III	4	7.79	$p<0.10$ (not sig.)
Calm vs turbulent air	2	21.28	$p<0.01$ (very sig.)
Good vs poor picture quality	2	4.20	$p<0.20$ (not sig.)

TABLE 5.—*Chi-Square Analysis of Touchdown Data*

Controlled variable	Degrees of freedom	Chi square	Level of significance
Display I vs. II vs. III	4	31.05	$p < 0.01$ (very sig.)
Calm vs. turbulent	2	3.57	Not sig.
Good vs. poor picture quality	2	12.46	$p < 0.01$ (very sig.)

TABLE 6.—*Altitude Error and Lateral Offset Statistics at 1520 and 304 m From the Threshold for All Flights in Calm and Turbulent Air; 48 Flights Per Statistic*

		1520-m range			304-m range		
		Altitude error		Offset	Altitude error		Offset
Display	Disturbance	Mean, m	Sigma, m	rms, m	Mean, m	Sigma, m	rms, m
I	Calm	−1.1	7.7	17.5	−0.6	2.3	4.5
	Turbulent	2.9	7.8	15.7	−2.1	3.4	4.8
II	Calm	−0.5	6.3	15.6	−0.5	2.1	5.8
	Turbulent	−0.8	7.1	14.3	−0.4	3.7	6.0
III	Calm	−1.9	5.5	11.6	−0.6	1.8	3.6
	Turbulent	−2.1	4.8	10.1	−1.1	3.2	4.5

Approach performance: 304-m range.—The chi-square test for display effects summarized in table 4 indicates that there were no significant differences among the approach window performance data for the three displays. The results suggest that the use of display I in turbulent air might result in poorer performance (fig. 7); however, as indicated above, this was not statistically significant. A Cochran's test of the altitude and lateral offset data in table 6 also showed that there were no significant differences among the displays. It appears that although the addition of the VASI beacons and the velocity vector symbol improved altitude performance at the 1520-m window, there was no similar improvement at the 304-m window. The pilot ratings (fig. 8) agreed with the 304-m window data in that the pilots felt there were no real differences among the displays of the current study in their utility for making the approach.

Figure 9, which compares data of the current study with the data of the prior study (fig. 2, display A), shows that there was a dramatic improvement in altitude performance due to the addition of the glide slope reference indicator. Though display I differed from display A in other ways, such as including a heading reference and

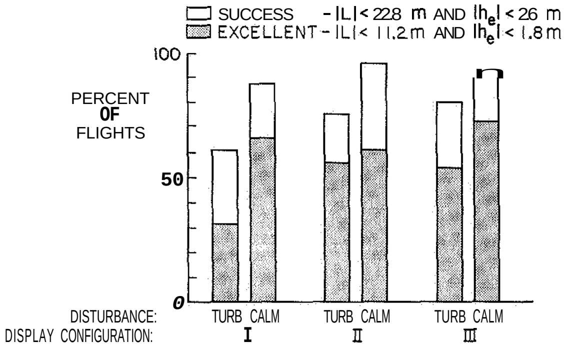


FIGURE 7.—Approach window performance—48 flights per condition.

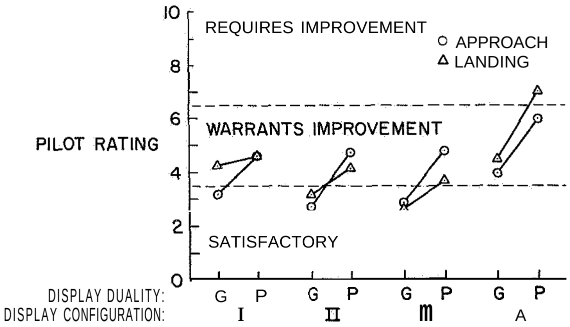


FIGURE 8.—Average Cooper-Harper ratings for each display and picture quality.

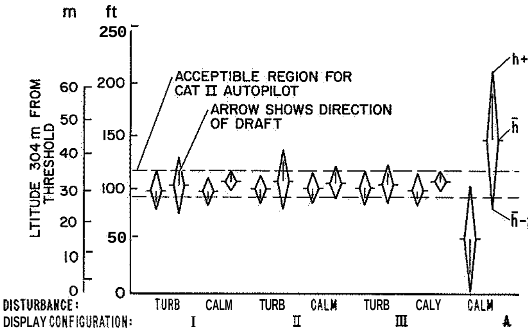


FIGURE 9.—Average altitude performance at the 304m approach window for both the current and prior study. Only flights with a ±0.9 m/sec vertical draft are shown. Flights in the prior study were made in calm air only.

digital instrument data, the addition of the glide slope reference is considered to be the principal factor that would account for the large improvement in reducing glide slope error.

