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SIMULATOR EVALUATION OF DISPLAY CONCEPTS FOR PILOT MONITORING AND CONTROL OF SPACE SHUTTLE APPROACH AND LANDING

Phase II: Manual Flight Control

by Walter B. Gartner and Kenneth M. Baldwin

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16. Abstract

The simulation research project documented in this report completes a study of display requirements for final approach management of the space shuttle Orbiter vehicle. An experimental display concept, providing a more direct, pictorial representation of the vehicle's position and movement relative to the selected approach path and aiming points, was further developed and assessed as an aid to manual flight path control. Both head-up, windshield projections and head-down, panel-mounted presentations of the experimental display were evaluated in a series of simulated Orbiter approach sequences.

Ten currently active airline pilots flew a total of 160 final approach sequences, using five different configurations of the experimental display, in order to assess the utility of the display concept for the manual control task.

Data obtained in this study extend the scope of the first simulator evaluation and indicate that the experimental display would enable Orbiter pilots to exercise greater flexibility in implementing alternative final approach control strategies. Touchdown position and airspeed dispersion criteria were satisfied on 91 percent of the approach sequences, representing various approach profile and wind effect conditions. Flight path control and airspeed management satisfied operationally-relevant criteria for the two-segment, power-off Orbiter approach and were consistently more accurate and less variable when the full set of experimental display elements was available to the pilot. Approach control tended to be more precise when the head-up display was used; however, the data also indicate that the head-down display would provide adequate support for the manual control task and that, with certain improvements, pilots could do just about as well with either version of the display.

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SIMULATOR EVALUATION OF DISPLAY CONCEPTS FOR PILOT MONITORING AND CONTROL OF SPACE SHUTTLE APPROACH AND LANDING

Phase II: Manual Flight Control

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SUMMARY

The simulation research project documented in this report completes a study of display requirements for final approach management of the space shuttle Orbiter vehicle which was initiated under Contract NAS2-6460. An experimental display concept, providing a more direct, pictorial representation of the vehicle's position and movement relative to the selected approach path and aiming points, was further developed and assessed as an aid to manual flight path control. Both head-up, windshield projections and head-down, panel-mounted presentations of the experimental display were evaluated in a series of simulated Orbiter approach sequences.

Ten currently active airline pilots flew a total of 160 final approach sequences, using five different configurations of the experimental display, in order to assess the utility of the display concept for the manual control task. Various levels of display aiding were represented in the experimental display configurations and data were obtained on the relative contribution of key elements of the display concept to specific components of the approach control task.

Data obtained in this study extend the scope of the first simulator evaluation and indicate that the experimental display would enable Orbiter pilots to exercise greater flexibility in implementing alternative final approach control strategies. Touchdown position and airspeed dispersion criteria were satisfied on 91 percent of the approach sequences, representing various approach profile and wind effect conditions. Flight path control and airspeed management satisfied operationally-relevant criteria for the two-segment, power-off Orbiter approach and were consistently more accurate and less variable when the full set of experimental display elements was available to the pilot. Approach control tended to be more precise when the head-up display was used; however, the data also indicate that the head-down display would provide adequate support for the manual control task and that, with certain improvements, pilots could do just about as well with either version of the display.

INTRODUCTION

In the first phase of the present study and in related studies of flight instrumentation requirements for space shuttle recovery operations, a promising approach to improved pilot display support for approach management and flight path control has been identified. Briefly, this approach calls for a more direct, pictorial representation of the key flight situation parameters monitored and/or controlled by the pilot rather than the more abstract and symbolic representations provided by conventional attitude-directors and flight situation instruments. Preliminary analysis of pilot task requirements and display requirements during the unpowered terminal area maneuvering and final approach sequences envisioned for a high cross-range Orbiter vehicle indicate that flight instrumentation based on this concept would enhance the pilot's management of the Orbiter recovery for both automatic and manual flight control (ref. 1). An experimental display derived from this analysis was evaluated in simulated Orbiter approach sequences during the preceding phase of this study and the data obtained support the contention that Orbiter pilots will require display support not currently available in conventional flight instrumentation for more accurate approach management (ref. 2).

The simulation research project documented in this report is an extension of the development and empirical assessment of this display concept. Simulator evaluations of various configurations of the experimental display concept (EDC) were conducted as a collaborative effort with the Man-Machine Integration Branch (MMIB) at Ames Research Center, using an existing Orbiter vehicle simulation and the computer graphics display generation capabilities available to the MMIB simulation laboratory. During the first phase of this study, the focus of the project activities was on the relative effectiveness of the EDC for pilot monitoring and assessment of automatically controlled, IFR approach sequences. The pilot's ability to monitor variable airspeed deceleration schedules characteristic of the unconventional two-segment Orbiter final approach, in the presence of wind effects, was distinguished as the primary issue and the first simulator evaluation was designed to contrast pilot performance of this task using the EDC with their performance on the same task using a conventional display of flight situation and guidance information. The utility of the EDC for flight path monitoring and optional manual control was examined as a secondary area of interest.

In the present study, the focus of project activities was shifted to the further development of the EDC as an aid to manual flight path control and to the assessment of head-up versions of the EDC for VFR recovery operations as well as a head-down, panel-mounted version for the IFR situation. The documentation of this study begins in this section with an overview of the experimental display concept and its intended application to more flexible and more precise Orbiter final approach control. The specific display support issues addressed in the present study are clarified and the objectives and intent of the simulator evaluation are stated. Subsequent sections of this report provide a more detailed description of the experimental variations of the EDC and their expected contribution to the Orbiter approach control task, an outline of the experimental plan adopted to assess these display configurations using the MMIB Orbiter simulation, and the results and conclusions of this study.

Overview of the Display Concept

The "See-Through" Concept

The defining feature of the display concept under development in this project is the integration of key ground-referenced elements (i.e., flight path aiming points, glide slope reference and runway alignment cues) with such conventional vertical flight situation displays as attitude, airspeed, and altitude. These ground-referenced elements move in correct azimuth, elevation and perspective relationship to the pilot's line of sight to provide a direct representation of the vehicle's relative position and movement, as they would if the pilot were flying by external visual reference or could see through the display field to corresponding points on the ground. The intended result is an integrated, semi-pictorial presentation of key flight situation parameters which can be readily interpreted by pilots using perceptual skills and expectancies similar to those required for flight control by external visual reference.

Following guidelines established by MMIB, earlier display development work on independent landing monitors and head-up displays was examined for potential applications to the Orbiter approach management task and the display principles inherent in these devices were applied in deriving the EDC. The "see-through" feature is clearly evident in the independent landing monitor (ILM) wherein computer-generated symbols, representing flight situation and/or guidance information, are superimposed on a video image of the external visual scene. Under appropriate conditions, the pilot is able to view, in the same display field, both a ground image (derived from such direct-imaging systems as forward looking radar, low-light-level TV, infra-red optical scanning, or radiometric scanning systems) and the symbolic data presented in registry with corresponding elements of the image. In conventional aircraft operations, the ILM is intended to provide a ground-reference display which is independent of the primary source of guidance information for flight path control (e.g., ILS) and thereby provide a reliable, second source of actual flight situation data which can be used to monitor an approach, whether automatic or manually controlled, when external visual reference is degraded or denied (hence the name). In turn, symbolic data elements may be used to enhance key ground-reference features such as the horizon, runway outline, approach lights, aiming points, etc., under low visibility conditions.

The see-through feature is also evident in head-up display (HUD) concepts which also present symbolic flight situation and guidance information in such a way that the pilot can view both the display and the external visual scene at the same time. The distinguishing feature of the HUD is that the display is located in the pilot's forward field-of-view and is available to him while he is "head-up" and looking out of the aircraft. While other types of displays are sometimes referred to as head-up devices (e.g., peripheral vision displays and head-mounted collimated displays), the term is generally restricted to collimated images projected on a transparent surface which is positioned so that it will be in the pilot's central field of view when he is looking ahead and outside the aircraft. Because the display is focused at optical infinity and because it is projected on a transparent surface, the display elements appear to be superimposed on the external visual field and at the same distance.

It is important to note that the synthesis of the experimental display was not constrained by any particular display mechanization concept and that the location of the display (i.e., on the instrument panel versus a head-up, windshield projection) is not a defining feature of the EDC. The focus of the project is on display functions rather than particular devices and, in principle, alternative sensor systems and image generation techniques could be adopted to implement the display functions of interest. The distinguishing features of the see-through EDC developed for the present evaluation of Orbiter final approach applications are:

1. Selection of display elements which provide a direct representation of the flight situation parameters monitored and/or controlled by the pilot (e.g., flight path angle relative to a specified ground aiming point rather than glide slope deviation or pitch command).
2. A pictorial representation of the vehicle's position and movement relative to the desired approach path and runway, presented in correct perspective relationship to the pilot's line-of-sight and readily interpreted using perceptual skills and expectancies characteristic of VFR flight control.
3. The presentation of key flight situation data which are independent of conventional flight path guidance systems and flight director commands (but the director element may be added as a separate feature).
4. The selective integration of additional display elements which are useful for increasing the precision of pilot judgment or for providing essential quantitative information (e.g., airspeed, altitude, etc.) within a comfortable visual scan pattern relative to the primary display elements.

Intended Application to Orbiter Approach Control

The specific experimental display configurations defined for the simulator evaluation are described in the next section of this report. The EDC configuration illustrated in Figure 6 is the most complete representation of the concept; the other configurations represent experimental variations in the level of display aiding incorporated for specific components of the manual approach control task. In concept, the EDC is an electronic attitude-director indicator, projected either head-up or on a panel-mounted CRT, and the test configurations should be construed as one operating mode of a more inclusive integrated flight management display which would be used for flight path control and situation assessment throughout the Orbiter recovery sequence. As the vehicle approaches a pre-selected position for establishing the final approach to the landing site, this display would be sequenced to an APPROACH mode as represented in Figure 6.

The general intent of the EDC development and simulator evaluation in this phase of the study was to provide a display that would better equip the Orbiter pilot to modify pre-planned approach management strategies and to exercise more flexible manual control of the final approach sequence when off-nominal conditions, such as unforeseen wind effects and marginal outcomes of energy management maneuvering earlier in the recovery sequence, are encountered. In order to exercise this kind of flexibility, the pilot will employ such techniques as adjusting pre-selected final approach entry and initial glide slope aim points, electing to fly a steeper or shallower glide slope than nominal, and adjusting the speed and altitude for transitioning to the final, decelerating glide to the touchdown point on the runway. The more specific display support functions envisioned for this approach management task may be illustrated by reference to Figure 1.

Initial conditions for the final approach to the landing site are determined by the outcome of a post-reentry maneuvering descent and initial approach to a final approach entry at a pre-planned altitude and distance from the runway. As indicated in Figure 1a, the initial approach to the final approach path (FAP) entry may originate from various "high key" positions and, in terms of the vehicle's altitude and airspeed, from various energy states. The approach to the FAP entry point will be planned with the primary objective of dissipating excess energy and establishing a final two-segment glide path to the runway, as represented by the bold line in Figure 1b. An optimum flight path angle, based on the L/D characteristics of the Orbiter in a landing configuration and the airspeed required at the transition point, is adopted for the steep descent to a transition altitude from which a precisely controlled flare to a shallow, decelerating glide path is executed. The pre-flare aim point, flare initiation height and airspeed at flare initiation are the key factors affecting touchdown conditions.

A number of terminal area guidance and control schemes are under investigation for this recovery sequence, ranging from computer-generated guidance and automatic flight path control (ref. 3) to simplified, manual control techniques requiring no onboard guidance computation and minimum navigational aids (ref. 4). Automated approach control schemes typically establish a fixed-path profile, as illustrated by the nominal approach path in Figure 1a. Under this scheme, pilots would be constrained to acquire a single prescribed glide slope at a specified minimum distance from the runway, descend toward a fixed pre-flare aim point to the specified altitude for transition and then acquire and track the shallow glide slope to a final flare initiation point and complete the landing manuever. The flight path angle adopted for the first segment of this approach profile is selected to assure operation on the front side of the L/D curve and nominal final approach acquisition altitudes and airspeeds are selected to produce the desired speed at transition.

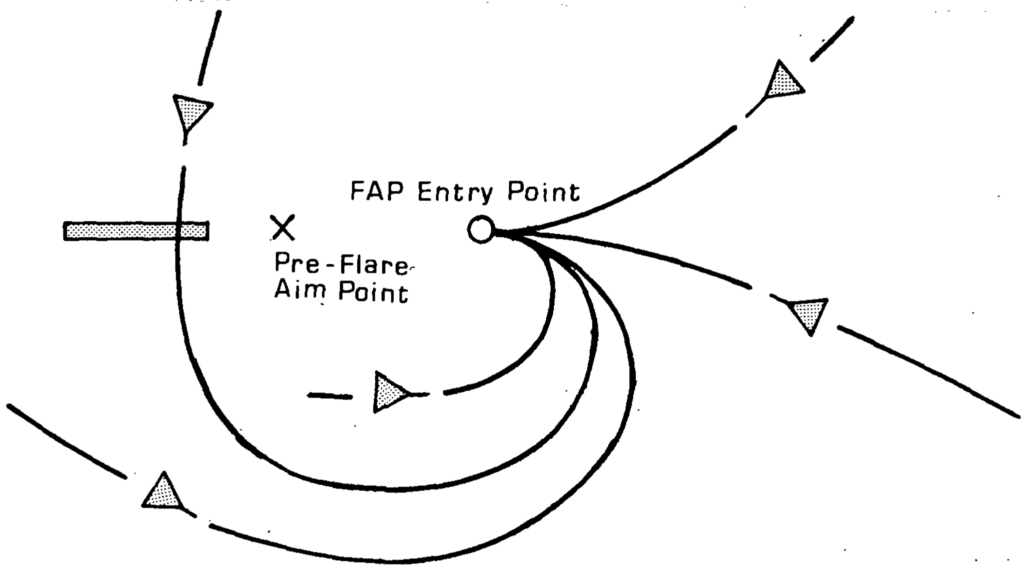


Figure 1a. Initial Approach from Various Positions and Energy States

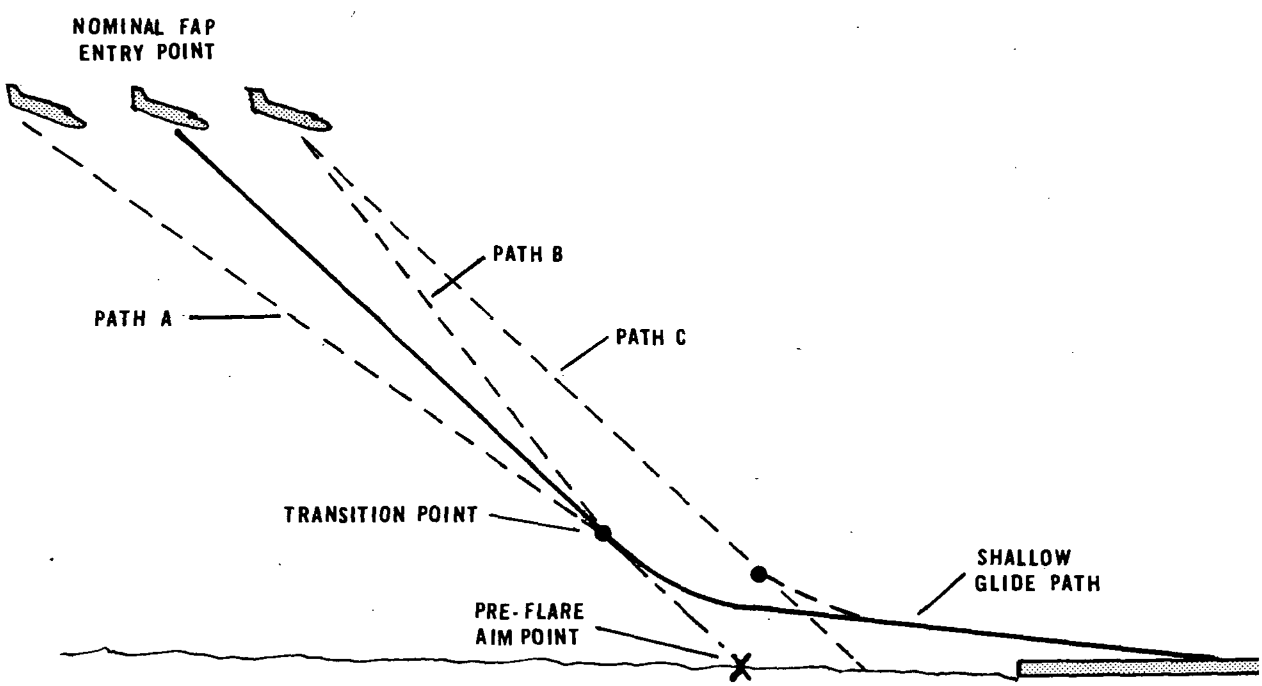


Figure 1b. Possible Adjustments to the Final Approach Path
for Coping with Off-Nominal Initial Conditions

If the Orbiter pilot is constrained to fly a fixed flight path of this kind when manual control is exercised, then conventional flight director instrumentation would appear to be the appropriate display and the EDC application might be limited to an independent source of flight situation information for monitoring the approach. However, the position taken in the present study is that the pilot should be able to adjust his final approach in order to cope with the actual outcomes of the maneuvering descent and with the actual wind and visibility conditions encountered. Using conventional flight director and/or flight path deviation indicators only, acquisition and tracking of the fixed approach path would be the only option available to the pilot. The fixed approach path defined by the guidance system may not be optimum for such operational conditions as variations in reentry position, the landing weight of the Orbiter with different payloads and weather at the landing site. With the ground-referenced features provided by the EDC, which are independent of terminal area guidance information, the pilot should be able to adjust his glide path angle and/or pre-flare aiming point based on his ongoing assessment of the reentry position, the approach to the landing site and prevailing environmental conditions.

Notice in Figure 1b that as a consequence of conditions encountered earlier in the recovery sequence, the Orbiter might arrive at the nominal FAP entry altitude with range or velocity errors, or both. The broken lines illustrate the pilot's options in coping with such conditions. He may adjust his vertical flight path angle to fly a shallower (path A) or steeper (path B) approach to the same transition point. Or he might elect to establish a new pre-flare aim point, closer in to the runway, and fly either the pre-selected optimum glide slope (path C) or a flatter, maximum L/D glide down to a new transition height and airspeed appropriate for the shorter second segment.

In addition to providing the necessary flexibility for coping with varying operational demands, the EDC is expected to allow the pilot to apply flight control techniques during IFR conditions that correspond directly with VFR procedures. This IFR-VFR compatibility is considered highly desirable by FRC pilots with experience in the lifting body and X-15 power-off approach techniques (ref. 1). A similar approach was proposed by ARC in an early investigation of displays for all-weather landing (ref. 5). The special advantages of this display concept are clearly indicated in the following excerpt from this study (italics added):

> Ames has undertaken a study of the zero-zero landing problem which is intended to fulfill two special requirements; first, to provide a display with which the pilot can land the airplane, making the same judgments, coming to the same conclusions, and applying the same control techniques that he does during visual landings...the pilot can approach with as steep or as shallow a flight path as he wants to. He can approach toward a point short of the runway and then flare to a point just beyond the threshold. Or he can make a long, shallow, no-flare landing. He can make any type of landing that he can VFR; *there is no programming in the display, no commands...* He must be able to use the display in conjunction with VFR landings, and in that way develop confidence in the system... Also, the display must minimize—to zero if possible—ambiguity or discord during transition from IFR to VFR under not quite zero-zero conditions.

This concept is considered to be especially well suited to Orbiter recovery operations, even when visibility conditions are considerably better than zero-zero. The first segment of a nominal approach and the transition to the shallow glide slope are executed at some distance from the runway where the usual visual reference points for approach control are not available to the pilot even under unrestricted visibility conditions. The EDC ground reference features are expected to enhance the precision of approach control under both VFR and IFR conditions.

Objectives of the Simulator Evaluation

The aim of this second phase of the EDC evaluation was to exercise qualified pilot-subjects in manual approach control tasks during simulated Orbiter final approach sequences and to obtain data on how well they were supported in the performance of these tasks by specific features of the experimental display. Simulated approach sequences were designed to represent both the nominal two-segment approach control technique adopted in the preliminary EDC evaluation (ref. 2) and the alternatives to the fixed-path technique discussed in the preceding section. A steeper, close-in approach, based on lifting body flight test experience at the NASA Flight Research Center and on a recent Lockheed simulation study (ref. 4), was adopted as one alternative and others represented reasonable variations in the first-segment flight path angle and pre-flare aim point. Wind effects were applied to these approach profiles to impose varying demands on the flight path and airspeed control tasks and the simulated approaches were flown under both VFR and IFR conditions.

A contrast between the EDC and conventional altitude-director flight instrumentation was made in the first simulator evaluation and a continuation of this contrast in the second study was not considered necessary. Instead, five different configurations of the EDC were defined, representing different levels and types of display aiding for the approach management task, and the assessment was concerned with the relative contribution of key elements of the EDC to specific components of the approach control task. The specific display support issues addressed in this study may be summarized as follows:

1. Could pilots meet reasonable Orbiter approach success criteria, in terms of target airspeeds and relative position constraints on arrival at the runway threshold, on a manually controlled approach by reference to the EDC?
2. How precisely can pilots track a selected glide slope using the full complement of EDC elements for vertical flight path control (as illustrated in Figure 6)?
3. Is the velocity vector element (Projected Impact Point) essential, i.e., could the same precision be obtained with just the Glide Slope Reference Bar and an Aim Point?

4. How precisely can pilots maintain flight path alignment with the runway using the Approach Path and Relative Heading markers? Using only the actual runway image, with no display of lateral alignment cues?
5. Will the pilot require flare guidance for the transition to the shallow glide slope?
6. How accurately can the pilot control the vehicle's indicated airspeed to arrive at the transition altitude with the pre-selected speed? To cross the runway threshold at the desired airspeed?
7. Are there any differential effects on approach success or pilot performance of either the flight path control or airspeed management task which can be attributed to variations in approach profiles or wind effects?
8. When the EDC is projected through the windshield in the head-up mode, is it necessary to include airspeed and altitude information in the head-up display format?
9. Is there any significant enhancement or degradation of pilot performance when the EDC is presented head-down on the instrument panel, without see-through reference to an actual runway image?
10. How successful are the landings following an approach by reference to the EDC? How do variations in the level of display support provided for the approach affect touchdown performance?

The simulator evaluation documented in this report was designed to provide data pertinent to the resolution of these issues. The description of EDC test configurations presented in the next section further defines the intended contribution of the EDC to Orbiter approach control and the Results and Discussion section presents an empirical assessment of this potential EDC application.

