Research in the Application of Windshield Projection Displays to the All-Weather Landing Task

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The windshield projection display system provides optically projected images for situation and flight control information. These images appear ahead of the aircraft appropriately superimposed on the natural visual environment. Instrument and visual flight control techniques are thereby made completely compatible. Windshield displays with and without flight director have been investigated in a flight simulation program conducted in a modified B-47 flight trainer. Standard panel instruments were also evaluated for comparison. Test subjects included pilots with scheduled air carriers and Federal Aviation Agency (FAA) pilots. Automatic approaches were simulated, and these had several types of flight control malfunctions introduced at different stages during the approach. Performance criteria were selected specifically to measure the pilot's assessment and backup manual control capability in critical all-weather landing situations. The results indicate that pilots exhibit superior performance in both assessment and control tasks when using the windshield display as compared with panel instruments. They can descend to significantly lower altitudes with steady localizer and glide-slope standoffs and recover safely from these conditions. Significantly fewer go-arounds are initiated with the windshield display subsequent to abrupt autopilot malfunctions at low altitudes than with panel instruments.

All-Weather Landing Paradox

IN a recent popular technical survey of the all-weather aircraft landing problem, the writer has reviewed the history of the development of instrument landing technology.[1] Almost all of the problems seemingly have been solved, and yet the author concludes that the objective of all-weather air transport remains elusive. His conclusion is consistent with the facts, and it is challenging to examine the reasons for this paradox.

A solution to the all-weather landing problem demands a systems approach in the broad sense in which this term is generally used today. Both men and equipment are involved in intimate juxtaposition. The performance of the equipment must satisfy the cockpit crew, and the equipment must respond to the commands imposed by the crew in a manner that the crew considers satisfactory. How can these generalizations be translated into specific requirements?

The following hardware requirements have long been recognized: a precise guidance system, and a high-performance flight control system. Most of the emphasis in equipment development to date has concentrated in these areas. Improved guidance systems have been designed and are undergoing flight evaluation. Advanced autopilots, beam couplers, flight directors, related flight instruments, and autoland equipment are also under continual development.

The human pilot is the true executive or manager of the all-weather landing operation. In this role, he must continually assess the conduct of the mission and exercise the judgment involved in electing any of the alternative options available to him. Should he continue with his automatic flight control system or revert to a manual mode of control? Should he attempt to land or initiate a go-around maneuver? These are the types of decisions with which he is inexorably confronted during the approach. He must, therefore, have the proper information suitably displayed to permit him to make these decisions correctly and consistently. Consequently, the following requirements should be added for the all-weather system: means for assessment of the situation by the pilot, and go-around capability.

The requirement for assessment capability is a broad one. It covers all aspects for assuring the pilot that his approach and landing performance is satisfactory and that he is, in fact, in the situation in which he considers himself to be. Monitoring and failure warning are, therefore, restricted aspects of the assessment problem. The pilot requires more than instrumentation that provides these simple functions and displays its information with panel lights and flag alarms. He must know the location of the aircraft in relation to the runway at all times, and he must also have information relating the trajectory of the aircraft in relation to the desired flight path in azimuth and elevation. Regardless of the quantity and quality of information presented to him in this regard, he imagines his situation in three-dimensional real-world terms.

Instrument displays in current use provide segments of information which either corroborate or refute the real-world picture that the pilot has conjured for himself under instrument-flight-rule (IFR) conditions. The effectiveness of an instrumentation system designed to assist the pilot in his assessment task will be determined by the ease with which the pilot can develop the real-world image of his situation with the instrumentation. There is also a related assessment consideration. Landing under low-weather conditions frequently involves periods during final approach in which some visual reference to the external world is available. These visual cues may not be adequate for visual flight, but they may be used for assessment purposes. In fact, the pilot may find it difficult or even impossible to ignore these cues, even if he were inclined to do so. The initial stages of the transition from instrument to visual flight are examples of

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these visual situations. An effective assessment system must be capable of assimilating these pieces of external visual information to help round out the picture for the pilot. At the very minimum, there must be no conflict generated by perceptual incompatibility between the instrument display and the visual cues in the real world, notwithstanding the complete physical consistency of the information from both sources. The confidence of the pilot in his assessment system can only be developed by repeated demonstration that the information he is given is sufficiently complete and correct over the complete gamut of external visual conditions from visual flight rules (VFR) to the most restricted visibility conditions operationally realizable.

All-weather landing remains elusive, because reliable and precise guidance and flight control techniques have not yet been welded into a system that permits the pilot to make the judgments and responses he demonstrates daily under visual flight conditions. Until such a system is available, or until a fully automatic system that does not require the exercise of human judgment is available, it seems likely that the low-weather operation to which government, industry, and the airlines are dedicated will remain elusive.

Limitations of Panel Instruments

Current cockpit panel displays for instrument approaches include attitude, heading, path deviations, altitude, airspeed, rate of climb, and flight-director command information in various segregated and integrated forms. The pilot must assimilate this information and translate it into a form related to the orientation of his aircraft in a three-dimensional spatial environment that varies with time. The information on the panel is generally presented in isolated bits, and there often is redundancy in the discrete display of related items. The small visual scale to which some of the information must be displayed to cover the required range aggravates the problem.

The form and resolution of panel information is so poor by comparison to the pilot's view of the real world in VFR that the pilot is effectively prevented from generating the fine neuromuscular responses he so easily and naturally accomplishes under VFR conditions. Limiting the pilot's capability to perform the motor skill functions and limiting his ability to assess his situation guarantees that a system limit will be reached before the landing is executed.

Yet, it is neither the fragmented form nor the frequent lack of sensitivity of panel instruments which is the most telling deficiency for the low-weather landing task. It is their lack of compatibility with the external visual world when it appears even in piecemeal form that is most serious. Furthermore, the psychological schism between the panel and the real world shows little promise of being bridged.

Why is the external visual world so important? Under VFR conditions, the pilot is able to capitalize maximally during approach and landing on many of the visual skills that he has been developing all of his life. His guidance is excellent, save possibly for some looseness in the elevation channel. His manual flight control capabilities are also good, presuming that he has adequate guidance. For assessment, the external visual world is today literally peerless in the eyes of the pilot. Under restricted visibility conditions, the pilot also obtains assessment information from the external visual field. The quantity and quality of this information depends on the airport, visual aids, ambient lighting conditions, and, of course, the exact weather conditions.

