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NASA/FAA Phase III Final Report

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This Head-Up Display (HUD) report
is number 16 in a series

NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

TABLE OF CONTENTS

Page

AN OPERATIONAL EVALUATION OF HEAD-UP DISPLAYS FOR CIVIL TRANSPORT OPERATIONS

NASA/FAA PHASE III FINAL REPORT

J. K. Lauber,* R. S. Bray,* R. L. Harrison,* J. C. Hemingway,* and B. C. Scott†

Ten airline captains currently qualified in the B-727 aircraft flew a series of simulated instrument-landing system (ILS) and localizer-only approaches in a motion base simulator using both a flight director head-up display (HUD) concept and a flightpath HUD concept as well as conventional head-down instruments under a variety of environmental and operational conditions to assess: (a) the potential benefits of these HUDs in airline operations; (b) problems which might be associated with their use; and (c) flight-crew training requirements and flight-crew operating procedures suitable for use with the HUDs. The results, based on objective simulator based performance measures, subject pilot opinion and rating data, and observer data, included the following: (1) The subject pilot group expressed a preference for both HUD concepts over conventional instruments; (2) accuracy and precision of pilot control of some flight parameters during approaches in a variety of conditions were improved when the pilots used either HUD, but the largest improvement was with the flightpath HUD; and (3) the HUD training programs developed for this study yielded good performance using unfamiliar display concepts and were highly regarded by the subject pilots.

INTRODUCTION

Background and Statement of the Problem

The experiment reported here is the culmination of a series of studies conducted under a joint agreement between the FAA and NASA. (See the paper by Haines (1978) for details of program plan.) As stated by Haines the objectives of the program were to evaluate the advantages and disadvantages of head-up displays (HUD) in commercial-jet-transport approach and landing operations. The program was organized into four major phases: Phase I, for which the FAA had major responsibility, was a review of the relevant literature and an analysis of the major issues surrounding HUD. The results of this effort were published by Shrager (1978).

The NASA-Ames Research Center had major responsibility for Phase II and Phase III. Phase II had two major objectives: (1) to evaluate certain fundamental human-factor issues relating to the design and operation of HUDs; and (2) to develop candidate HUD concepts to be evaluated in Phase III. These Phase II laboratory and simulator experiments have been reported elsewhere, and a complete list of authors and titles is given in appendix A.

Phase III of the program, the subject of this report, consisted of a simulator evaluation using two different head-up display concepts as well as conventional head-down instruments under a variety of environmental and operational conditions to determine: (1) the potential benefits of these HUDs in airline operations; (2) problems which might be associated with their use; and (3) flight-crew training requirements and flight-crew operating procedures suitable for use with the HUDs.

Finally, Phase IV of the program is an FAA responsibility and consists of actual flight tests of a HUD concept in an FAA B-727 aircraft. This effort is underway at present and will be reported in a future FAA paper.

The primary focus of this program was to conduct an operational evaluation of these HUD concepts during manually flown jet transport terminal area operations with CAT I or better visibilities and normal environmental conditions. Subjective evaluations and standard approach performance measures were collected. This program did not address very low visibility operations, the suitability of these HUDs for monitoring auto-land operations or any economic considerations relating to head-up displays.

Operational History of Head-Up Displays

The head-up display is not a new concept (see Naish, 1979). The modern head-up display is the product of a continuous evolution which began with airborne optical gunsights developed during World War II. In keeping with

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its military origin, the HUD concept has seen wide application in military aircraft, primarily as an assist to the tactical mission of attack and fighter aircraft, *viz*, in weapons delivery. Although some military HUDs have approach and landing guidance functions, it has not been until recently that an attempt has been made to fully develop and utilize military HUDs for final approach, flare, and landing guidance. Because of these factors, accumulated experience design and operational use of military HUDs is of limited value in trying to assess the advantages and disadvantages of HUDs in civil-jet-transport aircraft operations.

Civil experience with the HUD concept is much more limited. At present, there are only two known applications of HUDs in civil-transport operations world-wide, and both of these are electromechanical reticule devices designed to present limited special purpose information. In one case, a carrier flying twin-jet transports into Arctic gravel-runway airports with no electronic or visual glide-slope information available is using a simple, visual-meteorological-condition (VMC) – only head-up display to provide flightpath guidance during the final approach. In the other case, the HUD is being used to provide monitoring of and manual-backup capability for a fail passive autopilot for CAT III operations. A third application of HUD will be available in the near future. The Douglas Aircraft Company is offering a HUD option on the DC-9-80. This HUD is designed for use in manually controlled approaches and as a monitor of the performance of the autopilot during autoland. In the latter application, the ultimate objective of the HUD system is to provide the pilot with sufficiently accurate instrument guidance cues in the windscreen area to complete a manual approach following a failure of the autopilot at or below decision height (DH) in CAT IIIa (RVR less than 1200 ft).

A paucity of operational and experimental data with regard to the more general application of HUDs still exists. Many questions remain unanswered. Are there performance benefits to be gained by using a head-up display? Are there any difficulties or hazards associated with their use? What training will be required before initiating use of HUDs in line operations? Will the line pilots accept or reject these new displays? Questions like these and the recognition that the lack of sufficient vertical-guidance information has been a major contributory cause in jet transport accidents have provided the major justification for the NASA/FAA program.

Potential Benefits and Problems of the Head-Up Display Concept

Before the Phase III experiment and its results are described, the potential benefits which have been ascribed to the head-up display and some of the potential problems associated with its use will be discussed. The following paragraphs constitute an overview only; detailed discussions may be found in references by Shrager (1978) and Jenny, Malone, and Schwackert (1971).

The principal benefit claimed for the HUD concept is that the pilot's ability to utilize both instrument information and environmental visual cues is greatly enhanced because the symbology is presented at optical infinity through a semitransparent combiner plate placed at the pilot's through-the-windshield line of sight. This enhancement is presumed to come from the elimination of the necessity for physical movement of the head and eyes from the instrument panel to the windscreen and vice versa, and the elimination of the necessity for the eye to refocus (accommodate) as the point of regard moves from panel to windscreen. The total time required for these movements can be as much as several seconds (Tucker and Charman, 1979) and, therefore, their elimination presumably would enhance the use of both sources of information.

One potential benefit that is available only through the use of HUD is the notion of display conformality, that is, synthetic, electronically generated, and displayed elements overlay (or conform to) corresponding objects in the real world. Conformality offers two potential benefits: (1) Synthetic display elements which can be flown with reference to some real-world counterpart provide a synthesis of information otherwise unobtainable (e.g., a synthetic flightpath symbol flown with reference to the desired touchdown point on the actual runway); (2) The presence of the synthetic symbol shows the pilot where to "look for" the corresponding real-world element, thereby presumably enhancing his ability to detect and assess the real-world visual cues.

In arguing that these features are benefits, certain assumptions must be made. One is that no useful information is being obtained during the head/eye movements and refocusing. Also, in order to argue that HUD improves the pilot's ability to detect and utilize marginal real-world visual cues, it must be assumed that the degree of obscuration of the environmental visual cues by the HUD optics and symbology is acceptable. These considerations were of major importance in determining the general approach used to evaluate the HUD concept in this program. If the pilot's ability to utilize each source of information is enhanced by HUD, then corresponding changes in performance on tasks which are dependent upon information from either or both sources ought to be seen. This rationale was fundamental in the selection of the environmental and operational test conditions and the performance measures used in this study.

APPROACH

Description of Head-Up Display Concepts Used in Phase III

Three major functional capabilities were required of the HUDs used in Phase III: (1) The HUDs must provide the capability for conducting both precision and nonprecision approaches; (2) the HUDs must provide sufficient information so that they can be used for terminal area maneuvering (e.g., flying on radar vectors, intercepting and flying the final approach to a flare and landing, or initiating a missed approach maneuver); and (3) the HUDs must be "full time" in the sense that they must contain sufficient information to enable the pilot to conduct these maneuvers solely by reference to the HUD symbology. Flare guidance was not specifically required, nor were other secondary HUD design issues considered (e.g., the display of caution and warning information). It was believed, however, that the functional capabilities described previously were reasonable in the sense that any commercially viable HUD would probably contain at least some of these features.

Early in the Phase III program, a major question arose which had a significant impact upon the conduct of the study. In an experimental evaluation of a HUD which contains information currently not available to the pilot, how can the researcher discern whether any performance differences are due to the presence of the new information or to the fact that the information is displayed head-up (i.e., superimposed on the real-world scene)?

Initially, an attempt was made to consider one aspect of the question by requiring the use of two different design philosophies; for one of these, no restrictions were placed upon the kinds of information that would be included in the HUD; in the second case, the HUD could contain only information that is currently available on the instrument panel. This restriction precluded the use of flightpath or potential flightpath, and, in effect, dictated that only raw data and/or flight-director guidance be used. However, precluding the use of any "new" information would have limited the flight-director display concept to a laboratory curiosity with no commercial viability. Given that the major objective of the Phase III program was to evaluate the potential contributions and problems of head-up displays in line operations, the rule was relaxed to permit the addition of a simple flightpath display element for use during the VMC portion of nonprecision approaches. The question of new information versus symbology location was not further addressed in this study.

Flight-Director HUD

General description– The flight-director HUD (FD HUD) used in this study was basically an unreferenced display (i.e., no element of the display except the horizon was earth referenced) with provisions for nonprecision and visual approaches. Using computed information, the display provided fly-to roll and pitch steering commands in a manner exactly analogous to conventional head-down flight director displays. For nonprecision and visual-approach operations, the flight-director elements were replaced by switch-selectable fixed-depression or flightpath (delta gamma) elements flown with reference to the intended touchdown point on the runway.

Major central display elements– Flight-director guidwas provided on the display by a movable dot located at the apex of a stack of three crossbars (see fig. 1). The pilot's task was to fly the aircraft symbol (the circle with "wings" onto the steering dot). In reality, the aircraft symbol remained fixed in the center of the display and the dot moved, either parallel to the horizon for lateral commands or perpendicular to the horizon for vertical commands.

The three crossbars, which moved the steering dot, were designed both to assist the pilot in locating the steering dot without having to fixate upon it and to provide a roll reference for those situations in which the artificial horizon would disappear from the display (e.g., large pitch angles).

The artificial horizon was a long bar with a central gap to accommodate the aircraft symbol. Bank angles were indicated by keeping the horizon line parallel with the earth's horizon at all times. In order to keep the horizon line within the small field of view ($12^\circ \mp 12^\circ$) of this display, movements of the horizon in pitch were reduced by a factor of 5:1.

The aircraft symbol provided basic pitch and roll attitude information. In addition, airspeed error was displayed by means of a vertical bar which grew out of the top of the aircraft symbol to indicate positive speed errors and out of the bottom to show negative speed errors. The reference speed was manually set by means of a knob and movable "bug" on the panel-mounted airspeed indicator.

For visual-approach operations, the pilot selected either of two modes: a depression line which was fixed at 3° below the horizon, or a flightpath line (actually delta-gamma) (see fig. 2). These modes, selected by means of lateral movement of an otherwise conventional "coolie hat" thumb switch on the yoke, were used to determine deviation from a nominal 3° flightpath and to assist the pilot in flying to the desired touchdown point on the runway. (See Naish (1979) for a complete description of the delta-gamma flightpath display.)

Major peripheral display elements– Heading information was provided by a horizontally moving tape at the top of the display. Heading tabs were provided at 5° intervals, and heading was marked with two-digit numerals at 10° intervals.

Raw-data glide-slope and localizer information were shown on the right side and bottom of the display, respectively. Scaling and sensing were equivalent to conventional head-down instruments. In addition, gates showing maximum permissible deviations as functions of altitude were shown in the form of a pair of lines growing from the outermost dots on both scales.

On the left side of the display was a vertical scale which showed instantaneous vertical speed. Reference marks were provided for +1000 ft/min (top), 0 ft/min (center), and -1000 ft/min (bottom).

Airspeed and altitude were displayed in digital format on the upper left and right sides of the display, respectively. Airspeed was indicated to the nearest knot, and altitude (radio altitude in this study) was displayed to the nearest 10 ft.

On the lower left side of the display, a digital readout of engine pressure ratio (EPR) for the no. 2 (center) engine was provided to assist the pilot in setting power.

On the lower right side of the display was an annunciator box which normally would have been used to display the current flight-director pitch mode, for example, altitude hold, glide-slope capture, or vertical-speed select. Because of a computer programming problem, the flight-director annunciator was not functional for this study.

In addition to flight-director modes, the annunciator box was used to indicate which of the two visual-approach monitor modes, fixed depression (HI-LO) or delta-gamma (DEL-GAM), was being displayed.

Finally, just above the mode annunciator box, the letters OM, MM, or IM flashed while passing over the outer, middle, and inner markers, respectively.

Flight-director control laws and modes– The flight-director steering dot was driven by the output from the simulated flight-director used for the head-down panel. The control laws used were those for the Collins FD-109 flight-director. One modification was made to add an airmass-referenced flightpath-angle term to the pitch steering logic, thus making the flight-director a near-equivalent to current generation head-down flight-director logic.

Conventional B-727/FD-109 flight-director modes were selected by the same switch used to control the panel-mounted flight-director. Lateral modes included heading select, VOR/localizer, and approach steering. Vertical modes included altitude hold, manual pitch, and glide-slope tracking. A go-around mode was also provided; it consisted of heading hold for lateral steering and a +15° pitch attitude in the vertical plane.

Operating procedures– In precision approach operations, use of the FD HUD was identical to the head-down FD. Heading select and altitude-hold or manual-pitch attitude select were used to maneuver and intercept final approach guidance. Localizer and glide-slope capture occurred automatically (if armed), and the pilot simply used the raw data and FD guidance in a conventional manner. Once the runway was in sight, the pilot continued to fly the display and either at or just prior to initiating the flare, "transitioned" to use of outside visual cues to complete the landing.

Operating procedures for the nonprecision case were nearly identical until visual contact with the ground was acquired. Using the lateral steering in the VOR/LOC mode and the altitude-hold and manual-pitch attitude select functions, the pilot tracked the localizer and descended to minimum descent altitude (MDA) and leveled off. Upon visually acquiring the runway, the pilot could alternate between the flight-director and the fixed depression displays. When the fixed depression line appeared to cross the threshold, the pilot initiated his descent and switched to the DEL-GAM mode. The pilot then "flew" the delta-gamma line to the desired touchdown point on the runway, initiating the flare and landing on the basis of external visual cues as in the precision approach.

As mentioned earlier, airspeed reference was set by means of a knob and pointer on the airspeed indicator. The heading-select operation involved the use of the conventional heading bug on the panel-mounted horizontal-situation indicator. No other special operating procedures were required. Appendix B gives additional details.

Flightpath HUD

General description– The flightpath HUD used in this study was a conformal, or earth-referenced, display which under certain circumstances directly displayed the instantaneous flightpath of the aircraft. Through a combination of scaled-raw-data navigation signals, the flightpath symbol, and ancillary aircraft status information, the display provided the information required to conduct terminal area maneuvers, intercept, final approach guidance, flare and landing or miss-approach operations. A brief description of this display is given in the following paragraphs. Additional information may be found in Bray (1980) and appendix C.

Major display elements– The major elements of the flightpath HUD used in Phase III are shown in figure 3. The central circle with gull wings is the flightpath symbol. When established on the localizer, this symbol has full vertical and horizontal freedom and showed the instantaneous velocity vector of the aircraft. Because a B-727 was chosen for this study, it was assumed that an inertial platform was not available and, hence, the velocity vector was airmass referenced. With an airmass-referenced flightpath symbol, it is not possible to have lateral freedom for the symbol until the aircraft is nearly established on this localizer. Then, if the inbound course of the localizer, the localizer error, and the heading of the aircraft are known, it is possible to compute and display the horizontal component of the velocity vector. The velocity vector is the primary controlled controlled element of this display, and the pilot's task was to fly the flightpath symbol to the desired reference point.

On the left wing of the flightpath symbol is an airspeed error tape. The tape rises above the wing for positive (fast) speed errors, and descends below the wing for negative (slow) speed errors. In addition, when the airspeed error is in excess of -5 or +10 knots, the airspeed-error tape flashes at a 4/sec rate. The reference speed was set by means of a knob and movable bug on the panel-mounted airspeed indicator.

The artificial horizon and heading scales extend across the entire display field. Heading ticks are located at 5° intervals, and heading is marked at 10° intervals. This line overlays the real-world horizon at all times; that is, it is scaled 1:1 in both pitch and roll. A pitch ladder remains fixed relative to the horizon, and it is marked in 1° intervals to +10° and then in 5° intervals.

For negative pitch attitudes and flighpath indications, there are major marks at -5° and -10°. In addition, there is an adjustable, fixed depression line which is set to the angle of the electronic glide-slope or to a desired visual, nonprecision flightpath angle. (This depression line was fixed at -3° for this study.) When glide-slope information is available, glide-slope error is displayed as the distance between this fixed depression line and the glide-slope symbol, which is the small circle with the two adjacent horizontal lines. For visual approaches, the fixed depression provides a reference flightpath to the point on the ground "under" the depression line. The artificial horizon line is broken for ±2.5° either side of the selected inbound course (localizer course), and a reference mark shows the selected course. Localizer error is displayed as the distance between the localizer symbol (the two vertical lines) and the selected course "bug" on the horizon scale.

Both the glide-slope and localizer symbols are raw data. However, because they are amplified by appropriate factors, they can be flown *as if* they were flight-director commands. When the flightpath symbol is flown to the localizer and glide-slope symbols, the aircraft will converge on the ILS localizer course and glidepath.

The "greater than" symbol just to the left of the flightpath symbol is the acceleration or potential flightpath symbol. When read using the gull wings of the flightpath symbol as a reference, the symbol indicates whether the aircraft is accelerating (symbol above the wing) or decelerating (symbol below the wing) along the longitudinal flightpath. When read using the pitch scale as a reference, the symbol indicates the flightpath that can be maintained in constant-speed flight provided that current thrust and drag are maintained. In essence, the pilot "flies" this symbol by using the thrust levers to achieve the desired acceleration. If the pilot keeps the symbol adjacent to the gull wing on the velocity vector, he will maintain a nearly constant airspeed regardless of flightpath or configuration changes.