DESCRIPTION OF THE EXPERIMENTAL DISPLAY CONFIGURATIONS

As indicated in the preceding section, the key features of the experimental display concept (EDC) are (1) that it provides a direct representation of the vehicle's position and movement relative to the selected flight path and aiming points (ground reference feature), (2) that it is a pictorial situation display rather than symbolic, guidance-system constrained flight path deviation or flight director display, and (3) that it provides for the selective integration of quantitative flight situation data. In order to assess the relative contribution of distinguishable features of the EDC to specific components of the manual approach control task, five different configurations of the EDC were defined for the simulator evaluation. In terms of continuity with the EDC development effort during the first phase of this study, the fifth display configuration is the most complete representation of the display concept. It is presented head-down, on the instrument panel, and integrates pictorial, ground-referenced display elements with symbolic flight situation data in accordance with the see-through principle.

The first four EDC configurations were defined to provide a contrast between the head-down display and head-up versions which enable the pilot to literally see through the display field to the external visual scene, i.e., to the runway and its immediate surrounds. The four head-up configurations may be construed as representing increasing levels of display aiding to the pilot, culminating in display configuration four, which is identical to configuration five, except that it is projected through the windshield and superimposed on the external visual scene. The configuration descriptions which follow will begin with the most basic head-up version of the EDC. As subsequent configurations are defined, it will be clear that they are comprised of common display elements which, except for the flare guidance feature, function the same way in all five versions of the EDC.

It is important to note that none of the five EDC configurations include conventional flight director or ILS-type deviation indicators. Flight director elements were incorporated in the original EDC (ref. 2) and might still be considered as a potential addition to the display configurations presented here. However, the focus of the present study is on the utility of the EDC in supporting alternative approach control techniques which entail variable glide slope angles and pre-flare aim point adjustments that may not be practicable using conventional approach guidance systems. Moreover, the display assessment is concerned with techniques for enhancing the precision of head-up VFR approach control and with examining an instrument-reference control technique that can be implemented using the same perceptual frame of reference and control strategies as flight by external visual reference.

Basic Head-Up EDC Configurations

The first of the five EDC configurations (designated C-1 in subsequent discussions of the evaluation plan) represents the minimum augmentation of the out-the-window view and provides a baseline display condition for assessing the relative effectiveness of display elements incorporated in alternate configurations. As shown in Figure 2, this display is essentially a windshield projection of basic attitude symbology which appears to be superimposed on the external scene. It consists of an Artificial Horizon, an Expanded Aircraft Symbol, a Pitch Attitude Scale and a Glide Slope Reference Bar – a depressed sighting bar positioned to indicate the desired glide slope angle. Dotted elements in this schematic illustration represent actual terrain features, namely, the horizon, landing site and a terrain feature located at a known distance from the runway which is used for a pre-flare aim point. A photographic reproduction of this basic EDC configuration, as it was represented in the simulation, is presented in Figure 3.

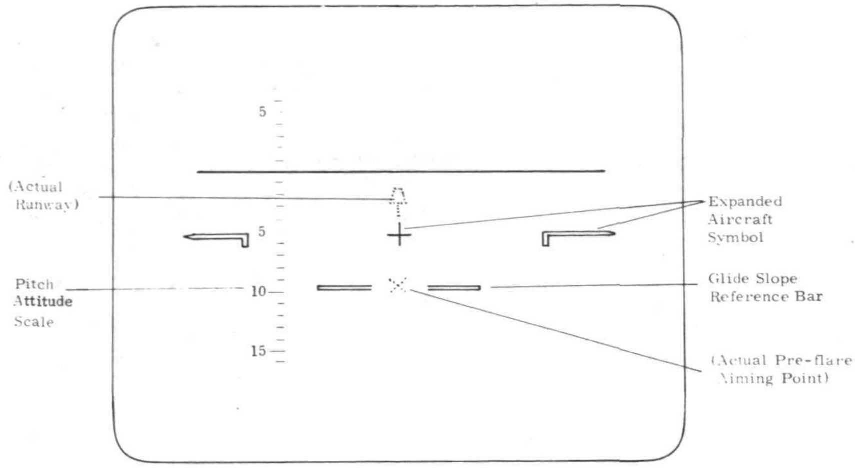


Figure 2. Illustration of the Basic VFR Head-Up Configuration of the Experimental Display (Configurations C-1 and C-2)

Display support for vertical flight path control and approach monitoring in this configuration is provided by the Glide Slope Reference Bar (GSRB) operating in a fixed-position mode. In this mode, the bar is set to indicate a desired approach angle relative to the ground (i.e., glide slope angle) and serves as a fixed sighting reference. Note that the bar is aligned with the pitch scale at a fixed depression angle relative to the horizon. The pitch scale is designed to indicate actual elevation angles relative to the horizon and thus serves to locate any ground feature in the pilot's field of view (e.g., the runway threshold is at a sight angle of -3°). In the fixed-position mode, the GSRB serves only as a sighting aid and does not directly indicate the vehicle's actual instantaneous flight path angle. The vehicle must be maneuvered until a desired ground aiming point is aligned with the bar; when bar alignment with this aim point is maintained, the vehicle is descending toward it on the selected glide slope angle.

For the two-segment Orbiter approach, the GSRB would first be set to the steep, first segment approach angle and then repositioned to the shallow glide slope angle at a pre-selected transition altitude. Following transition, the aircraft would be maneuvered to align the bar with a second aiming point (on the runway) in order to establish and maintain the desired glide slope angle for the shallow approach. In this basic configuration, no guidance is provided for the transition flare maneuver. This display configuration is similar in function to the head-up Visual Approach Monitor (VAM) developed by Sunstrand Data Control (ref. 6) operating in the Fixed Bar mode. This VAM display was developed to provide vertical flight path guidance for executing both steep, noise abatement approach profiles and standard VFR approach sequences in jet transport aircraft.

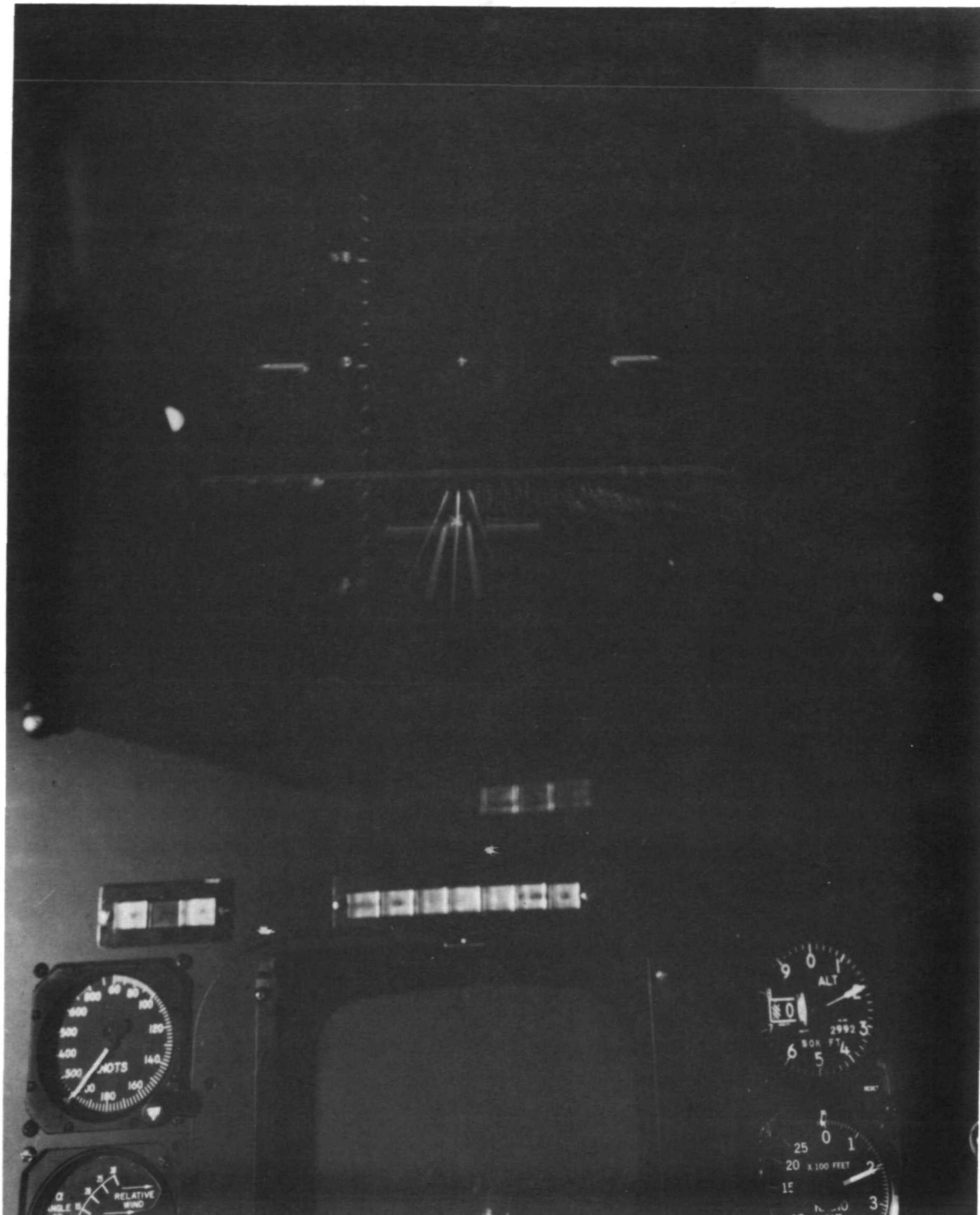


Figure 3. Photographic Reproduction
of the Basic Head-Up EDC Configuration (C-1 and C-2)

Display elements for the second configuration of the EDC, designated C-2, are the same as those illustrated in Figure 2. A flare guidance feature was added to define this configuration and is provided by modifying the operating mode for the Glide Slope Reference Bar. At an appropriate point in the initial approach segment, prior to arrival at the pre-selected transition altitude, the bar will begin to function in a transition guidance mode similar to the modified delta gamma mode defined for the VAM display. In this mode, the GSRB is biased to the shallow glide slope angle (2.5^o) and displays a command flight path angle derived from the difference between 2.5^o and actual flight path angle. As the pilot now maneuvers to align the bar with the runway aim point, the vehicle will execute a smooth transition to the shallow glide slope.

In addition to establishing a baseline display condition for assessing the full complement of EDC display elements, the examination of the first two configurations was intended to provide a preliminary evaluation of the applicability of the simplified head-up approach monitor represented by the Sunstrand VAM display concept to the Orbiter approach. A basis is thereby established for relating this study to other simulation and flight test programs at ARC. However, it was anticipated that additional display support would be required for both VFR and IFR Orbiter approach operations. This additional display support is represented in the more complete EDC configurations discussed in the next section.

Augmented VFR Head-Up Configurations

The third EDC configuration represents a further augmentation of the VFR head-up display (HUD) and illustrates the integration of ground referenced features, i.e., the Projected Impact Point (PIP), Approach Path, Aim Point and Relative Heading elements. This configuration is designated C-3 and is illustrated in Figure 4. The PIP is essentially a velocity vector and indicates both actual flight path angle relative to the ground (by reference to the Pitch Scale) and direction of flight relative to the runway (by reference to the Approach Path). The Approach Path and Aim Point elements represent corresponding points on the ground and move in correct azimuth, elevation and perspective relationship to the pilot's line of sight. The Approach Path replaces the Range Marker dots of the original EDC to provide an improved indication of lateral flight path alignment. The Aim Point marks both the pre-flare aiming point for the steep initial approach segment and the runway aiming point for the shallow glide slope. Relative Heading markers locate the runway heading (center mark) and move laterally relative to the center element of the aircraft symbol as the aircraft's magnetic heading deviates from the runway heading; the smaller markers indicate 10^o left and right. Figure 5 is a photographic reproduction of this display as it appeared in the simulator.

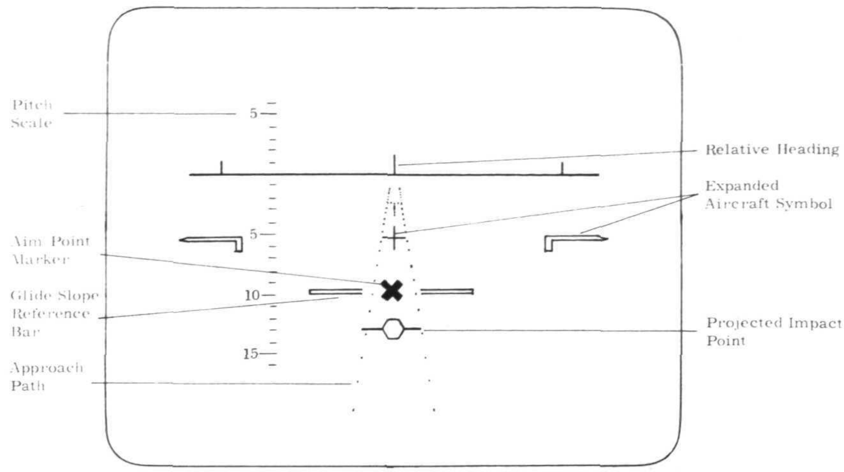


Figure 4. Head-Up VFR Configuration Augmented with Ground Reference Display Elements (Configuration C-3)

In configuration C-3, an alternative flare guidance technique for the transition maneuver was adopted. At the selected flare initiation altitude, the Glide Slope Reference Bar provides a command flight path angle derived from constraints imposed on the rate of change in this parameter to limit vertical g-force acceleration during the transition flare maneuver. The bar moves up to the 2.5° position at a rate designed to limit the acceleration to 32 feet/second/second (1 g) when the pilot follows this bar movement with the PIP.

The fourth configuration, illustrated in Figure 6, is a head-up presentation of the full complement of EDC elements. This configuration, designated C-4, retains all of the features of configuration C-3 and simply adds moving, vertical scales for Indicated Airspeed and Altitude. The availability of airspeed and altitude information in the head-up display is intended to eliminate the necessity for scanning conventional panel-mounted airspeed and altitude instruments which are located below the glare shield at some distance from the primary head-up display. Target airspeeds for the transition and for arrival at the runway threshold are indicated by the pre-set Airspeed Reference index. The altitude scale change at 2000 feet provides an anticipatory visual cue for the transition maneuver and the Flare Initiation Marker provides the cue for initiating the flare. The photographic reproduction of this display configuration is provided in Figure 7.

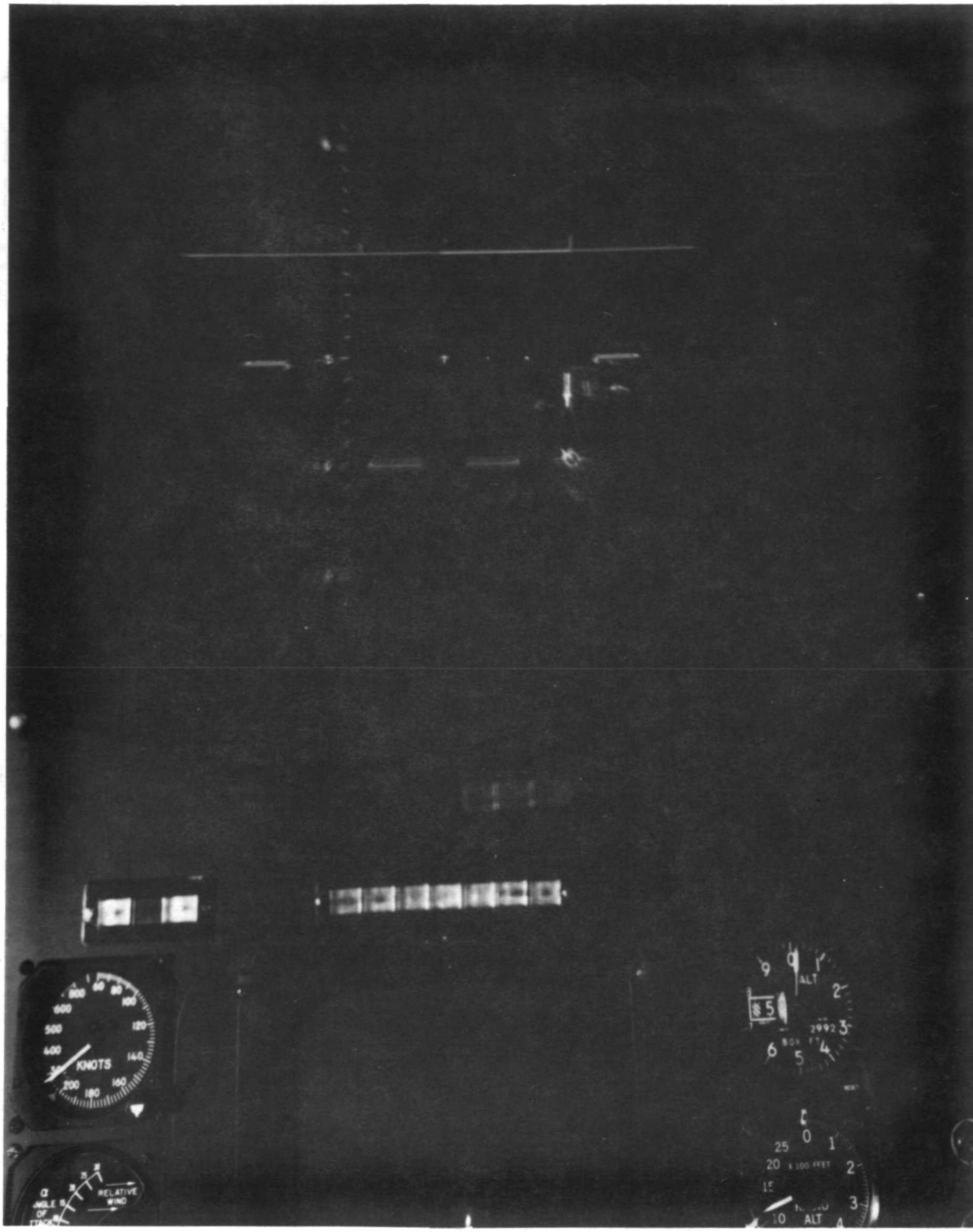


Figure 5. Photographic Reproduction
of the Augmented Head-Up EDC (Configuration C-3)

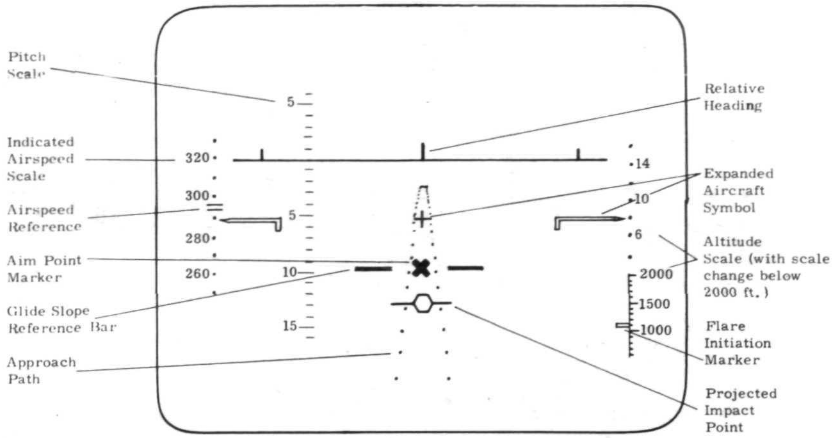


Figure 6. Illustration of the Full Complement of Experimental Display Elements for Both Head-Up and Panel Mounted Configurations (C-4 and C-5)

The Head-Down EDC Configuration

The fifth and final configuration defined for the simulator evaluation is presented head-down, i.e., on a panel-mounted cathode ray tube (CRT). The full complement of EDC elements, as illustrated in Figure 6, is available in this configuration which is designated as C-5. Configuration C-5 is intended to be used for IFR conditions and it is anticipated that this display will enable the pilot to fly the same approach profiles, using the same control strategy and technique as he would when making a VFR approach. Since the C-5 display is presented head-down, the external visual scene is not available to the pilot. In this display, the far end of the Approach Path element locates the runway threshold, but no additional representation of the runway is provided.

Pilot utilization of the EDC for vertical flight path control, lateral flight path control, and airspeed control is outlined in Appendix A for each of the display configurations. These outlines of the Orbiter approach control objectives and flight control techniques clarify the principles of display element movement relative to vehicle control actions taken by the pilot. The more important kinematic features of the experimental display, i.e., the way the display elements move relative to each other to represent the dynamic flight situation, cannot be clearly conveyed in the static descriptions given in this section. As the aircraft descends toward the runway, the Approach Path (and runway image for head-up display modes) expands and moves, with the Aim Point, in correct perspective relationship as aircraft attitude and relative position changes occur. The alignment of the Aim Point symbol relative to the GSRB is sensitive to angular deviations from the selected glide slope and actual direction of flight, and the PIP provides a very sensitive indication of the vehicle's velocity vector relative to the ground features.