The perceptual capabilities of the pilot make the situation for the assimilation of visual information extremely favorable. Human capabilities for pattern recognition with the type of visual information available during approach and landing are unparalleled. Furthermore, the pilot subjectively has more confidence in what he perceives directly, as contrasted with an instrument display with sensor and processed data inputs. The eyes, more often than not, believe what they see. This is the reason that optical illusions are so compelling when they occur.

Consequently, there are two assessment features with which the real world provides the pilot which panel instruments cannot rival. These are perceptual ease of assimilation and subjective confidence that the information is veridical.

Windshield Projection Display

The means for giving the pilot the information that he requires for all-weather landing in a form that overcomes basic deficiencies in cockpit panel display media became available in recent years with the advent of windshield projection displays. These devices permit collimated virtual images at optical infinity to be projected within the pilot's field of view as he looks through the windshield of his aircraft. The optical projection technique is substantially the one used in reflecting gunsights for aircraft employed extensively during World War II. This technique permits the superposition of information on the pilot's external visual field in a form that is compatible with his view through the windshield. This information is visible to the pilot by day or night, against a wide range of real-world background brightness. The display can accommodate reasonable head movement by the pilot and is effectively free of parallax effects between projected images and the outside world.

The application of the windshield display to enhance the precision with which pilots may accomplish visual approach and landing was studied almost simultaneously by the Sperry Gyroscope Company in the United States and by the Aeronautical Research Laboratory in Australia.[2, 3] These concepts represented the first true blending of information from the real world as seen by the pilot and flight control information generated within the aircraft. The extension of these concepts to instrument flight control problems, particularly the all-weather landing problem, followed.[4–6] Sperry has developed and flight-tested a windshield display for all-weather landing. The FAA recognized the possible potential for this type of display for all-weather landing, both as an assessment system for the pilot during automatic approach and landing and as a display for these maneuvers performed manually by the pilot. After an in-house analytical study,[7] the FAA decided to conduct further experimental research on specific versions of the display to evaluate its effectiveness for the all-weather landing task.

The essential elements of this display are presented in Fig. 1. The horizon line is a horizontal reference line that represents the trace of a plane normal to the vertical at the aircraft altitude. It is always parallel to the true horizon and is displaced from the horizon in elevation by the dip angle, which is quite small for the low altitudes associated with approach and landing. The dip angle in minutes is approximately equal to $h^{1/2}$ where h is the altitude of the aircraft in

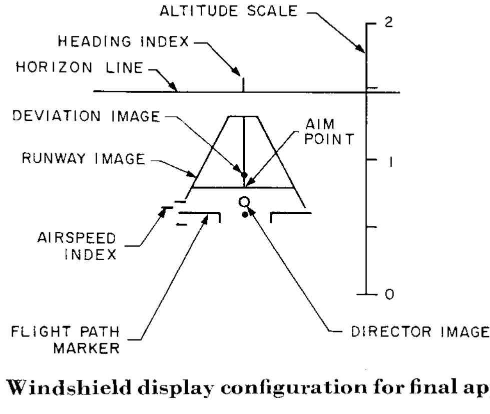

Fig. 1 Windshield display configuration for final approach.

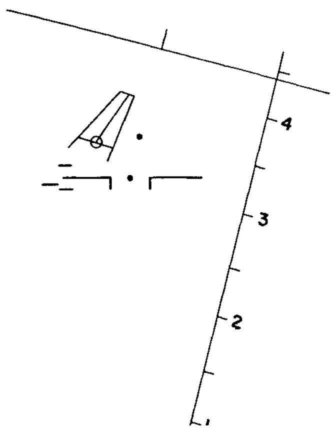

Fig. 2 Windshield display during typical final approach maneuver.

feet. This dip angle is, therefore, less than the accuracy with which the horizon can usually be delineated visually, particularly over land. Hence, the horizon line in the windshield display overlays the real horizon when the latter is in view. The horizon line is space-stabilized and will retain this orientation irrespective of the pitch and/or bank of the aircraft.

The heading index represents the runway or reference heading in the correct visual relationship with the actual heading of the aircraft. The heading index may be considered a pole at the intersection of the extended centerline of the runway with the horizon. Consequently, when the nose of the aircraft moves 1° to the left, the heading index will be displaced 1° to the right. This 1:1 relationship is characteristic of all of the elements in the windshield display which have direct visual counterparts in the real world. The combination of horizon line and heading index represents a space-stabilized attitude and heading coordinate system that is perceptually located in the outside world for the pilot. Questions regarding sensing and scale are eliminated with this display. These parameters must be anchored to the real world, and their compatibility with this visual world can be checked easily by pilot as he reviews the display and its background simultaneously.

The runway image represents the real runway and is consonant with the latter in orientation, perspective, and retinal size. Therefore, the runway image overlays the real runway when visibility conditions permit the pilot to see the runway. The aim point represents the intersection of the reference path for final approach (instrument landing system on-course) with the runway. The horizontal line on the runway through the aim point is the intersection of the glide slope plane with the ground. The extension of the runway centerline and the runway edges all intersect the horizon line at the base of the heading index, in accordance with principles of perspective.

The deviation image (dot) is the means for indicating to the pilot his angular deviations from the on-course measured at the aim point. This scheme in effect transforms the guidance system to an optical one emanating from the aim point with equal localizer and glide-slope sensitivities.[8] The position of the deviation dot in relation to the aim point represents the angular deviation of the aircraft from the on-course in both azimuth and elevation. In Fig. 1 the aircraft is on course laterally but is above the desired glide path. If the aircraft were to travel parallel to the on-course from its present position, it would strike the runway at the point superimposed by the deviation dot. The displacement of the dot from the aim point also represents the lineal deviation of the aircraft from the on-course to the same scale in which the runway is presented. For example, if the dot were on one edge of the runway image, the aircraft would be displaced from the on-course by half the width of the runway.