With respect to the requirement to penetrate a category II approach window (less than ±3.7 m (12 ft) height error and ±22.9 m (75 ft) lateral offset error (ref. 8)) 95 percent of the time, with the various wind conditions of this experiment, the displays provided inadequate glide slope information but adequate lateral offset information. The data in table 6 indicate that in calm air the displays allowed barely acceptable altitude control since the 2σ value of altitude dispersion is about 3.7 m (12 ft). With turbulence the variability was nearly twice this value. One reason for this inadequate longitudinal performance is believed to be the low display gain on glide slope deviation inherent in an imaging pictorial display. The display gain is fixed by perspective geometry and the image magnification. On these displays the magnification ratio of 0.5 caused a 0.3° error in glide slope to produce only a 0.15° deviation as measured at the pilot's eye. A standard ILS indicator has a display gain roughly four times this great. A second related reason for poor glide slope performance is that at an altitude of 30 m (100 ft) the pilot was naturally attending to the runway and was not very concerned about what appeared to be small deviations from the specified glide slope. The only way to provide a higher glide slope gain on a pictorial display is to provide artificial symbols such as highways in the sky (ref. 9). This type of symbology was not considered in the study because it depends on an external guidance source like the ILS.

The largest rms lateral deviation of 6.0 m (19.6 ft) was more than adequate to meet the category II criterion of a 22.9 m (75 ft) absolute limit from the centerline. None of the flights was as far as 22.9 m from the runway centerline at the 304-m (1000 ft) window.

As indicated in table 4, the effect of turbulence on performance was very significant. In figure 7, note the degradation in window performance for each display when the simulated (0.9 m/sec rms) turbulence was present. Table 6 presents the standard deviations for all flights (including all conditions of up- and downdrafts and crosswinds) in calm and turbulent air; the principal effect of turbulence was to almost double the variability in altitude, while little turbulence effect on the variability in lateral position is noted.

Touchdown performance.—The progression of improved touchdown performance from display I through display III is evident in figure 10. Both display II and III provided better control over distance to touchdown (table 7 and fig. 11). The maximum 2σ dispersion of 231.0 m (760 ft) was about one-half the FAA-specified 2σ limit of 456 m (1500 ft) for an autoland system (ref. 9). This demonstrates that the inclusion of a flare command scheme offers improvement in touchdown distance over the presentation of altitude alone.

Improved lateral performance was obtained with display III, which had the advantage of

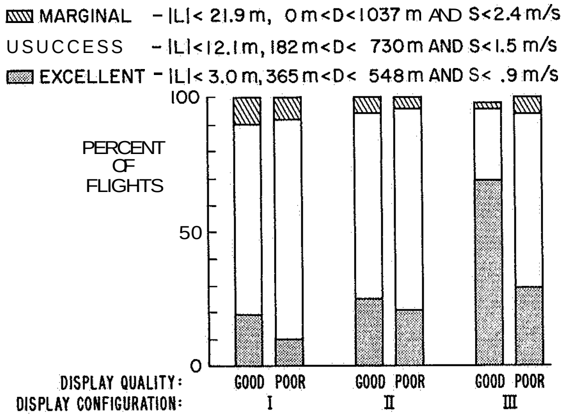


FIGURE 10.—Touchdown performance, all flights (48 landings per condition): *L*—lateral displacement from centerline of runway; D—distance down runway; *S*—sink rate.

TABLE 7.—*Touchdown Statistics for All Displays and For Good and Poor Display Quality; 48 Landings Per Statistic*

Display	Display quality	Distance, D		Sink rate, S		Offset, L
		Mean, m	Sigma, m	Mean, m/sec	Sigma, m/sec	rms, m
I	Good	461.7	134.4	0.85	0.42	4.1
	Poor	428.8	143.8	.91	.33	4.9
II	Good	437.6	90.2	.79	.33	5.1
	Poor	415.4	106.6	.82	.33	5.5
III	Good[1]	416.0	76.5	.70	.36	2.0
	Poor	429.7	115.8	.79	.42	4.02
A	Average of all conditions	417.3	157.8	1.21	.41	3.2

[1] Data for this condition exclude the one unsuccessful touchdown (D = 382.8, S = 3.62, and L = –0.9).