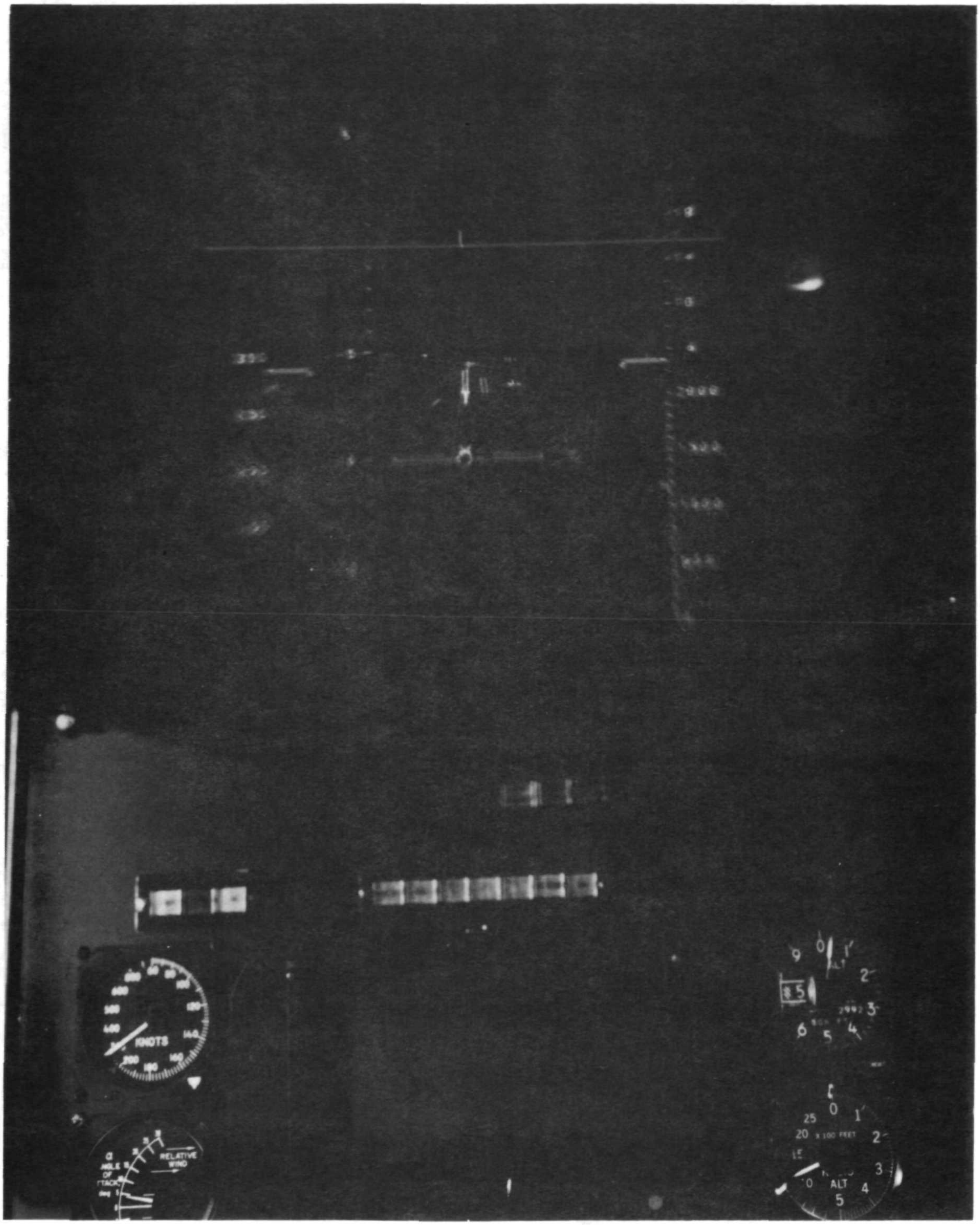


Figure 7. Configuration C-4 as Represented in the Simulation

SIMULATOR EVALUATION PLAN

The assessment of the EDC's potential application to Orbiter approach and landing operations was conducted in the MMIB simulation laboratory at ARC. The basic criterion for this assessment was the effectiveness of the pilot's attempts to control the vehicle's flight path and airspeed during the simulated Orbiter approach sequences. The simulated approach profiles and pilot task assignments were designed to represent the principal variations in final approach control technique which are now being considered in the development of terminal area guidance and control systems for the space shuttle. Currently active airline pilots were recruited to participate as subject-pilots in this study and trained to fly the simulated approach sequences by reference to the experimental displays.

Data were obtained on pilot performance of flight path and airspeed control tasks for four different approach profiles and under simulated headwind, tailwind, and crosswind conditions. An additional criterion for the EDC evaluation was provided by pilot critiques of the display's utility, content, presentation concept, and applicability to the manual Orbiter approach control task. This section outlines the simulation equipment set-up and programming established for the EDC evaluation and presents the experimental design and procedures adopted.

Simulation Facility and Experimental Set-Up

An overview of the simulation equipment configuration established for the EDC evaluation is schematized in Figure 8. This facility configuration is essentially the same as the one used for the first phase of the study and has been described in an earlier report (ref. 2). The significant modifications are cited in the following discussion of the principal components of this set-up.

Pilot's Station

Pilot-subjects flew the simulated approach sequences from the right seat of the MMIB fixed-base simulator cab, using a conventional control column and rudder pedals for the primary flight path control task. Head-up EDC configurations were presented on a 21-inch CRT display scope mounted behind the windscreen and viewed through collimated combining lenses, as shown in Figure 9. EDC configuration C-5 was presented to the pilot on the eight-inch video monitor mounted in the center of the instrument panel, using a closed-circuit TV transfer of the image generated on the same CRT as that used for the head-up display after removing it from the windshield position. (See discussion of display generation techniques below.)

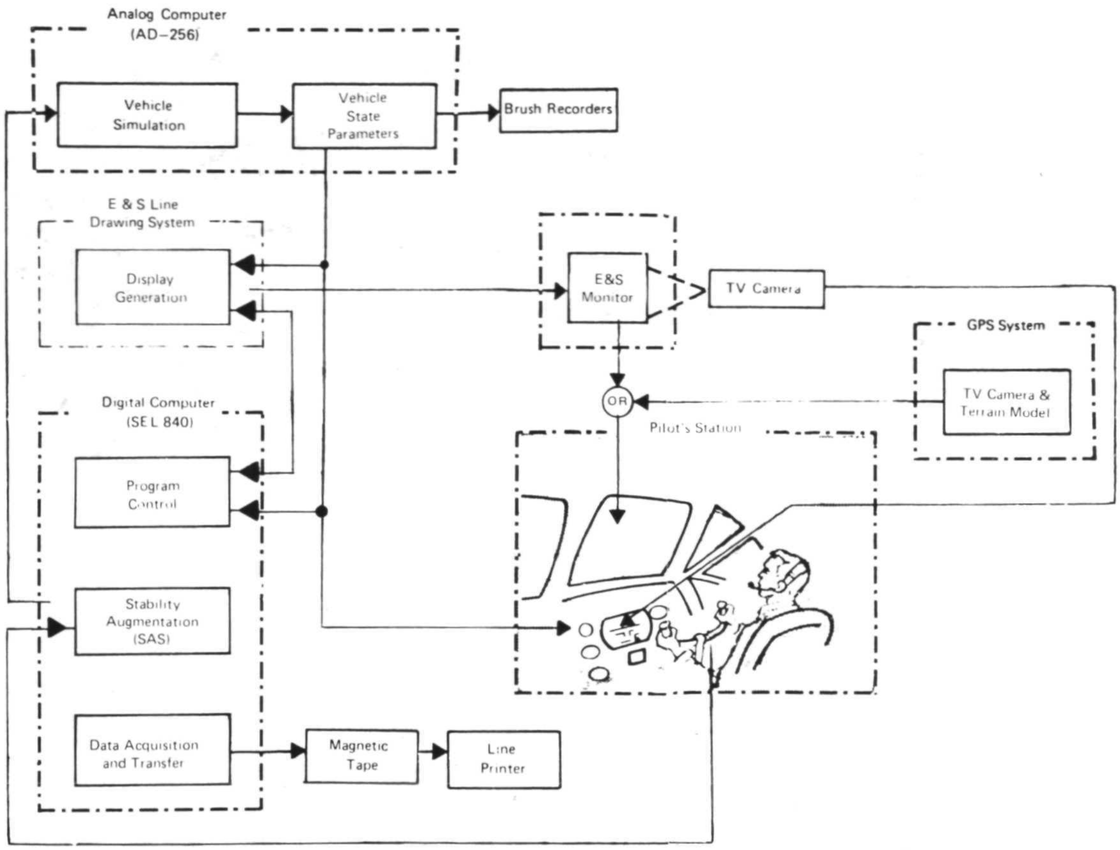


Figure 8. Schematic Representation of the MMIB Simulation Facility Configuration

The primary display locations and surrounding flight instruments available at the pilot's station are illustrated in Figure 9. All of the flight instruments shown were functional and available to the pilot, but for most display conditions they were not required for the experimental task. Except for the airspeed indicator and altimeter, they were disregarded. Manual trim controls located on the left horn of the control column (elevator trim) and on the center pedestal were functional. Speed brake control was implemented using the flap handle located on top of the center pedestal. A speed brake position indicator (not shown in Figure 9) was mounted on the center of the instrument panel immediately above the flap handle.

Figure 9. Illustration of the Pilot's Station

Vehicle Simulation

The basic analog vehicle simulation was the same as the one programmed by the MMIB personnel for the first phase of the study and represents the response characteristics of the NAR 134C high cross-range, delta wing Orbiter. Since all approach sequences were manually controlled by reference to guidance-free flight situation displays, the automatic control and guidance features of the program were not used in the present set-up. However, the stability augmentation system (SAS) programmed on the digital computer was used. As indicated in Figure 8, the pilot's control inputs from the cab were first processed by the SAS simulation and then transferred as inputs to the vehicle simulation and EDC generation programs.

The principal modifications to the vehicle simulation for the present EDC evaluation were the incorporation of speed brake effects and an improved wind effects simulation. Speed brake effects were based on data available from a simulation at ARC of a later Orbiter design concept, the NAR 161. Since the basic vehicle (NAR 134C) configuration does not include speed brakes, something of a hybrid vehicle was represented when the speed brakes were deployed. No attempt was made to develop a high-fidelity simulation of any particular type of speed brake or deceleration effect. For present study purposes, it was considered sufficient to generate a simple and effective drag modification signal that would provide for an airspeed control technique that was applied in the same way by all pilots and for all display configurations.

Four individually selectable wind effects were programmed on the analog computer in accordance with the wind speed versus altitude plots presented in Figure 10. These wind speed plots were derived, in part, from synthetic wind profiles constructed on the basis of radar/Jimsphere wind speed measurements at Cape Kennedy (ref. 7). Linearized representations of these airspeed schedules were incorporated into the vehicle simulation to apply the appropriate wind vector as the Orbiter descended. Note that two headwind profiles were defined. The light headwind (plot 2) was generated by scaling down the strong headwind (plot 3) to ¼ value. This lighter wind effect was applied as an alternative condition to the stronger headwind in order to preclude excessive deceleration on the first segment of the approach when the comparatively shallow 10° and 7° approach profiles (see profile descriptions below) were flown. This scaled-down wind velocity schedule was also used for the crosswind simulation (plot 2), which was generated by applying the scheduled wind vectors at a 45° angle to the runway heading.

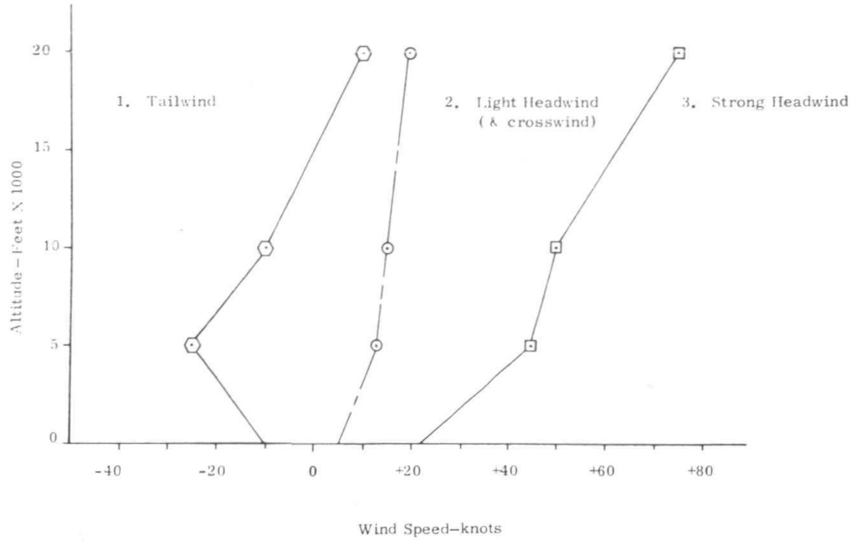


Figure 10. Definition of Wind Speed Profiles

Display Generation

The five experimental display configurations were generated by the Evans and Sutherland (E&S) Line Drawing System and displayed directly on the CRT installed at the pilot's station. Analog signals generated by the vehicle simulation were sampled by the 840 computer via analog-to-digital converters, as shown in Figure 8, and transferred to the E&S system under the control of the display generation program. The basic perspective computations for the runway image and ground-reference display elements were executed in the E&S computer. Alternative display configurations and run conditions were selected by program control instructions entered into the 840 computer using the ASR-33 teletype terminal.

Head-up configurations of the EDC were mixed with a simulated landing site image, also generated by the E&S computer. An existing program, developed to provide a six-degree-of-freedom night view of the San Jose Municipal Airport and some of the surrounding terrain features, was used for the landing site simulation. A photographic reproduction of this display was presented earlier in Figure 7; the EDC configuration shown is C-4, which incorporates the full complement of display elements. The field of view is 30° vertically and horizontally and the airport scene and EDC symbols are presented in registration and with unity magnification. All head-up displays were viewed through a collimating lens system which focused the image at optical infinity and enhanced the depth effects.

The head-down, C-5 EDC configuration was transferred from the E&S display scope using a closed circuit TV set-up and presented on the 525-line video monitor installed on the instrument panel. Figure 11* presents a photographic reproduction of this display configuration. Note that while the resolution of the display elements is adequate, the display is not as sharp as the direct display generated on the E&S scope. The airport scene is not included in the C-5 presentation and the image is smaller than the head-up display by a ratio of 2:1. For approach sequences carried out by reference to this head-down display, the E&S scope was relocated from its position behind the windscreen and collimative lenses and replaced with the color television monitor used with the GPS Visual Flight Attachment. This attachment was used to simulate an in-cloud condition early in the approach and, as the vehicle passed through an altitude of 300 feet, a full-color simulation of the external visual scene which could be viewed through the windscreen was shown (see Figure 11).

Data Acquisition and Recording

As the approach sequences were executed, ten flight situation parameters were sampled on each cycle of the display generation program by the SEL 840 computer, and these data were transferred directly to magnetic tape storage under the control of an integrated data acquisition program. Flight parameters monitored via the analog-to-digital converter channels were:

1. Range to runway threshold	(X)
2. Lateral displacement from the extended runway centerline	(Y)
3. Height above the runway	(Z)
4. Indicated airspeed	(IAS)
5. Vertical flight path angle relative to the ground	(γ_g)
6. Pitch attitude	(θ)
7. Roll attitude	(ϕ)
8. Normal vertical acceleration	(N_z)
9. Vertical velocity	($\dot{Z}$)
10. Lateral velocity	($\dot{Y}$)

*The runway image and airport surrounds shown in this photograph for the panel-mounted display should be disregarded. The C-5 display appeared in the simulation as shown in Figure 9.

Figure 11. Reproduction of the Head-Down EDC Configuration (C-5) as Represented in the Simulation

All summary performance data and criterion measures for the EDC assessment (see next section) were derived from this basic set of recorded data. In addition to the programmed acquisition and storage of digital data, analog data output from the vehicle simulation was recorded on an eight-channel, Brush strip chart recorder. The flight parameters recorded in this manner were X (from 25,000 feet to the threshold), Y, Z (1200 feet to touchdown), IAS, γ_g, N_z, and $\dot{Z}$. These records were used for cross-checking the digital printouts and for the qualitative assessment of the transition flare maneuver.

Experimental Design and Procedures

An overview of the experimental plan adopted for the EDC evaluation is presented in Figure 12. Participating pilots were briefed on the project objectives and experimental task and completed the necessary training, experimental run series and debriefing session in a single 6- to 8-hour visit to ARC. A standardized project orientation was presented to each pilot, briefly outlining the NASA Space Shuttle development program and the general character of the Orbiter recovery sequence and flight control techniques. The specific objectives of the simulation study and the pilot's role in the scheduled run series were then presented. A full briefing was provided on the display concept, the approach profiles to be flown, and manual flight path control and airspeed management tasks to be carried out in the simulator.

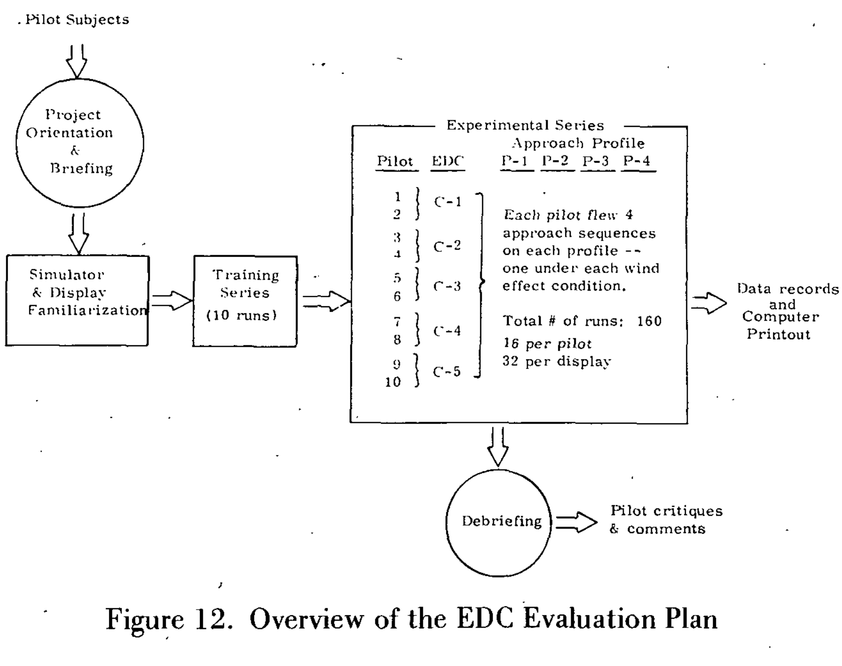


Figure 12. Overview of the EDC Evaluation Plan

After the orientation and briefing session, the pilot proceeded to the simulator cab and was familiarized with the location and operation of all controls and displays he would use for the simulator runs. Two demonstration runs were executed to introduce the pilot to the EDC, vehicle dynamics and simulator operating procedures. He then completed five unrecorded runs to acquire the "feel" of the vehicle simulation and a clear perception of the flight situation from the EDC. An outline of the experimental design used to structure the data collection runs and the procedures by which the experimental tasks were implemented is presented next.

Experimental Design

A three-factor experiment with repeated measures on the last two factors was used to structure the EDC assessment (ref. 8). This design provides for a comprehensive examination of the relative contribution of the five EDC configurations (Factor A) to pilot performance on the manual control task for four different approach profiles (Factor B) and under four different wind conditions (Factor C). Following this design, participating pilots were randomly assigned to one of the five EDC configurations and each pilot flew a 16-run experimental series as indicated in Figure 12.

The experimental design is schematized in Figure 13. Individual pilots were exercised in all four approach profiles, under all wind conditions, but they flew these approach sequences by reference to only one of the EDC configurations. Contrasts between display configurations were therefore confounded with differences between the two-subject groups of pilots assigned to each display. An alternative design was initially considered which would have permitted each pilot to fly all five display configurations. However, the additional training time requirements and multiple data collection run series which implementation of this design would entail exceeded the resource constraints and time available to the project. Since the pilots were very closely matched in terms of flying time and background, the experimental design represented in Figure 13 was expected to provide sufficient sensitivity for the assessment of display features incorporated in the five EDC configurations.

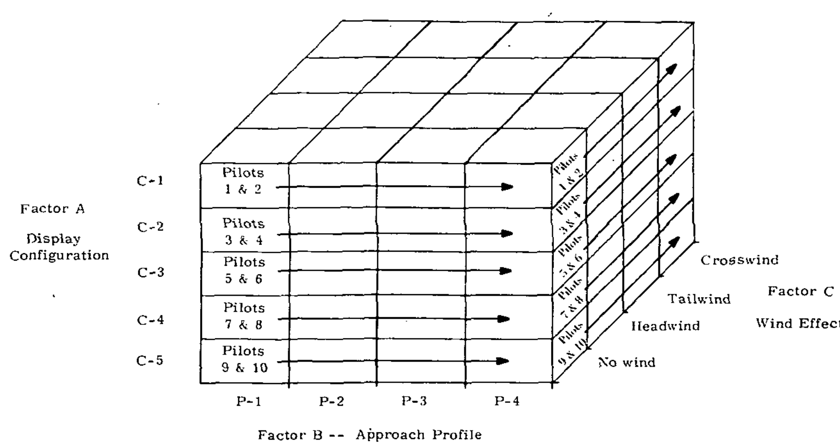


Figure 13. Schematic Representation of the Experimental Design

The simulator run schedules developed for implementing the experimental design established the order in which approach profiles and wind conditions would be flown on each run in the series for the assigned display configuration. As indicated in Figure 13, pilots flew four runs on each approach profile, one for each wind condition. The order in which pilots were exposed to the various combinations of approach profile and wind condition was completely counterbalanced across the ten pilots in order to preclude any systematic bias due to learning or fatigue effects which might carry over from one run condition to another.

Pilot Subjects

The ten participating pilots were all recruited from Pan American World Airways and were currently engaged in flight operations as First Officers. All of the pilots were currently type rated in the Boeing 707/720 and seven of the ten pilots had prior experience in high performance, fighter-type aircraft. Five of the pilots participated in the first simulator evaluation of the EDC and the other five were new to the project. None of the pilots reported any significant knowledge or experience related to advanced display technology, i.e., electronic attitude-director indicators or head-up display techniques. Relevant pilot background data is summarized in Table 1.

Table 1

Pilot Background Data

Datum	Range	Mean
Age	33 – 40	35.9
Total Flight Time (hrs.)	3750 – 11,300	6460
Fighter Time (hrs.)	100 – 2200	585

Procedures

Prior to initiating the experimental run series, each pilot flew five unrecorded approach sequences for general familiarization with the simulator and then completed a training series. During the training sequence, the flight path control and airspeed management tasks were performed as they would be on the subsequent runs for the record. The run conditions scheduled for the simulator familiarization and training runs are listed in Table 2.

The four final approach profiles were designed to represent the major variations in Orbiter approach control technique which are currently under consideration. These profiles are schematized in Figure 14. Profile P-1 is the reference profile adopted for the first EDC evaluation and represents the fixed-path control scheme developed by Sperry in their studies of automated guidance and control techniques for Orbiter recovery (ref. 3). The alternative profiles were defined to represent a steeper, close-in, 15° approach which may be more suitable for VFR operations (profile P-4), and two approaches representing a reasonable range of off-nominal initial conditions relative to the nominal P-1 approach.

Table 2

Training Series Run Schedule

Run #	Approach Profile	Wind Condition
Familiarization:		
1	Nominal (P–1)	No wind
2	Nominal (P–1)	No wind
3	Steep (P–2)	No wind
4	Steep (P–2)	Strong headwind
5	Shallow (P–3)	No wind (OW)
Training:		
6	Nominal (P–1)	Light headwind
7	Nominal (P–1)	Cross wind
8	Steep (P–2)	Strong headwind
9	Steep (P–2)	Light headwind
10	Shallow (P–3)	No wind
11	Shallow (P–3)	Tailwind
12	Close-in	Strong headwind
13	Close-in (P–4)	Cross wind (XW)
14	Pilot option	Pilot option
15	Pilot option	Pilot option

Profile P-2 represents a situation in which the vehicle is at a higher than nominal altitude and is closer in to the runway at the start of the approach. On this profile, the EDC is expected to allow the pilot to establish a steeper than nominal, 15° approach to the same pre-transition aiming point. At the beginning of profile P-3, the vehicle is at a lower than nominal altitude and the pilot elects to fly a shallow, maximum L/D, 7° approach to an adjusted aim point closer to the runway. With conventional flight director instruments or ILS deviation indicators, pilots would be constrained to acquire and track the fixed, nominal 10° glide slope prior to arrival at the transition point.

The manual flight control techniques used by the pilots for vertical flight path (glide slope) control, lateral flight path (runway alignment) control, and airspeed control are outlined in Appendix A. Variations in control technique employed when different EDC configurations were used are indicated in these outlines of pilot procedure. After completing the experimental run series, pilots were asked to comment on their experience with the approach control task and to critique the display features available in their assigned EDC configuration. The questions used to guide these debriefing sessions are reproduced in Appendix B.