Also on the display is a synthetic runway that overlays the real-world, and it can be set to disappear to indicate when decision height is reached. The small —v— symbol is the airplane reference symbol, and it displays aircraft attitude when read against the horizon and pitch ladder. Just above the airplane reference symbol is a distance from airport (DME) readout. The letters O, M, or I will flash just under the airplane reference symbol when it is passing the outer, middle, or inner markers, respectively. A manually adjustable MDA advisory line appears to come from the bottom of the display when the airplane is approaching MDA. The pilot can fly to the advisory line to capture and maintain a preselected MDA. The same symbol driven by radio altitude is used as a flare-advisory signal, and it can be used to assist in flaring the aircraft for the landing.

Finally, indicated airspeed is displayed in digital format just to the left of the flight symbol, and altitude (radio altitude in this study) is displayed digitally on the right.

Control laws– A complete description of the control laws which drive the various elements can be found in Bray (1980).

Operating procedures– From the pilot's point of view, operation of the flightpath HUD is straightforward. No mode switching is required; the presence or absence of valid localizer and glide-slope signals determines whether these symbols are present or not. For terminal-area maneuvering, the pilot flies the flightpath symbol to the desired headings and altitudes, maintaining airspeed by using the potential flightpath symbol, airspeed, and airspeed error. Localizer tracking is effected by flying the flightpath symbol to the localizer symbol. If a normal intercept from below the glide slope is assumed, that symbol will move down, and when it reaches the flightpath symbol it can be tracked to effect glide-slope capture.

For nonprecision approaches, the localizer is captured normally. At the outer marker, the flightpath symbol is "flown" down an approximate -5° flightpath until reaching MDA. (At the approach speeds of a B-727, a -5° flightpath is nearly a 1000 ft/min descent.) After visually acquiring the runway, the pilot maintains MDA until the fixed depression line crosses the threshold, and then he flies the flightpath symbol to the desired touchdown point. The flare advisory bar will appear to rise from the bottom of the display, and when it reaches the flightpath symbol the pilot flies the flightpath symbol so as to keep the flare advisory from rising above it.

Missed approaches involve flying a specific heading and maintaining an appropriate vertical flightpath. With go-around thrust set, the flightpath can be adjusted to maintain the desired airspeed by flying the flightpath symbol to the potential flightpath marker; no mode switching is required.

A declutter mode is available by operation of a finger switch on the control wheel. This allows the pilot to delete the localizer, glide slope, synthetic runway, and pitch and heading scale information in the final VMC portion of the approach if he so desires. Flightpath, potential flightpath, airspeed, and altitude remain, along with the flare advisory.

DESCRIPTION OF PHASE III SIMULATION FACILITIES

The equipment and facilities used in the Phase III experiment are described in the following paragraphs.

Mathematical Model

The basic mathematical model used represented a typical production configuration of the Boeing 727-200 airplane with JT8D-7 engines. This model had been purchased from the Boeing Aircraft Company for use in previous simulations. Configuration and flight conditions for this experiment were limited to the following:

Flap position	15, 25, 30
Gear	Up or down
Thrust	Idle to maximum
Weight, lb	140,000
Speed range	1 'g' stall speed to flap placard speed
Altitude, m (ft)	Sea level to 1524 m (5000 ft)
Angle of attack	Not to exceed 25° in stall
Temperature	Standard day
Center-of-gravity position	0.25 mean aerodynamic chord (MAC)

The following control surfaces were simulated: elevator, aileron, flight spoiler, rudder, stabilizer, and flaps. In addition, stick shaker, yaw damper, stabilizer trim, and wheel brakes were simulated. Ground spoilers and reverse thrust were not simulated.

Simulator Apparatus

The entire simulation program was carried out on the NASA/Ames Research Center's Flight Simulator for Advanced Aircraft (FSAA) equipped with a Redifon TV model-board visual-display system. The FSAA is a general-purpose aircraft simulator that was designed for general piloted-aircraft simulations. The motion system is a six-degree-of-freedom device designed to impart rotational and large-amplitude translational movement to the cockpit. The basic motion capabilities of this simulator are presented in table 1. A photograph of the simulator area containing the motion system and cockpit is shown in figure 4.

In the Redifon visual system, the visual image of the outside world is presented to the pilot by a color-television system whereby a camera looks at a model of a section of the earth's surface. The camera is driven relative to the model in the same way that the aircraft moves relative to the real-world, and a dynamic image of the outside world is created. A monitor placed before the pilot displays this scene through a collimating lens system that focuses the image at optical infinity.

The area of primary concern on the terrain model board contains a conventional airport with runway dimensions of 61 X 3048 m (200 X 8000 ft) and a Category II ILS lighting system. Also, a limited-visibility simulation device is incorporated in the television electronics; the simulation represents visibility conditions just under a low overcast, where objects on the ground (approaching the horizon) become less distinct until at some elevation angle the contrast is zero and no objects are visible. This capability can also be programmed as a function of distance to create variable visibility conditions.

Cockpit Layout

The cab of the FSAA was configured generally as a transport flight deck. Within the cockpit were mounted

B-747 flight deck seats for pilot and copilot as well as a third observer's seat. The cab has an instrument panel and front, center, side, and overhead consoles upon which a variety of controls and instruments may be mounted. For this simulation, the cab was configured to be generally representative of a Boeing 727-200 aircraft. No attempt was made to duplicate such things as a flight-engineer's station, communications equipment, warning systems, or other aircraft systems such as hydraulic, fuel, etc. The cockpit layout is shown in figure 5.

Both the captain and copilot stations had a complete set of fully functional instruments including airspeed indicator, radio and barometric altimeters, attitude director indicator (ADI), horizontal situation indicator (HSI), instantaneous vertical speed indicator (IVSI), and a clock. However, only the captain had a control column and could fly the aircraft. The center panel contained a full set of engine instruments, the flap indicators, and the landing-gear handle and indicating lights. The center console contained the throttles, spoiler handle, flap handle, and flight-director-mode select panel.

Everyone in the cockpit wore headsets with live microphones so that all conversations could be monitored. In addition, the FSAA is equipped with a sound generator that reproduced the sounds generated by the noise of air flowing past the aircraft, the turbujet-engine-compressor whine and exhaust rumble, and the landing gear.

It should be noted that one cockpit system which might have affected the way approaches were flown in this study was not simulated – the ground-proximity warning system.

HUD Generation Display

Since actual HUD hardware was not available, the symbology for the HUD was generated by a graphics display computer and displayed on a CRT. This image is reformed at optical infinity by two planoconvex lenses mounted before the pilot or copilot. A beamsplitter oriented at 45° between the lens and the monitors permits the pilot to view the HUD and the outside-visual-scene display simultaneously. The actual HUD CRT is mounted above the cockpit and its optical axis is at 90° to the line of sight. A schematic view of the lenses and beamsplitter is shown in figure 6.

The maximum field of view that could be provided was 24° wide by 18° high; the limiting factor was the size of the CRT on which the HUD image was displayed. Also, to add realism, a mockup of a HUD combiner plate was mounted on the overhead panel with a hinge mechanism which allowed it to be either stowed out of sight or locked approximately 15 cm (6 in.) in front of the pilot's eyes. The pilots were asked to adjust their seat position so that they viewed the display image through the combiner plate.

Experimenter Station

During the data-collection portion of the simulation, three experimenters were stationed in the control room. One experimenter acted as an air traffic controller and gave the pilot all necessary approach, landing, and go-around instructions. An X-Y plotter was set up to display aircraft position relative to the localizer so that the experimenter could give vectors to the pilot.

The second experimenter insured that all the initial conditions for each run were entered into the computer correctly and that all the data output was obtained after each run. The third experimenter monitored pilot commentary and recorded specific callouts and checkpoints.

SUBJECT PILOT SELECTION

Because the orientation of the Phase III study was operational, and because the basic objective to the experiment was to determine potential advantages and disadvantages of head-up displays in routine line operations, it was decided to use currently qualified line pilots as subjects for the study. Furthermore, since the simulator used for the study had only one fully operating pilot station, *viz*, the left side of the cockpit, it was decided to use only B-727 line captains. To insure a broad representation of air carriers, types of operations, regions of the country, and other factors, and aid of the air transport industry was enlisted in securing subject pilots. Carriers that wished to participate were asked to forward a roster of line-qualified B-727 captains to NASA project personnel. Candidates were selected from the roster by using a table of random numbers, with restrictions placed on carriers and location (i.e., to the extent possible, it was desired to have no more than one pilot from a given airline or a given location). It was necessary to request two pilots from two carriers in order to have a sufficient number of pilots to conduct the study.

The candidate subjects were contacted by the company, and, if they agreed to participate in the study, were subsequently contacted by NASA. NASA paid local expenses and travel expenses when necessary; the air carriers covered for lost flight time.

Thirteen subject pilots from nine airlines participated in the experiment. However, because of various difficulties, usable data were obtained from only ten pilots.

Table 2 lists the age, flight experience, and previous experience with HUDs for each of the pilots. As shown in table 2, only two of the subjects had any prior experience with HUDs, both while in military service. Only one of the two had actual flight experience with a HUD (in an A-7 aircraft); the other had flown a HUD installation in a military simulator (EA-6B).

SUBJECT-PILOT SCHEDULING AND TRAINING

Pilot training for the Phase III study was conducted by using three major instructional techniques. Subject pilots were initially given a training handbook to review. They were given detailed briefings on the HUD, and finally, given hands-on training and practice in the simulator.

Scheduling

Subject pilots were scheduled in pairs for three-day periods during which all training and experimental data runs were completed. Subjects were asked to arrive in the San Francisco Area during the afternoon or evening prior to their first full day at Ames. Upon checking into their hotel, they were given a ring binder which contained a background and experience questionnaire, a brief description of the study, and a training handbook for either the FD HUD or the FP HUD. The pilots were asked to review this material before reporting to Ames the following morning.

Training Handbook

Each training handbook contained five sections, which are described briefly as follows (complete handbooks are contained in appendices B and C):

Introduction to head-up displays– This section contained a brief description of major issues pertaining to head-up displays. It also provided a brief description of the scope and objectives of the Phase III study, the role of the line pilot as a test subject, and a breakdown of the training and data-collection schedule.

HUD description and review– Sections 2 and 3 of the HUD training handbook contained detailed operational descriptions of the HUD and a functional review of display elements. Each of the display elements was described and its function was discussed. Generally, the material was presented from the pilot's point of view, that is, how the pilot should use each display element when flying.

Analysis of sample problems– In order to maximize pilot understanding of the various display modes and the interpretation of symbol meanings, each handbook contained a section which presented the pilot with a series of sample "problems." Each problem provided a set of initial conditions (e.g., reference airspeed, attitude, visibility, etc.), and also a photograph of the HUD. The pilot was asked to answer a series of multiple-choice questions about his flightpath, acceleration, attitude, etc., using the initial-condition data and the photograph of the HUD. The pilot was also asked to analyze the situation shown and to make recommendations for corrective action. Answers to these problems were used by the instructor to provide a basis for discussion during classroom training.

Crew procedures– Section 5 of the training handbook contained the crew procedures used for the Phase III evaluation. Pilot and copilot duties and callouts were described in detail in this section. These procedures were adapted from one operator's B-727 Aircraft Operating Manual. One of the primary considerations which led to the use of this set of procedures was that many of the standard callouts (e.g., at outer-marker passage) are made by the pilot flying.

Copilot duties for all training and data runs were handled by the project instructor or by one of two NASA copilot/observers. A detailed description of pilot duties and callouts may be found at the end of appendix B.

HUD classroom instruction– Classroom instruction was conducted in a pilot's "ready room" located near the simulator. Instruction included lectures illustrated by slides, interactive analysis of problem situations contained in the handbook, and dynamic demonstrations using video tapes. In this manner, the subject pilot was taken from a static learning situation to a dynamic situation. Subjects were encouraged to ask questions about any aspect of the display or the pilot procedures to be employed during the study. Pilots were rehearsed in crew procedures by viewing video tapes of actual training flights and making the necessary callouts. During this period the instructor sat with the pilot and functioned as a cooperative copilot; he made callouts, prompted the pilot, and recommended appropriate pilot responses to display information.

FSAA familiarization and training– After completing the structured classroom training, subject pilots went, one at a time, into the FSAA for their first simulator training.

The initial training session was designed to familiarize the subjects with the FSAA cab, instruments, controls, and operating procedures. The HUD was not turned on for this preliminary training. Following a short incab briefing, a series of straight-in approaches were flown, first without motion, and then with the motion system turned on. Preliminary emphasis was upon the use of motion and visual cues to effect smooth approach and landing operations, and no attempt was made to integrate callouts and other flight-crew procedures. Between 10 and 12 landings were made during this period, which required approximately 40 min to complete. Following a break, during which the second subject pilot was given his FSAA familiarization training, the pilot returned to the cab for his second head-down (no HUD) training session.

The emphasis in the second training period was on the use of the cockpit instrumentation, especially the head-down flight director, and on the normal crew duties and callouts used for the study. Approximately 15 approaches, including ILS and localizer front-course approaches, were flown during the second period, which took about an hour. In the latter stages of this training, there were encounters with various visibilities, ceilings, and wind conditions, including some wind-shear conditions.

The instructor pilot attempted to provide sufficient training and instruction to bring all subject pilots to equivalent, satisfactory levels of proficiency before proceeding to the HUD training.

HUD Training

Following another break, during which the second subject pilot received his second head-down training session, the subject returned to the cab for his first HUD training session. This series of training approaches was essentially the same as the series used for the second head-down, no-HUD training session.

The HUD training sessions started with a short introductory period in which the pilot flew the aircraft in straight and level flight, then in gentle turns, climbs, descents, and finally through configuration and speed changes. Then a series of ILS approaches were flown, initially straight in, with the aircraft already configured and established on the ILS and onspeed; the approaches became increasingly more difficult and culminated in an approach which required intercept of both localizer and glide slope, effecting configuration changes, and slowing to approach speed with some crosswind and turbulence. Immediately after completing the series of ILS approaches, the pilot flew an equivalent series of nonprecision (localizer front course) approaches. This first HUD training session required approximately 45 to 50 min to complete.

Following a third break, the subject returned to the FSAA for his final HUD training period. Emphasis during this time was on the callouts and approach procedures and continued practice using the HUD during simulated terminal-area maneuvering, intercept of the final approach guidance, and flying the approach to a landing, or in some cases, a missed approach. This session, also approximately 50 min long, ended with a series of straight-in approaches flown through wind shears similar to those used for the last head-down training session.

Generally, the availability of the simulator was such that all head-down and HUD training and practice sessions could be completed for one subject pilot, and all except the second HUD training session for the second pilot during the first day. The second pilot's HUD training was completed during the first simulator period of the next day, and then data collection was begun for both pilots. All the data collections for the HUD approaches and half the no-HUD data runs were completed for each subject, and then training was begun on the second HUD. This training program was identical to the HUD training described previously, including the training handbook, classroom and lecture training, and the simulator training and practice.

Because the basic comparisons made in this study were between performance with and without the HUDs, every attempt was made in the training program to provide comparable training and familiarization on both head-up displays and on the basic FSAA instrument panel. Because of differing individual requirements, it was neither possible nor desirable to provide completed identical training. It is believed, however, that reasonably comparable levels of proficiency were achieved with this training program.

DATA SCENARIOS AND EXPERIMENTAL DESIGN

Selection of an appropriate approach and experimental design was one of the most difficult tasks that faced the Phase III project team. There are myriad factors which, ideally, ought to be systematically explored. As in any other situation involving limited resources, it was necessary to compromise with regard to the Phase III experimental design, and a brief review of some of the factors considered is given in the following paragraphs.

Although it was recognized that there may be some potential benefits of head-up displays in phases of flight other than the final approach and landing, the primary design objective was to provide better vertical guidance during visually referenced approach and landing operations. Accordingly, the experimental approach used for this study focused upon the straight-in final-approach segment, with particular emphasis given to the latter portion of the approach, flare, and landing operations.

Since vertical guidance was the major area of concern, factors which could potentially interfere with the pilot's ability to perceive or properly utilize the visual information required to effect a stabilized final approach were candidates for inclusion as independent variables in an experimental evaluation of HUDs. Included are the many environmental factors that might affect visual perception, for example, low visibilities, low ceilings, precipitation, runway lighting, runway slope, terrain slope and lighting, and sun angle, including day versus night. Other environmental variables affect the stability of the flightpath, for example, crosswinds, turbulence, and wind shear. Similarly, operational variables can affect both the acquisition and utilization of visual information by the pilot, for example, distractions caused by inter- or intra-cockpit communications and the stability of the flightpath, as, for example, an ATC request to "maintain 180 knots to the outer marker." Other factors may also be of interest, including pilot age and experience, pilot training received in the use of HUDs, flight crew operating procedures, and similar factors. Because time and resource limitations precluded a systematic review of all possible variables, it was necessary to identify those that are of most significance and then design an experiment that permitted a rigorous evaluation of their effects. If time and resources permit, it is desirable to explore as many other factors as possible so that some data may be obtained that provide at least a first-order assessment of the significance of these factors for operations with head-up displays. The experimental design used in the experiment reflects this rationale. A brief overview of the experimental design used in this study follows; and appendix D gives a complete technical discussion of the experimental design.

Essentially the experiment had two levels: (a) the core experiment in which all subjects encountered all independent variables; and (b) a second-order experiment in which a given subject encountered a limited subset of the independent variables.

The Core Experiment

The main factor in the experiment was display type: FD HUD, FP HUD, and NO HUD; the latter providing the baseline data against which performance with the head-up display was evaluated.