The altitude scale to the right in the display provides the pilot with a readout of his actual altitude above the runway. This altitude readout is on the horizon line. In Fig. 1 the aircraft is about 150 ft above the runway. These data would probably be obtained from a radar altimeter or equivalent signal source. The altitude representation is symbolic in form, since there is no geometrical angular counterpart of aircraft altitude in the real world. However, the altitude scale may, for convenience, be considered a pole in the visual field whose base representing zero altitude rises to meet the horizon line as the aircraft descends to the runway altitude.

The flight path marker in the form of a miniature airplane image represents the orientation of the velocity vector of the aircraft. If the direction of flight were to remain the same, the aircraft would strike the ground at the point indicated by the center of the image. In Fig. 1, for example, the aircraft is undershooting the aim point on the runway. The flight path marker is projected in elevation in a direction depressed from the aircraft reference line by the angle of attack of the aircraft. This angle-of-attack signal must generally be filtered to make the flight path marker display flyable manually. It represents the true flight path angle with respect to the ground in still air and must be compensated for wind if continuous flight path with high accuracy must be displayed. The bias caused by wind is eliminated when the flight path angle is generated by inertial means. Correct ground track representation by the lateral position of the flight path marker must include effects of drift and yaw or be energized by Doppler or inertial velocity data.

The airspeed index on the left side of the path marker presents the departure of the airspeed from the reference value. This index is slaved to the path marker as flight path changes. The top and bottom indices that are fixed to the path marker represent ±10-knot limits. In Fig. 1, the aircraft is about 5 knots fast with respect to the reference airspeed. The airspeed error display is necessarily symbolic in form, since airspeed error has no clear visual counterpart in the real world.

The director image (the circle in Fig. 1) presents lateral and vertical flight control commands. The commands are satisfied when the pilot or autopilot flies the circle so that it overlays the aim point on the runway image. The same procedure could be followed manually under VFR conditions by overlaying the director image on the aim point of a real runway that the pilot perceives visually in the real world.[8] The latter technique requires no ancillary guidance system, so that it may also be employed for approaches to noninstrument runways. Visual and instrument flight control techniques are, therefore, identical. Under IFR conditions, the real runway has a surrogate runway image in its exact position in visual space. This director system may be used for any dynamic order of coupling to the visual or instrument on-course.[8] For second-order systems for both axes, for example, the director image is displaced laterally with a bank input and vertically with a pitch input. Continuous superposition of the director circle on the aim point satisfies all of the roll and pitch commands during the coupling maneuver. When the aircraft is on the desired on-course, the deviation dot and runway aim point will also have become coincident, i.e., the aim point and its enveloping director circle have moved to the deviation dot. The center of the flight path marker will also be positioned at this point as the aircraft descends along the reference path.

The situation depicted in Fig. 1 has been selected for clarity in describing the functions of the various elements in the windshield projection display. It is interesting and instructive to consider a more general case during a maneuver, such as Fig. 2. Here the aircraft is 440 ft above runway altitude and displaced high and to the right of the on-course. The flight-director commands have been satisfied in roll and pitch. The aircraft is in a left bank, on the runway heading, and is undershooting the runway. Note that the entire display rotates about the flight path marker during a roll maneuver, since the aircraft rolls about its velocity vector, and visual compatibility with the real world is a precept for the windshield display system. The airspeed is 5 knots below the reference value.

It is convenient at this point to summarize the types of information which the windshield display provides in a perceptually integrated form that is compatible with the real world as viewed through the cockpit windshield.

A. Situation Information

This covers angular and positional orientation of the aircraft. Pitch and bank are obtained from the horizon line, whereas departure from the reference heading is indicated by position of the heading index. The windshield display is not a flight instrument in the conventional sense; there are no quantitative readouts of attitude and heading. The lateral and vertical position of the aircraft with respect to the approach on-course are presented by the orientation of the runway image with its aim point in relation to the deviation image. Runway image size is a cue to range, and the altitude scale provides a readout of absolute altitude above the runway.

B. Derivative Information

The flight path vector of the aircraft in space is presented to the pilot by the flight path marker. This information covers both flight path angle in elevation and ground track in azimuth. It represents the instantaneous direction of flight. The airspeed index provides information relating to the magnitude of the vector.

C. Command Information

Quickened flight director commands are included in the display by the director image. This image may be used in conjunction with the aim point on the runway image or the real runway when the latter is visible.

Research Program

The objectives of the research program are to compare the effectiveness of windshield projection displays with and without flight director functions for all-weather landing and to evaluate the effectiveness of the windshield display system in relation to a modern cockpit instrument panel that includes a flight director. The program is being conducted by the Research Division of the Systems Research and Development Service of the FAA‡ and by the Information and Communication Division of the Sperry Gyroscope Company. A simulation phase in a B-47E trainer modified as a simulator and a flight test phase in a DC-3 aircraft are involved. This paper will be restricted to the simulation effort.

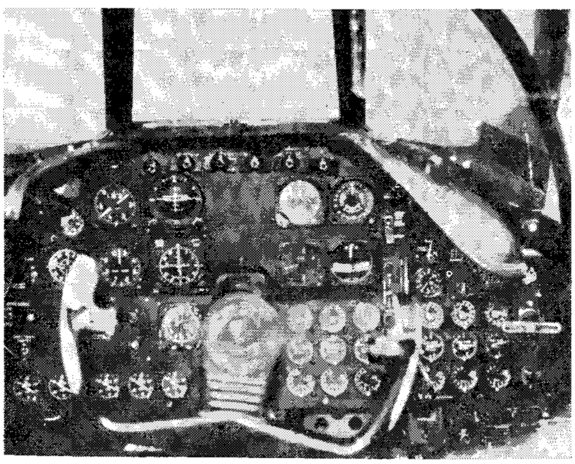

Fig. 3 Simulator cockpit panel.