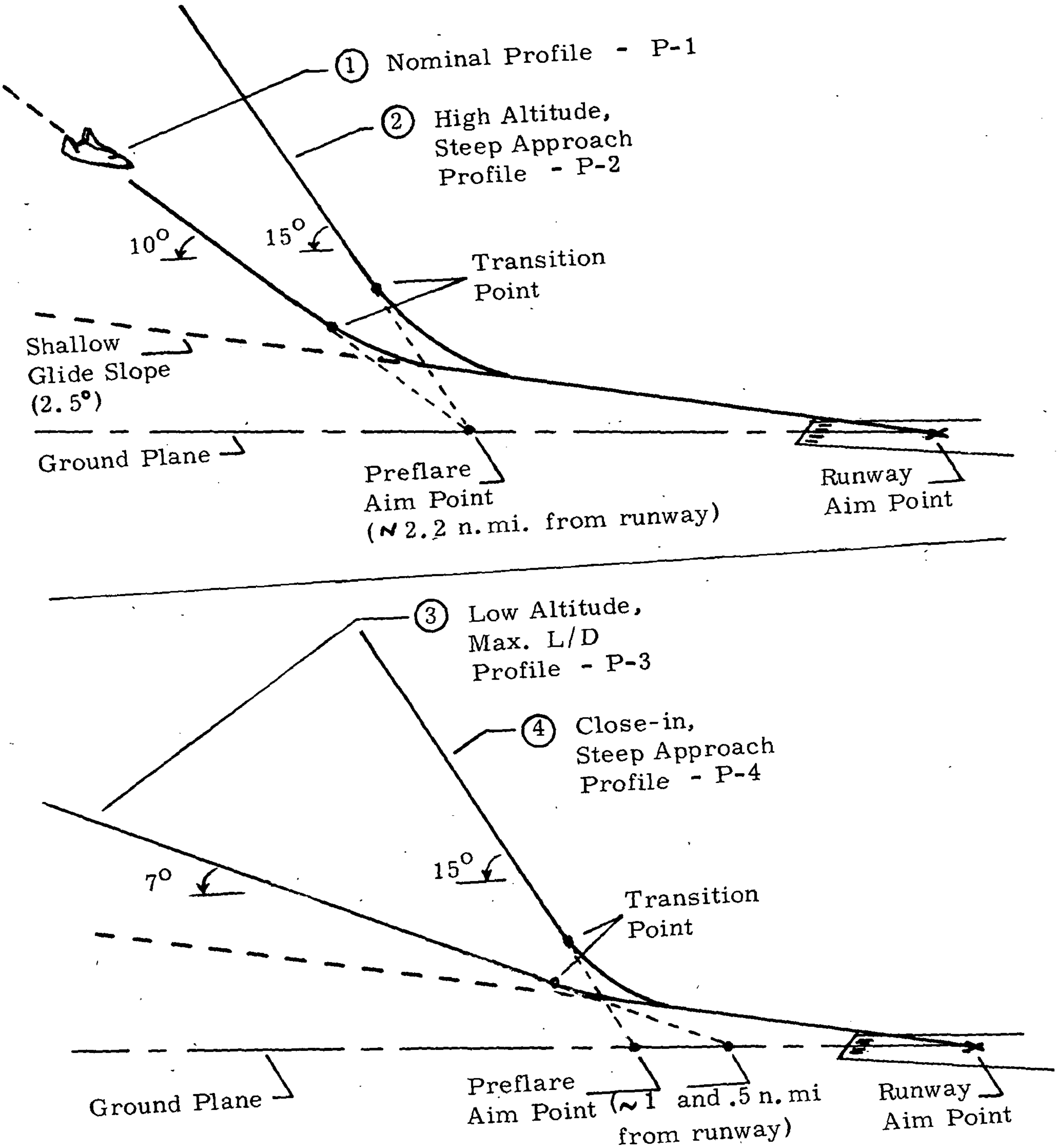


Figure 14. Alternative Final Approach Profiles for the EDC Evaluation

Data Recording and Analysis

The basic flight situation data recorded on each run of the experimental series has been identified in an earlier section. At the end of each scheduled run series, the SEL 840 computer compiled a "quick-look" printout of the value of selected flight situation parameters at key points in the approach and summary data on pilot task performance. The data content and format of "quick-look" printouts for one run are illustrated in the sample printout reproduced in Figure 15; similar printouts are available for each run in the series.

PILOT: 3

RUN NO.: 4 PROFILE: 4 TAILWIND DISPLAY MODE: C- 4

	X	Z	Y	IAS	HDOT	GAMMA	PITCH	NZ
IC	-61994.	15032.	1.	252.	-137.0	-15.0	-9.0	.0
TP	-8835.	799.	78.	244.	-111.0	-15.0	-10.0	3.0
TH	11.	58.	-15.	192.	-104.0	-1.0	6.0	1.0
TD	2186.	20.	4.	179.	-5.0	-1.0	8.0	.0

APPROACH SUCCESS INDEX	AIRSPEED ERROR AT TRANSISTION	AIRSPEED ERROR AT THRESHOLD
1	-6	2

RMS GAMMA SEG.1	RMS GAMMA SEG.2	RMS LATERAL SEG.1	RMS LATERAL SEG.2
.679	.832	104.012	18.755

Figure 15. Sample Computer Printout of "Quick-Look" Run Data

Data elements in the matrix just below the identification of run conditions on the first two lines are the values of designated flight situation parameters sampled at the initial run condition (IC), transition point (TP), runway threshold (TH) and at touchdown on the runway (TD). Designated parameters are:

X = range from present position to runway threshold (ft)
Z = altitude above the runway (ft)
Y = lateral displacement from the extended runway centerline (ft)
IAS = indicated airspeed (knots)
HDOT = vertical velocity (ft/second)
GAMMA = vertical flight path angle relative to ground plane (degrees)
PITCH = pitch attitude (degrees)
NZ = normal vertical acceleration (ft/sec/sec)

The approach success index for a single run reflects the outcome of the approach control task in terms of limiting values of Z, Y, and IAS upon arrival at the runway threshold. A successful approach, indicated by a "1" printout, must end with Z = 60 ±20 feet, Y = 0 ±50 feet, and IAS = 190 ±10 knots; whenever these criterion values are exceeded, a "0" printout occurs to indicate an unsuccessful approach. The airspeed-error printouts are the differences between actual indicated airspeed and designated target airspeeds for initiating the transition and for arrival at the runway threshold.

RMS GAMMA printouts are root mean square (rms) angular displacements from the specified glide slope for the first segment (RMS GAMMA SEG. 1) and for the second segment following transition (RMS GAMMA SEG. 2), in degrees. The last two data printouts reflect performance on the lateral flight path control task for the two approach segments and are expressed in feet from the extended runway centerline.

These performance measures and other criterion measures derived from the basic run data are discussed further in the next section of this report. Flight situation data were recorded on magnetic tape during the run series and were later sorted into a set of summary data tables using a separate data retrieval and analysis program. Analysis of variance was then carried out using selected measures and indices of pilot task performance. These data formats and statistical analyses are more clearly presented in the context of the presentation and discussion of results which follows.

RESULTS AND DISCUSSION

Data obtained from the simulator evaluation of the experimental display were intended to indicate the level of manual flight control performance which Orbiter pilots could achieve with the EDC and to assess the relative effectiveness of key display elements in supporting specific components of the approach control task. The primary criterion for this assessment is the effectiveness of the pilot's flight path control and airspeed management actions taken by reference to the EDC. Criterion measures were therefore derived, primarily, from flight situation data reflecting both the outcome of the approach and the accuracy and consistency of the flight control task. Critical comments and acceptance attitudes of participating pilots regarding the operational utility of the EDC were also used for the display assessment.

The assessment of the EDC, *per se*, refers to display configurations C-4 and C-5 which incorporate all of the defining features of this display concept. The data presented for alternative configurations examine contrasts between:

1. a simple approach monitor configuration with (C-1) and without (C-2) the flare guidance feature.

2. the basic VFR head-up configuration (C-1) with one incorporating ground reference feature (C-3).
3. the augmented head-up configuration with (C-4) and without (C-3) integrated airspeed and altitude scales.
4. a flare guidance feature based on flight path angle error (C-2) and one based on an acceleration-limited flight path angle command (C-3, C-4 and C-5).
5. the full EDC configuration presented head-up (C-4) and the same display presented head-down (C-5).

The following discussion of study results first examines the utility of the full EDC configuration (C-4) and then explores the contrasts of interest between display configurations. In general, the presentation of results follows the outline of display support issues given in the Introduction section of this report and summary data and analyses pertinent to these issues are disscussed. For further documentation of the study, a complete record of the basic flight situation and pilot performance data obtained on each simulated approach sequence (run), for individual pilots, is presented in Appendix C.

Approach Outcomes

Approach Success

The EDC was developed to support flight control during the approach to the landing site, but not the final landing maneuver and touchdown on the runway. An overall index of approach success was therefore derived from the vehicle's relative position and airspeed as it crossed the runway threshold, rather than at touchdown, as the principal measure of the general effectiveness of the display. Table 3 presents the number of successful approaches completed by each pilot on the 16-run experimental series. Individual runs were counted as successful only when limiting values on height above the ground (60 ±20 feet), lateral offset from the runway centerline (0 ±50 feet) and indicated airspeed (190 ±10 knots) were not exceeded as the aircraft crossed the threshold.

Data for configuration C-4 are highlighted in Table 3 to point up the potential of the EDC incorporating the full complement of display features. The reported approach success indices are simply the proportion of successful runs relative to the total number completed under the designated condition. A Chi-square (χ^2) test indicates that the differences in this success index across display configurations are significant at better than the .01 level. The reported proportion of successful runs under the C-4 condition is significantly higher than for the C-3 display ($p > .05$), which represents the next highest success count. The differences between the C-1, C-2, C-3 and C-5 display configurations are not statistically significant. The 32 runs represented by these success indices cover approach sequences flown by two pilots under all combinations of approach profile and wind effects (see preceding section).

Table 3

Approach Success Counts for Each Display Configuration and Pilot

Display	Pilot	Number Successful	Success Index by Pilot (n = 16)	Success Index by Display (n = 32)
C-1	1	1	.06	.28
	2	8	.50	
C-2	3	5	.31	.38
	4	7	.44	
C-3	5	3	.19	.41
	6	10	.62	
C-4	7	12	.75	.69
	8	10	.62	
C-5	9	7	.44	.38
	10	5	.31	

An approach success probability of only .69 for the full EDC may still seem unacceptable. However, airspeed dispersions at threshold (in excess of the 10-knot limit) account for most of the unsuccessful approaches under this display condition and, as subsequent data summaries will indicate, this condition can be corrected in the landing maneuver. The comparatively low approach success probabilities for the alternative displays are due to both airspeed dispersions and excessive altitude error, as later discussion will show.

Table 4 presents the complete count of successful approaches for each combination of approach profile and wind condition. The cell entries represent the performance of both pilots on the two runs flown under each profile/wind condition. There appears to be little difference in the approach success counts across the four profiles. The only notable trends are the consistently high success counts for the C-4 configuration and the tailwind condition across profiles.

Touchdown performance may also be construed as an approach outcome, although the final landing maneuver was executed solely by reference to a simulated runway image (EDC flight path control elements were deleted at 60 feet). Touchdown success counts are presented in Table 5; touchdowns were counted as successful when limiting values on position along the runway (between 250 and 3000 feet down the runway from the threshold), position across the runway (centerline ±45 feet), indicated airspeed (185 ±10 knots), and lateral velocity (0 ±8 feet/second) were not exceeded as the aircraft landed. Rate-of-descent at touchdown was recorded and is presented in Appendix C. This parameter was not used to define touchdown success because of the inflated values typically obtained in the simulator in contrast to actual flight data. High touchdown descent rates recorded in this study can be attributed to the absence of ground effect in the simulation and to the high approach speeds adopted for the Orbiter vehicle simulation.

Table 4

Number of Successful Approaches for Each EDC Configuration By Profile and Wind Condition (n = 2 runs per cell)

Approach Profile	Wind Effect	Display Configuration C-1	C-2	C-3	C-4	C-5	Success Count by Wind Effect and Profile
Nominal (P-1)	No wind	0	2	1	1	0	4
	Headwind	0	0	1	1	1	3
	Tailwind	1	2	0	1	2	6
	Crosswind	0	1	1	2	1	5
Success Count for Profile 1:		1	5	3	5	4	18
Steep (P-2)	No wind	1	0	0	1	0	2
	Headwind	0	1	1	2	0	4
	Tailwind	0	1	2	1	1	5
	Crosswind	0	0	1	2	1	4
Success Count for Profile 2:		1	2	4	6	2	15
Shallow (P-3)	No wind	2	0	1	2	1	6
	Headwind	1	1	0	2	2	6
	Tailwind	1	0	1	2	0	4
	Crosswind	1	0	0	2	0	3
Success Count for Profile 3:		5	1	2	8	3	19
Close-in (P-4)	No wind	0	1	1	1	0	3
	Headwind	0	0	1	0	2	3
	Tailwind	1	2	1	2	1	7
	Crosswind	1	1	1	0	0	3
Success Count for Profile 4:		2	4	4	3	3	16
Success Count for Each Display:		9	12	13	22	12	

In Table 5, data for the C-4 configuration are again highlighted and the χ^2 test indicates that the touchdown success indices differ significantly across display configurations ($p < .01$). Notice that pilot #8, using C-4 for approach control, completed all 16 landings successfully.

A more complete representation of touchdown performance is provided in Figure 16. Mean touchdown positions and airspeeds are plotted for the 32 runs completed under each display condition. The lines extending laterally from these data points represent one standard deviation around the mean and the criterion values cited above for defining a successful landing are indicated by the broken vertical lines. Completely unsuccessful landings occurred only when the C-1 display was used and some touchdowns occurred short of the runway threshold. The data plots in Figure 16 indicate that touchdown tended to occur closer to the target positions and airspeed, and that dispersions were smaller, when the full EDC configurations were used.

Table 5

Touchdown Success Counts for Each Display Configuration and Pilot

Display	Pilot	Number Successful	Success Index by Pilot (n = 16)	Success Index by Display (n = 32)
C-1	1	1	.06	.34
	2	9	.56	
C-2	3	10	.63	.66
	4	11	.69	
C-3	5	10	.63	.69
	6	12	.75	
C-4	7	13	.81	.91
	8	16	1.00	
C-5	9	10	.63	.63
	10	10	.63	

The touchdown success data summarized in Table 5 and Figure 16 represent outcomes of approaches flown under all approach profile and wind conditions. Table 6 presents the number of successful landings for each profile and wind effect combination and indicates that these variations in approach conditions had little effect on touchdown performance. There is a tendency for tailwind landings to be more consistently within limits and the crosswind approach condition appears to be associated with the lowest number of successful landings, but the differences are slight.

Flight Path Control

Vertical Flight Path Control

The assessment of the EDC's potential contribution to more precise control of the two-segment Orbiter glide slope, without using such guidance systems as the Instrument Landing System (ILS) or Visual Approach Slope Indicator (VASI), was a central concern of the simulator study. The pilot's ability to select alternate glide paths to pre-transition aiming points, and to track them accurately throughout the approach, is a key factor in achieving the intended flexibility in manual approach control technique. The criterion measure adopted for assessing this component of the flight control task is the root-mean-square (rms) angular displacement of the vehicle's flight path from the flight path angle specified for the approach (γ_g). Separate measures were derived for the first approach segment, from the initial position to the established transition altitude (RMS$\Delta\gamma_g$–1), and the second segment, from the pre-transition aim point to the runway threshold (RMS$\Delta\gamma_g$–2).

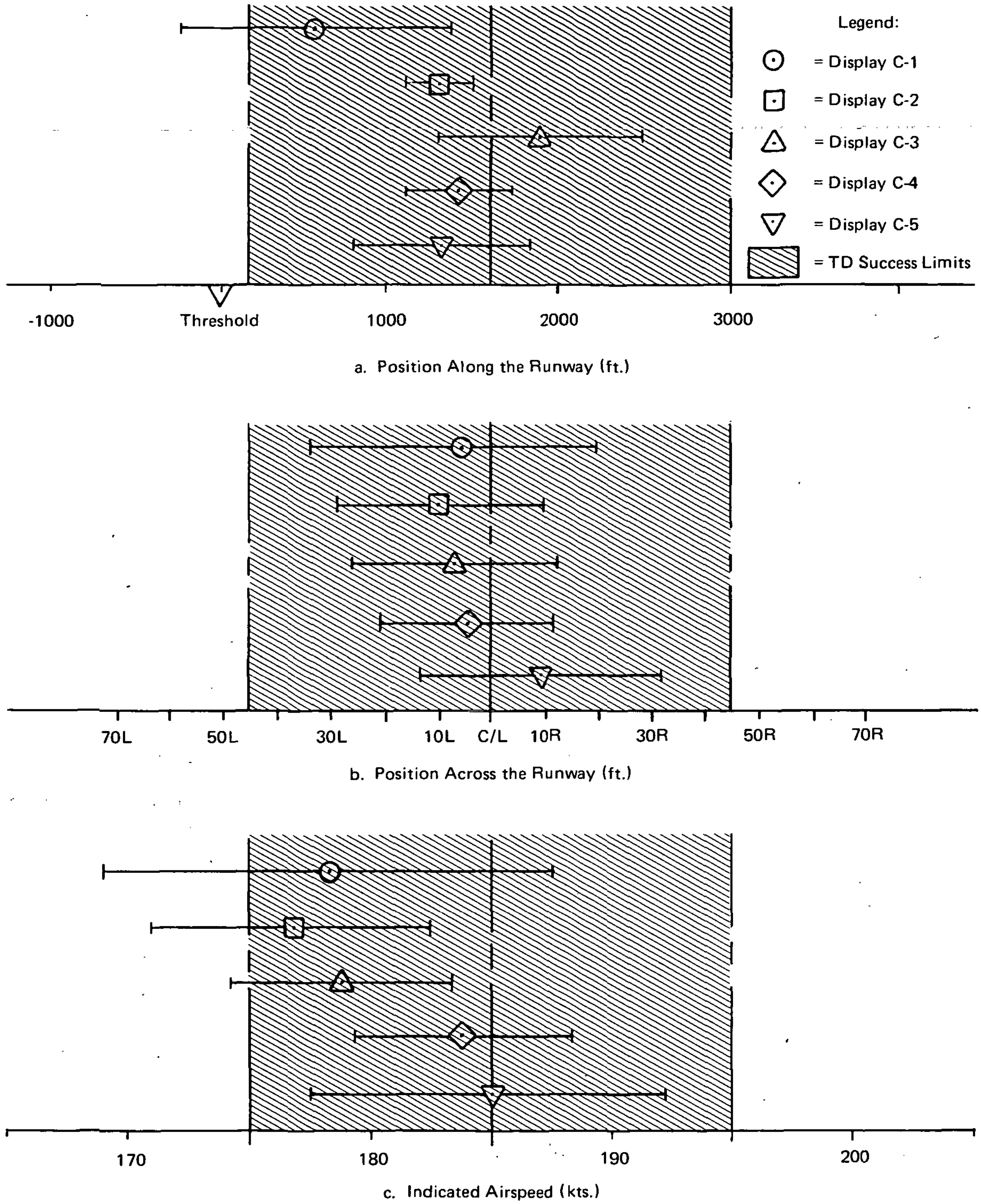


Figure 16. Touchdown Position and Airspeed Dispersions for Each Display Configuration.

Table 6

Number of Successful Touchdowns for Each Display Configuration by Approach Profile and Wind Effect (n = 2 runs per cell)

Approach Profile	Wind Effect	Display Configuration C-1	C-2	C-3	C-4	C-5	Success Count by Wind Effect and Profile
Nominal (P-1)	No wind	0	1	1	2	2	6
	Headwind	0	1	1	2	1	5
	Tailwind	1	1	2	2	2	8
	Crosswind	0	1	1	2	1	5
Success Count for Profile 1:		1	4	5	8	6	24
Steep (P-2)	No wind	0	1	1	1	1	4
	Headwind	0	0	1	2	1	4
	Tailwind	0	1	2	2	1	6
	Crosswind	0	0	2	2	1	5
Success Count for Profile 2:		0	2	6	7	4	19
Shallow (P-3)	No wind	2	2	1	2	2	9
	Headwind	1	2	1	2	2	8
	Tailwind	1	2	1	1	1	6
	Crosswind	1	2	1	2	1	7
Success Count for Profile 3:		5	8	4	7	6	30
Close-in (P-4)	No wind	1	2	2	2	0	7
	Headwind	1	1	2	1	2	7
	Tailwind	1	2	2	2	2	9
	Crosswind	1	2	1	2	0	6
Success Count for Profile 4:		4	7	7	7	4	29
Success Count for Each Display:		10	21	22	29	20	

The relative accuracy of glide slope tracking during the first segment for the five EDC configurations is plotted in Figure 17. The data points in this plot are mean values of RMS$\Delta\gamma_g$−1 for the 16 experimental approach sequences and the lines extending vertically from each point represent one standard deviation around these means. Note the drop in glide slope tracking error of about .5 degrees between configurations C-1 and C-2, which provide only the Glide Slope Reference Bar (GSRB) for vertical flight path control, and the next three EDC configurations, which incorporate the Projected Impact Point (PIP). Variability in flight path tracking is also reduced when the PIP is available, as indicated by the standard deviation markers. On the first segment, glide slope tracking was slightly better using the C-3 configuration than it was by reference to C-4. The only difference between the two displays is the addition of airspeed and altitude scales to C-4 (see Figures 4 and 6). Notice that the best tracking performance recorded is an rms angular displacement of .67 degrees (pilot #6) and that this record reflects performance on all four approach profiles and under four different wind conditions.