Independent variables in the core experiment were: (a) winds and turbulence, and (b) ceiling and visibility. Two basic ceiling and visibility conditions were selected: (1) a situation in which the ceiling and visibility were well above the appropriate minima for the type of approach flown; and (2) a situation in which the ceiling and visibility were very near the appropriate minima. Three basic wind conditions were chosen for the core experiment: (a) a light headwind with low turbulence; (b) a moderate quartering tailwind with an intermediate level of turbulence; and (c) a moderate-to-strong crosswind with a high level of turbulence. Specific values for each variable are shown in tables 3 and 4.

It should be noted that the wind data in table 4 are the nominal winds at 304 m (1000 ft) above ground level (AGL). The wind model used in the FSAA facility incorporates an exponential decay of speed as a function of altitude. Thus, wind speed at the runway surface was approximately half the nominal wind shown in table 4.

Because vertical guidance for precision and nonprecision approaches, is, by definition, different, it was necessary to evaluate these separately. Accordingly, the core experiment above was conducted twice: once for ILS approaches and once for localizer front-course approaches.

In summary, the core experiment consisted of three display types (FD HUD, FP HUD, and NO HUD); two ceiling and visibility conditions (near minima and well above minima); and three wind conditions (headwind, quartering tailwind, and crosswind). The core was conducted for each of two levels of approaches (precision and nonprecision). Thus, each subject pilot flew 36 approaches during Phase III data collection. Table 5 is a summary of the core experimental design.

Secondary Experiment

The design of the core experiment was a complete factoral design that not only offered several important advantages for evaluating the reliability and significance of the data, but it also severely restricted the number and range of variables that could be studied. In order to increase the utility of the Phase III experiment and yet not decrease its analytic rigor, a second-order, or fractionally replicated, experiment was superimposed on the core. This process allowed the experimenter to increase the scope and range of observations. Although the analytic or statistical rigor inherent in the core experiment is not available for these factors, this technique did permit an approximate evaluation of the effect of these variables.

Two kinds of second-order variables were used: (a) air traffic control handling; and (b) miscellaneous wind, visibility, and operational factors as described below.

ATC Handling

Although the primary focus of this investigation was upon the final approach, flare, and landing, it was recognized that performance during these phases of flight can be affected by preceding events. Furthermore, the HUD design guidelines adopted for this study required that the HUD be capable of use during terminal-area maneuvering and intercept of the final-approach guidance in addition to the latter stages of an approach. Accordingly, all approaches were begun from a base leg position approximately 12 flying miles from the airport. Three different starting altitudes were used: (a) 457.2 m (1500 ft), which is the initial approach altitude; (b) 762 m (2500 ft); and (c) 1219.2 m (4000 ft). These three starting altitudes formed the basis for the three ATC handling conditions; each scenario required a different sequence of heading and altitude commands from ATC. Because this ATC handling variable was used, it was possible to sample performance under a variety of workload and time-stress conditions. The 457.2 m (1500 ft) initial altitude involved no altitude changes (nor associated ATC communications) prior to crossing the final approach fix; the 1219.2 m (4000 ft) initial altitude required altitude changes and associated communications in addition to the heading, configuration, and speed changes required for all approaches. Because of the distance from the airport (about nine straight-line miles), the 1219.2 m (4000 ft) initial altitude resulted in a relatively high pilot workload during this stage of the approach.

Miscellaneous Factors

In addition to varying pilot workload by the use of ATC handling, four other factors were explored in the second-level experiment: (1) lower-than-reported visibility at the missed-approach point; (2) variable-visibility conditions, which involved intermittent visual ground contact; (3) encounter with a 15 knot decreasing wind condition between 53.3 m (175 ft) and 22.9 m (75 ft) AGL; and (4) the presence of a partial runway obstruction in the touchdown zone in the form of a scale-model aircraft situated with its forward fuselage extending onto the runway from an intersecting taxiway. This latter factor was included in order to gather more information on the perceptual switching issue described earlier, and it was an extension of some work conducted during one of the Phase II studies (see Fischer, Haines, and Price, 1980).

For any given subject pilot, six out of the 36 total approaches involved an encounter with one of the four factors described previously; they are referred to as "anomalies" in appendix D. The specific anomaly and the sequence in which it appeared was assigned on a psuedo-random basis. The exact number of observations for each of these factors is given in the Results section of this report.

Counterbalancing and Randomization

Whenever appropriate, randomization and counterbalancing were accomplished to prevent systematic biases from appearing in the data. Factors which were counterbalanced and/or randomized included: (a) display orders for both initial training and data collection; (b) order of core experimental conditions; and (c) selection and order of second-order factors (ATC handling and "anomalies"). In addition, other factors, including whether the initial position of the aircraft was on a right base leg or a left base leg, and the wind direction relative to the localizer course (e.g., left crosswind or right crosswind), were randomized and balanced throughout the experiment.

Data Scenarios

All approach scenarios were begun from either a right or left base-leg position approximately 12 miles from the airport. Initial altitude was either 457.2, 762, or 1219.2 m (1500, 2500, or 4000 ft) AGL (also mean sea level (MSL) since the simulated airport was at sea level). The landing gear was up, flaps were positioned at 15°, and the initial airspeed was 160 knots.

The subject pilot always occupied the left seat, and one of two NASA copilot/observers occupied the right seat. The copilot/observer had a clipboard on which the appropriate initial conditions and other relevant data for each approach were printed (appendix E). The copilot/observer used a brief checklist to insure that all aircraft controls and instruments were properly set prior to initiating a run.

A packet of landing data cards, which contained the approach type, winds, weather, aircraft gross weight, reference speed, and go-around thrust settings, was used to brief the pilot and copilot/observer prior to each approach. No approach charts were used because all approaches were to the same runway (09), and the decision height (DH) and minimum descent altitude (MDA) were always 61 m (200 ft) and 137.2 m (450 ft), respectively.

After the cockpit was set up and the crew briefed, the approach was commenced according to standard FSAA operating protocol. As soon as the simulator was released, an "air traffic controller" located at the FSAA console established communications with the simulator and issued ATC instructions in accordance with a standardized script (see appendix F).

Subject pilots were told to handle the aircraft in the same way they would if they were operating "on the line." Thus, for example, if they wanted a lower altitude, they were encouraged to ask for it. Therefore, occasional deviations from the ATC script occurred but every attempt was made to keep these deviations minor.

Each scenario was flown by using the standard crew procedures described previously. Thus, the copilot/observer handled all ATC communications, read the final-descent checklist, and made the assigned callouts. The pilot-in-command flew the aircraft, commanded configuration changes, checklists, and special callouts (if he so desired), and made his required callouts.

All approaches terminated either in a landing, in which case the simulator was reset for the next approach, or in a missed approach, in which case the simulator was reset when the aircraft was stabilized in the missed-approach maneuver.

For any given HUD, data collection was usually accomplished in two simulation periods per subject pilot. This procedure required approximately nine approaches per period so that during the two periods 18 approaches were flown. Twelve of these were flown using the appropriate HUD and six were NO-HUD baseline-data approaches. Approximately 1-1/2 hr were required to complete one simulator period.

DATA COLLECTION AND PERFORMANCE MEASURES

Three broad categories of data were collected during the Phase III experiment: (a) objective, simulator-based performance measures; (b) observer data from the copilot/observer and the observer located at the FSAA operations console; and (c) subjective data from the subject pilots in the form of general comments and responses to questionnaires and rating scales. Each of these is described below in the following paragraphs.

Objective Performance Measures

Simulation performance data were collected in three different formats: (a) on magnetic tape; (b) on summary printouts following each approach; and (c) on analog strip-chart recorders.

Because the set of "most relevant" performance measures changes as a function of phase of flight, each approach was divided into five segments, as described in the following paragraphs.

1. Intercept segment – This segment began at the initial position of the aircraft and ended when the aircraft crossed the final approach fix (FAF). Because of the dynamic nature of operations in the intercept segment, it is extremely difficult to develop suitable, objective performance measures. Accordingly, only observer and pilot-comment data were used during this phase of flight.

2. Approach segment – This segment began one half mile inside the final approach fix and ended at a point that was two miles from the glide-slope intercept at the runway. Under ideal circumstances, operation in this segment should be stabilized, thus providing useful objective performance measures (e.g., airspeed error, glide-slope error, localizer error, etc.).

3. Decision segment – This segment began at the end of the approach segment and continued to a point approximately 1000 ft short of the runway threshold. During an ideal ILS approach, aircraft performance will again be stabilized. Nonprecision approaches are generally not stabilized during this segment, and therefore, are much more difficult to describe and measure objectively.

4. Flare segment – This segment was that part of the approach between the end of the decision segment and a 15 ft radar altitude. Performance during this segment is likely to be relatively unstable because the flare is initiated sometime during the segment. Other changes (e.g., airspeed decay), are also likely during this segment.

5. Landing segment – This segment terminated at touchdown.

Because it is possible for a missed approach to occur at any point in an approach, it was not possible to define a missed-approach segment in the same sense as the other segments are defined. Furthermore, when a missed approach did occur, any subsequent segments, usually the flare and landing segments, were missed. Because the missed approach is another dynamic situation the performance during a missed-approach segment has to be described in qualitative terms.

The actual parameters recorded during an approach were a function of the approach segment. These parameters are discussed in detail in the Results section of this report, but generally those aircraft-state variables that most directly reflected the pilot's ability to control airspeed, vertical flightpath, and lateral flightpath were recorded at all times. Two kinds of data were recorded:

1. Continuous measures – For those segments and variables for which reasonably stabilized performance could be expected, several continuous-performance measures were recorded. For example, during the approach segment, glide-slope tracking should be relatively stable and, therefore, the root-mean-square (rms) glide-slope error was recorded for this segment. Similarly, airspeed should be reasonably stabilized during this segment. However, since target airspeed is, in part, a matter of pilot discretion, rms airspeed *error* is probably not a good measure, but rms airspeed *deviation* is. The selection of all continuous

performance measures discussed in the Results section was based on this kind of rationale.

2. Window measures – Window measures are essentially "snapshots" of aircraft-state variables taken at some specified, discrete point in time or space. Selection and specification of window measures were based on rationale similar to that used for the continuous measures. For example, when the aircraft crosses the threshold, several variables can reflect pilot and aircraft performance, and they are highly correlated with subsequent events. Specifically, altitude and lateral position determine whether the aircraft is "in the slot," and sink rate and airspeed control are critical during this phase of flight.

Window measures were taken at various points throughout the approach, including the beginning and end of each approach segment, the passage over each marker beacon, the threshold, and at touchdown. The specific measures used are described in the Results section.

Observer Data

The copilot/observer and the observer at the FSAA console recorded significant observations during or at the end of each approach. These observations were augmented by using a video recording of the pilot's visual scene; cockpit and ATC communications were recorded on the audio track of the video tape.

Generally these observers recorded operational blunders committed by the pilot as, for example, pilot failure to call for the final-descent checklist. These data were useful for qualitative analyses of pilot performance, and they frequently helped to lend insight in interpreting performance differences seen in the objective data.

Subjective Data

Questionnaire and rating scale data were obtained from all subject pilots at various times during the experiment. After they completed the approaches for each HUD, pilots were given a questionnaire and rating scale which were directed toward specific design and operational characteristics of that HUD. The questionnaires for the two HUDs were identical. Similarly, when a pilot had completed all data runs, other questionnaires and rating data were obtained on the training program, crew procedures, callouts, simulator facilities, scenarios, and other features of the experiment.

Subject pilots were further debriefed after they had completed all questionnaires. Significant comments and observations were recorded and they are discussed in the following paragraphs.

RESULTS

This section contains a summary of the results obtained in the Phase III experiment. Most of the quantitative data presented have been extracted from the complete set of analyses performed by the Control Analysis Corporation, whose report is presented in appendix D. The report presents the mean, standard deviation, maximum and minimum value for every measure for each of the three display conditions. Forty-one different variables were analyzed by means of a series of one-way analysis of variance (ANOV) tests. Twenty-two of these resulted in F ratios which were significant at or beyond the 0.05 level of confidence. As an aid to understanding the engineering impact of the data, histograms are presented. Note that separate analyses were performed for ILS and nonprecision approaches.

The results will be discussed by flight segment as previously described in the Data Collection and Performance Measures section of this report.

Intercept Segment Results

This segment began at the start of the run and ended at the outer marker. Because of the dynamic nature of operations in this segment due to ATC vectors and configuration changes, it is difficult to specify suitable objective performance measures. While five variables were identified, most of the useful data in this segment are from pilot or observer comments. The performance data is summarized in table 6. Only two of these measures showed statistically significant differences: (a) outer marker crossing altitude for ILS approaches (OMALT); and (b) airspeed error for nonprecision approaches (OMVQVR). However, there is some practical significance to the other data. The data for the aircraft lateral displacement from the runway centerline at the outer marker (OMYCG) shows consistent performance for all approaches head down but larger scatter for both HUDs as well as some large maximum excursions especially for the FP HUD. Table 7 contains a summary of the runs in which there was a lateral displacement equal to or greater than one dot localizer error at the outer marker. In all cases, the wind condition was either the quartering tailwind or the crosswind case. On the base leg and during radar vectors to the final intercept, the wind was from behind and tended to push the airplane away from the localizer during the actual intercept segment. For the flight director cases, either head up or head down, the director control laws would compensate for the effect of wind and command larger pilot inputs. For the flightpath HUD, since there is no command information, the pilot is compensating for wind himself. Any failure to recognize the wind condition or delay in starting the localizer intercept maneuver will result in an overshoot. Half of the subjects commented that they had varying degrees of trouble with the flightpath HUD interpreting what information the course line and localizer line was giving them. Also, during the steeper descents required for the 4000 ft starting altitude, the heading information would disappear from the HUD field of view causing some confusion during the intercept maneuver.

Approach Segment Results

This segment began one half mile inside the final approach fix and ended at a point that was two miles from the glide-slope intercept at the runway. This means that all approach data was for IFR portions of each run only. Generally, operation in this segment should be more stabilized since configuration changes would normally have been completed and final approach speed established. Thus, more useful objective performance measures are available (e.g., airspeed error, glide-slope error, localizer error, etc.). Seven variables were selected for analysis in this segment. Their means, standard deviations, and maximum and minimum values are summarized in table 8. Note that the rms glide-slope error (AGS) was measured for the nonprecision approaches even though the pilot was not given glide-slope information. This was done to allow a comparison of the performance with the three displays against a known reference.

For ILS approaches, five variables displayed significant differences as a function of display condition. These variables were rms localizer error (ALOC), rms glide-slope error, and the maximum, mean, and rms deviations of sink rate (AHDOTMAX, AHDOTM, and AHDOTD), respectively. For the nonprecision approaches, ALOC and AHDOTM differed significantly.

As would be expected, the ALOC data was consistent between ILS and nonprecision approaches since the pilot's lateral tracking task was the same. These data are shown in figure 7. While the performance with both the FD HUD and FP HUD was better than the NO HUD case, the actual amount of improvement was quite small since performance with the conventional instruments was already very good. Maximum and minimum values were comparable with the exception of the FD HUD in the ILS approach. This maximum point occurred during a run where the pilot had overshot the localizer by a considerable amount during the intercept from a 4000 ft starting altitude and was recapturing the localizer. Strip chart recordings of this approach showed good pilot performance during the recapture maneuver.

Similar results are seen in the glide-slope tracking data in figure 8. Again performance with both HUDs is better than with the conventional instruments but the absolute amount of improvement is small since overall performance with the standard panel display was excellent. The maximum values reached were comparable and, again, usually occurred during the approaches initiated from the 4000 ft starting altitude.

The airspeed performance data, AEASM and AEASD, while not statistically significant are very interesting in a practical sense. The remarkable consistency of these data for all displays across all test conditions is noteworthy. The digital readout of airspeed and the airspeed error worm in both displays was quite different from the typical needle presentation on an airspeed indicator, yet performance was slightly better with the two HUDs.

The remaining variables, AHDOTMAX, AHDOTM, and AHDOTD are shown in figures 9, 10, and 11 for both ILS and NPA. It should be noted that all of these variables are direct measures of vertical flightpath control. For the ILS approaches, the data followed the same pattern seen in the glide-slope and localizer tracking data, that is, more accuracy and precision for the HUDs than the instrument panel. For the NPA cases, there is a remarkable similarity between the conventional panel and the FD HUD data and, in general, an improvement in performance with the FD HUD.

Decision Segment

This segment covered the approaches from approximately two miles out to a point 1000 ft short of the runway threshold. It was within this segment that the pilot had to make his decision to land or go-around. Table 9 contains a summary of the total number of approaches and go-arounds for each category. The go-arounds on approaches with an anomaly condition were expected since the anomalies were designed to create a potential go-around situation. For all other approaches, less than 3% resulted in go-arounds. In fact, these seven go-arounds were all during nonprecision approaches and were distributed between NO HUD and FD HUD runs. Analysis of these seven runs reveals that most of the go-arounds were made after a decision to land had been made at MDA. Also, they were all either the crosswind or quartering tailwind cases. One factor that may have led to the go-arounds in the NO HUD case was a general lack of experience using a flight director for nonprecison approaches. Comments to this effect were made on the Supplemental Questionnaire.

For the FD HUD, some slight confusion existed in how to use the display in the final stages of the approach. The DELTA-GAMMA and HI-LO lines were offset laterally from the runway during the tailwind or crosswind cases and consequently some mental extrapolation had to be made by the pilot to assess his vertical path. If the pilot elected not to use the DELTA-GAMMA or HI-LO lines, there was some problem in ignoring the flight director command as the flare segment was approached, since there was no flare command guidance provided. These problems were not observed with the FP HUD since the pilot technique required was essentially the same for both ILS and nonprecision approaches.

The most useful data in this decision segment were the middle marker "snapshot" data. The four most interesting parameters are presented in table 10. The altitude (MMALT) and lateral displacement from the runway centerline (MMTCG) are plotted in figures 12 through 17 to depict the overall distribution at the middle marker "window." For the ILS approaches it is very clear that performance with either HUD was more accurate and precise than with the conventional head down instrument presentation. Of the two HUDs, the FP HUD performance was the best.

For the nonprecision approaches, the conventional panel and FD HUD data show large scatter at the "window." In fact, the FD HUD performance is not as precise or accurate as the performance head down. Again, performance with the FP HUD was clearly better.