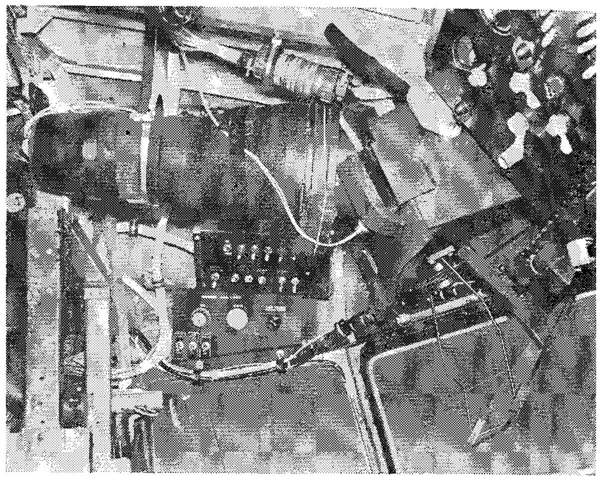

Fig. 4 Windshield projection display unit.

A. Experiment Equipment

A model S6A flight trainer for the B-47E jet-powered aircraft was used as the test vehicle in the simulation program. This equipment has a fixed-base, dual, tandem cockpit. The front cockpit was used for test purposes, and the pilot was therefore given a solo task for the simulated approach and landing. The cockpit has a control wheel and a set of throttle controls to the right of the pilot, duplicating the arrangement of these primary controls in a modern commercial transport.

The cockpit panel was modified to replace the older navigation instruments with modern equipment more typical for scheduled air carriers operating to Category I weather minima. A HZ-4 horizon flight director and a R-4A pictoral deviation indicator were installed in the panel. The HZ-4 provides the attitude and flight-director information. The R-4A presents heading and lateral path deviation in a pictorial form representing the horizontal situation, as well as glide-slope deviation. The modified panel is shown in Fig. 3.

The windshield projection display used for this program was the overhead, refractor type, with a flat combining glass sloping down and aft toward the pilot (Fig. 4). In the simulator, the overhead equipment was mounted on a rack that could be made to slide laterally to store the windshield display equipment to the right of the cockpit when not required. Provisions for the installation of this optical equipment in the cockpit of a DC-3 aircraft have already been made during a previous Sperry developmental flight test program. These provisions permit use of the same display equipment for the subsequent FAA flight evaluation in the aircraft.

The optics consist of two channels superimposed by a beam splitter prior to collimation and reflection to the pilot's eyes by the combining glass (Fig. 5). One channel includes the flight path marker and the airspeed index as illuminated, moving reticle assemblies. All other display elements are generated by a cathode-ray tube (CRT) in the second optical channel. This scheme provides flexibility in color coding. The path marker with its airspeed reference is in the form of a red image, whereas the CRT images are green. Provisions for single-channel operation, in which all images including the path marker are generated by the CRT, are also available in the equipment.

The B-47 trainer lacked an autopilot function and the computers for generating flight-director commands for both the panel and windshield display directors. These were provided by a Reeves Electronic Analog Computer (REAC), with a demodulator interface to convert the 60-cycle simulator

‡ The views expressed in this paper are those of the authors and do not reflect any policy of the FAA.

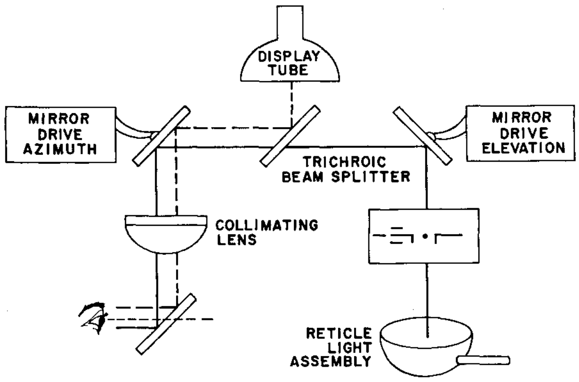

Fig. 5 Two-channel optical display system.

signal from the B-47 to d.c. signals for the REAC. The autopilot signals from the REAC were superimposed on the stick inputs to the simulator as electrical signals only and did not produce stick motions. A two-axis autopilot was simulated for lateral and vertical automatic control of the aircraft during initial approach (localizer mode), final approach, and the landing flare. The primary data from which the bank and pitch command for the autopilot were generated for the various modes are summarized in Table 1. A cross-course velocity signal from the simulator was used to provide the damping for lateral control. Pitch was used conventionally for altitude control in the localizer mode and coupling to the glide slope during approach. The landing flare was implemented by a pitch command.

These autopilot functions were also used for the panel-mounted flight director, with the same sensitivities. Hence, gross coupling performance was the same for both automatic control and manual control with the flight director. Furthermore, the pilot could monitor the response to the autopilot with the flight director; the autopilot was satisfying the coupling computer commands when both flight director indications were nulled. The flight director also included a go-around mode in which heading control was maintained laterally, and a reference pitch command was used in conjunction with a reference airspeed for elevation control.

Two configurations were employed for the windshield display. These displays were identical in all respects save for the presence of a flight director image in one of them (Fig. 1). Localizer and glide slope coupling functions for the windshield director were identical to those provided for the autopilot and the panel-mounted flight director. Hence, coupling performance was effectively eliminated as a variable in the research program. In the absence of a flight director in the windshield display, the pilot provided the coupling computation by positioning the flight path marker to provide a lateral and/or vertical flight path that would intercept the on-course. The flight path of the aircraft would then reduce the deviation error. If, for example, the deviation image were above the aim point, indicating that the aircraft is high, the pilot is required to undershoot by positioning the path marker below the aim point. He would be required to reduce this undershoot as the positional deviation diminished. A comparable procedure is used for lateral control by adjusting the ground track as a function of lateral displacement. Manual first-order coupling could then be achieved by the display of displacement and rate for both axes.

For the landing flare, the flight path marker could be matched against the base of the altitude scale to achieve a smooth reduction in flight path angle from the approach angle of 2.5° to a small angle at touchdown. This small touchdown descent angle is achieved when the flight path marker is just below the horizon line. The sensitivity of the altitude scale has been selected so that the base of the altitude scale is at the same depression angle from the horizon as the aim point when the aircraft is on the glide slope at flare altitude, about 60 ft above the runway.

At the flare altitude, the runway image configuration changes to eliminate the aim point and the horizontal glide slope intersection line through this point. Only the centerline of the runway, positioned by the localizer signal, and the runway edges remain, as in Fig. 6. The pilot loses the runway size cue to range from touchdown and the flight director image. He thus has lateral guidance from the runway centerline only and elevation guidance from the altitude scale and the slope of the runway edges in perspective.