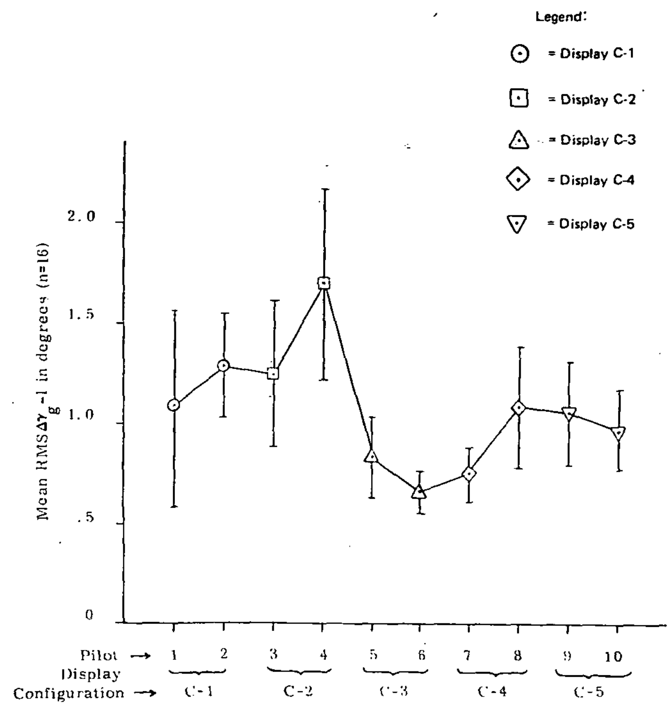


Figure 17. Relative Accuracy of Glide Slope Tracking on the First Segment of the Approach for All Profiles and Wind Effects

A similar trend is apparent in the data plot for the second segment of the approach, as shown in Figure 18. Mean $\Delta\gamma_g$ measures are again lower for display configurations which incorporate the PIP and the best shallow glide slope tracking performance is again on the order of .6 degrees. The one-sigma markers indicate a greater variability in tracking accuracies for this segment than those recorded for the first part of the approach. This increased variability may, in part, be attributed to shallow glide slope acquisition maneuvering following the transition flare (see Flare Guidance discussion below). RMS$\Delta\gamma_g$−2 sampling was initiated at the transition aim point, after the flare was expected to be completed, and was not intended to include the transition maneuver. A late flare or excessive under- or overshooting of the shallow glide slope would, of course, be reflected in these data.

An analysis of variance indicates that the recorded differences in glide slope tracking across the five EDC configurations are statistically significant for both the initial approach segment ($p<.10$) and the shallow segment ($p<.05$). However, the largest mean difference in tracking accuracy between displays (C-3 versus C-2) does not reach significance at the .05 level. This analysis also indicated significant differences in first-segment tracking performance on alternate approach profiles ($p<.01$) and under different wind conditions ($p<.01$). The interactions of these conditions with the different displays were also significant and may have obscured the relationship between particular displays. The differential effects of approach profile and wind conditions are plotted in Figure 19.

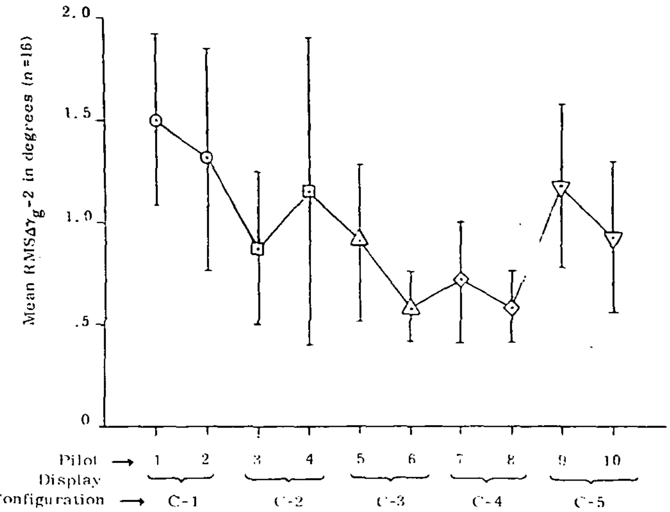
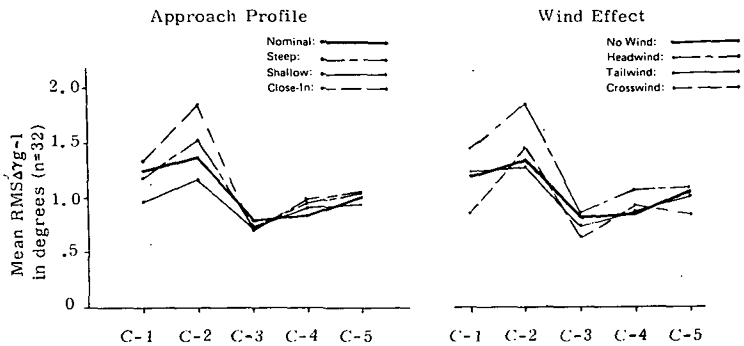
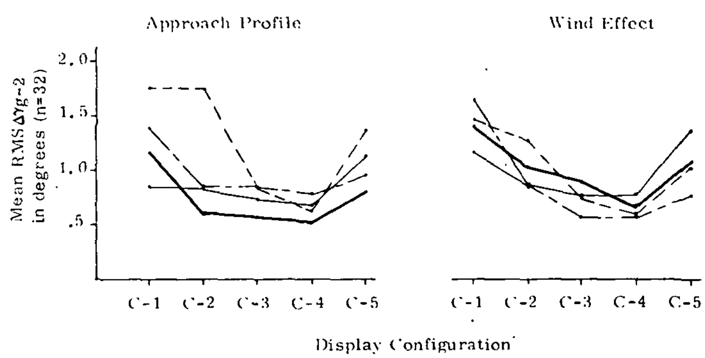


Figure 18. Relative Accuracy of Shallow Glide Slope Tracking Across All Profiles and Wind Effects



a. First Segment Glide Slope Tracking



b. Second Segment Glide Slope Tracking

Figure 19. Accuracy of Glide Slope Tracking for Each Profile and Wind Effect

As indicated in Figure 19, the significant variability in glide slope tracking on both approach segments, when different approach profiles and wind conditions were flown, was recorded only when EDC configurations C-1 and C-2 were used. Configurations C-3, C-4 and C-5 all included the PIP aiding element and, as expected, glide slope tracking was consistently better when these displays were used. The comparatively poor glide slope tracking on the shallow second segment (Figure 19b) when display configuration C-5 was used can be attributed to the pilot's transition, at 200 feet, from the panel display to the head-up, out-the-window visual scene for executing the landing maneuver (see pilot procedures for C-5, Appendix A). Notice also in Figure 19b that shallow glide slope tracking was not differentially affected by alternative wind conditions. Simulated wind effects were attenuated at lower attitudes (see wind speed versus altitude plots in Figure 11) and had a negligible effect on the short, second shallow approach segment.

Lateral Flight Path Control

Display support for lateral flight path control was a secondary consideration in the derivation of the EDC and specific features incorporated for this component of the flight control task are minimal, even in configuration C-4. In the C-1 and C-2 configurations, flight path alignment with the runway is maintained solely by reference to the external view of the runway; in the more complete displays, the Approach Path and Relative Heading markers provided additional runway alignment cues. Data on lateral flight path tracking were thus intended to assess the utility of the "see-through-to-the-runway" feature and the improvement, if any, when the Approach Path and Relative Heading elements were used.

Summary data on lateral control during both segments of the approach are plotted in Figure 20. The data points are mean rms lateral displacements, in feet, from the extended runway centerline, recorded on sixteen runs for each pilot, and reflect performance on all approach profile and wind conditions. The differences in lateral flight path control across display configurations are not significant on either the first or second approach segment. Notice, though, that a sharp reduction in the variability in lateral control, as indicated by the standard deviation markers, is apparent in the contrast between displays with no aiding (C-1 and C-2) and those incorporating the runway alignment elements (C-3, C-4 and C-5).

Most of the variability in lateral control shown in these data plots derives from the inclusion of the crosswind approaches. As anticipated, the analysis of variance disclosed a significant effect due to wind condition ($p < .01$) on both approach segments. Mean lateral displacements for each wind condition are plotted in Figure 21. The highly divergent lateral tracking performance under the crosswind condition is apparent in these plots for both approach segments. Notice in Figure 21b that one of the shallow segment data points for the crosswind condition dropped down into the average range of offsets for the non-crosswind conditions. This trend toward more accurate lateral tracking under crosswind conditions occurred when the C-3 display was used but did not show up for the C-4 and C-5 displays which also provided the Approach Path and Relative Heading markers.

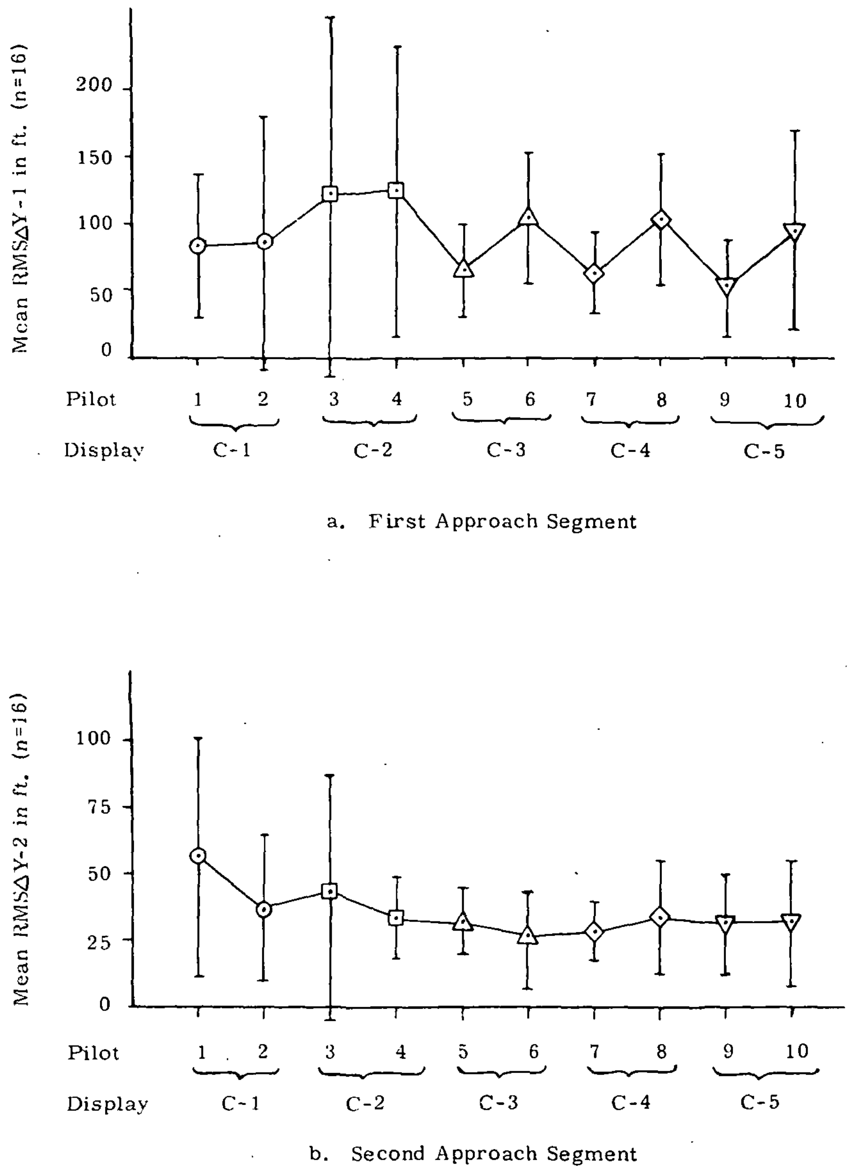
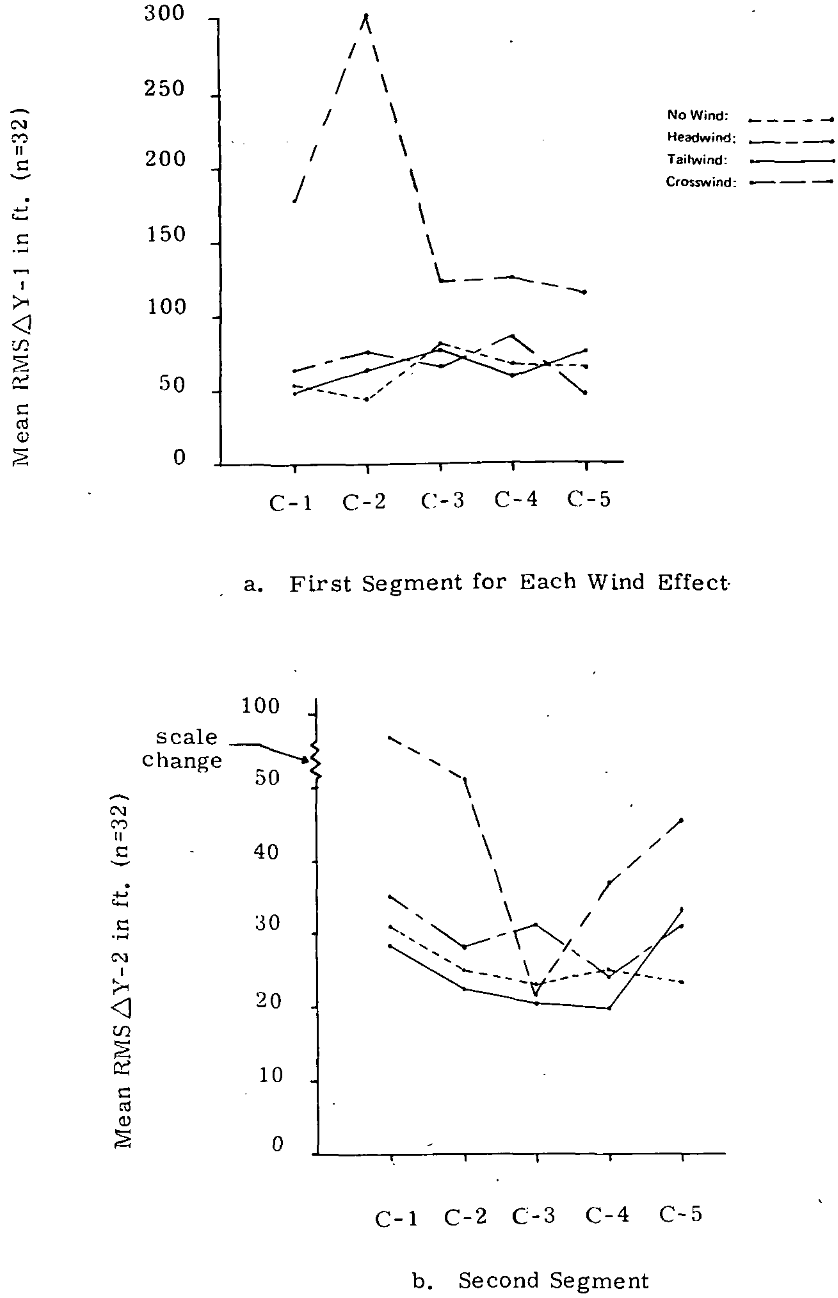


Figure 20. Relative Accuracy of Lateral Flight Path Control



a. First Segment for Each Wind Effect

b. Second Segment

Figure 21. Accuracy of Lateral Flight Path Control for Each Wind Effect

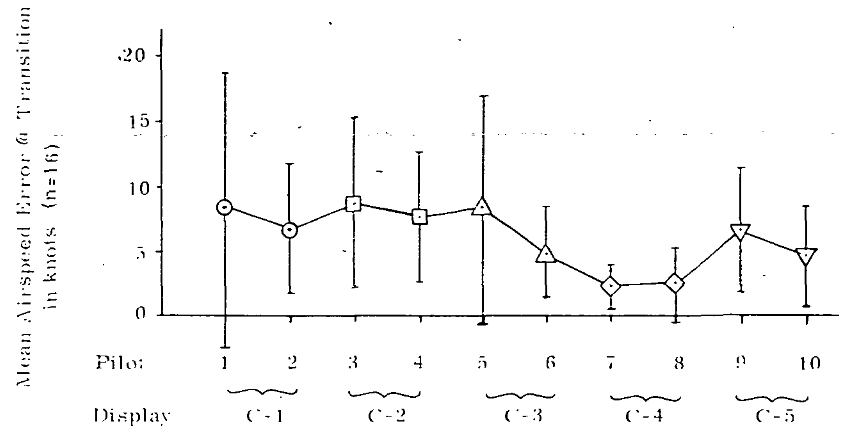
Airspeed Control

In terms of special EDC features, airspeed control was also a minimally supported component of the manual flight control task. Head-up configurations C-1, C-2 and C-3 provided no display elements for airspeed control and the pilot had to refer to a conventional panel-mounted airspeed indicator for this information with the attendant requirement to change his eye accommodation as well as his scan pattern. The full EDC configurations (C-4 and C-5) include a moving-scale display of indicated airspeed, with a reference bug for marking target airspeeds for the transition and for arrival at the runway threshold (see Figure 6). Subject-pilots attempted to manage their approach speed, using speed brakes to control excessive airspeed build-up, in order to arrive at these key approach control points at the target airspeeds specified below:

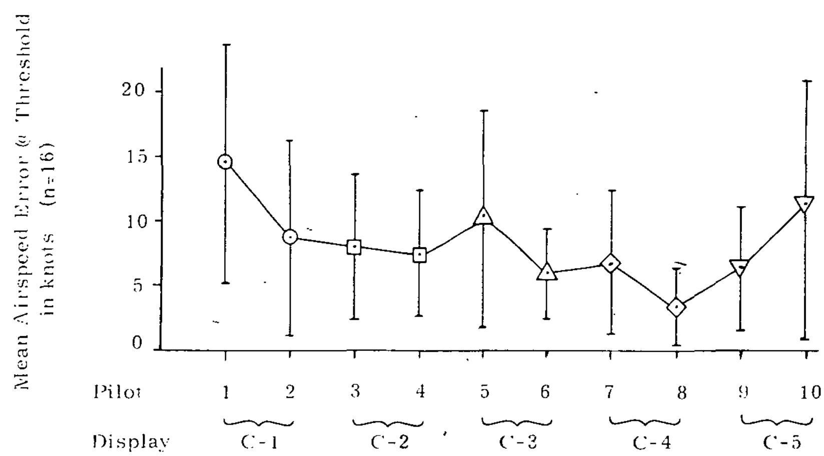
Approach Profile	Target Airspeed (knots) for: Transition	Over Threshold
Nominal (-1)	295	190
Steep (P-2)	295	190
Shallow (P-3)	215	190
Close-in (P-4)	250	190

The criterion measure for assessing airspeed control was airspeed error, i.e., the difference between the indicated airspeeds recorded at the approach control points of interest and the corresponding target speeds. Mean airspeed errors for each pilot and display condition, across the 16-run data series, are plotted in Figure 22, for both the transition point and the runway threshold. The pattern across display configurations is similar to the earlier plots for flight path control: consistently lower average errors and a marked decrease in the variability of pilot performance when control is exercised by reference to configuration C-4. The trend toward higher errors at the transition point (Figure 22a) using the same display elements of the head-down C-5 configuration may be attributable to the compression of the airspeed scale on this display and its comparatively poor resolution (see Figure 11). The higher threshold airspeed errors (Figure 23b) for the C-5 display are undoubtedly influenced by the transition from this panel display to the external visual scene at 200 feet and the consequent loss of relative airspeed information as the vehicle approached the runway.

An analysis of variance designed to sort out approach profile and wind effects shows the differences between mean airspeed errors at the transition point (Figure 22a) to be statistically significant ($p < .01$). Airspeed error at transition did not differ significantly when alternate approach profiles were flown, but a significant difference due to winds ($p < .05$) was disclosed by the analysis. As indicated in Figure 23a, relatively higher transition point airspeed errors were recorded for the different wind conditions, for the most part, when EDC configurations C-1 and C-2 (no airspeed scale) were used for airspeed control. The crosswind and tailwind conditions appear to produce the higher and more variable airspeed errors.



a. The Transition Point



b. Crossing the Runway Threshold

Figure 22. Airspeed Errors and Dispersions for Each Pilot and Display Configurations

Airspeed errors at the runway threshold (Figure 22b) did not differ significantly across the five display configurations and the pattern of approach profile and wind effects were found to be just the reverse of that just noted for the transition point. Wind effects had no significant influence on airspeed control at the threshold, but airspeed errors at this approach control point did differ significantly on alternate profiles ($p < .01$). The data plot by approach profile is presented in Figure 23b.

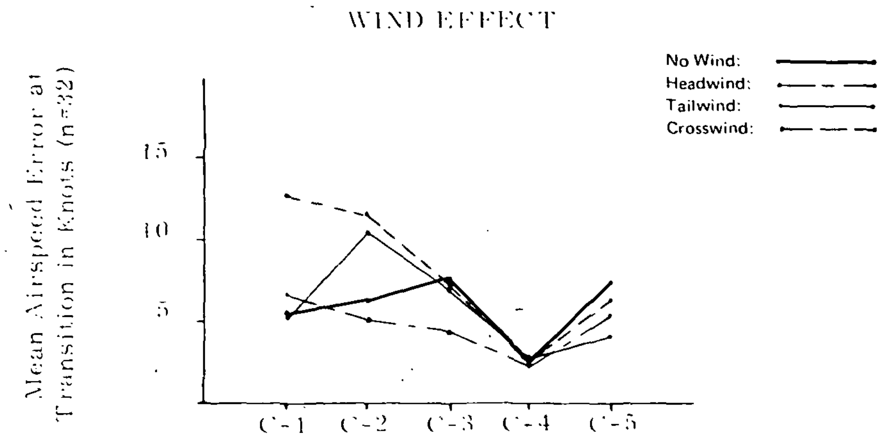


Figure 23a. Airspeed Errors at the Transition Point for Each Wind Effect

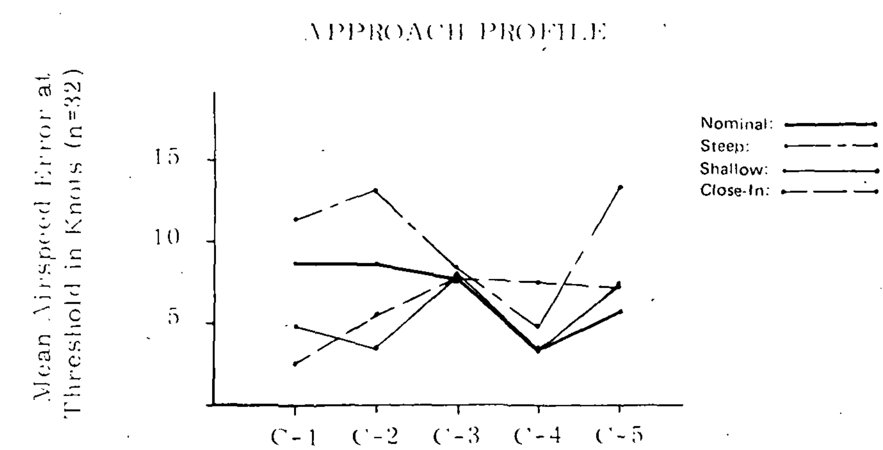


Figure 23b. Airspeed Errors at the Runway Threshold for Each Approach Profile

Again, the spread in airspeed errors at the runway threshold is most apparent for the C-1 and C-2 configurations, the errors converge somewhat when the C-3 and C-4 are used, and the errors increase for the head-down, C-5 configuration. The higher threshold errors were recorded on the steep approach (P-2) and, to a lesser extent, on the nominal 10-degree profile (P-1). A longer, decelerating shallow approach to the threshold (about two nautical miles) was required for both of these profiles in contrast to the very short second segments for profiles P-3 (.5 nautical miles) and P-4 (one nautical mile). These differences in the second approach segment are illustrated in Figure 14.