The sink rate data at the middle marker (MMHDOT) are presented graphically in figure 18. The same general trend is seen again, that is, improved performance with either HUD over conventional instruments. Since sink rate is a direct measure of vertical flightpath control, it is not surprising that the FP HUD provided the best performance.

Flare Segment

The only consistent data taken in the flare segment are the parameters measured at the runway threshold window. The four most useful parameters are tabulated in table 11. Again, the altitude (FALT) and lateral displacement from the runway centerline (FYCG) are plotted in Figures 19 and 20 to give a picture of the overall aircraft position for all cases at what is essentially the start of the flare. It is interesting to compare these figures with the middle marker window data. The same pattern of improved precision and accuracy with the FP HUD is still very apparent. However, the performance with the FD HUD does not show any improvement and actually may be slightly worse. These data seem to support the observation that the use of this display became somewhat confusing to some subjects in the last stages of the approach and landing.

Landing Segment

Vertical velocity at touchdown (LMAXHDOT), airspeed at touchdown (LMAXVEQ), lateral displacement from runway centerline (LYCG) and distance down the runway at touchdown (LXCG) were all measured and are summarized in table 12. Figures 21 and 22 are scatter plots of the landing footprints for ILS and nonprecision approaches. The distribution pattern follows that seen at the threshold. While landing data for the FP HUD showed the most consistent performance with the least scatter, it must be noted that overall performance across all displays for all conditions was quite good. The average vertical velocity at touchdown for over 300 landings was -3.1 ft/sec with no "crashes" occurring. It is interesting that the shortest, longest, and hardest landings all occurred on NO HUD runs.

Anomalies

As described previously, one in six approaches was to involve an encounter with one of four "anomalies." Due to simulation problems, somewhat less than this was actually obtained. Because of the relatively low numbers of observations per case for each of the three display conditions, it is not possible to apply rigorous analytical techniques to these data; they were included to expand the range and scope of the general observations regarding head-up displays in civil transport operations. Table 13 summarizes the number of landings and missed approaches for each of the four anomalies as a function of display type.

For the wind shear encounters, there were only two go-arounds out of 12 approaches, and both of these were with the FD HUD. For the other two displays, all seven encounters ended with a landing. In fact, the actual performance for all landings following a shear encounter was quite good. While the general level of the shear could be considered moderate, it appeared that the pilots were able to recognize and cope with the shear adequately. In response to the questionnaire, pilots indicated a preference for both displays over conventional instruments for wind shear detection.

For both the variable visibility and minimum visibility cases, the results are not very conclusive. In the "scud" case, at least one missed approach was executed with each display, with most of them occurring during nonprecision approaches. For the minimum ceiling cases, out of seven approaches, one missed approach was executed and that was with the FD HUD.

For the runway obstruction anomaly, all 13 approaches ended in a missed approach. A summary of the visibility and ceiling conditions as well as missed approach information for these runs is given in table 14. Eight of the pilots felt that the FP HUD was superior to conventional head-down approaches in coping with runway obstructions. In general, pilots commented that because they were focussed at infinity and already looking out at the runway environment, they felt that earlier detection of obstructions would occur. However, several comments were made about symbology cluttering the view and attention to the FD HUD command dot distracting the pilot from viewing the runway.

Questionnaires, Rating Scales, and Pilot and Observer Comments

During the course of the study, subjects completed 11 questionnaires. In addition, a post-study questionnaire was mailed to all subjects soliciting additional information about previous flying experience with cross-pointer displays and the amount of training provided during Phase III. Both open-ended questions and rating scales were incorporated in the battery.

Wherever possible, quantitative data derived from pilot ratings and pilot responses were subjected to appropriate statistical tests and measures. All pilot comments were reviewed for indications of possible trends or useful insights.

Pilot Ratings of Head-Up Displays

After completing simulator data collection runs with one of the HUDs, each pilot filled out a 13 part questionnaire evaluating that particular display (see appendix G). The same questionnaire was used for both display types. Five of the parts were structured as rating scales where pilots were asked to compare a particular aspect, or operational feature, of the HUD in question with the conventional head-down display. In each case the scale values ran from a -10 (worse than) to a +10 (better than).

Three of the questions were structured to require "yes" or "no" responses; the other three questions were open-ended and asked for comments that would explain or amplify, the responses given to the rating scales.

Rating scales were analyzed by conducting a one-sample "t" test on a question-by-question basis. The following premises were involved:

1. A rating near or at the midpoint of the scale was equivalent to a judgment of "no difference" between HUD and head down.

2. On the basis of pure chance, subjects would tend to scatter their ratings throughout the available range (-10 to +10), with a mean equal to zero.

3. A distribution of scores significantly different from pure chance was a reliable indicator of pilot consensus.

Tables 15-30 contain summaries of the responses to the pilot rating scale questions and the specific comment questions. The numbers above the rating scale are the individual subject pilot numbers who assigned that rating.

Summary of Results

Results show that there were few significant differences among the pilot ratings comparing the FD HUD with the panel instruments. The only exceptions are found for questions 2, 3, and 11, and in each of these cases there was a significant preference for HUD as compared with panel instruments. The areas of preference were:

1. Lateral flightpath control (localizer) (question 2).

2. Vertical flightpath control (glide slope) (question 3).

3. Personal preference, considering safety, economics, passenger comfort: an overall rating (question 11).

For the FP HUD, subject pilots rated the display higher than the head-down panel on nine of the 11 scales. The two exceptions were:

1. General situation awareness and aircraft position (question 4).

2. Initiation of missed approach (question 9).

In summary:

1. Although the FD HUD was generally not rated significantly different from the head-down condition, it was rated as equal to or better than head down on all except two scales.

2. For all cases the FP HUD was rated superior to the head-down instruments. In nine of 11 cases these preferences were statistically significant.

Pilot Responses to Yes/No Questions

Questions 6, 9, and 10 of the HUD debriefing questionnaire required a simple "yes" or "no" response. Sixty percent of the pilots indicated that they used the head-down panel at least once for either primary reference or a cross-check on the HUD. Subject pilots 3, 4, and 11, all stated that they did not use the head-down panel displays with either HUD. Subject 8 used head-down information for the FD HUD approaches but not for the FP HUD. Use by subject 10 was the opposite; he used panel instruments for FP HUD but not for FD HUD approaches.

Although the size of user and nonuser groups did not depart significantly from "chance," as measured by statistical techniques, it is clear that the majority of pilots felt the need to monitor the panel instruments at least on occasion.

According to pilot comments, the panel instruments during FD HUD operations were monitored for go-around information, pitch attitude, general cross-checks, and DME. When using the FP HUD, pilots monitored their panel displays for go-around information, pitch attitude, sink rate, heading, power settings, general cross-checks, and position information. One pilot commented that he checked the HSI because he "did not feel confident of this aircraft position" with the FP HUD.

Pilot response to question 9 was unanimous; all pilots felt that both HUDs offered advantages over existing head-down displays. Those advantages mentioned most often in connection with the FP HUD were "more precise" control of airspeed and altitude and the conformal cues of the synthetic runway. Several pilots referred to how "easy" it was to fly the FP HUD in varied environmental conditions. A major perceived advantage was being able to see the "world" at breakout, and this advantage was also the major one attributed to the FD HUD by the subject pilots. In general, comments about the FP HUD were more explicit than those for the FD HUD.

In response to question 10, pilots were again in nearly perfect agreement. Only one of the ten subject pilots felt that there were no disadvantages to either HUD. In general the disadvantages noted were common to both HUDs. Comments included "insufficient" pitch reference, situation awareness, lack of IVSI, and a general reduction in forward visibility. Altitude hold was mentioned as a problem area peculiar to the FD HUD.

HUD Training Questionnaire

Pilot reactions to the training program for Phase III were assessed by means of an eight part questionnaire in which the subjects were asked to rate the various phases of training. Four of the eight questions dealt with such topics as the handout material, the classroom lectures, the video tapes employed, and the simulator training. The other two rating questions asked for an overall assessment and a prognosis for a revised and updated training program. Two questions were devoted to soliciting general comments from the subjects and desired changes, if any.

Quantitative Results

Tables 31 to 36 are summary plots of the training questionnaire data. In all cases the distribution of pilot responses was significantly different from chance. As a group, the pilots felt that all phases of HUD training were highly effective. They also tended to give a high overall rating to the training program.

When the subjects were asked if an upgraded training program might produce different results, the ratings, although still statistically significant, tended to show more scatter. This apparent uncertainty applied only to the FD HUD training. Ratings for the FP HUD were much more consistent, that is, they showed a smaller scatter. FP HUD ratings were also slightly higher, although the difference between the two HUDs was not statistically significant.

Pilot Comments

The pilots made relatively few comments in response to the training questionnaires. Most of the comments related to topics such as editing the handout materials and general structuring of the program. In general the pilots felt that the training program was quite good; they made no specific comments that reflected a general inadequacy in any given area of training.

Comments relating to the FP HUD training were similar to these comments; they sometimes reflected technical problems encountered during the study rather than inadequacies in the training program. Certain problems, such as simulator motion failures, equipment breakdowns, and software failures, were common to both types of HUD training and are, therefore, reflected in both questionnaires.

Crew Procedures and Callouts

Crew procedures used in the Phase III HUD study were evaluated by means of a seven part questionnaire. Pilots were unanimous in finding the copilot callouts useful during the study, and all pilots felt that, as the Captain, they would use a HUD during airline operations if it were available. Pilots also predicted that repeating the study using different procedures would produce little or no change. None of the pilots felt that there were too many callouts.

Pilots were also asked to provide specific recommendations as to appropriate changes in crew procedures or callouts. In response, six of the ten pilots indicated that the pilot *not* flying should make all or most of the callouts. Two of the subjects recommended specific changes in the callouts, but did not indicate which crewmember should make these calls.

Simulation Debriefing

One of the major concerns of any laboratory experiment concerns the element of realism. In any attempt to answer operational questions, it is imperative that the laboratory adequately "simulate" the "real world." Although the theoretical arguments as to the required degree of simulation fidelity were avoided, the pilots were asked to evaluate simulator "realism" by rating various simulator characteristics. The results are summarized in the following paragraphs.

Flying Characteristics

When pilots were asked to rate simulator flying characteristics as "exactly like the B-727" (10) or "totally unlike the B-727" (0), their responses were widely scattered, ranging from a high of 9 to a low of 2. Pilot opinion was widely spread, and the distribution was not statistically different from pure chance. It is interesting to note that those subjects who were most enthusiastic about the head-up display concept tended to rate the simulator flying characteristics higher than those subjects who either had some difficulty with the HUD concepts or experienced a long waiting period because of simulator problems.

Pilots were asked to rate simulator visibility effects as "like the real world" (10) or "unlike the real world" (0). The mean rating was 7.6 on a 10-point scale with a low rating of 4 and a high rating of 9. In this case, group opinion was uniform and it differed statistically from pure chance.

Wind and Turbulence

Whereas the mean rating for wind and turbulence of 6.3 did not depart significantly from chance, the general distribution of ratings was bimodal. The ratings of three subjects clustered at 4, and the rating of three subjects clustered at 7. Ratings range from a low of 3 to a high of 10. Pilot opinion was clearly divided on wind and turbulence. Forty percent of the group felt that wind conditions were less than realistic while 60 percent of the group felt that they were quite realistic.

Runway Obstructions

Pilot reactions to the runway obstructions employed in the study were uniform and significant. The group mean rating of 8.9, with a standard deviation of 1.1, indicates that pilots felt that the runway obstruction was quite realistic.

It should be noted that, although pilots had been instructed during training to watch out for unexpected conditions such as severe wind shear, reduced ceiling, runway obstructions, etc., they received no warning before being exposed to such conditions in the data-taking portions of the study. In all cases in which the runway obstruction was introduced, pilot response was dramatic.

Repeat of Study

Although the pilot ratings tended to be scattered from a low of 3 to a high of 10, the general rating indicated that most subjects felt that reproducing the study using an aircraft rather than a simulator would do little to change the results or conclusions.

Distribution of Pilot Scores

Examination of the distribution of pilot responses shows that some pilots tended to rate consistently on the low side of the distribution, while others consistently rated on the high side. For example, ratings of subject 6 were always below the mean, while ratings of subjects 4 and 10 were above the mean 100 percent of the time. Further inspection reveals that subjects 3 and 5 rated below the mean 80 percent of the time, while subjects 2, 8, and 11 rated above the mean 80 percent of the time. While such a conservative/liberal bias was not totally unexpected, it does raise some questions.

When the test-subjects data runs were reviewed for possible answers, it was noticed that those subjects who were "low" raters had experienced severe or repeated technical problems during the course of their simulator runs. These problems resulted either in delays, which resulted in interruptions and unscheduled waiting periods during the data runs, or in simulator failures, which produced unexpected control responses in the simulator handling or motion characteristics. "High" raters, on the other hand, experienced none or fewer simulator breakdowns, and, in general, experienced fewer frustrating delays. It does appear, therefore, that personal evaluations of simulator effectiveness were at least partially affected by the subjects' personal experiences during the course of the study.

Supplemental Questionnaire

After the study was completed, a supplemental questionnaire was sent to the pilots to get additional information on several issues. The pilots were asked if they had previous experience with a cross-pointer flight director display. All pilots in the study currently fly aircraft equipped with the single-cue flight-director display. Answers revealed that all except one of the subject pilots had extensive line experience with a cross-pointer flight director.

Pilot Response Summary

The following paragraphs summarize the pilot responses to the supplemental questionnaire:

1. Nine of the ten pilots felt that they had sufficient practice with the flight simulator prior to testing. One subject said that 1 to 2 hr "might" help, and one subject suggested adding 4 to 20 practice hr. This subject felt at 20 hr of training on the HUD would give a better basis for comparison because this is "normally the amount of time in the simulator given to head-down instruments by the airlines."

2. Only one of the subjects had no previous line experience with a cross-pointer flight director. He did not, however, feel that additional time was needed for further training on the use of this display.

3. Six of the ten subjects indicated that, during line operation, they typically used the flight director for "tight" tracking and monitored the raw data, whereas three of the subjects said that they tracked the flight-director command signal "loosely."

4. When asked about airline policy and flight director usage during nonprecision approaches, four subjects said that the flight director was not used during nonprecision approaches; one said that it was used; two said that use was optional; and two subjects said that they used raw data.

5. Forty percent of the subjects said that further practice would have improved their FD HUD performance, whereas 60 percent of the subjects said that further practice would not have helped. Those who felt that additional time would be useful estimated the amount of additional simulator practice time to be 10 to 20 hr.

6. In the case of the FP HUD, 70 percent of the subjects felt that additional simulator practice time (estimates ranged from 1 to 15 hr) would have improved their performance.

DISCUSSION AND CONCLUSIONS

This discussion is based primarily upon the formal results of the Phase III experiment as reported in the previous paragraphs. However, wherever possible, other sources of information are considered as well, including the intangible but valuable experience with head-up displays that has accumulated during the course of the program.

Because the primary objective of the study was to determine the potential advantages and disadvantages of the head-up display *concept* for line operations, much of the discussion is directed toward generic issues; that is, this study was not intended to be a *product* evaluation, but rather a concept evaluation. Obviously, it was necessary to use a specific implementation of the HUD concept, and the results herein are given for two HUD concepts. In this section, those device-specific results are interpreted in terms of their implications for the broader, more generic issues.

In this discussion, two major questions are addressed: (1) Are there advantages and benefits to be gained by using head-up displays in civil-transport operations? (2) Are there problems associated with their use?

Advantages and Operational Benefits of HUDs

The most general statement that can be made regarding the results of the objective performance maneuvers used in this experiment is that, when compared with the conventional instrument panel, both the FD HUD and FP HUD improved the accuracy (i.e., smaller errors) and precision (i.e., smaller dispersions) of pilot control of numerous flight parameters during approaches in a variety of environmental and operational conditions.

During ILS approaches, both the localizer and glide slope tracking performance was better for both HUDs than the NO HUD case, with the FP HUD showing the best performance. The magnitude of the performance differences is of great interest. For example, localizer error was reduced by better than a factor of 2 when using the FP HUD. Similar changes are seen for glide slope error. These two parameters were determined to be statistically significant. However, it is important to distinguish between statistical significance and operational significance. Statistical significance is simply a measure of the probability that an observed difference is caused by experimental treatment and not by chance fluctuations in the measured variables that is, a type of unwanted "noise." Statistical significance implies little, if anything about operational significance. In this light, it is interesting to look closely at these data. For example, for the NO HUD case in the approach segment where stabilized localizer tracking is expected (and operationally important), the rms localizer error averages 0.13°. Performance with the FP HUD averages 0.06°, a ratio of 2.2:1. Translated into "dots" deflection on the raw data localizer, however, these differences appear to be much smaller; 0.13° corresponds to approximately 0.1 dot deflection.

In order not to lose or obscure some important individual performance characteristics by only using summary statistical data, considerable effort was spent examining the outlier data points represented by the maximum and minimum values for the various parameters. For example, in the glide slope and localizer tracking data, the larger values almost always occurred on runs that started at the 4000 ft starting altitude. On these runs, the pilots overshot glide slope and localizer during the intercept maneuver and by the time they had begun the recapture maneuver, they were into the approach segment. The reasons for overshooting during the intercept are discussed in the Results section and will be addressed in the Potential Problems section that follows. However, it is important to recognize that during these runs, once the pilot recognized the overshoot and started to recapture, the task was easily accomplished using either of the HUDs. This has some practical significance since in line operations, deviations from otherwise normal approaches can be expected occasionally and new displays must provide the pilot with the capability to handle them.

The airspeed performance measures for all displays across all conditions showed that remarkably consistent performance was obtained. Since the digital readout of airspeed and the airspeed error worm available in both HUDs and the potential flightpath symbol found in the FP HUD only were new presentations, the pilots' acceptable level of performance with them is significant. In response to the question about speed control and thrust management, the pilots preferred both HUDs over the instrument panel but only the FP HUD results were statistically significant. It would appear that the greater acceptance of the FP HUD in this area is to a large degree due to the addition of potential flightpath information.