For go-around, a command circle is presented in the windshield display at the reference climb-out angle above the horizon line (Fig. 7). The pilot raises his flight path marker gradually to this circle to increase his flight path angle while increasing his airspeed to the climb-out reference speed commanded by the airspeed index on the path marker. Speed and path control are thereby maintained simultaneously during the go-around. The horizontal line above the command circle represents a reference level-out altitude. It is convenient to consider the reference line as another aircraft in front of the pilot's vehicle at the reference altitude. As the reference line passes the command circle, the pilot may begin to reduce his climb angle by tracking the line with the flight path marker. At the reference altitude, the aircraft is flying level with the reference line and path marker on the horizon

Table 1 Functions included in control systems for simulated all-weather landing tests

System and axis	Mode	Localizer	Approach	Landing flare	Go-around
Instrument	Lateral	Bank Cross-course velocity Localizer	Bank Cross-course velocity Localizer	Bank Cross-course velocity Localizer	Bank Heading
	Vertical	Pitch Altitude	Pitch Glide slope	Pitch command	Pitch command
Automatic approach	Lateral	Bank Cross-course velocity Localizer	Bank Cross-course velocity Localizer	Bank Cross-course velocity Localizer	
	Vertical	Pitch Altitude	Pitch Glide slope	Pitch command	
Windshield display					
Without flight director	Lateral	Heading Localizer	Heading Localizer	Heading Localizer	Heading Localizer
	Vertical	Altitude Flight path angle	Glide slope Flight path angle	Altitude Flight path angle	Command flight path Actual flight path
With flight director	Lateral	Bank Cross-course velocity Localizer	Bank Cross-course velocity Localizer	Heading Localizer	Heading Localizer
	Vertical	Altitude Flight path angle	Pitch Glide slope	Altitude Flight path angle	Command flight path Actual flight path

line. This maneuver involves first-order coupling to the reference altitude by flight path angle.

B. Experimental Design

The research program is designed to answer the following questions regarding the windshield display:

1) How well can the pilot use the display to assess the conduct of an all-weather approach and landing with an automatic primary flight control system?

2) Can the display be used for a manual backup system in the event that the pilot elects to disengage the autoland system and complete the landing manually?

3) How does the windshield display compare with a modern panel instrument system in providing these functions?

The success and validity of a test program designed to elicit answers to these broad questions requires unusual care in selecting the criteria upon which conclusions will be based. The assessment function plays a key role in the all-weather landing task, and the windshield display is designed to enhance this function. How can this feature be demonstrated in the simulation tests? The answer to this question derives from a comparison of visual and instrument approach and landing. Under visual flight conditions, pilots show little reluctance in carrying automatic landings to touchdown. This, in fact, was the safety pilot's task during the more than 1000 automatic landings made by the FAA with the blind-landing experimental unit (BLEU) autoland system. Under full instrument conditions with no external visual reference, however, the stress level on the flight crew is increased radically. With panel instruments, the pilot must now depend upon fragmented information from which he can reasonably infer his situation only for small departures in position, flight path, and attitude from those for a normal on-course trajectory along the beam. The panel displays are essentially null monitors and provide information for making small attitude and flight path changes when displacements from the null positions are realized. Contrast these severe restrictions to be "in the groove" with the freedom the pilot enjoys under VFR conditions. These are the reasons why pilots making instrument approaches today will disengage the autopilot and/or discontinue manual approaches for any but small departures from normal position and flight path.

On this basis, the following test conditions were generated. Pilot subjects were requested to make automatic approaches. Normally, these approaches would be consummated in automatic landing flare to touchdown. However, simulated malfunctions were inserted in the automatic control system. These generated localizer or glide-slope standoffs of approximately one-half scale on deviation indicators. The pilot was instructed to indicate by stick switch signal when he first detected the malperformance in the system. He was also instructed not to disengage the autopilot until reaching the lowest altitude from which he felt he could still effect a safe manual landing with his instrument system, either panel or windshield display. He could also elect to go-around at any time he felt this maneuver was the only safe alternative. Both autopilot hardover signals and normal approaches without malfunctions were also simulated to reduce pilot expectation and to obtain additional data on performance. When the pilot reached the lowest altitude to which he was willing to fly with the automatic landing system, he could disengage the autopilot and attempt to complete the landing with the display system available to him.

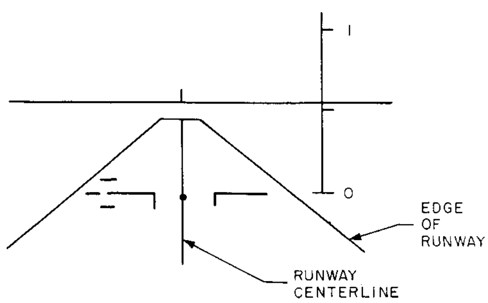

Fig. 6 Windshield display configuration in landing mode.

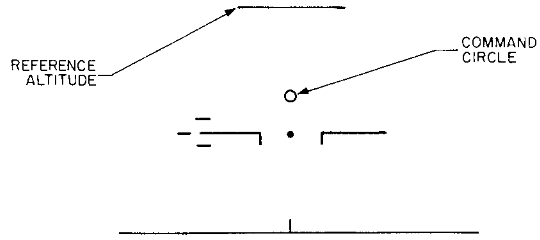

Fig. 7 Windshield display configuration in go-around mode.

Six pilots were employed as test subjects. The FAA arranged to obtain the services of the pilots. Five of these were active in current scheduled-air-carrier service, three were with Pan American World Airways, one with Trans-World Airlines, and one with Allegheny Airlines. The sixth subject was an experimental test pilot with the FAA. Three basic display conditions were used: a windshield display system with a flight-director function, the same system without flight director, and a cockpit panel instrument system. Each pilot made a total of 44 test landings (or go-arounds) with each system. The set of 44 runs covered four replications of a set of 11 test conditions, involving eight localizer and glide-slope standoffs, two hardover autopilot maneuvers, and a normal approach and landing. This experimental design therefore required a grand total of 792 test runs.