[2] Large value due to one touchdown at 18.5 m left of center.

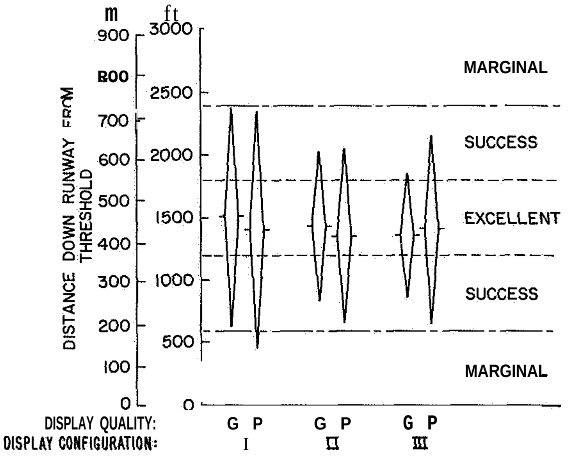


FIGURE 11.—Average distance down the runway at touohdown.

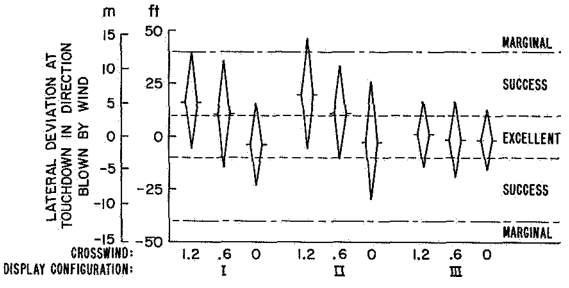


FIGURE 12.—Average lateral dispersions at touchdown for different crosswinds and displays: N – 24 for nonzero crosswinds; N =48 for zero crosswind.

indicating the true direction that the aircraft was tracking near the runway (table 7 and fig. 12); in fact, performance with display III was relatively impervious to crosswinds during the landing (fig. 12).

Table 7 indicates that there were no essential differences among the performance measures with the displays relative to sink rate at touchdown. Thus, contrary to expectations, neither display II nor display III, both of which included information on sink rate, showed any improvement over display I, which only showed altitude above the runway. In the prior study (ref. 6), one conclusion was that the unaided pictorial of the runway provided inadequate information to control sink rate near touchdown. The mean touchdown sink rate for that study was 1.2 m/sec (4.0 ft/sec) with a standard deviation of 0.43 m/sec (1.4 ft/sec); thus, the displays of the current study indicated a sizable overall improvement of about 0.39 m/sec (1.3 ft/sec) less sink rate at touchdown.

The finding that there was no apparent effect due to turbulence was unexpected; even when the turbulence was reduced to zero between 30 and 21 m, the turbulence caused a significant increase in altitude dispersion at the 304-m window, which could have affected touchdown performance. However, there was very little correlation between altitude at the window and touchdown performance (product-moment correlations were less than 0.25).

Display Quality Effects

Approach performance.—The results of varying the runway image quality were similar to prior results (ref. 6) in that there was no significant difference in performance due to image quality at either **1520** or **304** m, even though the pilots preferred the better display. The better quality display was rated two units lower on the Cooper-Harper rating scale (fig. 8). The responses to questions **2** and 3(c) during the debriefing (appendix B) further substantiated the pilot's preference for the better runway image quality. Most of the pilots complained that with the poor display quality they had trouble seeing the runway image as that of a real runway, and two pilots responded that poor display quality was the most disturbing aspect of the display configuration they preferred over the other two.

Touchdown performance.—The effect of display quality on overall touchdown performance is shown in figure **10.** Although performance with displays I and II was slightly better with the better picture quality, performance with display III was more significantly affected by display quality. When performance data for displays I and II were subjected to the chi-square test, there was no significant effect from display quality ($\chi^2=1.74$, $df=2$); display III data tested alone still revealed highly significant effect of picture quality ($\chi^2=15.05, df=1$). In the case of display 111, there were so few failures and marginals that they were added to the successes, yielding a fourfold table for the chi-square test and one degree of freedom.