One area in which the FP HUD was apparently beneficial was in the nonprecision approach. Because of the unique potential afforded by use of a conformal flightpath element, which the pilot can "fly to" a desired touchdown point on the runway, the final approach vertical profile is much closer to the ideal 3° glide slope. When using the FD HUD and NO HUD, the pilots showed a marked tendency to wait too long to begin the final descent to the runway from the MDA. However, with the FP HUD, crossing altitudes (and associated deviations) at the middle marker and the threshold correspond very closely with those obtained on the full ILS approaches. Subject pilot comments and observer data strongly corroborate these findings. This observation may be one of the more significant ones with regard to a FP HUD. There are other ways to improve precision or reduce dispersion during approach and landing operations, a properly designed autoland system being one good example. However, autoland requires appropriate ground facilities. A FP HUD is self-contained and can be used for any kind of approach to any runway. Because of economic and operational realities, it is reasonable to assume that a significant proportion of jet-transport approaches will continue to be flown manually and without electronic-glide slope information. The results of this study demonstrate that a properly designed FP HUD may contribute to improved precision in these kinds of operations, but it is also necessary to point out that this simulation did not include a visual-approach-slope-indicator (VASI). The benefits of this device are widely recognized but it does have limitations, one being that it cannot be used below approximately 200 ft. It is beyond the scope of this study to determine which of the two techniques offers the best solution to the visual approach problems, but it seems likely that they may offer complementary benefits.

In the flare and landing segment, pilots performed best with the FP HUD. The scatter of data at the runway threshold window was minimum and the landing footprint showed the least scatter. Sink rate at touchdown was smallest for the FP HUD but the mean distance down the runway was slightly longer than for the NO HUD runs. This is most likely due to the flare guidance information provided in the FP HUD. Past experience demonstrated that following the flare line closely often resulted in reduced sink rates at touchdown but at some greater distance down the runway. However, this seemed to be counterbalanced by the reduced dispersion in landing distance across all runs.

On the other hand, the FD HUD data did not follow the same pattern seen in the previous segments. Performance was the same or worse than for the NO HUD approaches. Some reasons for this are discussed in the next section. However, pilot comments indicated there was still a preference for the FD HUD over the NO HUD condition.

Potential Problems with HUD

One area of potential concern with regard to HUD design relates to the integration of horizontal and vertical situation information. Although the FP HUD contained enough information to support the localizer intercept maneuver, some of the subject pilots had difficulty determining their horizontal situation from this HUD during that phase of operation. The exact cause of this difficulty was not determined. It may have been due to insufficient training in the use of the symbology in that particular segment of flight. In response to one of the questionnaire items, many pilots indicated that they used the HSI to cross-check or verify their position during the radar vectoring part of the data scenarios. This problem was noted frequently during subject pilot training.

Another possible cause might be the design of the symbology itself for that maneuver. These subjects had all accumulated vast experience with panel displays that use separate instruments for horizontal situation information (HSI) and vertical situation information (ADI). Position and orientation with respect to ground facilities is relatively easy with a conventional HSI and/or radio magnetic indicator (RMI); both have arrows or flags, which "point to" the facility, and information which pictorially displays the relative positions of aircraft and facilities. With the advent of electronic displays, including HUD, it is possible to integrate horizontal-and vertical-situation information into one common display format. The effective design of such displays is not an easy task, however, and subject pilots offered many comments about this problem. The major factor accounting for the most adverse pilot comments seemed to be the fact that the perceptual frame of reference for the HUD is oriented vertically compared to the horizontal frame of reference for the HSI. All of these observations may have implications for HUD operating procedures. Given the difficulties observed with both HUD formats used in this study, especially during the approaches from 4000 ft altitude with the crosswind and tailwind cases, it is fair to say that HUD design and/or training procedures might be improved. It is also possible that full time use of a HUD during terminal area maneuvering might not be a desirable operational objective. Design efforts might focus instead upon the straight-in approach and landing operations; terminal-area maneuvering and intercept operations might continue to be best accomplished by using conventional panel instruments.

One of the major issues often raised with regard to head-up displays is that of attentional or perceptual switching. Past experience with the HUD concept indicates that there is a definite attentional "cost" associated with using a HUD. While it is true that the physical movement of the head and eyes required to scan the instrument panel and the outside world is drastically reduced by using a HUD, it is still necessary for the pilot to mentally scan, that is, to alternate his attention between the HUD symbology and the outside visual cues. This scanning appears to require deliberate action on the part of the pilot; the mere presence of a stimulus in the visual field does not guarantee that it will be perceived.

Several examples of this were noticed during the Phase III experiment. One case involved the use of the FD HUD. Pilots commented that in following the command dot closely, they were unable to attend to the outside scene. Similarly, in the flare segment where the flight director information was not valid, it became difficult to ignore it and use the outside scene alone. Another example involved the use of the flare guidance in the FP HUD. If the pilot followed the flare line very closely but to the exclusion of the outside scene, he would get a low sink rate at touchdown but possibly at considerable distance down the runway.

Another example was the runway obstruction anomaly. In the 13 runs where this anomaly was introduced into the simulated external visual scene, the pilots recognized the obstruction and executed a missed approach in all cases. However, in each case there was a delay in the pilot recognition of the presence of the anomaly. It was not possible within the experimental design to determine the exact source or the operational significance of the delays. It is possible that the simulation itself might have contributed to the generation of the observed phenomena either through the physical and visual qualities of the simulator or through the psychological effect of the research environment.

Two important consequences follow from these observations. First, the design of the HUD may radically alter this "attentional switching," and it may be possible to design a HUD in such a way that scanning behavior is considerably enhanced. A specific example is found in the FP HUD used in this study. For the precision approach case, this HUD is "self-contained," that is, the display contains sufficient information to fly the entire approach, flare, and landing maneuver without references to outside visual cues. The display does not inherently require "attentional scanning" of the external scene. A simple change to the display, namely, the elimination of the flare guidance symbol, would change this situation. At some point prior to and during the flare, the pilot would be forced to attend to the visual environment. It seems probable that this necessity would affect other related tasks, including the detection of obstacles on the runway.

The second area of consideration regards the importance of training and experience and the influence of these factors upon the "attentional scanning" task. Several project personnel noted that the task of scanning the HUD, including directing attention to the runway environment, appeared to become easier as proficiency and experience with either of the HUDs increased. It is reasonable to believe that "attentional scanning" is a skilled behaviour that can be acquired through appropriate training and experience; a pilot's development of conventional instrument flight skills is an obvious example. A unique training requirement may exist in the case of HUD. It is therefore recommended that programs for training line pilots in the operation and use of a HUD include elements specifically directed toward this "attentional scanning."

As with any new technology, it is never possible to anticipate all potential problems. Thus, a cautious, conservative approach should be taken during the early stages of line operations using these devices. As experience is gained with the displays, training programs, and operating procedures, problems can be identified and solved in an orderly and safe manner.

Observations and Conclusions on Secondary Issues

In addition to evaluating the impact of HUD upon system performance during approach and landing operations, Phase III was designed to make a preliminary assessment of other issues not directly related to HUD design. The two most important are crew training requirements and flight-crew operating procedures associated with HUDs. Although it is beyond the scope of this study to conduct a thorough, systematic evaluation of the various approaches that might be taken to resolve these issues, it is possible to comment upon both on the basis of experience gained during the present program.

As indicated earlier, the subject-pilot training program was based upon current approaches to flight-crew training-program development. The decision to utilize a combination of handbook materials, classroom exercises, video tapes, slide materials, and simulation training was based on this consideration. The result was a training program that largely achieved its objective and had a generally high degree of acceptance by the pilots who participated in this experiment. On the basis of pilot performance at the end of the training program, it appeared that subject pilots generally understood the operational procedures and concepts involved in using each of the HUDs and that they were reasonably proficient in applying that knowledge. Some caution is necessary, however, since training requirements for the two HUDs were appreciably different. The FD HUD, excluding for the moment its nonprecision visual approach monitor (VAM) modes, was an easy concept for the pilots to grasp; essentially, it is a head-up equivalent of what they have flown for years. The flightpath displays, including the VAM modes on the FD HUD, were somewhat more difficult to learn. For most line pilots, the concept of a flightpath or velocity vector symbol is a new one. Furthermore, an understanding of the relationship between the flightpath symbol and other display elements may require special training, particularly if the display is designed in such a way that some pilot discretion is allowed. For example, typically an aircraft is flown in level flight at the initial approach altitude until glide-slope capture occurs. With a FP HUD as implemented for this study, it is possible to conduct a smooth, gentle convergence maneuver by initiat-sequence and length of elements of the training program are "in the ballpark." It should be noted however, that learning ing a shallow descent when the glide-slope signal intercepts the flightpath symbol. Alternatively, the pilot can fly the glide-slope intercept in a conventional fashion. This added flexibility requires some additional training and/or experience before flight crews become fully proficient with the display. Similar comments apply to other features of the display, including flare guidance, MDA capture, and the use of the potential flightpath symbol for thrust management.

It is believed that the training program developed for this project represents a good starting place for an operational training program. The general approach and the is not complete after a training program as short as the one used for this study. As the pilot gains more experience with the concept under a wider variety of conditions, he will become more proficient in its use. Thus, an operationally acceptable training program should include a period of line experience, perhaps with higher than normal minima. During this time the line pilot could consolidate his knowledge and skills. The specific details of this program would depend upon the display, the air carrier, and its operating procedures; they would have to be determined on a case-by-case basis.

The question of operating procedures suitable for use with a HUD is in many ways more complex than the training question. The procedures used in this study worked well and were acceptable to the subject pilots. However, it is believed that many other possible procedures would work equally effectively. Generally, the development of suitable operation procedures is a matter of airline and regulatory philosophy, it is not generally an empirical issue. The philosophy adopted herein was straightforward: an attempt was made to maximize crew coordination and communication by distributing callouts and acknowledgments in such a way that both pilots were "in the loop" and both could cross-check and monitor each other through the use of independent, redundant displays. The fact that the copilot monitored the approach by using the instrument panel was, in part, because good HUD information was present only on the left side in the simulator. However, it also appears that this approach maximizes the redundancy of information, even in aircraft equipped with a dual HUD installation. Thus, if there are problems with attention switching, flash blindness, or other factors uniquely associated with HUDs, the conservative approach to the development of flight-crew operating procedures would be to have the pilot not flying monitor the approach by using conventional instrument information. Obviously, this is partly a system-design question. A detailed examination of these issues is beyond the scope of this study.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, CA 94035, February 8, 1982

APPENDIX A

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APPENDIX B

FLIGHT DIRECTOR HEAD-UP DISPLAY

Phase III Training Handbook

INTRODUCTION TO HEAD-UP DISPLAYS

Head-up displays have been in use for several years. Probably the most familiar form of head-up display is as the "sight" portion of a weapons delivery system on military aircraft. On these displays, commands and information are displayed directly in the field of view of the pilot/gunner. With advances in head-up technology, displays are being proposed that would incorporate aircraft operative modes other than for weapons delivery.

Head-up displays may be advantageous to the pilot. If primary aircraft-operating information is presented directly within the pilot's field of view, he has less need to scan the instrument panel and divide his time between the inside (cockpit) and outside worlds.

As the need to "come inside" for information is reduced, there may be a greater proportion of time available to scan outside, and, therefore, the adaptation of head-up displays should lead to greater aircraft safety during operation.

The head-up display may, however, present some disadvantages. Superimposed images may be distracting and may clutter the external visual scene, "masking" objects of vital interest to the pilot. The probability of errors may increase, with a reduction in safety rather than an increase. This study is designed to provide insight into some of these issues and questions.

Head-up displays (or HUDs) are of many forms, ranging from simple glass plates to acrylic blocks. Display information ranges from simple steering commands to complex "conformal" displays in which selected dynamic display elements bear a one-to-one relationship to the "real" or outside world.

Phase III – Scope

Within the Phase III HUD study, the area of HUD application is limited to final approach, landing, and go-around piloting operations. Two types of HUDs will be examined, an unreferenced flight director and a conformal flightpath display. The flight director essentially duplicates the information presently displayed on the instrument-panel flight director and presents this information along with airspeed, altitude, and attitude within the visual field of view. The conformal display presents information some of which is not presently available on standard aircraft instruments.

The pilot's primary task in any case is the same: He flies selected instrument approaches and landings under various environmental conditions. These approaches, conditions, and pilot procedures provide a reasonable simulation of airline operations for experimental purposes.

All pilots in this study will fly experimental runs using three display types: (1) the standard instrument panel; (2) an unreferenced flight-director HUD; and (3) a conformal flightpath HUD.

Phase III – Pilot Training

During training for Phase III, each pilot will receive both classroom and simulator training in the use of the head-up displays.

Classroom training– During classroom training, the pilot will become familiar with HUD symbology and operation by means of a training pamphlet and visual aids such as slides and video tape. In all cases pilots will be trained in both ILS and nonprecision modes of operation. Pilots will be asked to fill out worksheets and questionnaires to determine their understanding of the display symbology. After the classroom training, pilots will fly specific training runs in the simulator.

Simulator training– In the simulator, pilots will fly 11 different training runs, consisting of varying conditions of visibility and winds as well as course offsets. Each pilot will receive 2 hr of training in the classroom and 2 hr in the simulator for each HUD display, plus 1 hr of simulator orientation. Thus each pilot will receive 4 hr of training (in the classroom) and 5 hr in the simulator, and an additional 1-2 hr will be spent for debriefings and filling out questionnaires.

HUD TYPE I FLIGHT-DISPLAY

HUD Type I is an unreferenced flight-director display. In concept, the display provides guidance without specific reference to any ground object. Using processed information, the display provides a fly-to command in geographical coordinates.

General Description

Command guidance is provided on the display by a movable dot symbol located at the apex of a stack of three crossbars. The pilot's task is to fly a "fixed" circle onto the dot. This fixed circle represents the aircraft, and the wings of the circle are parallel with the lateral axis of the aircraft. While the aircraft circle remains in the center of the display, the command dot moves parallel to the horizon for heading (azimuth) commands and perpendicular to the horizon for height (elevation) commands (see fig. 23).

The aircraft circle is also equipped with a variable-length vertical fin that bisects the circle. As the velocity of the aircraft deviates from a given reference speed, the vertical fin will project above the circle to show positive error (fast) and below the circle to show negative error (slow). Speed-error is equal to a one-dot deviation for every 10 knots of airspeed. When the artificial horizon is not visible, such as at extreme pitch angles, the crossbar stack provides the pilot with a roll reference as it rotates about the command dot. It also serves to assist the pilot in locating the command dot.

Supporting Elements

An artificial horizon is provided in the form of a bar with a gap spanning the aircraft circle. It shows bank angles by rotating with the earth's horizon and shows elevation ("pitch attitude") at a reduced scale. Other supporting elements are digital readouts of altitude (upper right), airspeed (upper left), and engine pressure ratio (lower left). Additional information includes a heading scale at the top of the display, raw glide slope (on the right), raw localizer (on the bottom), and instantaneous vertical speed (on the left). The last information provided is an annunciator in the lower right-hand corner of the display, which annunciates the various flight-director modes. Directly above this indicator, a flashing designator appears momentarily to announce outer-, middle-, and inner-marker crossing points.

Annunciator Legends

The five basic modes of interest within the present scope of study are annunciated in the lower right-hand corner of the display as:

1. GS CAP (glide-slope capture)
2. GS APR (glide-slope approach)
3. ALT HLD (altitude hold)
4. HT RTE (height rate)
5. GO ARD (go-around)

In typical flight-director usage, the annunciator will read GS CAP during the level segment of a beam intercept in a precision approach and GS APR during the ensuing descent. In a nonprecision approach, the legend reads ALT HLD when altitude hold is selected, which is usually set before final-approach fix and at MDA. When the nonprecision mode is being used and altitude hold is not selected, the annunciator will normally read HT RTE. In the HT RTE mode, the flight-director command dot is preprogrammed for a 1000 ft/min rate of descent. When the go-around mode is selected, a predetermined pitch attitude is commanded and GO ARD is annunciated in the "window."

Driving Signals

During precision approach the flight-director command dot is driven by signals derived from the ILS deviations in azimuth and elevation (localizer and glide slope). For the nonprecision approach, the glide-slope deviation is unavailable and an alternative driving signal is required. This signal is generated by comparing the actual rate of descent of the aircraft with a desired rate of descent. In actual practice this desired rate of descent would be selected by the pilot after a consideration of airpeed, altitude, and desired glidepath. During this study, it is set at 1000 ft/min for descent to MDA. When altitude hold is engaged, level flight is commanded. When the winged circle is alined vertically with the dot, the pilot will achieve his desired rate of descent or "height rate." In the nonprecision approach, the raw glide slope is blanked to reduce clutter.

MAJOR DISPLAY ELEMENTS

The major display elements consist of (1) peripheral elements whose positions and orientations are fixed relative to the aircraft; and (2) central elements whose positions and orientations generally move as functions of changes in aircraft control inputs and aircraft orientation. One exception in the central elements is the aircraft symbol, which is fixed in the center of the display.

Peripheral Elements

Peripheral elements of this display include the following:

1. Heading scale located at the top of the display and numbers at the 10° marks with intermediate marks at the 5° intervals.

2. Airspeed and altitude digital readouts on the upper left and upper right of the display.

3. Engine-pressure-ratio digital readout at the lower left of the display.

4. Annunciator callouts at the lower right of the display.

5. Instantaneous-vertical-speed-indicator scale along the left side of the display; at the bottom is the localizer scale and on the right is the glide-slope scale.

Central Elements

Central elements, with the exception of the aircraft symbol, have a general geographical relationship to the outside world as follows:

1. The speed-error tape attached to the aircraft symbol maintains a constant relationship to the aircraft reference and is always perpendicular to the wings of the aircraft symbol.