The following data were continuously recorded for the duration of each of the runs on two six-channel graphic recorders: localizer and glide-slope deviation signals, pitch, bank, heading, airspeed error, altitude, altitude rate, elevator, airleron positions, flight path angle, and discrete events such as disengagement of the autopilot. The vertical trajectory of the aircraft was recorded on an X-Z plotter. Pilot comments were recorded after each run, and a detailed interview was conducted with each pilot at the completion of his schedule of tests.

C. Performance Criteria

The performance criteria for evaluating the display systems must discriminate differences in both the confidence and control capability which the displays make possible. The statistical distribution of the minimum altitudes to which the pilots will descend with a standoff in localizer or glide slope measures the confidence that the pilot places in both the assessment and control aspects of each display. Both the panel and windshield displays have the same flight-director capability that was demonstrated to the pilots in transient recoveries in the course of pretrial familiarization with the displays. Therefore, any differences must rest in the organization of the information in the displays. The pilot will continue his descent only as long as he feels he understands his situation in the real world, and he has the flight control capability to complete the landing manually with the additional assessment capability required throughout the terminal maneuver. Therefore, takeover altitude can be used to measure pilot confidence in the display system and, by implication, to measure its effectiveness. Differences among display systems should be reflected by differences in the altitude at which the pilot takes over manually. The lower the takeover altitude, the more confidence the pilot has in the display, the situation confronting the pilot being the same.

However, the degree of confidence expressed in this manner by the pilot is, to some extent, based on subjective impression;

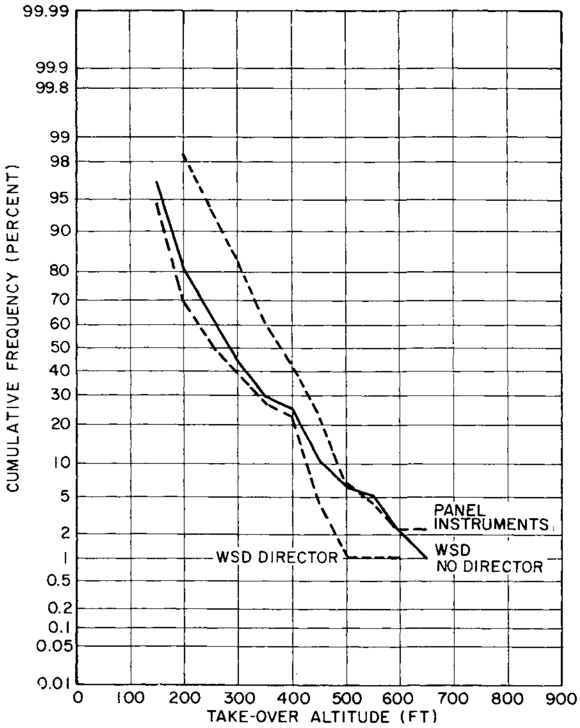

Fig. 8 Cumulative relative frequency distributions of takeover altitude for localizer standoff conditions.

it is conceivable that this judgment is objectively in error. It is possible for a person to trust unreliable information and, conversely, to mistrust reliable data. The occurrence of visual illusions and the reluctance felt by some older pilots in relying on instrument readings instead of "seat-of-the-pants" cues illustrate a misplaced trust in faulty sensory information. For this reason it is not sufficient to use a measure of pilot confidence as the sole criterion for display system effectiveness. The confidence must be substantiated by aircraft performance after manual takeover.

Since the desired end result of the experimental trials is a safe landing, the most appropriate point at which to examine manual control performance is at touchdown. Among the parameters indicating the state of the aircraft at touchdown are rate of descent, lateral deviation from the runway centerline, airspeed, heading error, bank and pitch, flight path angle, and longitudinal touchdown point on runway. Of these, rate of descent, lateral deviation, heading error, and touchdown point are especially meaningful in comparing performance among the two windshield displays and the panel instrumentation. An important difference between the windshield and the panel systems is the attempt, with the windshield display, to present information superimposed on the real runway, equivalent to direct-vision cues centering on an image of the runway. Parameters most likely to differentiate system performance would therefore be those involving use of the runway image in landing the aircraft. Lateral deviation and heading error reflect the orientation of the aircraft with respect to the runway, whereas rate of descent involves an appreciation for rate of closure with the runway. With a narrow range of airspeed, flight path angle is reflected in rate of descent.

In the experimental trials, malfunctions were inserted at altitudes high enough so that the pilot could recover manually and land the aircraft. No trial was designed to make a go-around mandatory. Under these conditions, initiation of a go-around by the pilot is assumed to result either from his judgment that assessment or control information is not sufficient to permit recovery and landing or from a loss of control capability through inadequate information. In either case, if pilot competence is assumed, the go-around is the result of a failure of the display system to be an effective aid to the pilot. The number of go-arounds initiated with each display system therefore provides another performance criterion.

D. Test Results

The altitude at which the pilot disengaged the autopilot and assumed manual control of the aircraft for each run involving a localizer or glide-slope standoff was determined from a discrete event marker on the graphic recording of altitude vs range from the glide-slope intercept with the runway. Compilations of these altitudes provided the statistical distributions of takeover altitudes for each of three displays for three classes of standoff conditions, i.e., localizer (left or right), high glide slope, and low glide slope. These three test conditions are considered sufficiently distinct in the demands they make on the pilot to warrant separate analyses. A statistical summary of the results is presented in Table 2, and the associated cumulative relative frequency distributions are shown plotted in Figs. 8–10. A general qualitative comparison in performance may be made from this type of plot. Relative position of curves to the right indicates a distribution of takeover altitudes at higher levels for a particular display.

The pattern is the same in all three plots in Figs. 8–10. There is relatively small difference between the data for both types of windshield displays. Where a difference exists, the display with director is generally favored, i.e., the pilot could proceed to lower altitudes before assuming manual control. However, the takeover altitudes with the panel display are distinctly higher than these altitudes associated with either of the windshield displays.