Table **7** indicates that the effects of poor display quality with display III were apparent in greater dispersion in lateral and distance down the runway but not in sink rate (fig. **11).**

The height bar, the velocity vector symbol, and the horizon were not affected by picture quality; thus, there is no apparent reason for the influence of poor display quality on the distance-down-the-runway measure when the pilots were using display 111. It was presumed that these three symbols were used to establish the flare and sink rate just prior to touchdown.

The poorer performance in lateral dispersion due to picture quality with display III can be associated with the fact that to make a touchdown near the centerline, the pilot was required to first be over the centerline and then to set and hold the velocity vector symbol on the center of the far end of the runway. With poor resolution and a time delay in updating the runway pictorial, it is possible that the pilots had difficulty in holding the velocity vector centered on the end of the runway and thus were distracted from the flare maneuver, resulting in more variability in lateral and distance performance.

The pilot ratings for display quality (fig. 8) showed little preference for the better picture quality with display **I** and a one-unit preference for the better display quality with displays II and **111.**

Performance Monitoring

Of the total of 286 flights in which the pilots made judgments as to whether they were inside or outside of the specified category II approach window at an altitude of **30** m (±**3.7** m in altitude or ±**0.3**" in glide slope and ±**22.9** m laterally), **42 (15** percent) of the judgments were incorrect. These judgment errors were biased such that the pilots estimated their performance to be better than was actually the case. Of the **38** flights that failed to make the specified performance window (all failures were in altitude), **19 (50** percent) were judged by the pilots to be inside the window; of the **248** flights that were inside the window, **23 (9** percent) were judged to be outside. The lack of precision in making these judgments is indicated in figure **13;** as extreme examples, a flight as deviant as **1.4**" from the glide slope nominal was judged to be within **0.3**" and one flight within **0.1°** of the glide slope nominal was judged to be outside. It ap-

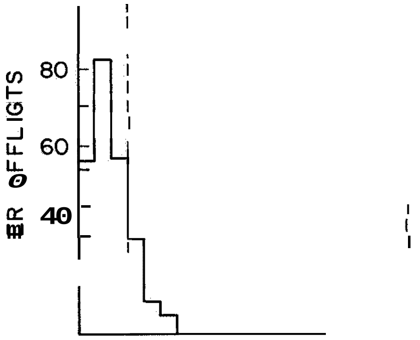


FIGURE 13.—Pilot judgment data averaged over all display conditions, display qualities, and disturbances; N =286.

pears that the requirement for a pilot to make accurate judgments of glide slope error, at least while also manually flying the aircraft, is beyond his capability with the displays of this study. In another study conducted at Ames (ref. 1), it was shown that pilot judgments of lateral offsets with a pictorial display designed for pilot monitoring were considerably more accurate than those made with a conventional flight director and associated instrumentation.

The judgment data were examined to determine if the different displays, the turbulence, or the display quality had any effect. The results were negative. Pilot judgments were equally good (or bad), regardless of the display, turbulence condition, or display quality.

Pilot Interviews

A summary of the pilots' responses on each question of the interview is given in appendix B. In general, for the good runway image quality, none of the six pilots had any trouble seeing the picture of the runway as a real runway. However, four pilots said that they had some difficulty with the poor runway image quality, which was the most disturbing feature of the display. During the approach the pilots preferred the displays with the VASI lights. Three pilots also felt that the velocity vector was helpful during the approach. During the flare and touchdown, the pilots preferred displays II and III with integrated vertical velocity information. With regard to the category II judgment task, the pilots generally felt that their responses were accurate.

CONCLUDING REMARKS

A study has been conducted in which airline pilots flew manual approaches and landings using simulated ILS-independent, imaging pictorial landing displays. Approach and touchdown performance was evaluated as a function of display configuration, turbulence, and display quality. In addition, pilots' judgments of their success in penetrating a category II approach window during manual approaches were obtained. In general, the results indicated that the displays with added guidance symbology allowed control considerably more precise than that obtained with an unaugmented pictorial display studied in a prior study, and the pilots' acceptance of these displays was good. Moderate degradation in image resolution and update rate did not affect performance but was disliked by the pilots. Simulated turbulence doubled the variability in altitude at 304 m from the threshold but had little effect on lateral or altitude performance at 1520 m from the threshold.