2. The artificial horizon spanning the aircraft symbol provides pitch and roll information.

3. The command dot represents the crossing points of the lateral and pitch steering commands.

4. Three bars of graduated length are grouped below the command dot and provide roll information at extreme pitch angles where the horizon is not in view; they also guide the pilot's eyes to the command dot.

SAMPLE PROBLEMS

Sample situations as depicted on the head-up display (HUD) are presented in this section. For each situation, a set of initial conditions or constraints is given, and the pilot is asked to analyze the display and recommend corrective action, if necessary.

Situation A

Initial conditions are:

1. Reference airspeed: 135 knots
2. Altitude: 1400 ft
3. ILS approach
4. Runway heading: 090°
5. Visibility: 5 miles
6. Ceiling: 1000 ft

As the pilot, you are instructed by ATC to maintain a 1400-ft altitude and 135 knots to the outer marker. You have reached the outer marker and are cleared for landing. Refer to figure 24 and circle the correct answer in the following:

1. Airspeed:	Fast	Slow	On	Unknown
2. Altitude:	High	Low	On	Unknown
3. Localizer:	Right	Left	On	Unknown
4. Glide slope:	High	Low	On	Unknown
5. Flightpath:	Climbing	Descending	Level	Unknown

From your analysis of the display, what corrective action, if any, would you take and why? Do you have sufficient information for analysis? If not, what additional information do you require?

Situation B

The initial conditions are the same as in Situation A. Refer to figure 25 and circle the correct answer in the following:

1. Airspeed:	Fast	Slow	On	Unknown
2. Pitch angle:	High	Low	On	Unknown
3. Heading:	Right	Left	On	Unknown
4. Flightpath:	Climbing	Descending	Level	Unknown
5. Sink rate:	High	Low	Normal	Unknown

After you consider figure 25, what corrective action, if any, would you take and why? Do you have sufficient information for analysis, If not, what additional information do you require?

Situation C

You are making a nonprecision approach to a runway heading of 90°, with an MDA of 450 ft, airport visibility of 5 miles, and a ceiling of 600 ft. Your reference airspeed is 135 knots and this is a localizer-only approach. The flight director is in the nonprecision mode (HT RTE) and is commanding a 1000-ft/min sink rate. Refer to figure 26 and circle the correct answer in the following:

1. Airspeed:	Fast	Slow	On	Unknown
2. Altitude:	High	Low	On	Unknown
3. Heading:	Right	Left	On	Unknown
4. Flightpath:	Climbing	Descending	Level	Unknown
5. Acceleration:	Increasing	Decreasing	Steady	Unknown

From you analysis of figure 26, what corrective action, if any, would you take and why? Do you have sufficient information for analysis? If not, what additional information do you require?

CREW PROCEDURES

Crew procedures practiced by major airlines for similar aircraft are modified and generalized for this study. The aircraft being simulated is the Boeing 727. However, the flight engineer's position is not simulated. The crew for this study is a captain, a copilot, and an observer. The observer will not function as part of the flying crew.

Pilot Duties

In all experimental cases, the left-hand seat will be occupied by the captain, the flying pilot for all experimental runs. The general duties of the captain require that, once the simulator is placed in "operate," he will fly the prescribed profile as given by the simulated air-traffic controller and terminate his flight with either a landing or a go-around, whichever is appropriate. The captain will ask the copilot to go through the final-descent checklist and handle landing gear and flaps. The captain will be assisted by the copilot only "as requested."

Copilot Duties

The copilot for all experimental runs will be an Ames employee. As copilot he will make flap and landing-gear-handle settings at the pilot's request. He will monitor airspeed, altitude, and aircraft attitude during final approach and make callouts as prescribed in the summary that follows. At the captain's request he will initiate and complete the final-descent checklist. He will respond to ATC communications and will initiate ATC communication at the captain's request.

SUMMARY OF FLIGHT-CREW PROCEDURES FOR HUD PHASE III

Captain (Pilot Flying)

The captain will determine the approach target speed by using V_{ref} (124 knots at 140,000 lb) plus one half the headwind component plus the gust factor. Total add-on should not exceed 20 knots.

The captain should call for landing gear and flaps as required. The captain should also request the copilot to select desired flight-director modes.

Standard callouts for the captain are:

Outer-marker crossing altitude, target speed, minimums and time to missed approach point (MAP) (nonprecision only)

1000 ft AGL

100 ft above minimums

Minimums

In addition to the standard callouts, the captain should verbally announce ground contact, approach lights, or runway threshold as appropriate (HUD approaches only).

Copilot (Pilot Not Flying)

The copilot will handle all ATC communications and operate the landing gear, flaps, and flight-director-mode control panel as requested by the captain.

The copliot should acknowledge all standard callouts by the captain.

The copilot will monitor the approach and will callout the following deviations:

Airspeed deviations in excess of +10 or -5 knots.

Localizer and glide-slope deviations in excess of 1 dot.

Below 1000 ft above field level (AFL), sink rates in excess of 1000 ft/min.

The copilot will monitor time on nonprecision approaches and will call out "Missed Approach Point."

For head-down approaches, the copilot will announce "ground contact, approach lights, runway threshold" as appropriate.

APPENDIX C

FLIGHTPATH HEAD-UP DISPLAY

Phase III Training Handbook

INTRODUCTION TO HEAD-UP DISPLAYS

Head-up displays have been in use for several years. Probably the most familiar form of head-up display is as the "sight" portion of a weapons delivery system on military aircraft. On these displays, commands and information are displayed directly in the field of view of the pilot/gunner. With advances in head-up technology, displays are being proposed that would incorporate aircraft operative modes other than for weapons delivery.

Head-up displays may be advantageous to the pilot. If primary aircraft-operating information is presented directly within the pilot's field of view, he has less need to scan the instrument panel and divide his time between the inside (cockpit) and outside worlds.

As the need to "come inside" for information is reduced, there may be a greater proportion of time available to scan outside, and therefore, the adaptation of head-up displays should lead to greater aircraft safety during operation.

The head-up display may, however, present some disadvantages. Super-imposed images may be distracting and may clutter the external visual scene, "masking" objects of vital interest to the pilot. The probability of errors may increase with a reduction in safety rather than an increase. This study is designed to provide insight into some of these issues and questions.

Head-up displays (or HUDs) are of many forms, ranging from simple glass plates to acrylic blocks. Display information ranges from simple steering commands to complex "conformal" displays in which selected dynamic display elements bear a one-to-one relationship to the "real" or outside world.

Phase III – Scope

Within the Phase III HUD study, the area of HUD application is limited to final approach, landing, and go-around piloting operations. Two types of HUDs will be examined, an unreferenced flight director and a conformal flightpath display. The flight director essentially duplicates the information presently displayed on the instrument-panel flight director and presents this information along with airspeed, altitude, and attitude within the visual field of view. The conformal display presents information some of which is not presently available on standard aircraft instruments.

The pilot's primary task in any case is the same: He flies selected instrument approaches and landings under various environmental conditions. These approaches, conditions, and pilot procedures provide a reasonable simulation of airline operations for experimental purposes.

All pilots in this study will fly experimental runs using three display types: (1) the standard instrument panel, (2) an unreferenced flight-director HUD, and (3) a conformal flightpath HUD.

Phase III – Pilot Training

During training for Phase III, each pilot will receive both classroom and simulator training in the use of the head-up displays.

Classroom training– During classroom training, the pilot will become familiar with HUD symbology and operation by means of a training pamphlet and visual aids such as slides and video tape. In all cases pilots will be trained in both ILS and nonprecision modes of operation. Pilots will be asked to fill out worksheets and questionnaires to determine their understanding of the display symbology. After the classroom training, pilots will fly specific training runs in the simulator.

Simulator training– In the simulator, pilots will fly 11 different training runs, consisting of varying conditions of visibility and winds as well as course offsets. Each pilot will receive 2 hr of training in the classroom and 2 hr in the simulator for each HUD display, plus 1 hr of simulator orientation. Thus each pilot will receive 4 hr of training in the classroom and 5 hr in the simulator, and an additional 1-2 hr will be spent for debriefings and filling out questionnaires.

HUD TYPE II CONFORMAL DISPLAY

Introduction

Display elements of the Type II HUD are intended to provide complete flight guidance and navigation information, as well as situation data, for terminal-area maneuvering, landing, and go-around.

General Description

The display field of view is 24° wide and 21° high. The field is horizontally symmetrical about the aircraft's longitudinal axis but is depressed 5.5° in the vertical plane. Being designed as "conformal," some elements of the display overlap earth references and move at the same angular scaling as the outside visual references. A primary feature of the display is a velocity-vector symbol that provides an instantaneous indication of the aircraft's flightpath. Additional elements include altitude, airspeed, horizon, pitch ladder, glide-slope and localizer bars, heading scale, airplane symbol, synthetic runway, speed-error tape, and a potential flightpath marker.

Sensor Requirements

The basic display is designed to be operated by electrical signals from an air-data system. Signals representing indicated airspeed, true airspeed, barometric altitude, and altitude rate are required. Navigational information displayed can include ILS glide slope and localizer (or VOR), marker beacon, radio altitude and distance measuring equipment (DME).

Manual settings available to the display computer include:

- Runway headings
- "Target" airspeed
- Field altitude
- "Reference" altitude (assigned, MDA, or DH)
- ILS glide-slope angle

Aircraft Fixed Elements

Those display elements fixed with reference to the "frame" of the display (and to the aircraft axis) are shown in figure 27 and are as follows:

1. Aircraft reference symbol
2. DME reading
3. Marker-beacon passage annunciation
4. "Limit angle-of-attack line"

Attitude References

The presentation of roll, pitch, and heading for the case when the runway heading (localizer heading) is displayed is shown in figure 28 for an angle of bank of 6°, a pitch angle 6° above the horizon, and a heading of 087°, 3° off the preset runway heading of 090°. The 5° and 10° interval markers (above the horizon) are centered laterally about the aircraft-reference symbol, but the 1° markers above the horizon and the attitude reference below the horizon are centered laterally about the runway-heading indication. If the difference between aircraft and runway heading is greater than 9°, these latter references are centered laterally about a point on the horizon ±9° from the aircraft heading (see fig. 29). If "within ILS tolerance" conditions (defined later in the sections on VOR/Localizer Navigation ILS Glide Slope) are satisfied, the attitude references below the horizon do not appear.

Flightpath Symbol Array

As previously indicated the display features a symbol that defines the direction of the instantaneous flightpath of the airplane relative to the longitudinal axis of the airplane and to inertial (earth) references. This symbol is intended for use as the primary controlled element of the display, thus enabling the pilot to control directly his longitudinal flightpath and track rather than indirectly control it through the more conventional control of pitch attitude and heading. In order to take advantage of the flexibilities inherent in a CRT conformal display, speed and altitude display elements are arrayed with the flightpath symbol to minimize the visual field encompassing all the continuously controlled flight parameters. The flightpath symbol and related elements are shown in figure 30, and they are shown in the context of aircraft attitude in figure 31.

Flightpath symbol– As illustrated in figure 30, this display element is a circle with "wings" deflected 30° down from the horizontal and terminating in short horizontal "wing tips." The center of the circle defines the direction of the flightpath. The symbol remains fixed in roll with reference to the aircraft.

Indicated airspeed– A digital presentation of indicated airspeed is located outboard and below the left "wing tips" of the flightpath symbol. Upon interrogation, the digits will indicate target speed.

Speed error– The deviation in indicated airspeed from a preset target speed is displayed by a tape, or "worm", extending vertically from the left tip of the flightpath symbol, upward for "fast," at a scaling of 1° subtended visual angle for 4 knots error. If speed is more than 5 knots below target, the tape is flashed at 4 cycles/sec.

Acceleration along flightpath– Referenced to the left tip of the flightpath symbol is an indication of the longitudinal rate of change in the speed of the aircraft. The signal used to drive this symbol combines, by complementary filtering, inertial acceleration (high frequency) and rate of change of indicated airspeed (low frequency). Appropriate scaling of the deflection of this symbol (approximately 3° subtended angle per knot per sec) allows its interpretation as an indication of the flightpath angle that could be maintained, at constant speed, at the aircraft's current thrust and configuration. Earlier mechanizations of this concept have been termed "potential flightpath."

Altitude– A digital readout of altitude is located to the right of and below the right tip of the flighpath symbol. Upon interrogation the digits will read target altitude. The digital readout represents main-gear altitude above the terrain when this value is less than 200 ft; otherwise the digits represent altitude above the runway, derived from air data reflecting barometric altimeter setting and on input value of runway altitude. When the aircraft altitude is within 30 ft of the target altitude, the digits flash at 4 cycles/sec.

VOR/Localizer Navigation

Aircraft position relative to the approach course is indicated by the symbol shown in figure 32. The distance from the course is proportional (at a given range from the station) to the horizontal distance between the reference heading and the symbol segments shown. In the example, the aircraft is left of course and on a converging heading. This symbol is fixed vertically with reference to the horizon, its center element depressed below the horizon by an angle equal to the ILS glide-slope angle. Lateral deflection of the symbol is limited to ±11° from the reference axis of the display. If the difference between aircraft and reference heading is greater than 9°, or if the localizer error is greater than 2.5°, a "course-line" symbol appears (see fig. 33). This line originates at the horizon, ±9° from the aircraft heading, and is deflected right or left from the perpendicular to the horizon proportionally to the displacement from course. In the case shown, the aircraft is converging on a 090° course on a heading of 075°. If the heading were maintained, the "localizer" symbol would move from left to right, seeking its zero-error position coincident with the runway-heading indication (out of view to the right), and the "course line" would swing toward the perpendicular to the horizon that would be seen at course crossing.

ILS Glide Slope

In figure 34, the indication of error from the ILS glide slope is added in the form of a small circle and two horizontal line segments centered laterally on the localizer symbol. Error from the ILS glidepath is proportional (at a given range from the station) to the vertical distance between the "glide-slope symbol" and its zero-error reference defined by the center of the localizer symbol and the four short dashes previously identified. If the aircraft is below the ILS glidepath, the glide-slope symbol appears above the reference.

Runway Symbol

ILS data and the altitude above the runway are used to define the shape and position of a symbolic representation of the runway. This symbol will overlay the runway as seen in VMC. In figures 35 and 36, several configurations of combined ILS and runway symbols are shown, representing different positions of the aircraft relative to the ILS approach path. These sketches are intended to demonstrate the objective of the logic and scaling of the localizer and glide-slope symbols. In perspective, as an analog of an exterior view, the intersection of these symbols (denoted by the circle) can be visualized as an object on the ILS approach path some distance ahead of the viewer's aircraft. In figure 37, the flightpath symbol array is added to illustrate the normal mode of flying an ILS approach. If the flightpath of the aircraft is maintained and directed at the intersection circle, a pursuit course, converging on the ILS path, will be flown. The ultimate result will be the condition illustrated in figure 38, in which the viewer's aircraft can be perceived as being in trail behind the circle on the ILS path toward the runway.

Reference-Altitude Symbol

In HUD configurations not displaying ILS glide-slope information, the symbol illustrated in figure 39 is available for use to annunciate and capture a preselected target altitude. The distance of the symbol below the horizon is proportional to the aircraft's altitude above the reference altitude. In the illustration, the aircraft is descending on a 5° flightpath (~1000 ft/min) toward a target altitude (MDA) of 450 ft. Tracking the symbol with the flighpath symbol will result in a flare to level flight at 450 ft. Again the analogy of flying in trail behind another aircraft is seen, but this time it is in level flight.

Ground-Proximity Symbol

A symbol similar in geometry and operating principle to the reference-altitude symbol is provided as a landing-flare guide. In this case, the symbol is displayed below the horizon a distance proportional to a radio altitude measurement of the main-gear height above the runway. In figure 40, the symbol is shown rising from the bottom of the display as flare altitude is approached. In figure 41, the "flare" symbol is being tracked shortly before touchdown.

REVIEW OF MAJOR DISPLAY ELEMENTS

The major display elements can be divided into four general categories or elements: conformal elements bearing a one-to-one relationship and scaling to specific earth references; advisory elements that show certain relationships with the outside world; reference elements that provide general relationships within the display; and lastly, the dynamic and controllable elements.

Conformal Elements

Conformal display elements, or elements that match the real world in shape, size, and movement, include the following

1. Artificial horizon that overlays the real horizon and pitch, roll, and heading information.

2. Heading scale (combined with the artificial horizon).

3. Glide slope (only partially conformal). In initial stages of glide-slope capture it provides pitch-position information. Once on the glide slope, it helps to define (and will overlay) the touchdown zone on the runway.

4. Localizer (only partially conformal). Initially the localizer provides right or left steering reference; it is coincident with runway centerline only after localizer capture.

5. Runway symbol (fully conformal with real-world runway at all times). This symbol matches the real runway in size and pictorial orientation.

Advisory Elements

Advisory elements can be further divided into two classes: those that provide primarily cognitive information such as DME, marker beacon, speed error, altitude reference, acceleration marker, and airspeed reference; and those that provide spatial or geographic orientation, including heading scale, glide slope, localizer, and flare command.

Reference Elements

Elements that primarily provide spatial reference and have a stadimetric relationship to the outside world include the pitch ladder and fixed-depression references. To a certain extent the heading scale and horizon bar can be included in these elements. These references provide an aiming point in space at which to direct or aim the aircraft symbol and/or velocity vector. Pitch-ladder references start with positive pitch marks at 3° and progress every degree up to 20°. Major index marks are located at 10° and 20°. Negative pitch is defined by pairs of minor tick marks centered on either side of the reference heading and located at -5° and 10°. At -2.75°, and also centered on the reference heading, is a fixed depression line that is set at the glide-slope reference. (In the display shown, it is set at -2.75°, but it can be set to any desired glide-slope reference.)

Dynamic Elements

The dynamic elements referred to herein are those directly controlled or controllable by the pilot. These elements include the aircraft symbol, velocity vector, speed-error tape, and the acceleration marker. In each case, the symbol is directly responsive to a pilot control input such as pitch or roll commands, or a change in throttle position.