The means and standard deviations for distributions in Figs. 8–10 are summarized in Table 2. Statistical comparisons of performance between each display and the other two have been performed by means of F-tests for a one-way analysis of variance.[9] The F-test is equivalent to a t-test for a comparison of means when used in this manner. The results of these analyses are presented in Table 2. All differences between the panel displays and each of the windshield displays are statistically significant at very low probability levels, indicating a remote possibility that these differences may be attributed to chance. The smaller differences be-

Table 2 Statistical analysis of takeover altitude data

Test condition		Takeover altitude, ft: I WSD no director	II WSD director	III Panel instruments	Comparison of means: I and II F	I and II P	I and III F	I and III P	II and III F	II and III P
Localizer standoff	Mean	259	235	336	2.17	>0.05	24.66[a]	<0.001	49.28[a]	<0.001
	σ	118	104	91						
High glide-slope standoff	Mean	201	203	370	0.004	>0.05	35.67[a]	<0.001	36.40[a]	<0.001
	σ	139	134	129						
Low glide-slope standoff	Mean	191	163	340	1.35	>0.05	36.14[a]	<0.001	59.71[a]	<0.001
	σ	123	106	115						

[a] Significant at 0.001 level.

tween the windshield displays, however, may possibly be the result of chance influences at probability levels in excess of 5%.

The results demonstrate that takeover altitude is significantly lower when the windshield displays are used. For all standoff conditions combined, the mean takeover altitudes are 200 ft for the windshield display embodying a flight director function, 217 ft for the windshield display without the flight director, and 349 ft for panel instruments. This same pattern of differences exists when the display systems are compared for the classes of test conditions, i.e., localizer and high and low glide-slope standoffs. The difference of about 140 ft between windshield display and panel instruments at the low altitudes involved represents a reduction of approximately 45% in available maneuvering time from manual takeover to the start of the landing flare at 50 ft. Clearly then, the pilots had more confidence in their ability to land the aircraft from the standoff condition when their information was provided by either windshield display than when it was provided by the panel instruments.

For localizer standoff conditions, the mean takeover altitudes are 235 ft for the windshield display with director, 259 ft for the windshield display without director, and 336 ft for panel instruments. It is interesting to compare these data with the altitude at which recovery must be initiated from a one-half scale localizer standoff under idealized maneuvering conditions, limited only by the capabilities of the aircraft and reasonably conservative pilot control procedures. The maneuvering distance required under these conditions is called a "visual maneuvering distance." The techniques for computing visual maneuvering distances have been developed in Refs. 10 and 11. Applying the data from Fig. 21 of Ref. 11 to an aircraft approach at a speed of 140 knots with a half-scale (1.25°) localizer standoff, 14.4 secs of recovery time are required with an associated maneuvering range of 3390 ft. The lateral maneuvering limitations upon which these data are based are a maximum bank angle of 0.25 rad (14.3°) and a maximum roll rate of 0.2 rad/sec (11.5 deg/sec). If the maneuver is to be completed when the aircraft reaches 50 ft altitude, it must be initiated at an altitude of 198 ft. The mean recovery altitudes with both windshield displays are within about 60 ft of this value, whereas the mean value for the panel is 138 ft above this figure. Clearly, performance with the windshield displays is much closer to that obtainable under idealized, visual flight conditions.

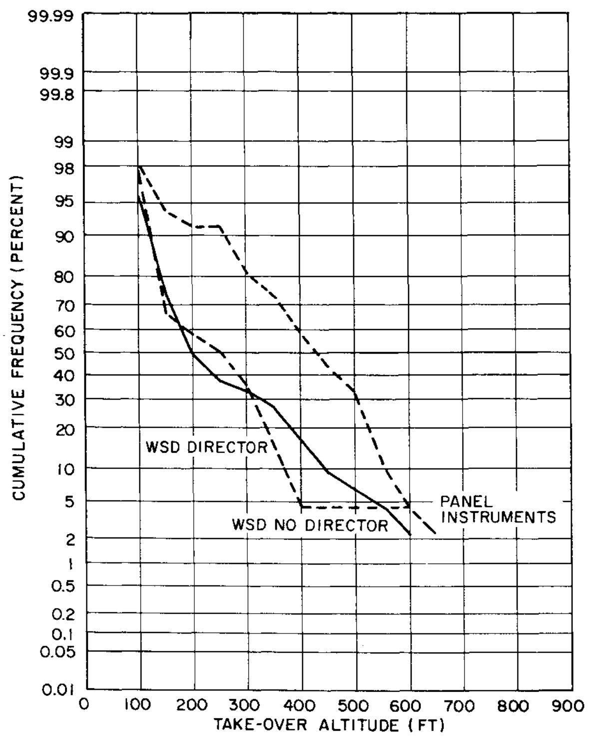

Fig. 9 Cumulative relative frequency distributions of takeover altitude for high glide-slope standoff conditions.

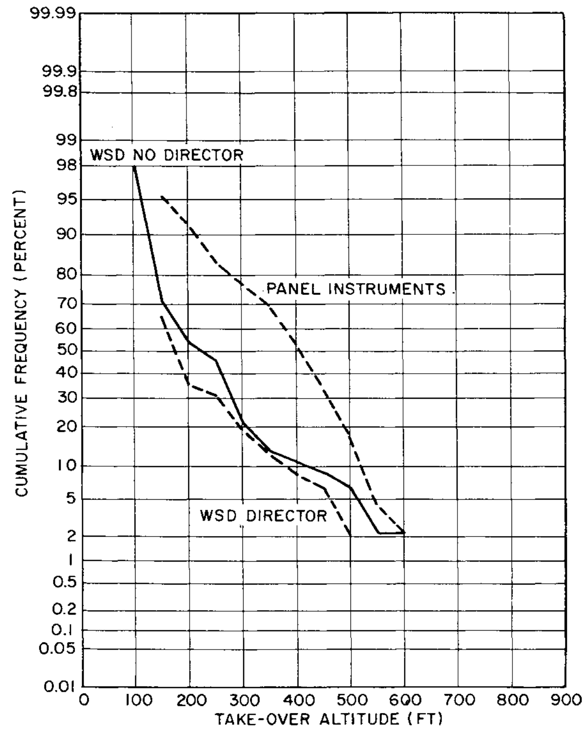

Fig. 10 Cumulative relative frequency distributions of takeover altitude for low glide-slope standoff conditions.