During the approach, lateral control with these displays was good, and the pilots made no lateral judgment errors at the 30-m (100 ft) decision height. Although altitude control performance with the addition of the glide slope reference bars, VASI, and velocity vector symbols was improved dramatically relative to results with an unaugmented display from a prior study, consistent (95 percent probability) penetration of a category II approach window in turbulence was not accomplished. Furthermore, 15 percent of the pilot's judgments as to whether they were within a category II approach tolerance were in error, indicating that the displays did not provide adequate information for the pilot to judge glide slope deviations during manual approaches.

Touchdown performance also showed an improvement over results of a prior study in which no guidance symbology was added to aid the pilot in making the flare. Touchdown distance dispersion and mean sink rate were both reduced, but the lateral offset dispersion was only marginal.

SYMBOLS AND ABBREVIATIONS

Ae	altitude error from 3" glide slope, m
D	distance down runway from threshold, m
g	acceleration due to gravity, m/sec^2
GSR	glide slope reference
HR	horizontal resolution, deg
ILM	independent landing monitor
ILS	instrument landing system
L	lateral displacement from runway centerline, m
LDR	lateral deviation reference
MDH	minimum decision height
p	roll rate, rad/sec
q	pitch rate, rad/sec
r	yaw rate, rad/sec
s	Laplace operator, rad/sec

S	sink rate, m/sec
u	perturbed forward velocity, m/sec
U_0	steady-state forward velocity, m/sec
UI	update interval, sec
VASI	visual approach slope indicator
VR	vertical resolution, deg
w	perturbed downward velocity, m/sec
w_g	vertical wind gust, m/sec
X	forward ground velocity, m/sec
Y	side ground velocity, m/sec
$\dot{Z}$	vertical velocity, m/sec
p o	lateral wind gust, rad/sec
δ_a	aileron control surface deflection, rad
δ_e	elevator control surface deflection, rad
e	pitch angle, rad
ϕ	roll angle, rad
ψ	yaw angle, rad

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APPENDIX A

Aircraft Simulation

The following linear differential equations were programmed on a digital computer to simulate the dynamics of a Navion single-engine, four-place light aircraft.

AIRFRAME DYNAMICS

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} & & \\ Z_u & Z_w & -U_0's \\ 0 & M_w & M_q \end{bmatrix} \cdot \begin{bmatrix} u \\ w \\ q \end{bmatrix} + \begin{bmatrix} 0 \\ Z_{\delta_e} \\ M_{\delta_e} \end{bmatrix} \delta_e - \begin{bmatrix} 0 \\ Z_w \\ M_w \end{bmatrix} w_g$$

$$\dot{p} = L_p \cdot p + L_{\delta_\alpha} \cdot \delta_\alpha - L_\beta \cdot \beta_g$$

The following values of the stability derivatives were obtained from reference **11.**

$Z_{\delta_e} = \mathbf{-8.45}$ msec^{-2} $\quad$ $M_w = \mathbf{-0.166}$ msec^{-1}

$M_{\delta_e} = \mathbf{-11.1892}$ sec^{-2} $\quad$ $M_q = \mathbf{-2.0767}$ sec^{-1}

$X_w = \mathbf{0.03607}$ sec^{-1} $\quad$ $U_0 = \mathbf{53.0}$ sec^{-1}

$X_u = \mathbf{-0.0451}$ sec^{-1} $\quad$ $L_p = \mathbf{-8.402}$ sec^{-1}

$Z_w = \mathbf{-2.0244}$ sec^{-1} $\quad$ $L_{\delta_\alpha} = \mathbf{23.984}$ sec^{-2}

$Z_u = \mathbf{-0.3697}$ sec^{-1} $\quad$ $L_\beta = \mathbf{16.0}$ sec^{-1}

The following approximation for yaw rate r resulted in coordinated turns for small bank angles.

$$r = p \cdot g / (U_0 \cdot s)$$

Control forces.—An MSI Model **438** 2-axis side-arm force controller with a flexible fiber control stick was used. The fiber stick had a **28** N/cm restoring force. The stick gains were:

Longitudinal: **113.0** N/rad of δ_e
Lateral: **69.2** N/rad of 6,

Turbulence.—w_g and β_g were both first-order filtered white noise with a break frequency of ***0.5*** rad; rms turbulence levels for w_g and β_g were **0.9** m/sec and **0.017** rad/sec. The turbulence was faded out below an altitude of **30** m.