Head Up and Head Down

Further review of display elements is provided in figures 42(a) and (b), 43(a) and (b), and 44(a) and (b). Each figure shows both the head-up and head-down display of the same information. In figure 42(a) the aircraft is at approximately 500 ft altitude, airspeed 135 knots, on glideslope, and slightly to the right of the localizer. Figure 42(b) shows the same information on the head-down instrument panel. (Minor variations between the head-up and head-down display readings is the temporary result of simulator display drive signal calibration errors.) Figures 43 and 44 provide similar comparisons with the aircraft at 100 ft and the runway in sight, and at touchdown.

SAMPLE PROBLEMS

In this section are presented sample situations as depicted on the head-up display (HUD). For each situation, a set of initial conditions or constraints is given, and the pilot is asked to analyze the display and recommend corrective action, if necessary.

Situation A

Situation as follows:

1. Reference airspeed: 170 knots
2. Altitude: 1400 ft
3. ILS approach
4. Outer marker at 4.5 DME
5. Runway heading: 090°
6. Visibility: 4000 ft
7. Ceiling: 250 ft
8. Winds: calm

The pilot's instructions from ATC were to maintain 170 knots to the outer marker for aircraft separation. The glide slope angle is 2.75°.

Refer to figure 45 and circle the correct answer in the following:

1. Airspeed:	Fast	Slow	On	Unknown
2. Altitude:	High	Low	On	Unknown
3. Aircraft relative to localizer:	Right	Left	On	Unknown
4. Aircraft relative to glide slope:	High	Low	On	Unknown
5. Flightpath:	Climbing	Descending	Level	Unknown
6. Acceleration:	Positive	Negative	Zero	Unknown

Based on your analysis of the display, what corrective action, if any, would you take and why? Do you have sufficient information for analysis? If not, what added information do you require?

Situation B

Initial conditions are:

1. Reference airspeed: 135 knots
2. ILS approach
3. Runway heading: 090°
4. Visibility: 4000 ft
5. Ceiling: 250 ft

Refer to figure 46 and circle the correct answer in the following:

1. Airspeed:	Fast	Slow	On	Unknown
2. Aircraft relative to glide slope:	High	Low	On	Unknown
3. Heading:	Right	Left	On	Unknown
4. Flightpath:	Climbing	Descending	Level	Unknown
5. Acceleration:	Positive	Negative	Zero	Unknown

Based on your analysis of the display, what corrective action, if any, would you take and why? Do you have sufficient information for analysis? If not, what additional information do you require?

Situation C

You are making a nonprecision approach to a runway heading of 090°, with an MDA of 450 ft, DME at the MAP, airport visibility of 7500 ft, and a ceiling of 600 ft. The reference airspeed is 135 knots. Refer to figure 47 and circle the correct answer in the following:

1. Airspeed:	Fast	Slow	On	Unknown
2. Altitude:	High	Low	On	Unknown
3. Heading:	Right	Left	On	Unknown
4. Flightpath:	Ascending	Decending	Level	Unknown
5. Acceleration:	Positive	Negative	Zero	Unknown

Based on your analysis of the display, what corrective action, if any, would you take and why? Do you have sufficient information for analysis? If not, what additional information do you require?

CREW PROCEDURES

Crew procedures practiced by major airlines for similar aircraft are modified and generalized for this study. The aircraft being simulated is the Boeing 727. However, the flight engineer's position is not simulated. The crew for this study is a captain, a copilot, and an observer. The observer will not function as part of the flying crew.

Pilot Duties

In all experimental cases, the left-hand seat will be occupied by the captain, the flying pilot for all experimental runs. The general duties of the captain require that, once the simulator is placed in "operate," he will fly the prescribed profile as given by the simulated air-traffic controller and terminate his flight with either a landing or a go-around, whichever is appropriate. The captain will ask the copilot to go through the final-descent checklist and handle landing gear and flaps. The captain will be assisted by the copilot only "as requested."

Copilot Duties

The copilot for all experimental runs will be an Ames employee. As copilot he will make flap and landing-gear-handle settings at the pilot's request. He will monitor airspeed, altitude, and aircraft attitude during final approach and make callouts as prescribed in the summary that follows. At the captain's request he will initiate and complete the final-descent checklist. He will respond to ATC communications and will inititate ATC communication at the captain's request.

SUMMARY OF FLIGHT-CREW PROCEDURES FOR HUD PHASE III

Captain (Pilot Flying)

The captain will determine the approach target speed by using V_{ref} (124 knots at 140,000 lb) plus one half the headwind component plus the gust factor. Total add on should not exceed 20 knots.

The captain should call for landing gear and flaps as required. The captain should also request the copilot to select desired flight-director modes.

Standard callouts for the captain are:

Outer-marker crossing altitude, target speed, minimums and time to missed approach point (MAP) (nonprecision only)
1000 ft AGL
100 ft above minimums
Minimums

In addition to the standard callouts, the captain should verbally announce ground contact, approach lights, or runway threshold as appropriate (HUD approaches only).

Copilot (Pilot Not Flying)

The copilot will handle all ATC communications and operate the landing gear, flaps, and flight-director-mode control panel as requested by the captain.

The copilot should acknowledge all standard callouts by the captain.

The copilot will monitor the approach and will callout the following deviations:

Airspeed deviations in excess of +10 or -5 knots
Localizer and glide-slope deviations in excess of 1 dot
Below 1000 ft above field level (AFL), sink rates in excess of 1000 ft/min

The copilot will monitor time on nonprecision approaches and will call out "Missed Approach Point."

For head-down approaches, the copilot will announce "ground contact, approach lights, runway threshold" as appropriate.

APPENDIX D

EXPERIMENTAL DESIGN AND STATISTICAL ANALYSIS FAA/NASA HEAD-UP DISPLAYS – PHASE III

Final Report
J. Michael Steele, Ph.D.
Control Analysis Corp.
April 14, 1980

PURPOSE AND STRUCTURE

The main objectives of this report are (1) to provide a description of the experimental design used in the HUD Phase III project and (2) to provide a careful statistical analysis of the data which was obtained.

To serve these objectives the report has been divided into five sections as follows:

- EXPERIMENTAL DESIGN
- INTRODUCTION TO THE PRINCIPAL ANALYSIS
- HISTOGRAMS AND ANOVA ON 20 FLIGHT VARIABLES
- SUPPLEMENTAL ANALYSIS AND CONSISTENCY TESTS
- GENERAL CONCLUSIONS

EXPERIMENTAL DESIGN

Layer One

Any experimental design as complex as that employed in HUD Phase III is best understood (and best analyzed) in layers. The first layer in HUD Phase III consists in understanding the flight situations which were flown by every pilot. These situations can be easily visualized in terms of the cells of the following table 37.

As an introduction to the table one should note that HUD1, HUD2, HUD3 refer to the three types of displays under study. The headings C1 and C2 denote two types of ceiling conditions and W1, W2, W3 denote three types of wind condition. The principal headings Precision and Nonprecision effectively divide the whole study into two separate studies.

The very important problem of making actual specifications of the wind and ceiling conditions will not be discussed here since they do not impact on the *structure* of the experimental design. These specifications will ultimately have importance for the interpretation of the experimental results, but for now we content ourselves with noting that the conditions C1, C2, C3 and W1, W2 have different specifications under the different headings of Precision and Nonprecision.

The Experimental Design called for each pilot to fly 36 flights; one flight for each of the 36 cells of table 37. (In the actual implementation there were modest amounts of missing data. The considerations made for such missing data will feature prominently in the detailed data analysis, but will not be discussed until the analysis segment.)

For each of the flights which were simulated a large number of continuous and window measurements were made. For the purpose of analysis these data were compressed into 41 response statistics; the 29 most important are considered in the present analysis. Since some understanding of these is necessary before discussing the second level of the Experimental Design, these response statistics are listed below in their natural groupings.

VARIABLES TO BE STUDIED

Outer Marker	Intercept
OMALT	IALT
OMYCG	IVQVR
OMVQVR	

Approach segment		Flare segment	
ALOC	AEASD	FALT	FVQVR
AGS	AHDOTMAX	FYCG	FHDOT
AEASM	AHDOTM		
AHDOTD			

Landing segment	
LXCG	LMAXVEQ
LYCG	LMAXHDOT

NAME	DESCRIPTION	UNITS
OMALT	Altitude at the outer marker	ft
OMYCG	Aircraft lateral displacement from runway centerline extended	ft
OMVQVR	Speed error from "bug" at outer marker	knots
IALT	Mean altitude during intercept segment	ft
IVQVR	Mean error from bug during intercept segment	knots
ALOC	RMS localizer error during approach segment	deg
AGS	RMS glide slope error during approach segment	deg
AEASM	Mean airspeed during approach segment	knots
AEASD	RMS deviation of airspeed from mean airspeed during approach segment	knots
AHDOTMAX	Maximum sink rate during approach segment	ft/sec
AHDOTM	Mean sink rate during approach segment	ft/sec
AHDOTD	RMS deviation of sink rate from mean sink rate during approach segment	ft/sec
FALT	Altitude at the runway threshold	ft
FYCG	Lateral error from runway centerline at threshold	ft
FVQVR	Airspeed error from "bug" at threshold	knots
FHDOT	Sink rate at threshold	ft/sec
LXCG	Touchdown distance from threshold	ft
LYCG	Touchdown distance from runway centerline	ft
LMAXVEQ	Maximum airspeed at touchdown	knots

NAME	DESCRIPTION	UNITS
LMAXHDOT	Maximum sink rate at touchdown	ft/sec
OMHDOT	Mean sink rate at the outer marker	ft/sec
MMALT	Altitude at the middle marker	ft
MMYCG	Lateral error from runway centerline extended at middle marker	ft
MVQVR	Airspeed error from "bug" at middle marker	knots
MMHDOT	Mean sink rate at middle marker	ft/sec
IMALT	Altitude at inner marker	ft
IMYCG	Lateral error from runway centerline extended at inner marker	ft
IMVQVR	Airspeed error from "bug" at inner marker	knots
IMHDOT	Mean sink rate at inner marker	ft/sec

Level Two

The task at the second level of the experimental design is to understand those factors which are not the same for each pilot. There are two such factors: the level of air traffic control (ATC) communications and the presence of anomalies.

The ATC level is the easier of these two factors to explain. There were three levels of ATC in the experiment, and their exact specification (although important) is unessential to the structure of the design. The levels are denoted simply as ATC level 1, 2, and 3, and these are precisely the numbers which occupy the cells of table 37. The *pattern* of ATC levels differs from pilot to pilot, but this is done in such a way that each flight condition (P/N, HUD, C, W) occurs precisely 4 times under each of the three ATC levels.

The conceptually more interesting factor which is met at level two is that of the "anomaly." The basic idea was that any choice in Display must be measured in some way to see how it influences the appropriateness of response to events which require an unusual action. The study design considers four conditions for which the accepted practice is a "fly around." Collectively these are called anomalies, and the four anomalies considered are wind shear, low ceiling, scud, and runway obstruction.

The experimental design calls for each pilot to fly six flights in which an anomaly is to take place. The anomalies which a pilot gets as well as the times he gets them are determined by an allocation procedure which is governed by chance (an actual rolling of dice). This random allocation was conducted subject to the constraints of a 4-day week schedule and to minimize the effect of carry-over of stress from one flight to the next.

With the specification of flight condition, anomaly type (possibly none) and ATC level the specification of all factors to be analyzed by the study is complete.

INTRODUCTION TO THE PRINCIPAL ANALYSIS

The main analytical tool used in the present analysis was the one-way analysis of variance performed by BMDP7D. A key benefit of this package is that it also provides histograms which are an essential check on what the F-ratio is actually revealing.

The purpose of the following table is to provide summary information for the full analyses given in the next section. The first message provided by this table is that in terms of the variables measured in this study there are large and statistically significant differences in the three displays. By looking first at those variables which show very low F-probabilities (very high significance), a picture quickly emerges of the differing effects of the displays. For an understanding of the engineering or planning impact of these differences, the histograms of the next section provide considerable assistance.

TABLE OF SIGNIFICANCE

Variable	Significance Level	
	Precision	Nonprecision
OMALT	0.0003**	0.4190
OMYCG	.9243	.0626
OMVQVR	.8050	.0450*
IALT	.6808	.2638
IVQVR	.1071	.0964
ALOC	.0179*	.0000**
AGS	.0000**	.0098**
AEASM	.2561	.3639
AEASD	.6341	.8383
AHDOTMAX	.0000**	.4508
AHDOTM	.0396*	.0000**
AHDOTD	.0000**	.8670
FALT	.0337*	.0000**
FYCG	.2879	.1165
FVQVR	.2142	.0359*
FHDOT	.0067**	.0000**
LXCG	.0607	.7120
LYCG	.2796	.6894
LMAXVEQ	.0618	.0078**
LMAXHDOT	.1437	.0128**

NOTE: The symbols * and ** are used here, as traditionally, to bring attention to levels beyond the 0.05 and 0.01 significances, respectively.

HISTOGRAMS AND ANOVA ON 20 FLIGHT VARIABLES

The tables of this section contain the heart of this report. Each table has its own message in addition to the basic measure of differences given by significance level. The presence of out-liers, the possibility of patterns, and a visual check on reasonability are all part of the benefits given the histograms. It is also important to make systematic note of the difference of means.

The tables are first given for all the 20 precision variables and then for all the 20 nonprecision variables. The order of the tables is the same as on the previous table of significance levels. In fact, that tables serves as a useful table of contents for this section.