Additional Contrasts Between EDC Configurations

The primary assessment of the potential application of the EDC to Orbiter approach control has been presented in the preceding sections. Data obtained on alternate EDC configurations provided the basis for a further exploration of the utility of a flare guidance feature which might be incorporated into the display and of the relative effectiveness of head-up and head-down versions of the EDC. These additional contrasts between EDC configurations are presented in this section.

Flare Guidance

A successful execution of the two-segment Orbiter approach profiles examined in this study requires a timely initiation of the transition flare from the steep first segment, a flare rate that is fast enough to preclude excessive altitude loss without exceeding reasonable normal acceleration limits, and a smooth acquisition of the shallow glide slope. As indicated in the description of EDC configurations, the C-1 display provided no aid to the pilot for this transition flare maneuver and the flare guidance feature available in configurations C-2 and C-3 represent two different techniques for supporting this control task.

The contrasts between EDC configurations, using data reflecting pilot performance on the transition flare, examines the relative effectiveness of no flare guidance (C-1), a flare guidance feature based on the difference between actual flight path angle and the 2.5° shallow glide slope (C-2), and a flare guidance feature based on a vertical acceleration limit of 1 g on the flare rate (C-3). The criterion measures adopted for assessing the quality of the flare maneuver were:

1. Altitude error at flare initiation – the difference between actual altitude and the pre-selected transition altitude for the scheduled approach profile, in feet.
2. Undershoot – the maximum displacement, in degrees, of the recorded flight path angle (γ_g) trace below the 2.5° shallow glide slope during the flare maneuver.
3. Overshoot – the maximum displacement, in degrees, of the recorded γ_g trace above the 2.5° shallow glide slope.

These measures were derived from strip chart records for each experimental approach sequence and are illustrated in Figure 24. The actual altitude recorded at the flare initiation point was compared with the scheduled transition altitude (see Figure 14) to derive the altitude error measure. Undershoots and overshoots were read directly from the γ_g trace relative to the 2.5° reference line. In many instances, the actual γ_g trace remained above the 2.5° line (no undershoot) and gradually merged or "stepped down" to the shallow glide slope. In these instances, the maximum displacement of the γ_g trace prior to its first contact with the 2.5° reference line was taken as the overshoot measure.

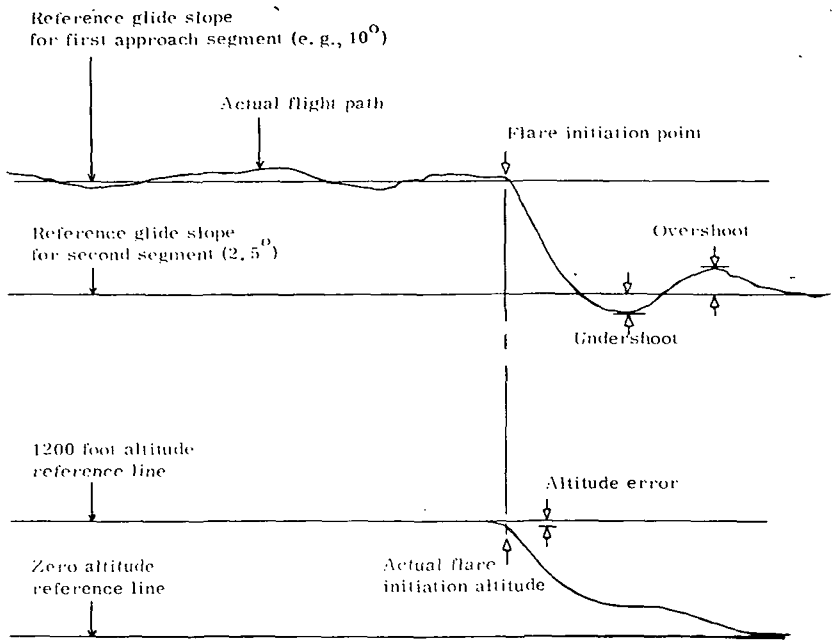
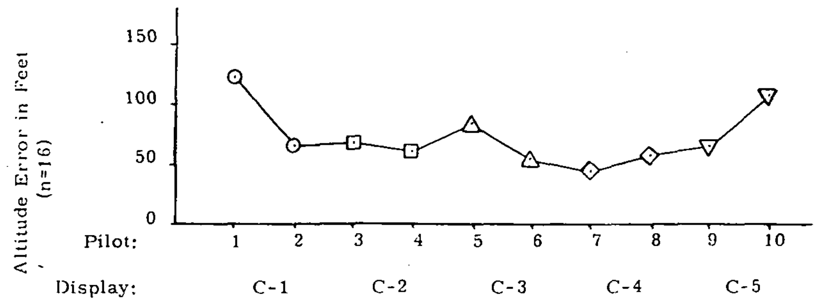


Figure 24. Illustration of the Criterion Measures Used to Assess the Transition Maneuver

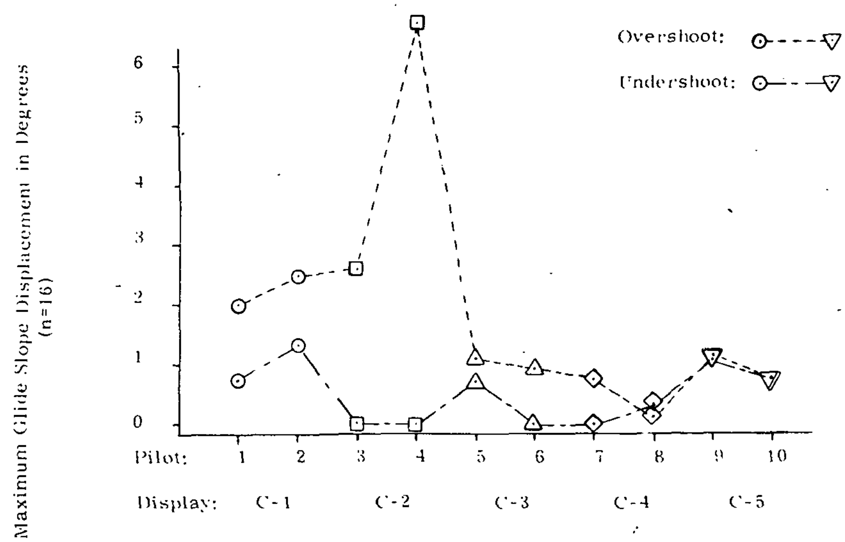
Summary data on transition flare performance by reference to designated EDC configurations are plotted in Figure 25 for each subject-pilot. The mean altitude errors plotted in Figure 25a provide an indication of the relative timeliness of the flare initiation; a flare initiated precisely at the scheduled transition altitude would be represented by a negligible altitude error. Mean altitude errors on the order of 60 feet, most of them below the scheduled altitude, were recorded for all five EDC configurations. The Kruskal-Wallis one-way analysis of variance (ref. 10) indicates that these mean error measures do not differ significantly across the ten pilots.

Under this same analysis, difference in the mean undershoot measures across pilots, plotted in Figure 25b, also failed to reach statistical significance at the .05 level. But notice that no undershoots were recorded on any of the 16 experimental runs for pilots 3 and 4, using the C-2 display, or for pilots 6 and 7 using the C-3 and C-4 configurations. The mean overshoot measures, however, did differ significantly across display configurations ($p < .01$).

The flare performance data plotted in Figure 25 may be interpreted as follows. A clear flare initiation cue was available in each of the five displays, namely, the Glide Slope Reference Bar either disappeared and reappeared at the 2.5° position (C-1) or it moved up from the first-segment reference position toward 2.5° in accordance with the programmed flare guidance computation. Since the same basic information was available in all displays, significant differences in the timeliness of transition initiation would not be expected. The only apparent contribution of the flare guidance feature to the initiation of the transition flare was in the variability of altitude errors. The average deviation around the mean altitude errors for the no-guidance C-1 display was 50 feet; variability was only half as great for the C-2 display (25 feet) and only slightly higher (33 feet) for the displays which included the acceleration-limited guidance technique (C-3, C-4 and C-5).



a. Altitude Error at Transition Flare Initiation



b. Maximum Displacement from the Shallow Glide Slope at Flare Completion

Figure 25. Quality of the Transition Flare Maneuver for Each Pilot and Display Configuration

The undershoot and overshoot measures plotted in Figure 25b provide a more meaningful indicator of flare quality when they are considered together. A smooth shallow glide slope acquisition would be represented by minimal flight path displacement above (overshoot) as well as below (undershoot) the 2.5° reference glide slope. The two data plots considered together show a clear trend toward lower displacement when configurations C-1 and C-2 are contrasted with the displays providing both the PIP and the acceleration-limited flare guidance feature. The principal difference between the two different flare guidance techniques (C-2 versus C-3, C-4 and C-5) is the clearly excessive overshoot conditions that occur when the C-2 technique is used.

Head-Up Versus Head-Down EDC

In its initial development during the first phase of this study, the EDC was conceptualized as a head-down, panel-mounted display which would incorporate the key features of the see-through concept (ref. 2). In the present study this display is represented by the C-5 configuration. As indicated earlier, the C-4 configuration contains the same display elements in a head-up, windshield projection, superimposed on the actual out-the-window visual scene. The most direct contrast between the head-up and head-down EDC is thus provided by the data on the C-4 versus C-5 displays.

Table 7 summarizes this contrast for the approach control measures presented in the preceding discussion. With the exception of lateral tracking errors on the first approach segment (RMSΔY-1), pilot performance by reference to the head-up C-4 display was consistently better, i.e., more successful approach outcomes, lower glide slope tracking errors and more accurate airspeed control. Due to the high variance across run conditions, however, the differences recorded in Table 7 for the 32 approach sequences, except for shallow glide slope tracking, are not statistically significant. The contrast on measures identified in Table 7 provide no information on differences in pilot workload, control activity or manual control strategies when the alternative display configurations are used.

Since the information content and display element dynamics were the same in these two EDC configurations, no clear differences in pilot performance were expected. The reported trend toward more precise approach control using the head-up EDC may be attributed, in part, to the 1:1 magnification factor (display image to real world counterpart) used in this configuration in contrast to .5:1 magnification (approximately) for the head-down presentation. The comparatively poor resolution of the C-5 display elements has been mentioned earlier as contributing to the degraded performance on this display, especially for airspeed control. Approach control on the shallow segment was also less precise using the head-down display due to the necessity for the transition, at 200 feet, to the windshield view for the landing maneuver.

It is also reasonable to assume that the availability of both the display elements and the actual runway image in the same display field enhanced pilot performance. The familiar runway image may have contributed to a clearer perception of the approach geometry and interpretation of the ground-reference display elements. It is likely that the significantly more accurate lateral flight path tracking using the C-4 display is attributable to the runway alignment information provided by the runway image. It is interesting to note, however, that the contrast presented in earlier sections, between the head-down display and the other three head-up configurations (C-1, C-2 and C-3), is more favorable to the head-down display. These data suggest that a head-down EDC would adequately support the pilot and that, potentially, manual approach control could be as accurate by reference to this display as it would be using a head-up presentation.

Table 7

Comparison Between Approach Control Performance Measures for Head-Up Versus Head-Down EDC Configurations

Criterion Measure	Head-Up EDC (C-4)	Head-Down EDC (C-5)	Statistical Significance
Approach Success:			
(Success count/32 runs)	.69	.38	NS
Touchdown Success:			
(Success count/32 runs)	.91	.63	NS
Glide Slope Tracking:			
Mean RMS $\Delta\gamma_g$ -1 (deg.)	.92	1.02	NS
Mean RMS $\Delta\gamma_g$ -2 (deg.)	.65	1.06	$p < .05$
Lateral Tracking:			
Mean RMS ΔY-1 (ft.)	82.9	79.8	NS
Mean RMS ΔY-2 (ft.)	26.5	33.2	NS
Airspeed Control:			
Airspeed Error at:			
Transition point (kts.)	2.3	5.7	NS
Threshold (kts.)	5.0	8.6	NS

Pilot Comments and Critique

Pilot comments and critiques of the EDC configurations which they used during the simulator exercise are recorded in Appendix B for each item in the debriefing guide. All ten participating pilots expressed positive acceptance of the see-through display concept and said that they felt fully confident that they would be able to complete an actual approach sequence by reference to the EDC. The experimental design did not provide for pilots to fly more than one version of the EDC, so their assessment of the relative effectiveness of the alternative displays could not be recorded.

It was anticipated that pilot comments might differ in some respects for the different EDC configurations. With few exceptions, however, pilots expressed similar reactions to the displays. The exceptions were as follows:

1. Both of the pilots who used the C-5 display commented on the poor resolution of the airspeed scales.
2. The pilots who used the C-1 and C-2 displays all recommended that airspeed and altitude information be added to these two head-up configurations.
3. Positive acceptance of the acceleration-limited flare guidance feature was expressed by all of the pilots who used it (C-3, C-4 and C-5 displays). The flare guidance feature in the C-2 display was considered unacceptable to one of the two pilots who flew this display.
4. The only pilot who felt he could not manage the approach about as well with the EDC as he could with conventional flight director instrumentation was one of the two using the C-1 display.

While most of the pilots expressed a high degree of acceptance of the EDC and confidence that they could use it effectively for the Orbiter approach profiles, they were generally unwilling to say that they would prefer this display to conventional flight path deviation and flight director instruments. Most of them were aware of the influence of their long familiarity and experience with conventional instrumentation and volunteered that additional experience with the EDC would undoubtedly lead to a better appreciation of its advantages for the power-off Orbiter approach control application.

CONCLUSIONS

In the Introduction to this report, ten specific display support issues were outlined to indicate the focus of the simulator evaluation of the experimental display. Following this outline, the major conclusions supported by the data obtained in this study are enumerated below. For ease of reference, page numbers are cited in parentheses to locate the supporting data and discussion of these conclusion statements in the text.

1. The data on approach outcomes indicate that pilots could successfully manage the power-off, two-segment Orbiter approach by reference to the EDC. Sixty-nine percent of the approaches flown by reference to the full EDC (C-4) satisfied all of the relative position and airspeed dispersion criteria for a successful approach and 91% of the landings satisfied touchdown criteria. Only 12 of the 160 approach sequences flown for the record, representing all EDC configurations and approach conditions, resulted in completely unacceptable landings, (i.e., touchdowns short of the runway threshold). All of the unacceptable landings were made by one pilot using the basic C-1 display without the ground-reference features. (32)

2. Average glide slope tracking accuracies on the order of .6 degrees angular displacement from the reference glide path were recorded for both segments of the approach when the full EDC was used. This level of pilot performance, obtained without flight path guidance or flight director information, compares favorably with tracking accuracies attainable using ILS deviation instruments (a full, 2-dot displacement from the conventional ILS glide slope represents an angular displacement of .7 degrees; this represents a vertical displacement of 55 feet at a range of 3500 feet from the runway. (35)

3. Glide slope tracking was consistently more accurate when the basic Glide Slope Reference Bar and Aim Point were augmented with the Projected Impact Point (PIP), i.e., when the C-3, C-4 and C-5 displays were used. Performance on the concurrent lateral control and airspeed management tasks was also consistently better when the PIP was available. The data therefore suggest that the PIP does contribute substantially to the precision of manual approach control. (37)

4. Primary alignment during the first approach was maintained at an average offset of about 45 feet, using the Approach Path and Relative Heading markers; average lateral offsets on the shallow glide slope were held to about 25 feet. Lateral tracking was only slightly less accurate using only the runway image, but variability in pilot performance was clearly greater when the runway alignment symbology was not available. (40)

5. The flare guidance did produce smoother transitions from the steep initial approach segment to the shallow glide slope. Without flare guidance (configuration C-1), pilots more often dished-out and/or overshot the 2.5^{o} shallow glide slope and took more time to stabilize on the second approach segment following transition. The acceleration-limited flare technique produced the smoothest transitions, with significantly fewer overshoots occurring. (46)

6. The best airspeed management performance was recorded for the C-4 display. Pilots held airspeed errors at the transition point to less than five knots using this display. Average airspeed errors at the runway threshold were somewhat higher (but less than eight knots) and more variable. (42)

7. Approach outcomes were essentially the same for all four approach profiles and under all of the wind effect conditions applied in the simulated Orbiter approach sequences. Glide slope tracking was less accurate on the steep, close-in approach and when headwinds were applied, but only when the unaugmented, C-1 and C-2 displays were used. As anticipated, lateral tracking was significantly less accurate under the crosswind condition. Airspeed control was also less precise when crosswinds were applied and airspeed errors were higher on the steep approach profile, but again only when the C-1 and C-2 displays were used. In general, when the full EDC was used (C-4), pilot performance did not differ significantly under the alternative approach profile and wind conditions. (38, 40, 43)

8. Airspeed errors were significantly higher for the display configurations which did not incorporate the airspeed scale and all of the pilots who flew these displays recommended that airspeed information be included to improve the presentation. However, the inclusion of altitude information in the EDC was not considered essential. (43)

9. There was a clear trend toward more precise approach control when the head-up EDC was used, i.e., more successful approach outcomes, lower flight path tracking errors and more accurate airspeed control. With the exception of runway alignment, the differences were not statistically significant. Improvements in the resolution of the head-down EDC coupled with additional pilot experience would enable pilots to manage the approach just as well with either the head-up or head-down version of the display. (49)

10. As indicated in the first conclusion statement, almost all of the landings were successful, in terms of touchdown position and airspeed dispersions. Touchdown success was significantly greater when the full, head-up EDC configuration (C-4) was used. (33)

The foregoing outline of the results of the EDC evaluation in this simulation study confirms the indications derived in the first phase of the study that this display concept would provide improved display support for Orbiter approach management. The data obtained in this second evaluation extends the scope of this evaluation and indicates that the EDC would, indeed, support Orbiter pilots in the implementation of more flexible manual approach control strategies than conventional instrumentation would permit. Further refinement of this display concept, applying human engineering technology to improve the distinguishability and dynamics of the display elements, and additional in-flight testing is strongly recommended. It would then be of interest to obtain additional measures of the potential EDC contribution to Orbiter approach control, including an assessment of pilot workload and the relative ease of implementing alternative manual control strategies.

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APPENDIX A

PILOT PROCEDURES FOR PERFORMING THE EXPERIMENTAL TASK

Flight control procedures followed by the pilot-subjects in the execution of the simulated Orbiter approach profiles are presented in this appendix. The document reproduced here is a composite of the separate procedure outlines used in the study to introduce the pilots to the flight control techniques peculiar to each experimental display configuration.

Pilot Procedure

Your task in this experiment will be to fly a simulated, power-off Orbiter approach and landing sequence by reference to the experimental flight situation display described in the project briefing session. You will fly four different, two-segment approach profiles under varying wind conditions and your principal flight control objectives on each approach are to:

1. establish and maintain an assigned glide path angle to the designated offset aiming point,
2. keep the vehicle's flight path aligned with the extended runway centerline,
3. use speed brakes as required to control airspeed for arrival at the pre-selected transition altitude at the prescribed indicated airspeed,
4. on arrival at the pre-selected altitude, initiate a smooth transition flare to the shallow 2.5° glide path and maintain this flight path angle to the runway aiming point,
5. use speed brakes as necessary to arrive at the runway threshold (60 feet above the runway if you are right on the 2.5° glide slope) indicating 190 knots,
6. execute the landing maneuver by reference to the simulated runway display, attempting to touchdown on the centerline, within the first 3000 feet and at about 185 knots.

Initial conditions, glide path angles and target airspeeds for the transition maneuver, and target airspeeds for the final segment and landing maneuver are outlined on the flight data cards for each profile. General procedures for initiating and terminating a simulation sequence are as follows:

1. Note that the simulation set-up light is GREEN.
2. Adjust trim as required.
3. When you are ready to go, depress operate (OP) button on center console (simulation will now go dynamic–if any difficulties arise at any time, return simulator to initial condition by depressing I.C. button).
4. After touchdown (landing gear lights illuminate GREEN, gear rumble noise begins), lower nose wheel and return to I.C. after short rollout.

Flight path and airspeed control techniques to be used with the assigned experimental display are outlined below.

Vertical Flight Path Control (Configurations C-1 and C-2)

1. Stabilize pitch attitude at the initial value (see flight data card).
2. Monitor aim point (X) position relative to fixed glide slope reference bar (GSRB).
3. If X moves *above* GSRB, you are below the reference glide slope to X. (Remember, the GSRB is essentially a sighting bar—actual flight path angle is not displayed.) If X moves *below* GSRB, you are above the reference glide slope (see illustration).
4. Vertical maneuvering to recapture X is accomplished by reference to pitch attitude. When you are *below*, *pitch up* (to about -3° on the 10° profile, -6° on the 15° profile and 0° on the 7° profile and shallow glide slope) and monitor X movement relative to the GSRB. As X moves back into the GSRB gap, pitch down again to maintain the X-GSRB alignment. In headwind conditions, the adjusted pitch attitude will be slightly flatter than nominal (no winds) and in the tailwind condition, it will be slightly steeper.
5. If your flight path tends to go *above* the reference glide slope (X moves below GSRB), you must *pitch down* (to about -15° on the 10° profile, -20° on the 15° profile and -12° on the 7° run) and again watch the X movement back toward the GSRB. Pull-up again as the two display elements come together and adjust pitch to maintain this alignment.

6a. (Configuration C-1 only)

When you have descended to the pre-selected flare initiation altitude, the GSRB will disappear momentarily and then re-appear at -2.5° for shallow glide slope reference. Monitor altitude and initiate the flare without going below the pre-selected altitude. You must execute the transition flare by reference to pitch attitude. Pull up smoothly to about $+2^{\circ}$ and then note the position of the runway aim point (X is now 1500 feet down the runway) relative to the repositioned GSRB. Adjust pitch attitude as required to maintain X-GSRB alignment, using the same orientation as on the initial approach segment but smaller pitch attitude displacements.

6b. (Configuration C-2 only)

When you have descended to a pre-selected altitude (1500 feet for the Nominal and Steep profiles, 1000 feet for the other two), the GSRB will move up the display toward the -2.5° shallow glide slope and provide guidance for the flare maneuver. Monitor altitude to anticipate this event and initiate a smooth pull up when the GSRB moves. Note the alignment of the GSRB with the runway aim point (X is now positioned 1500 feet down the runway) and adjust pitch attitude as necessary to align the GSRB with X and maintain this alignment. Remember, the GSRB is now providing flare guidance and is not fixed at -2.5° on the pitch scale. As you adjust pitch attitude to maintain GSRB-X alignment, your glide path should gradually shallow to produce a -2.5° approach to the runway aim point.

7. Upon arrival at the runway threshold, the GSRB and X symbols will disappear and you must complete the landing maneuver by reference to simulated runway. Pitch attitude at touchdown will be about $+4^{\circ}$ and only a slight final flare adjustment will typically be required. Try to touchdown at 185 knots, close to the centerline and within the first 3000 feet.