The rate of descent of the aircraft at touchdown for all classes of test conditions are presented in the form of cumulative frequency distributions in Fig. 11. These data include standoff conditions and three categories of abrupt maneuvers: roll, pitch-up, and pitch-down. The data covering full automatic landings in which no malfunctions were introduced and the pilot did not assume manual control of the aircraft are also included in Fig. 11 and are designated as normal runs. Rates of descent at touchdown are higher with panel instruments than with either of the windshield displays. Generally, these differences are larger than those between the two types of windshield displays. Statistical analyses confirm that performance is better, i.e., lower descent rates at touchdown, with either of the windshield displays than with panel instruments. However, differences in performance between the windshield displays are not statistically significant.

The sharp differences in touchdown rate of descent between the windshield and panel displays illustrates an important difference between these two types of systems in imparting integrated information. In terms of pilot control, rate of descent at touchdown depends on how well the pilot can sense his rate of closure with the ground. For this he needs information telling him where the ground is and what his vertical velocity is. With panel instruments, it is probable that the pilot's attention is focused principally on the flight director, which essentially is commanding pitch attitude. The pilot has no appreciation for where the ground is and, unless he follows the flight director faithfully, must essentially resort to raw scalar altitude and rate of descent. The windshield display, on the other hand, gives the pilot a veridical image of the approaching runway. In addition, by providing a flight path marker and horizon, all moving dynamically with respect to each other as they would in the real world, the pilot has information regarding vertical rate of closure and can control for softer contact with the ground. Differences in lateral position and heading at touchdown for all displays were not large or statistically significant.

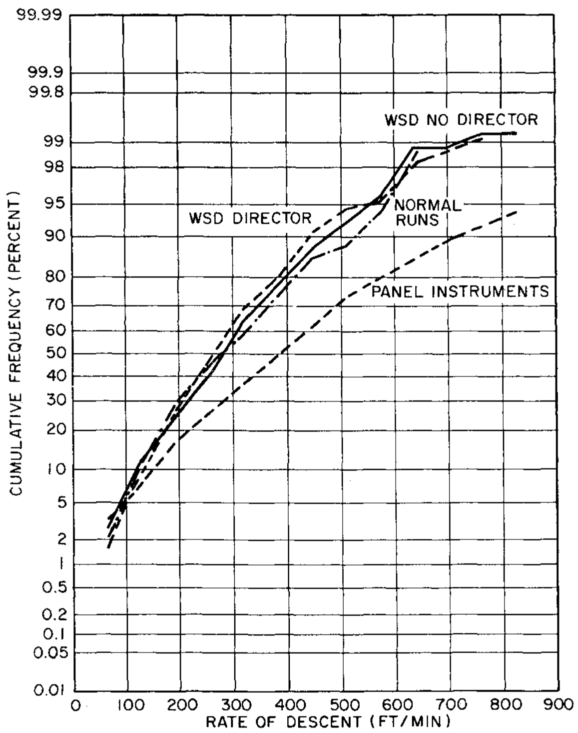

Fig. 11 Cumulative relative frequency distributions of rate of descent at touchdown for all test conditions combined.

Enhanced confidence provided by the windshield displays is also manifest in the number of go-arounds initiated by the pilots. For all test conditions combined, the percentage of go-arounds with windshield displays was 2.9%, whereas it was 9.6% for panel instruments. This difference, which is statistically significant, is due primarily to the difference in performance in abrupt roll and pitch maneuvers. Here the statistics are 7.3% for the windshield displays and 33% for panel instruments. The windshield displays provide superior orientation information, which facilitates recovery from unusual flight altitudes at low altitudes.

The results of the postexperiment interviews with the subject pilots indicated unanimous favor for the windshield displays. The source of this preference is the real-world form of the pictorial representation, in a three-dimensional format, which the windshield display presents. One pilot succinctly summarized this feature by saying that the display "gives you a real-world picture in terms that you're used to seeing." In operational terms, the display gave the pilot a quick, clear picture of the situation as a whole. This facilitated the assessment task that is so critical for all-weather landing, irrespective of the mode of control (automatic or manual). As one subject put it, the display "does not require cross checking other instruments as on the panel to verify the situation. All pertinent information is presented together." The enhanced assessment information facilitated the decision whether to land or go-around and the execution of these maneuvers.

Manual control, in general, seemed more accurate to the pilots. Since the pilots did not, of course, know the exact precision they were achieving, this is a manifestation of the increased confidence in the feedback of information provided by the windshield display during the maneuvers.

The critical comments of the pilots are limited to details in the display configuration as implemented in the experimental equipment. A key deficiency was the lack of an altitude scale above 250 ft. For altitudes between 1500 ft, where the final approach started, and 400 ft, where the altitude scale came into view, the pilots had to rely on runway size to estimate position. This cue was not available above 700 ft, where the runway size remains fixed. One pilot stated that he reverted to the panel for altitude information in the intermediate stage of the approach. Several pilots indicated that a continuous altitude readout for the entire approach would be desirable.

The limitations of the airspeed error indication within the limits of ± 10 knots in the display were also indicated. A precise readout of airspeed, particularly for speeds beyond the 10-knot error limits, seems desirable.

Lateral runway alignment with manual control was easy for the pilots with the windshield display. Perception of attitude and heading error were also achieved naturally, as in visual flight.

Conclusions

The following conclusions are based on the results of the flight simulation conducted in the course of the research in windshield projection displays for all-weather landing.

1) Pilots exhibit superior performance in both the assessment and control tasks associated with all-weather landing when using the windshield projection display as compared with panel instruments.

2) Pilots can descend to significantly lower altitudes with steady localizer and glide-slope standoffs and recover safely from these conditions, when using the windshield display as compared with panel instruments.

3) Significantly fewer go-arounds are initiated with the windshield display subsequent to abrupt autopilot malfunctions at low altitudes than with panel instruments.

4) Manual landings after recovery maneuvers can be executed more smoothly with the windshield display than with panel instruments.

5) Pilot behavior during the instrument landing is more comparable to VFR conditions with the windshield display than with panel instruments.

6) Performance with a windshield display including a flight director and with a similar display without the director function is generally comparable.

The in-flight evaluation of this windshield display equipment in a DC-3 aircraft has recently been completed, and the results will be reported at a future date.

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