COORDINATE TRANSFORRIATIONS

Approximate Euler transformations.—

$$\dot{\theta} = q \cdot \cos(p) - r \cdot \sin(\$)$$

$$\dot{\psi} = q \cdot \sin(\phi) + r \cdot \cos(\phi)$$

$$\dot{\phi} = p$$

Ground coordinate approximations.—

$$\dot{X} = U_0 \cdot \cos(\theta) \cdot \cos(\$)$$

$$\dot{Y} = U_0 \cdot \sin(\$) + \text{crosswind velocity}$$

$$\dot{Z} = U_0 \cdot \sin(\theta) + (w + 0.05236 \cdot U_0) \cdot \cos(\$) + \text{draft velocity}$$

APPENDIX B

Pilot Concluding Interviews

At the end of the last session, each pilot was asked a number of questions and the responses were recorded. The following paragraphs summarize these interviews.

Question 1. How did the workload of the approach and landing task with the displays compare with that with an instrumented ILS system?

Two pilots said a flight director command display was easier down to **30** m altitude; one said the pictorial display required more attention; and the other three said the display was as easy or easier than an ILS.

Question 2. Did you have difficulty in seeing the picture of the runway as being a real runway?

Four of the pilots said they had some trouble with the poor image quality, but none had any difficulty with the good image quality picture. One pilot said it looked surprisingly good—like Pittsburgh in bad weather.

Question 3(a). Which display did you like best? Did you develop any special strategy for this display?

One pilot preferred display I, one preferred display II, and four preferred display 111. None of the pilots said that he developed any special strategy.

Question 3(b). How would you like this display improved?

One pilot wanted the digital instruments moved in closer to the center. One wanted a dial instrument for sink rate. One wanted the lead-in beacons placed farther out from the runway, and the pilot who preferred display I wanted the VASI lights added to it.

Question 3(c). What was the most disturbing aspect of this display?

Two pilots complained about the poor runway image quality. One felt that the airplane symbol got in the way when he was high and had to pitch down. One of the pilots who preferred display III was confused by the velocity vector on the approach and only used it during the flare.

Question 4(a). Which display did you like next best? Any special strategy?

One pilot preferred display I, three preferred display II, and two preferred display 111. The pilots did not mention any special strategy other than what they were instructed to do.

Question 4(b). How improved?

One pilot had trouble flaring with display II and felt it needed better sink rate information near the ground. A pilot who preferred display II wanted to add the velocity vector of display III, and a pilot who preferred display III wanted to add the touchdown symbol of display 11.

Question 4(c). Most disturbing aspect?

The poor image quality was mentioned by one pilot. Another complained that the velocity vector symbol did not stand out enough from the runway beacons.

Question **5.** Discuss the CAT II window judgment task.

The pilots generally felt that their judgments were quite accurate. Two pilots stated that they sometimes said that they were in the window if they felt they could make a good landing or if they were almost in and were correcting in the right direction.

Question **6.** Would you use one of these displays if installed in your aircraft? How?

All pilots said that they would use the display. Four pilots said that they would use it to monitor an autocoupled approach and to crosscheck other instruments. One pilot felt that if it was developed enough he could use it right down to touchdown.

Question 7. Were your instructions clear?

All pilots answered ('yes."

Question 8. Did you have enough practice to do a reasonably good job?

All pilots answered "yes," although one pilot did not think he had a feel for the display after only one day.

Question 9. Do you think that your performance would improve much with more practice?

Five pilots answered in the affirmative, the other felt that his performance would not improve much.

Question 10. Have you had any recent light plane experience?

Only one pilot had flown a light plane recently.

Question 11. What did you think of the two-control Navion?

The pilots felt that the simulation was adequate, though two complained about the control being too sensitive.

Question 12. What are your usual errors in making an ILS approach as a percent of full scale?

Five pilots stated they kept the glide slope indication within **25** percent of full scale. One pilot kept it less than **50** percent of full scale. All of the pilots stated that they were able to maintain the localizer needle within **25** percent of full scale.