Vertical Flight Path Control (Configurations C-3, C-4 and C-5)

1. Observe initial, vertical displacement, if any, of PIP from the aim point (X). Maneuver vehicle to fly the PIP to the X and maintain PIP-X alignment.
2. Monitor X alignment with the fixed glide slope reference bar (GSRB) while maintaining PIP-X alignment.
3. If X moves *above* GSRB, you are going *below* the reference glide path to X. If X moves *below* GSRB, you are going high.
4. Vertical maneuvering to realign X with the GSRB is accomplished by deliberately offsetting the PIP in the appropriate direction and monitoring X movement relative to the GSRB. When you are below, *pitch up to position the PIP above* the X; when you are too high, *pitch down*. Maintain the PIP offset until the X moves back to the GSRB and then recapture the X and again maintain PIP-X alignment. Appropriate PIP displacements required to achieve smooth and timely vertical flight path adjustments will be demonstrated in the training session.
5. When you have descended to the pre-selected flare initiation altitude, the GSRB will begin to move up from its fixed position toward the -2.5° shallow glide slope and provide guidance for the flare maneuver. Monitor altitude to anticipate arrival at the pre-selected flare height and initiate the flare without going below this altitude. Pull up smoothly and deliberately, attempting to maintain PIP alignment with the GSRB without pulling up too sharply to lead the GSRB or too leisurely and lagging behind.
6. After the GSRB stabilizes at -2.5°, note that the aim point X is now positioned at 1500 feet down the runway and that it is aligned with the GSRB. If the X is not aligned, offset the PIP again, following the same relative motions as those cited in 4 above, but using smaller adjustments in pitch attitude.

7a. (Configurations C-3 and C-4 only)

Upon arrival at the runway threshold, the GSRB and X symbols will disappear and you must complete the landing maneuver by reference to simulated runway. Pitch attitude at touchdown will be about $+4^{\circ}$ and only a slight flare adjustment will typically be required. Try to touchdown at 185 knots, close to the centerline and within the first 3000 feet.

7b. (Configuration C-5 only)

Monitor altitude as the vehicle approaches the runway and note that at 300 feet the external visual scene begins to fade in on the windshield display. As the vehicle goes below 200 feet, transition fully to the head-up display and complete the approach and landing by external visual reference. After going "head-up" you may refer to panel instruments for airspeed control, but do not attempt to refer back to the experimental display for flight path control.

Lateral Flight Path Control (Configurations C-1 and C-2)

1. Maintain alignment with the runway by reference to the simulated runway scene. The runway and approach lights will move in correct perspective relationship and you can judge centerline tracking as you would on a night VFR approach.
2. On a cross wind approach, the runway image will be offset from the center of the display as you establish an appropriate drift angle. Perspective cues and relative motion will still serve to provide lateral flight path alignment information. Note that the gap in the GSRB is always fixed in the center of the display and under cross wind conditions it will be offset laterally from the X.
3. Remember, there is no localizer deviation or other direct display of cross-track position—you must judge your approach strictly by reference to the runway image.
4. Try to establish and maintain close lateral tracking of the extended runway centerline.

Lateral Flight Path Control (Configurations C-3, C-4 and C-5)

1. Observe initial lateral displacement of the PIP from X, if any.
2. Maneuver the vehicle to fly the PIP to the X and maintain PIP-X alignment.
3. On a cross wind approach, the runway image* will be offset from the center of the display as you establish an appropriate drift angle. However, flight path alignment with the runway can still be accomplished by tracking the X with the PIP.
4. Use the Approach Path Marker and simulated runway to crosscheck lateral flight path alignment. These elements will move in correct perspective relationship to indicate lateral offset and tracking tendencies. Remember, the PIP indicates actual direction of flight; faster corrections of perceived offsets can be accomplished by deliberately positioning the PIP beyond the X and monitoring the runway and approach path. When realignment is established, recapture the X and maintain PIP-X alignment.
5. Try to establish and maintain close lateral tracking of the extended runway centerline.

Airspeed Control

1. Airspeed build-up during the initial approach segment will vary with glide path angle and wind conditions. Your main concern will be to keep the speed from exceeding prescribed target speeds for the transition and for arrival at the runway threshold (see flight data cards).

*Delete reference to runway image for Configuration C-5.

2. On 15° profiles, airspeed will always exceed target airspeeds if speed brakes are not deployed. On the 10° profile, speed brakes will be needed only when tailwinds are applied and speed brakes will not be needed on the 7° approach (prior to transition) for any wind condition. Appropriate speed brake deployment under various conditions will be demonstrated during the training session.

3. In general, speed brakes should be retracted for the transition flare and deployed again, if necessary, to control excessive airspeed approaching the runway threshold on the shallow glide slope. However, on the close-in, steep approach under tailwind conditions it may be desirable to keep the speed brakes out during the transition maneuver and close them up following shallow glide slope acquisition if airspeed bleed-off is too fast.

APPENDIX B

PILOT DEBRIEFING GUIDE AND SUMMARY OF RESPONSES

This appendix presents a reproduction of the debriefing guide used to structure the discussion of pilot comments and their critique of the experimental display. Pilot responses to the open-ended questions which comprise this guide are summarized in the spaces following each item.

Pilot Debriefing Guide

Your comments and reactions to the simulation exercise you've just completed will be helpful to us in the interpretation of study results and in providing an additional assessment of the experimental display. We are particularly interested in any critical comments you'd like to make in regard to the display concept or its potential application to Space Shuttle final approach management.

The questions which follow will cover the principal areas of interest. Please feel free to elaborate on anything that comes up in our discussion—even if it doesn't seem directly relevant to the question. It will also be helpful if you will give us any negative reactions or impressions regarding the display or the procedures followed in the experiment.

1. Did you consider the study orientation and simulator familiarization you received to be adequate preparation for the task you were asked to perform?

   All ten pilots stated that the orientation and training was fully adequate.

2. Did you feel fully confident that you could fly the prescribed approach profiles by reference to the experimental display? If not, what information or display feature seemed to be inadequate or missing?

   All ten said that they would have full confidence in the EDC for flying in actual approach.

   Pilot #8 (C-4 display) would have felt more comfortable with conventional cross-pointers included for GS and LOCALIZER deviation.

   Pilot #5 (C-3 display) expressed reservations regarding the sensitivity of the PIP element, especially on the shallow glide slope.

3. Would you prefer to have conventional electronic flight path guidance (e.g., ILS, GS and LOC deviation) and flight director displays for the approach control task?

Eight of the ten pilots said that they would, primarily because of their experience and familiarity with the conventional deviation (director instrument). One of the two pilots expressing a preference for the EDC flew the C-2 configuration and the other flew the C-4. The C-4 pilot felt that the EDC was "... much more realistic in that it is possible to perceive depth and distances."

4. With additional practice, do you feel that you could do just about as well with the situation information provided in the experimental display as you could with a command type display?

Eight pilots said yes.

One of the C-1 pilots felt he could do better with a flight director and one of the C-3 pilots thought he could do about as well with the EDC, but that the flight director was more precise.

5. For the power-off Orbiter approach profiles you have just flown, do you see any advantages to having a situation display rather than a flight director referenced to one particular two-segment glide slope?

Five pilots could envision definite advantages in using the EDC including:

a. a clearer context and frame of reference (C-5 pilot)

b. a source of cross-checking information for approach control task (C-1 pilot)

c. its utility for transition from IFR to VFR conditions (C-2 pilot)

d. the flexibility it permits in the selection of approach angle (C-3 pilot)

e. its highly realistic representation of the approach situation (C-4 pilot).

6. How timely do you think your flare initiation actions were for the transition to the shallow glide slope?

a.	Right on	1
b.	Somewhat erratic	2
c.	Consistently late	7
d.	Consistently early	
e.	Other (specify)	

Most of the pilots recognized that they were usually late (i.e., below the scheduled transition altitude) in initiating the flare. The one who thought he was almost always "right on" was a C-3 pilot. The record shows that his average initiation height was about 80 feet low.

The pilots reported that they tended to ignore the altitude information and used the GSRB for the flare cue; they felt that altitude monitoring could be the second pilot's responsibility.

7. Did you feel that you had adequate information for executing the transition flare? Acquiring the shallow glide slope?

Nine pilots said yes for the flare maneuver, but one expressed doubts about glide slope acquisition (a C-1 pilot). One of the C-3 pilots felt that the behavior of the ground reference elements (i.e., PIP and Aim Point) was confusing at transition and preferred to use the aircraft symbol and runway image for the transition.

8. How precisely do you think you were able to control airspeed for arrival at the transition altitude?

a.	Within 5 knots	6
b.	Within 10 knots	4
c.	I'm not sure, but it was close enough	
d.	Not sure, but it was unacceptable	
e.	Off more than 10 knots on most runs	

The four pilots who checked b. flew the C-1, C-2, C-3, and C-4 displays and those who thought they were more precise represented all five displays. Note in Figure 23a that the pilots were generally correct in judging their performance, indicating that available airspeed information was adequate for all displays.

9. How precisely could you control airspeed for arrival at the runway threshold?

a.	Within 3 knots	
b.	Within 5 knots	4
c.	Within 10 knots	5
d.	Not sure	1
e.	Off more than 10 knots on most runs	

The unsure pilot used the C-5 display and had to go head-up at 200 feet for the landing. Figure 23b suggests that the four pilots who checked b. above overestimated the accuracy of their airspeed control efforts (two were C-4 pilots, one flew the C-3 display and one flew the C-2).

10. What features of the display did you find confusing, distracting or difficult to get used to?

The following comments were elicited by this item:

a. *Poor resolution on altitude scale (reported by both C-5 pilots).*

b. *The principle of flying the PIP and GSRB to the Aim Point (reported by a C-3, C-4, and C-5 pilot).*

c. *The HORIZON reference is unusable for pitch attitude reference. It's too high in the display field, especially for the 15° approach (reported by three pilots).*

d. *A C-1 pilot felt that the display provided inadequate information for judging runway alignment, i.e., no guidance regarding extent of correction required.*

e. *Inadequate roll attitude information (one C-1 pilot and both C-2 pilots).*

11. What changes or additions to the display do you feel would improve your ability to manage an Orbiter approach?

Suggested changes were:

a. *Add airspeed and altitude to head-up display (both C-1 pilots and both C-2 pilots).*

b. *Delete flare guidance feature (C-2 pilot).*

c. *Add flight director (one C-3 pilot).*

d. *Add localizer deviation (C-1 pilot).*

e. *Replace airspeed scale with digital readout (C-5 pilot).*

f. *Add light or aural alert for anticipating transition (both C-5 pilots).*

g. *Delete flare guidance feature—didn't use it (C-2 pilot).*

h. *Make PIP less sensitive close-in to runway (C-3 pilot).*

i. *Use color-coding to distinguish display symbols.*

12. Any additional comments or impressions?

All pilots expressed positive acceptance of the display concept and felt that with aditional familiarity and experience with the EDC it would provide excellent support for the manual approach control task.

All ten pilots found the experiment to be highly interesting and were pleased to have an opportunity to contribute to the EDC evaluation.

APPENDIX C

COMPLETE RECORD OF PILOT PERFORMANCE DATA

In this appendix, computer printouts of flight situation data recorded on each run—by pilot, EDC configuration, approach and wind condition—are reproduced. These data printouts provided the basic record of pilot performance for the derivation of criterion measures for the EDC evaluation. The flight situation parameter presented in each printout is identified at the top of the page; additional definition of these parameters is presented in the body of the report.

The legend for wind conditions is as follows:

OW	=	No Wind
LHW	=	Light Headwind
HW	=	Strong Headwind
TW	=	Tail Wind
XW	=	Crosswind

BASIC DATA TABLE
APPROACH SUCCESS INDEX

PROFILE	WIND	DISPLAY C-1 PILOT 1	DISPLAY C-1 PILOT 2	DISPLAY C-2 PILOT 3	DISPLAY C-2 PILOT 4	DISPLAY C-3 PILOT 5	DISPLAY C-3 PILOT 6	DISPLAY C-4 PILOT 7	DISPLAY C-4 PILOT 8	DISPLAY C-5 PILOT 9	DISPLAY C-5 PILOT 10
1	OW	11111*	0	1	1	1	0	1	0	0	0
1	LHW	11111	0	0	0	0	1	1	0	1	0
1	TW	11111	1	1	1	0	0	1	0	1	1
1	XW	0	0	0	1	0	1	1	1	0	1
2	OW	0	1	0	0	0	0	11111	1	0	0
2	HW	11111	11111	0	1	0	1	1	1	0	0
2	TW	0	0	1	0	1	1	1	0	1	0
2	XW	11111	0	0	0	0	1	1	1	1	0
3	OW	1	1	0	0	0	1	1	1	0	1
3	LHW	0	1	0	1	0	0	1	1	1	1
3	TW	11111	1	0	0	1	0	1	1	0	0
3	XW	0	1	0	0	0	0	1	1	0	0
4	OW	11111	0	1	0	0	1	0	1	0	0
4	HW	11111	0	0	0	0	1	0	0	1	1
4	TW	11111	1	1	1	0	1	1	1	1	0
4	XW	11111	1	0	1	0	1	0	0	0	0
	SUM:	1.00	8.00	5.00	7.00	3.00	10.00	12.00	10.00	7.00	5.00
	MEAN:	.17	.53	.31	.44	.19	.62	.80	.62	.44	.31
	SD:	.41	.52	.48	.51	.40	.50	.41	.50	.51	.48

* A 11111 printout indicates missing data due to touchdown short of the runway threshold.

BASIC DATA TABLE
RMS GAMMA - SEGMENT 1

PROFILE	WIND	DISPLAY C-1 PILOT 1	DISPLAY C-1 PILOT 2	DISPLAY C-2 PILOT 3	DISPLAY C-2 PILOT 4	DISPLAY C-3 PILOT 5	DISPLAY C-3 PILOT 6	DISPLAY C-4 PILOT 7	DISPLAY C-4 PILOT 8	DISPLAY C-5 PILOT 9	DISPLAY C-5 PILOT 10
1	OW	1.48	1.53	1.10	1.11	1.52	.60	.59	.97	1.84	.72
1	LHW	1.71	1.07	1.03	2.19	.93	.58	.73	1.08	1.00	.92
1	TW	.86	1.31	1.27	1.57	.81	.56	.78	1.12	.88	1.21
1	XW	.65	1.05	.91	1.82	.64	.68	.74	1.01	.63	.86
2	OW	1.01	1.27	1.27	2.03	.90	.62	.68	1.14	.94	.86
2	HW	1.43	1.34	1.77	1.99	.89	.90	.95	1.84	1.25	1.29
2	TW	1.73	1.11	.92	1.17	.99	.55	.71	.87	.97	.91
2	XW	.65	1.01	1.44	1.59	.62	.63	.62	.70	1.18	.86
3	OW	.88	1.12	.94	1.33	.83	.75	.90	.98	1.25	.69
3	LHW	.74	1.27	.95	1.56	.75	.69	.90	.94	1.01	.99
3	TW	.97	1.29	1.05	1.36	.81	.68	.93	.89	1.11	.84
3	XW	.65	.98	.99	1.30	.76	.72	.71	1.11	1.02	.71
4	OW	.68	1.61	1.24	1.66	.60	.66	.67	.82	1.00	1.26
4	HW	2.15	1.93	2.28	2.91	.90	.97	1.02	1.20	.94	1.36
4	TW	.95	1.51	1.33	1.67	.86	.56	.68	.97	1.20	.95
4	XW	.62	1.28	1.56	2.18	.70	.50	.56	1.84	.68	.82
	SUM:	17.16	20.57	20.04	27.43	13.52	10.74	12.18	17.48	16.89	15.45
	MEAN:	1.07	1.29	1.25	1.71	.84	.67	.76	1.09	1.06	.97
	SD:	.48	.26	.37	.47	.21	.12	.14	.32	.27	.20

BASIC DATA TABLE
RMS GAMMA - SEGMENT 2

PROFILE	WIND	DISPLAY C-1 PILOT 1	DISPLAY C-1 PILOT 2	DISPLAY C-2 PILOT 3	DISPLAY C-2 PILOT 4	DISPLAY C-3 PILOT 5	DISPLAY C-3 PILOT 6	DISPLAY C-4 PILOT 7	DISPLAY C-4 PILOT 8	DISPLAY C-5 PILOT 9	DISPLAY C-5 PILOT 10
1	0W	1.17	.89	.61	.67	.68	.50	.50	.50	1.47	.57
1	LHW	1.45	1.03	.50	.50	.51	.50	.50	.50	.52	.55
1	TW	1.07	.76	.56	.79	.60	.50	.50	.50	.89	.77
1	XW	1.73	1.21	.54	.63	.67	.60	.50	.50	.93	.70
2	0W	.96	1.56	.50	.91	1.21	.50	1.15	.50	.90	.68
2	HW	2.11	1.34	.78	.74	.96	.50	.54	.97	.68	.85
2	TW	1.24	1.00	.66	.89	1.31	.50	1.32	.50	1.30	1.36
2	XW	1.65	1.61	1.49	.74	1.18	.50	.65	.63	1.01	.90
3	0W	1.94	1.82	.73	1.22	.73	1.23	.50	1.02	1.01	1.06
3	LHW	1.29	1.06	.76	.89	.52	.50	.50	.50	1.02	.63
3	TW	1.37	1.26	.66	.73	.75	.50	1.22	.68	1.97	1.32
3	XW	1.57	.50	.89	.82	1.15	.56	.50	.50	1.44	.50
4	0W	1.13	1.72	1.22	2.34	1.77	.50	.66	.50	1.57	1.29
4	HW	2.36	2.86	1.16	1.60	.50	.50	.50	.50	1.39	.56
4	TW	1.19	1.37	.85	1.72	1.36	.63	.83	.50	1.78	1.54
4	XW	1.87	1.47	1.83	3.24	.50	.81	.96	.50	1.04	1.54
	SUM:	24.00	21.19	13.75	18.42	14.41	9.27	11.33	9.31	18.91	14.83
	MEAN:	1.50	1.32	.86	1.15	.90	.58	.71	.58	1.18	.93
	SD:	.41	.55	.38	.74	.39	.19	.29	.17	.40	.37

BASIC DATA TABLE
RMS LATERAL OFFSET - SEGMENT 1

		DISPLAY C-1		DISPLAY C-2		DISPLAY C-3		DISPLAY C-4		DISPLAY C-5	
PROFILE	WIND	PILOT 1	PILOT 2	PILOT 3	PILOT 4	PILOT 5	PILOT 6	PILOT 7	PILOT 8	PILOT 9	PILOT 10
1	OW	147.29	18.39	38.31	31.55	36.48	31.00	49.86	71.97	60.47	112.27
1	LHW	83.18	24.46	52.10	98.26	43.11	33.67	81.99	47.69	15.42	51.73
1	TW	37.98	40.94	14.95	96.10	138.86	66.08	42.92	23.32	123.96	38.94
1	XW	198.83	339.03	215.93	380.39	60.12	184.21	58.93	112.16	66.58	71.38
2	OW	72.89	26.95	12.76	43.15	44.53	190.49	43.96	118.39	39.01	83.76
2	HW	70.64	33.61	79.73	28.45	26.64	71.57	72.91	95.35	41.34	33.31
2	TW	44.89	33.66	77.54	61.19	41.86	134.17	14.27	111.66	86.96	110.11
2	XW	82.11	221.38	442.83	332.07	128.38	205.51	96.95	204.06	119.64	105.42
3	OW	63.38	45.37	87.67	122.55	53.39	59.81	22.44	85.78	36.36	44.73
3	LHW	40.33	84.54	67.50	127.75	65.42	193.41	84.89	119.14	36.00	124.23
3	TW	46.86	59.30	59.58	109.91	72.70	33.36	17.53	36.96	13.84	57.09
3	XW	185.13	163.85	335.97	175.05	44.08	82.70	86.59	96.91	57.13	92.85
4	OW	14.98	31.31	26.39	29.24	98.81	127.92	47.44	102.63	30.69	95.36
4	HW	37.18	126.69	93.86	64.40	44.97	45.13	74.17	104.63	9.86	55.16
4	TW	70.09	61.59	13.75	69.14	60.73	79.25	104.01	124.13	72.49	91.70
4	XW	139.62	103.52	315.57	238.66	110.75	162.08	104.97	196.49	67.14	347.33
	SUM:	1338.38	1923.16	1934.43	1990.86	1070.84	1700.38	1003.82	1651.27	876.90	1515.39
	MEAN:	83.68	88.38	120.90	124.43	66.93	106.27	62.74	103.20	54.81	94.71
	SD:	55.39	95.53	132.60	107.55	34.10	63.89	30.00	48.43	34.27	73.13

BASIC DATA TABLE
RMS LATERAL OFFSET - SEGMENT 2

		DISPLAY C-1		DISPLAY C-2		DISPLAY C-3		DISPLAY C-4		DISPLAY C-5	
PROFILE	WIND	PILOT 1	PILOT 2	PILOT 3	PILOT 4	PILOT 5	PILOT 6	PILOT 7	PILOT 8	PILOT 9	PILOT 10
1	0W	45.47	45.27	35.35	20.55	9.94	20.94	13.47	29.66	12.02	34.72
1	LHW	31.17	21.44	32.41	46.53	36.93	68.39	35.62	32.40	62.85	22.87
1	TW	43.05	44.38	19.10	62.75	57.95	24.61	19.05	22.77	70.55	29.22
1	XW	87.68	119.34	41.35	55.10	22.01	25.56	31.05	57.13	25.45	39.89
2	0W	55.90	9.88	37.78	30.70	29.85	25.18	52.81	34.12	21.64	21.47
2	HW	31.71	45.71	33.04	24.04	26.87	50.40	17.45	27.46	23.46	22.21
2	TW	31.54	34.11	50.29	20.24	10.60	16.18	10.79	24.29	60.54	22.27
2	XW	133.72	52.02	190.24	32.65	21.28	22.09	21.95	95.31	17.58	85.12
3	0W	17.10	20.18	7.89	11.60	27.87	23.90	32.12	19.44	23.00	23.63
3	LHW	50.10	9.66	15.40	7.77	30.01	23.97	29.77	18.08	28.70	36.77
3	TW	11.59	8.76	3.69	21.87	14.61	24.42	27.43	24.89	20.77	5.73
3	XW	54.35	4.24	22.39	15.36	39.09	11.58	16.82	18.78	56.27	5.30
4	0W	22.30	30.53	39.10	14.29	40.56	6.42	10.00	7.78	8.65	43.97
4	HW	59.26	35.12	45.77	18.21	12.26	2.32	19.84	14.86	12.81	33.30
4	TW	31.75	19.45	10.63	34.12	12.97	8.48	18.76	11.57	18.81	37.89
4	XW	105.18	23.52	37.13	34.07	24.09	8.08	18.88	32.34	35.57	98.80
	SUM:	901.86	523.61	630.56	449.85	416.89	362.50	375.79	470.85	498.66	563.14
	MEAN:	56.37	32.73	39.41	28.12	26.06	22.66	23.49	29.43	31.17	35.20
	SD:	47.44	27.49	44.87	15.66	13.12	16.62	10.95	20.95	19.97	24.84

BASIC DATA TABLE
IAS ERROR AT TRANSITION

		DISPLAY C-1		DISPLAY C-2		DISPLAY C-3		DISPLAY C-4		DISPLAY C-5	
PROFILE	WIND	PILOT 1	PILOT 2	PILOT 3	PILOT 4	PILOT 5	PILOT 6	PILOT 7	PILOT 8	PILOT 9	PILOT 10
1	0W	2	-5	-6	1	-2	-4	-5	-2	5	-7
1	LHW	0	-1	-4	-6	1	-1	-4	-1	1	-1
1	TW	-9*	4	-23	-19	-2	4	-2	-2	0	1
1	XW	0	-17	-17	-15	6	6	0	-1	-4	-5
2	0W	-16	1	-2	7	32	-5	0	1	-9	1
2	HW	-8	-15	0	4	-14	-3	0	-3	7	-4
2	TW	-6	-12	2	-9	18	-9	4	0	-2	-5
2	XW	-44	-8	-6	-1	6	-13	-2	-9	-18	5
3	0W	3	-6	-11	-1	12	-2	1	0	5	5
3	LHW	4	-7	-7	-8	7	5	3	0	-9	8
3	TW	3	-5	-11	-7	17	-2	-3	-2	5	5
3	XW	-10	-13	-12	-12	3	-7	2	-2	1	4
4	0W	-2	-8	-10	11	2	2	2	8	11	16
4	HW	-14	4	5	6	-3	-1	-1	-5	7	-4
4	TW	0	2	-5	6	1	-3	-6	0	-13	1
4	XW	-9	-2	-19	10	-6	-12	1	2	8	5
	SUM:	130.00	110.00	140.00	123.00	132.00	79.00	36.00	38.00	105.00	77.00
	MEAN:	8.12	6.87	8.75	7.69	8.25	4.94	2.25	2.37	6.56	4.81
	SD:	10.76	5.00	6.51	5.00	8.47	3.68	1.81	2.73	4.80	3.66

*Negative values indicate average speeds below the target airspeed.

BASIC DATA TABLE
IAS ERROR AT THRESHOLD

		DISPLAY C-1		DISPLAY C-2		DISPLAY C-3		DISPLAY C-4		DISPLAY C-5	
PROFILE	WIND	PILOT 1	PILOT 2	PILOT 3	PILOT 4	PILOT 5	PILOT 6	PILOT 7	PILOT 8	PILOT 9	PILOT 10
1	HW	11111*	-18	-4	5	-10	7	6	1	-2	12
1	LHW	11111	-13	-7	-19	-13	-3	1	-1	2	-13
1	TW	11111	0	-10	-6	2	12	10	3	-4	7
1	XW	-20	-19	-12	-7	6	-9	0	5	-4	-3
2	HW	-22	-8	-9	-13	3	-12	11111	-1	-14	-3
2	HW	11111	11111	-13	-10	-30	-7	9	-2	-7	-29
2	TW	-24	-15	-9	-11	-3	-4	-4	-12	4	-17
2	XW	11111	-23	-25	-15	1	-7	-5	-6	-7	28
3	HW	0	-5	-3	-4	16	6	3	3	-2	9
3	LHW	9	-4	-3	-2	12	11	7	1	-9	3
3	TW	11111	-1	-3	-1	8	0	1	6	16	10
3	XW	-13	-7	-6	-6	7	-4	6	0	-2	9
4	HW	11111	4	-5	7	8	3	13	1	4	28
4	HW	11111	11	-3	-5	19	-3	19	-3	10	-4
4	TW	11111	-3	-4	-4	1	-4	2	4	9	0
4	XW	11111	2	-12	5	26	-4	16	-2	1	3
	SUM:	88.00	133.00	128.00	120.00	165.00	96.00	102.00	51.00	97.00	178.00
	MEAN:	14.67	8.87	8.00	7.50	10.31	6.00	6.80	3.19	6.06	11.12
	SD:	9.16	7.24	5.76	4.89	8.72	3.54	5.67	2.99	4.51	9.64

*Missing data — touchdown short of the runway.

BASIC DATA TABLE
IAS AT THRESHOLD

PROFILE	WIND	DISPLAY C-1 PILOT 1	DISPLAY C-1 PILOT 2	DISPLAY C-2 PILOT 3	DISPLAY C-2 PILOT 4	DISPLAY C-3 PILOT 5	DISPLAY C-3 PILOT 6	DISPLAY C-4 PILOT 7	DISPLAY C-4 PILOT 8	DISPLAY C-5 PILOT 9	DISPLAY C-5 PILOT 10
1	0W	11111	172	186	195	180	197	196	191	188	202
1	LHW	11111	177	183	171	177	187	191	189	192	177
1	TW	11111	190	180	184	192	202	200	193	186	197
1	XW	170	171	178	183	196	181	190	195	186	187
2	0W	168	182	181	177	193	178	11111	189	176	187
2	HW	11111	11111	177	180	160	193	199	188	183	161
2	TW	166	175	181	179	187	186	186	178	194	173
2	XW	11111	167	165	175	191	183	185	184	183	218
3	0W	190	185	187	186	206	196	193	193	188	199
3	LHW	199	186	187	188	202	201	197	191	181	193
3	TW	11111	189	187	189	198	190	191	196	206	200
3	XW	177	183	184	184	197	186	196	190	188	199
4	0W	11111	194	185	197	182	193	203	191	194	218
4	HW	11111	201	187	185	209	187	209	187	200	186
4	TW	11111	187	186	186	191	186	192	194	199	190
4	XW	11111	192	178	195	216	186	206	188	191	193
	SUM:	1070.00	2751.00	2912.00	2954.00	3077.00	3022.00	2934.00	3037.00	3035.00	3080.00
	MEAN:	178.33	183.40	182.00	184.62	192.31	188.87	195.60	189.81	189.69	192.50
	SD:	13.37	9.49	5.76	7.28	13.56	7.04	6.94	4.45	7.71	14.77

BASIC DATA TABLE
ALTITUDE ERROR AT THRESHOLD

PROFILE	WIND	DISPLAY C-1 PILOT 1	DISPLAY C-1 PILOT 2	DISPLAY C-2 PILOT 3	DISPLAY C-2 PILOT 4	DISPLAY C-3 PILOT 5	DISPLAY C-3 PILOT 6	DISPLAY C-4 PILOT 7	DISPLAY C-4 PILOT 8	DISPLAY C-5 PILOT 9	DISPLAY C-5 PILOT 10
1	0W	11111	2	11	17	16	23	6	26	25	23
1	LHW	11111	1	23	7	75	11	-9	32	7	2
1	TW	11111	-18	4	15	37	18	5	27	1	13
1	XW	-25*	-28	10	12	24	10	17	19	-13	-13
2	0W	-20	8	21	14	54	20	11111	16	-6	32
2	HW	11111	11111	19	19	-14	16	20	20	-25	-6
2	TW	-34	11	15	-9	18	12	13	5	6	0
2	XW	11111	-3	17	4	26	2	14	-5	-20	11
3	0W	-13	16	26	24	28	15	15	7	33	5
3	LHW	10	15	29	20	24	23	20	9	-20	1
3	TW	11111	17	34	27	20	24	-17	13	11	29
3	XW	-7	-19	21	23	44	25	-5	13	-37	41
4	0W	11111	-22	17	24	1	13	-13	17	66	48
4	HW	11111	5	26	23	25	17	29	23	11	14
4	TW	11111	20	4	15	39	-3	2	9	-10	43
4	XW	11111	3	16	8	22	8	5	28	48	52
	SUM:	109.00	188.00	295.00	261.00	467.00	240.00	190.00	269.00	339.00	333.00
	MEAN:	13.17	12.53	18.44	16.31	29.19	15.00	12.67	16.81	21.19	20.81
	SD:	10.19	8.45	8.41	6.98	17.58	7.14	7.40	8.66	17.55	17.74

*Negative values indicate altitudes below the 60-foot target altitude.

BASIC DATA TABLE
LATERAL ERROR AT THRESHOLD

PROFILE	WIND	DISPLAY C-1 PILOT 1	DISPLAY C-1 PILOT 2	DISPLAY C-2 PILOT 3	DISPLAY C-2 PILOT 4	DISPLAY C-3 PILOT 5	DISPLAY C-3 PILOT 6	DISPLAY C-4 PILOT 7	DISPLAY C-4 PILOT 8	DISPLAY C-5 PILOT 9	DISPLAY C-5 PILOT 10
1	OW	11111	-35	-15	-22	-20	-11	-3	-24	6	33
1	LHW	11111	-12	-18	-2	1	-15	-23	-19	37	57
1	TW	11111	-10	-23	4	11	-16	-24	-14	-7	40
1	XW	89	-7	35	12	-18	16	-12	26	55	6
2	OW	53	-3	11	-13	-4	-21	11111	-20	-8	1
2	HW	11111	11111	-36	-39	-23	5	-31	-33	1	30
2	TW	5	-36	-3	-28	-27	-21	4	-5	-15	2
2	XW	11111	2	73	5	-12	-33	-4	-5	18	70
3	OW	20	-27	13	-7	-37	-21	-29	-18	-25	13
3	LHW	53	1	-15	-15	-15	-37	-29	-33	-11	-22
3	TW	11111	-3	5	-6	-18	-19	-28	-30	9	4
3	XW	-72*	10	20	-29	-15	-27	3	-20	-14	13
4	OW	11111	-22	-17	-12	-22	-14	-21	-4	-25	16
4	HW	11111	-31	-2	-11	9	-4	-7	-6	-22	-13
4	TW	11111	-25	-5	-19	-20	-15	-15	-3	-2	20
4	XW	11111	7	45	-11	-32	-13	-12	-15	41	122
	SUM:	298.00	231.00	336.00	235.00	284.00	288.00	245.00	275.00	298.00	462.00
	MEAN:	49.67	15.40	21.00	14.69	17.75	18.00	16.33	17.19	18.62	28.87
	SD:	32.10	12.61	18.55	10.31	9.50	8.85	10.63	10.39	15.03	31.61

*Negative values indicate lateral offsets to the left of the runway centerline.

BASIC DATA TABLE
DISTANCE FROM THRESHOLD AT TOUCHDOWN

		DISPLAY C-1		DISPLAY C-2		DISPLAY C-3		DISPLAY C-4		DISPLAY C-5	
PROFILE	WIND	PILOT 1	PILOT 2	PILOT 3	PILOT 4	PILOT 5	PILOT 6	PILOT 7	PILOT 8	PILOT 9	PILOT 10
1	0W	-399*	1956	1311	1542	2276	2514	1179	2031	911	1862
1	LHW	-1221	2022	1317	1216	1122	1909	753	1453	737	985
1	TW	-331	969	1255	1171	1723	2765	1348	1372	1150	1248
1	XW	1611	378	961	957	2702	1754	1407	1884	353	1526
2	0W	587	1897	1366	1185	2937	1444	-109	1361	714	1855
2	HW	-2621	-592	1706	1340	622	1279	1753	1532	276	258
2	TW	691	695	2363	893	2058	1622	1339	1466	1204	1511
2	XW	-131	955	1288	1436	2136	923	1390	996	385	1446
3	0W	1162	650	1245	1003	1606	1933	1869	1059	1276	2235
3	LHW	1425	780	1203	1176	1587	1622	1247	1026	455	706
3	TW	-262	1082	1106	1362	3120	1539	914	1070	1089	1844
3	XW	1642	739	1151	1272	1763	3234	1055	1313	63	1894
4	0W	-539	429	1301	1243	929	1516	1372	1847	2707	2254
4	HW	-263	1744	2024	990	2815	1198	1425	1313	1076	1708
4	TW	-132	1978	927	1073	2059	1116	2186	1462	1822	1371
4	XW	-79	2039	1079	794	1305	1577	1639	1573	2224	1111
	SUM:	13096.00	18005.00	21606.00	18653.00	30760.00	27995.00	20885.00	22758.00	16442.00	23814.00
	MEAN:	71.28	1125.31	1350.37	1165.81	1922.50	1749.69	1285.72	1422.37	1027.62	1488.37
	SD:	816.32	598.45	379.49	204.27	732.73	626.84	241.58	308.58	725.00	538.76

*Negative values locate touchdowns short of the runway threshold.

BASIC DATA TABLE
LATERAL OFFSET AT TOUCHDOWN

PROFILE	WIND	DISPLAY C-1 PILOT 1	DISPLAY C-1 PILOT 2	DISPLAY C-2 PILOT 3	DISPLAY C-2 PILOT 4	DISPLAY C-3 PILOT 5	DISPLAY C-3 PILOT 6	DISPLAY C-4 PILOT 7	DISPLAY C-4 PILOT 8	DISPLAY C-5 PILOT 9	DISPLAY C-5 PILOT 10
1	DW	84	-19	-23	-52	-24	-31	-7	-40	7	11
1	LHW	-27	-37	-38	-17	-11	-12	-27	-19	27	59
1	TW	9	-19	-20	4	-7	-26	-18	-19	-20	32
1	XW	23	-2	24	8	-7	-1	6	17	52	6
2	DW	38	-15	-6	-17	42	-32	-28	-24	-6	-9
2	HW	13	-12	8	-40	-27	-19	-9	-37	7	27
2	TW	22	-22	-31	-33	-26	-18	-14	-13	-5	1
2	XW	-64	-5	51	4	-26	-27	3	6	24	58
3	DW	2	-25	7	-9	-46	0	-24	-22	-19	-4
3	LHW	51	-4	-26	-30	-39	-59	-34	-47	-8	-4
3	TW	29	9	-1	-7	-4	-35	-4	-31	0	20
3	XW	-71	12	7	-35	26	-15	22	-14	-14	23
4	DW	32	-18	-24	-5	-26	-17	-24	-28	-84	-7
4	HW	-27	-41	7	-14	19	-12	9	-15	-23	17
4	TW	-37	-26	-14	-13	-23	-30	4	-16	-24	12
4	XW	-108	-15	45	-9	-33	-28	-26	-4	55	79
	SUM:	642.00	284.00	332.00	297.00	386.00	362.00	259.00	352.00	375.00	369.00
	MEAN:	40.12	17.75	20.75	18.56	24.12	22.62	16.19	22.00	23.44	23.06
	SD:	29.41	10.78	14.93	14.79	12.41	14.32	10.32	11.97	22.49	23.11

BASIC DATA TABLE
IAS AT TOUCHDOWN

PROFILE	WIND	DISPLAY C-1 PILOT 1	DISPLAY C-1 PILOT 2	DISPLAY C-2 PILOT 3	DISPLAY C-2 PILOT 4	DISPLAY C-3 PILOT 5	DISPLAY C-3 PILOT 6	DISPLAY C-4 PILOT 7	DISPLAY C-4 PILOT 8	DISPLAY C-5 PILOT 9	DISPLAY C-5 PILOT 10
1	OW	197	160	181	189	168	184	189	182	187	194
1	LHW	198	165	178	165	175	178	198	183	188	172
1	TW	163	183	174	180	184	186	191	189	181	188
1	XW	153	169	174	180	183	172	184	184	185	177
2	OW	164	168	176	172	178	172	200	183	174	180
2	HW	184	174	167	173	156	176	190	177	182	161
2	TW	161	174	168	175	178	179	181	171	190	165
2	XW	161	162	156	168	181	179	179	177	180	210
3	OW	184	133	183	184	199	184	184	184	179	188
3	LHW	191	184	184	184	194	194	193	186	178	189
3	TW	193	185	184	183	172	185	186	188	197	192
3	XW	156	190	181	180	188	167	188	185	188	188
4	OW	192	191	180	185	174	186	182	179	182	201
4	HW	186	185	171	181	186	182	197	177	192	177
4	TW	187	180	133	133	183	181	179	186	188	186
4	XW	179	180	175	184	209	178	188	179	182	191
	SUM:	2874.00	2323.00	2815.00	2866.00	2908.00	2883.00	2999.00	2910.00	2953.00	2959.00
	MEAN:	179.62	176.44	175.94	179.12	181.75	180.19	187.44	181.87	184.56	184.94
	SD:	13.09	9.27	7.64	6.67	12.48	6.60	6.01	4.83	5.89	12.62

BASIC DATA TABLE
RATE OF DESCENT AT TOUCHDOWN

		DISPLAY C-1		DISPLAY C-2		DISPLAY C-3		DISPLAY C-4		DISPLAY C-5	
PROFILE	WIND	PILOT 1	PILOT 2	PILOT 3	PILOT 4	PILOT 5	PILOT 6	PILOT 7	PILOT 8	PILOT 9	PILOT 10
1	OW	-26	-15	-10	-20	-5	-6	-7	11111*	-16	-8
1	LHW	-4	-16	-13	-5	-34	-4	-7	11111	-17	-13
1	TW	-9	-7	-9	-12	-12	-13	-3	11111	-8	-7
1	XW	-22	-8	-13	-14	-5	-7	-9	11111	-9	-8
2	OW	-10	-10	-13	-13	-11	-6	-14	11111	-12	-10
2	HW	-12	-13	-13	-9	-9	-7	-3	11111	-11	-28
2	TW	-4	-21	-10	-15	-5	-6	-11	11111	-9	-7
2	XW	-5	-3	-11	-8	-7	-7	-10	11111	-13	-14
3	OW	-22	-13	-11	-31	-8	-9	-5	11111	-9	-23
3	LHW	-3	-17	-15	-8	-12	-6	-12	11111	-11	-14
3	TW	-4	-16	-18	-11	-12	-3	-3	11111	-12	-21
3	XW	-33	-4	-14	-15	-15	-18	-7	11111	-17	-9
4	OW	-20	-16	-13	-17	-10	-6	-5	11111	-24	-17
4	HW	-7	-10	-13	-12	-7	-9	-6	11111	-10	-17
4	TW	-14	-14	-12	-13	-17	-5	-5	11111	-11	-17
4	XW	-20	-8	-15	-25	-16	-9	-1	11111	-9	-19
	SUM:	215.00	191.00	203.00	228.00	185.00	121.00	108.00	.00	198.00	232.00
	MEAN:	13.44	11.94	12.69	14.25	11.56	7.56	6.75	.00	12.37	14.50
	SD:	9.29	5.03	2.24	6.60	7.11	3.63	3.64	.00	4.22	6.25

*A printout of 11111 indicates missing data.

BASIC DATA TABLE
PITCH AT TOUCHDOWN

PROFILE	WIND	DISPLAY C-1 PILOT 1	DISPLAY C-1 PILOT 2	DISPLAY C-2 PILOT 3	DISPLAY C-2 PILOT 4	DISPLAY C-3 PILOT 5	DISPLAY C-3 PILOT 6	DISPLAY C-4 PILOT 7	DISPLAY C-4 PILOT 8	DISPLAY C-5 PILOT 9	DISPLAY C-5 PILOT 10
1	OW	4	7	7	4	8	7	7	11111*	5	6
1	LHW	7	6	7	10	1	8	7	11111	5	6
1	TW	6	6	8	6	6	5	7	11111	7	9
1	XW	5	9	8	6	7	8	7	11111	7	6
2	OW	8	7	7	7	6	9	4	11111	7	6
2	HW	6	5	6	8	9	8	8	11111	6	1
2	TW	9	5	6	6	8	8	7	11111	7	5
2	XW	10	11	9	8	7	8	7	11111	6	4
3	OW	2	7	7	1	6	6	7	11111	6	-2
3	LHW	8	5	6	7	5	8	6	11111	7	5
3	TW	7	5	5	7	5	8	8	11111	5	3
3	XW	1	9	7	7	6	6	7	11111	6	7
4	OW	4	4	7	5	0	7	6	11111	4	2
4	HW	6	4	4	6	6	7	7	11111	6	3
4	TW	6	6	7	6	5	8	8	11111	6	6
4	XW	5	6	6	1	4	7	7	11111	7	6
	SUM:	94.00	103.00	107.00	95.00	89.00	118.00	110.00	.00	97.00	77.00
	MEAN:	5.87	6.44	6.69	5.94	5.56	7.37	6.87	.00	6.06	4.81
	SD:	2.39	1.90	1.20	2.35	2.37	1.02	.96	.00	.93	2.14

*Missing data.

BASIC DATA TABLE
ROLL AT TOUCHDOWN

PROFILE	WIND	DISPLAY C-1 PILOT 1	DISPLAY C-1 PILOT 2	DISPLAY C-2 PILOT 3	DISPLAY C-2 PILOT 4	DISPLAY C-3 PILOT 5	DISPLAY C-3 PILOT 6	DISPLAY C-4 PILOT 7	DISPLAY C-4 PILOT 8	DISPLAY C-5 PILOT 9	DISPLAY C-5 PILOT 10
1	OW	-8*	0	-3	-5	-1	0	-3	11111**	0	1
1	LHW	5	-3	-4	-2	-6	-3	-3	11111	1	9
1	TW	1	0	-2	-1	-3	-4	-4	11111	0	-4
1	XW	10	0	-1	2	0	-1	-1	11111	-3	3
2	OW	-1	0	0	0	-5	-2	-6	11111	3	0
2	HW	-1	1	0	-3	-1	-3	-3	11111	-2	-5
2	TW	7	-3	6	-1	-1	-2	0	11111	0	-2
2	XW	3	-1	0	3	-3	0	-1	11111	-4	0
3	OW	0	-1	-1	-2	-1	-2	-5	11111	3	-2
3	LHW	-11	0	-1	-2	-4	-3	-5	11111	-3	-2
3	TW	3	-2	0	0	-1	-1	-3	11111	1	-1
3	XW	-2	-1	0	-2	-4	1	-1	11111	-5	2
4	OW	0	-1	0	0	0	-3	-2	11111	13	4
4	HW	8	0	-2	-2	0	0	-4	11111	0	0
4	TW	17	-2	-1	-3	-2	-3	0	11111	2	-1
4	XW	12	0	-2	0	-1	-4	-1	11111	-2	0
	SUM:	89.00	15.00	17.00	28.00	35.00	32.00	42.00	.00	42.00	36.00
	MEAN:	5.56	.94	1.06	1.75	2.19	2.00	2.62	.00	2.62	2.25
	SD:	5.07	1.06	1.24	1.39	2.20	1.37	1.86	.00	3.16	2.38

*Negative values are left-wing-down roll attitudes.
**Missing data.

ABSTRACT

A simulation evaluation of a pictorial display concept for final approach management of the Orbiter space shuttle was conducted. Both head-up and head-down presentations were evaluated.

Ten airline pilots flew a total of 160 simulated Orbiter final approach sequences, using five display configurations differing in levels of display aiding. Data were obtained on the relative contribution of key elements of the display concept to specific components of the approach control task.

Results indicate that the experimental display would increase flexibility in implementing alternative final approach control strategies. Flight path control and airspeed management were more accurate and less variable with the full set of experimental display elements.

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