As a matter of notation, one should note that the three displays are labelled HUDP1, HUD2, HUD3,. under precision conditions and HUDN1, HUD2, HUD3 under nonprecision conditions.

```
1TABULATION OF VARIABLE        2 OMALT


         HUDP1        HUD2         HUD3
         .........+..........+..........+..........+..........+.........
 MIDPOINTS
 2120.000)
 2080.000)
 2040.000)*
 2000.000)
 1960.000)
 1920.000)
 1880.000)
 1840.000)                    *
 1800.000)
 1760.000)
 1720.000)                    *
 1680.000)*
 1640.000)
 1600.000)
 1560.000)***        *          **
 1520.000)*********  *****      *
 1480.000)M*******19 ***        *****
 1440.000)********15 M*******23 M*******12
 1400.000)*********  ********22 ********31
 1360.000)*          ****       *******
 1320.000)
 1280.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN      1479.117   1429.238   1429.813       .000       .000       .000
 S. DEV.      91.903     43.396     78.741       .000       .000       .000
    N         58.000     58.000     60.000       .000       .000       .000
 MAXIMUM    2041.000   1541.000   1853.000       .000       .000       .000
 MINIMUM    1374.000   1349.000   1359.000       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN           1445.871
 S. DEV.          77.467
    N            176.
 MAXIMUM        2041.000
 MINIMUM        1349.000
           SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
  BETWEEN  95626.8750          2     47813.4375    8.6653        .0003
  WITHIN  954582.5000        173      5517.8164
  TOTAL  1050209.0000        175
```

```
1TABULATION OF VARIABLE        3 OMYCG


          HUDP1        HUD2         HUD3
          .........+..........+..........+..........+..........+..........
 MIDPOINTS
 2400.000)
 2200.000)
 2000.000)                          *
 1800.000)
 1600.000)
 1400.000)
 1200.000)
 1000.000)           *            **
  800.000)
  600.000)*
  400.000)***                     ****
  200.000)********13 ********11 ********11
     .000)M*******26 M*******40 M*******22
 -200.000)********11 ****       ********14
 -400.000)**         *          ****
 -600.000)*                     *
 -800.000)*
 1000.000)                      *
 1200.000)
 1400.000)
 1600.000)
 1800.000)           *
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN        9.224       .017     23.033        .000        .000        .000
 S. DEV.    225.283    300.143    399.309        .000        .000        .000
    N        58.000     58.000     60.000        .000        .000        .000
 MAXIMUM    519.000   1035.000   2053.000        .000        .000        .000
 MINIMUM   -827.000  -1825.000  -1058.000        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
OMEAN           10.898
 S. DEV.       315.785
    N          176.
 MAXIMUM      2053.000
 MINIMUM     -1825.000

          SUM OF SQUARES     DF      MEAN SQUARE  F RATIO    PROB. F EXCEEDED
  BETWEEN  15865.2344         2       7932.6172     .0787         .9243
  WITHIN 7435216.0000       173     100781.5625
  TOTAL  7451072.0000       175
```

```
1TABULATION OF VARIABLE        4 OMVQVR



          HUDP1      HUD2       HUD3
          ..........+..........+..........+..........+..........+..........+.........
 MIDPOINTS
   42.000)
   39.000)
   36.000)
   33.000)
   30.000)                      *
   27.000)*
   24.000)                      **
   21.000)*          *          *
   18.000)**         **
   15.000)**                    *
   12.000)***        ***        *****
    9.000)********11 ********13 **********
    6.000)M********  M*******11 M*******11
    3.000)********12 ********12 ********14
     .000)********** ********** **********
   -3.000)*****      ****       ***
   -6.000)*          **         *
   -9.000)                      *
  -12.000)*
  -15.000)
  -18.000)
  -21.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN        5.226      4.936      5.717       .000       .000       .000
 S. DEV.      6.861      5.556      7.000       .000       .000       .000
    N        58.000     58.000     60.000       .000       .000       .000
 MAXIMUM     28.400     20.200     29.600       .000       .000       .000
 MINIMUM    -11.500     -5.100     -9.100       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN            5.298
 S. DEV.         6.481
    N          176.
 MAXIMUM        29.600
 MINIMUM       -11.500

          SUM OF SQUARES     DF      MEAN SQUARE   F RATIO    PROB. F EXCEEDED
  BETWEEN    18.4108          2        9.2054       .2172          .8050
  WITHIN   7332.9805        173       42.3872
  TOTAL    7351.3906        175
```

```
1TABULATION OF VARIABLE        2 IALT


           HUDP1       HUD2        HUD3
           .........+..........+..........+..........+..........+.........
 MIDPOINTS
 3100.000)
 3000.000)
 2900.000)          *
 2800.000)
 2700.000)
 2600.000)
 2500.000)
 2400.000)
 2300.000)
 2200.000)*
 2100.000)
 2000.000)                     **
 1900.000)*
 1800.000)**        **
 1700.000)**        *          ****
 1600.000)M*******12 M*******14 ******
 1500.000)********24 ********28 M*******34
 1400.000)***       *****      **
 1300.000)
 1200.000)
 1100.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN      1568.531   1566.644   1542.373       .000       .000       .000
 S. DEV.     139.947    207.978    121.470       .000       .000       .000
    N         45.000     51.000     48.000       .000       .000       .000
 MAXIMUM    2218.000   2902.000   2027.000       .000       .000       .000
 MINIMUM    1436.000   1396.000   1431.000       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN           1559.143
 S. DEV.         161.685
    N            144.
 MAXIMUM        2902.000
 MINIMUM        1396.000

        SUM OF SQUARES     DF     MEAN SQUARE   F RATIO   PROB. F EXCEEDED
BETWEEN  20335.3086         2     10167.6523     .3856          .6808
WITHIN 3717962.0000       141     26368.5234
TOTAL  3738297.0000       143
```

```
1TABULATION OF VARIABLE        3 IVQVR


          HUDP1       HUD2        HUD3
          ..........+..........+..........+..........+..........+..........
 MIDPOINTS
   40.000)
   36.000)
   32.000)
   28.000)                        ***
   24.000)**          *           ****
   20.000)*           *           *
   16.000)****        ***
   12.000)*******     ******      ****
    8.000)M*******11  ********15  M*******11
    4.000)********11  M*******    ********17
     .000)*********   ********12  *****
   -4.000)            *           *
   -8.000)            ***         *
  -12.000)                        *
  -16.000)
  -20.000)
  -24.000)
  -28.000)
  -32.000)            *
  -36.000)
  -40.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN          7.562      4.863      8.012      .000      .000      .000
 S. DEV.        6.129      8.194      9.143      .000      .000      .000
    N          45.000     51.000     48.000      .000      .000      .000
 MAXIMUM       23.700     22.900     30.000      .000      .000      .000
 MINIMUM        -.900    -30.500    -10.900      .000      .000      .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN              6.756
 S. DEV.           8.032
    N            144.
 MAXIMUM          30.000
 MINIMUM         -30.500

        SUM OF SQUARES    DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
BETWEEN     287.8369       2      143.9185    2.2702        .1071
WITHIN     8938.6133     141       63.3944
TOTAL      9226.4492     143
```

```
1TABULATION OF VARIABLE        4 ALOC


          HUDF1       HUD2        HUD3
          .........+..........+..........+..........+..........+..........
MIDPOINTS
   1.260)
   1.190)
   1.120)          *
   1.050)
    .980)
    .910)
    .840)
    .770)
    .700)
    .630)
    .560)
    .490)*
    .420)*                    *
    .350)*                    *
    .280)**                   *
    .210)***       *
    .140)M*******15 *********  ****
    .070)********20 M*******30 M*******20
   -.000)**         ********** ********21
   -.070)
   -.140)
GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

 MEAN          .132        .093        .064        .000        .000        .000
S. DEV.        .098        .149        .080        .000        .000        .000
  N          45.000      51.000      48.000        .000        .000        .000
MAXIMUM        .520       1.090        .390        .000        .000        .000
MINIMUM        .030        .010        .010        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN               .096
 S. DEV.            .116
    N            144.
 MAXIMUM           1.090
 MINIMUM            .010

        SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
BETWEEN       .1076         2          .0538    4.1397         .0179
WITHIN       1.8329       141          .0130
TOTAL        1.9405       143
```

```
1TABULATION OF VARIABLE        2 AGS


          HUDP1       HUD2        HUD3
          ..........+..........+..........+..........+..........+..........
MIDPOINTS
    .570)
    .540)
    .510)*
    .480)
    .450)
    .420)
    .390)
    .360)
    .330)                         *
    .300)
    .270)*
    .240)*          *
    .210)**         *             *
    .180)****                     *
    .150)*
    .120)M*******   ****
    .090)*******13  ********      ****
    .060)*******11  M*******18    M*******11
    .030)***        ********19    ********28
    .000)                         **
   -.030)
GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

 MEAN         .114       .065       .051       .000       .000       .000
S. DEV.       .081       .044       .056       .000       .000       .000
   N        45.000     51.000     48.000       .000       .000       .000
MAXIMUM       .510       .250       .320       .000       .000       .000
MINIMUM       .030       .020       .010       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN             .076
 S. DEV.          .066
   N          144.
 MAXIMUM          .510
 MINIMUM          .010
           SUM OF SQUARES     DF     MEAN SQUARE   F RATIO    PROB. F EXCEEDED
 BETWEEN        .1009          2          .0505   13.4274          .0000
 WITHIN         .5300        141          .0038
 TOTAL          .6309        143
```

```
1TABULATION OF VARIABLE        3 AEASM


           HUDP1         HUD2         HUD3
          ..........+..........+..........+..........+..........+.........
 MIDPOINTS
  156.000)
  154.500)
  153.000)
  151.500)*
  150.000)          *
  148.500)                     *
  147.000)****                 *
  145.500)***       **         *
  144.000)*         **         **
  142.500)**                   **
  141.000)****      ***        ***
  139.500)*         *******    ***
  138.000)M*****    ***        ******
  136.500)******    M****      M******
  135.000)********  ********11 *****
  133.500)****      *********  ********11
  132.000)          *******    *****
  130.500)***       *          *
  129.000)**
  127.500)
  126.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       138.192    136.709    137.029       .000       .000       .000
 S. DEV.       5.395      4.068      4.174       .000       .000       .000
    N         45.000     51.000     48.000       .000       .000       .000
 MAXIMUM     151.760    149.280    148.320       .000       .000       .000
 MINIMUM     128.860    130.540    130.930       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
OMEAN           137.279
 S. DEV.          4.568
    N           144.
 MAXIMUM        151.760
 MINIMUM        128.860

          SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
 BETWEEN     57.1027          2       28.5513    1.3754         .2561
 WITHIN    2926.8982        141       20.7581
 TOTAL     2984.0007        143
```

```
1TABULATION OF VARIABLE        4 AEASD


          HUDP1        HUD2        HUD3
          .........,+..........+..........+..........+..........+..........
 MIDPOINTS
   16.000)
   15.000)
   14.000)
   13.000)
   12.000)
   11.000)
   10.000)            *
    9.000)
    8.000)
    7.000)            *          *
    6.00^)**          ****       **
    5.000)***         ****       *
    4,000)********    ***        *********
    3.000)M*******15  M*******15 M*******11
    2.000)********14  ********16 ********17
    1.000)***         *******    *******
     .000)
   -1.000)
   -2.000)
   -3.000)
   -4.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN          3.002      3.044      2.775       .000       .000       .000
 S. DEV.        1.182      1.786      1.408       .000       .000       .000
    N          45.000     51.000     48.000       .000       .000       .000
 MAXIMUM        6.410     10.140      7.370       .000       .000       .000
 MINIMUM        1.270       .740       .540       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
OMEAN               2.941
 S. DEV.            1.487
    N             144.
 MAXIMUM           10.140
 MINIMUM             .540

          SUM OF SQUARES    DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
  BETWEEN      2.0369        2       1.0185      .4571         .6341
  WITHIN     314.1648      141       2.2281
  TOTAL      316.2017      143
```

```
1TABULATION OF VARIABLE        2 AHDOTMAX


          HUDP1        HUD2         HUD3
          ..........+..........+..........+..........+..........+.......
 MIDPOINTS
   -9.000)
  -10.500)
  -12.000)                          ********11
  -13.500)             *****        *****
  -15.000)**           ****         ******
  -16.500)******       ********16   M*******11
  -18.000)****         M*****       *******
  -19.500)******       ******       *****
  -21.000)*****        ******
  -22.500)M*           ***
  -24.000)******       ***          **
  -25.500)****         *
  -27.000)**
  -28.500)*            *
  -30.000)***
  -31.500)*
  -33.000)*
  -34.500)                          *
  -36.000)**
  -37.500)
  -39.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       -22.689     -18.338     -16.282        .000        .000        .000
 S. DEV.       5.429       3.396       3.957        .000        .000        .000
    N         45.000      51.000      48.000        .000        .000        .000
 MAXIMUM     -14.740     -12.920     -11.890        .000        .000        .000
 MINIMUM     -36.680     -28.720     -34.390        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN            -19.012
 S. DEV.           5.017
    N            144.
 MAXIMUM         -11.890
 MINIMUM         -36.680

           SUM OF SQUARES      DF      MEAN SQUARE   F RATIO    PROB. F EXCEEDED
  BETWEEN      989.5012         2         494.7505   26.7315         .0000
  WITHIN      2609.6462       141          18.5081
  TOTAL       3599.1475       143
```

```
1TABULATION OF VARIABLE        3 AHDOTM


          HUDP1        HUD2        HUD3
          ..........+..........+..........+..........+..........+........
 MIDPOINTS
   -5.000)
   -6.000)
   -7.000)
   -8.000)
   -9.000)*
  -10.000)**         *******     ***
  -11.000)********12 ********20 ********15
  -12.000)*******    M*******    M*********
  -13.000)M*****     ********** ********15
  -14.000)*********  ***         **
  -15.000)*******    **          *
  -16.000)           *
  -17.000)                       *
  -18.000)
  -19.000)
  -20.000)                       *
  -21.000)*
  -22.000)
  -23.000)
  -24.000)
  -25.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       -12.828     -11.904     -12.260        .000        .000        .000
 S. DEV.       2.045       1.417       1.819        .000        .000        .000
    N         45.000      51.000      48.000        .000        .000        .000
 MAXIMUM      -9.260     -10.080     -10.390        .000        .000        .000
 MINIMUM     -21.030     -16.170     -20.040        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN            -12.312
 S. DEV.           1.794
    N            144.
 MAXIMUM          -9.260
 MINIMUM         -21.030

            SUM OF SQUARES      DF      MEAN SQUARE   F RATIO    PROB. F EXCEEDED
  BETWEEN      20.6107           2        10.3053     3.3033          .0396
  WITHIN      439.8806         141         3.1197
  TOTAL       460.4912         143
```

```
1TABULATION OF VARIABLE        4 AHDOTD


            HUDP1        HUD2         HUD3
            ..........+...........+...........+...........+...........+...........
 MIDPOINTS
   17.000)
   16.000)
   15.000)
   14.000)
   13.000)
   12.000)*
   11.000)
   10.000)*
    9.000)
    8.000)****
    7.000)***
    6.000)*****        ***          *
    5.000)M*********   *****
    4.000)*********    ******       **
    3.000)*********    M*******21   ******
    2.000)****         ********14   M*******20
    1.000)             **           ********19
     .000)
   -1.000)
   -2.000)
   -3.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE
```

MEAN	4.962	3.172	1.903	.000	.000	.000
S. DEV.	2.197	1.205	1.060	.000	.000	.000
N	45.000	51.000	48.000	.000	.000	.000
MAXIMUM	12.100	6.220	6.390	.000	.000	.000
MINIMUM	2.090	1.130	.750	.000	.000	.000

0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0

0MEAN	3.308
S. DEV.	1.973
N	144.
MAXIMUM	12.100
MINIMUM	.750

	SUM OF SQUARES	DF	MEAN SQUARE	F RATIO	PROB. F EXCEEDED
BETWEEN	218.7544	2	109.3772	45.6520	.0000
WITHIN	337.8203	141	2.3959		
TOTAL	556.5747	143			

```
1TABULATION OF VARIABLE        2 FALT


          HUDP1       HUD2        HUD3
          ..........+..........+..........+..........+..........+.........
 MIDPOINTS
  110.000)
  105.000)
  100.000)*          *
   95.000)
   90.000)           **
   85.000)*          *
   80.000)*          **
   75.000)           ***
   70.000)*          **
   65.000)**                     *
   60.000)**         ****
   55.000)***        *******     ******
   50.000)********   M*****      *********
   45.000)M********  ********    M*******13
   40.000)********13 *****       ********13
   35.000)**         ***         ****
   30.000)****       ****        *
   25.000)           **          *
   20.000)*          *
   15.000)
   10.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN        47.458     52.255     44.875        .000        .000        .000
 S. DEV.      14.637     18.180      7.034        .000        .000        .000
    N         48.000     51.000     48.000        .000        .000        .000
 MAXIMUM     100.000    100.000     63.000        .000        .000        .000
 MINIMUM      19.000     22.000     25.000        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN             48.279
 S. DEV.          14.410
    N            147.
 MAXIMUM         100.000
 MINIMUM          19.000
         SUM OF SQUARES     DF     MEAN SQUARE   F RATIO   PROB. F EXCEEDED
 BETWEEN   1394.7100         2       697.3550    3.4722         .0337
 WITHIN   28920.7461       144       200.8385
 TOTAL    30315.4531       146
```

```
1TABULATION OF VARIABLE        4 FYCG



          HUDP1         HUD2         HUD3
          ..........+..........+..........+..........+..........+..........+.........
 MIDPOINTS
  120.000)
  110.000)
  100.000)
   90.000)                           *
   80.000)
   70.000)
   60.000)*            *             *
   50.000)*            **
   40.000)             *
   30.000)**           *             *
   20.000)******       ********** *
   10.000)********     *********     ********
     .000)M*******11 M********* M*******28
  -10.000)***          *********     ******
  -20.000)*******11   ***            *
  -30.000)*            **            *
  -40.000)**           **
  -50.000)**           *
  -60.000)
  -70.000)
  -80.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN        -2.250      3.078       4.062        .000        .000        .000
 S. DEV.      22.672     22.136      17.964        .000        .000        .000
    N         48.000     51.000      48.000        .000        .000        .000
 MAXIMUM      57.000     59.000      90.000        .000        .000        .000
 MINIMUM     -50.000    -46.000     -33.000        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN              1.660
 S. DEV.          21.090
    N            147.
 MAXIMUM          90.000
 MINIMUM         -50.000

          SUM OF SQUARES     DF     MEAN SQUARE  F RATIO    PROB. F EXCEEDED
 BETWEEN    1113.4878         2       556.7439   1.2561          .2879
 WITHIN    63825.1992       144       443.2305
 TOTAL     64938.6836       146
```

```
1TABULATION OF VARIABLE        2 FVQVR


          HUDP1        HUD2        HUD3
          ..........+..........+..........+..........+..........+..........
 MIDPOINTS
   22.500)
   21.000)
   19.500)
   18.000)*          *
   16.500)
   15.000)
   13.500)
   12.000)
   10.500)*          ****
    9.000)**         *           **
    7.500)**         **          **
    6.000)******     ***         ****
    4.500)*******    ********    ******
    3.000)M*******   M********   ******
    1.500)*******    *********** M*******12.
     .000)********   *********11 **********
   -1.500)*****                  *****
   -3.000)*          **          *
   -4.500)
   -6.000)
   -7.500)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN         3.310       3.322       2.202        .000        .000        .000
 S. DEV.       3.843       3.902       2.916        .000        .000        .000
    N         48.000      51.000      48.000        .000        .000        .000
  MAXIMUM     18.200      17.800       8.500        .000        .000        .000
  MINIMUM     -2.900      -3.700      -2.900        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN              2.952
 S. DEV.           3.603
    N            147.
 MAXIMUM          18.200
 MINIMUM          -3.700
         SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
BETWEEN      40.1256         2        20.0628    1.5573        .2142
WITHIN     1855.1482       144        12.8830
TOTAL      1895.2737       146
```

```
1TABULATION OF VARIABLE        3 FHDOT


          HUDF1       HUD2       HUD3
          .........+..........+..........+..........+..........+..........
 MIDPOINTS
   -2.000)
   -3.000)
   -4.000)
   -5.000)
   -6.000)
   -7.000)*          **         *
   -8.000)***        *          ***
   -9.000)***        ********   ********
  -10.000)****       *******    ********
  -11.000)*******    ********   M*******11
  -12.000)********   M********  ****
  -13.000)M*****     *****      ********
  -14.000)****       *****      **
  -15.000)***        **         ***
  -16.000)***        **
  -17.000)****
  -18.000)*          **
  -19.000)*
  -20.000)
  -21.000)
  -22.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       -12.602     -11.627     -11.002         .000         .000         .000
 S. DEV.       2.857       2.518       1.888         .000         .000         .000
    N         48.000      51.000      48.000         .000         .000         .000
 MAXIMUM      -6.900      -6.800      -7.300         .000         .000         .000
 MINIMUM     -19.000     -18.200     -15.400         .000         .000         .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN           -11.741
 S. DEV.          2.525
    N           147.
 MAXIMUM         -6.800
 MINIMUM        -19.000

         SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
 BETWEEN     62.4557         2       31.2278    5.1788        .0067
 WITHIN     868.3162       144        6.0300
 TOTAL      930.7717       146
```

```
1TABULATION OF VARIABLE        4 LXCG


          HUDF1        HUD2         HUD3
          ..........+..........+..........+..........+..........+........
 MIDPOINTS
 3450.000)
 3300.000)             *
 3150.000)*
 3000.000)             *
 2850.000)*            *
 2700.000)**           ******
 2550.000)*                         *
 2400.000)*            ***          **
 2250.000)             ***          ***
 2100.000)*            *            *******
 1950.000)****         *****        ****
 1800.000)****         **           M*******
 1650.000)****         M*           *****
 1500.000)M**          ********     **********
 1350.000)******       ****         *****
 1200.000)*****        ***          *
 1050.000)******       *****
  900.000)**                        **
  750.000)*****        ****
  600.000)*            **
  450.000)*
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN      1491.653   1719.968   1751.216        .000        .000        .000
 S. DEV.     626.243    692.466    371.652        .000        .000        .000
    N         48.000     51.000     48.000        .000        .000        .000
 MAXIMUM    3120.000   3252.500   2570.000        .000        .000        .000
 MINIMUM     510.000    531.000    864.000        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN            1655.619
 S. DEV.          590.102
    N             147.
 MAXIMUM         3252.500
 MINIMUM          510.000
        SUM OF SQUARES    DF     MEAN SQUARE   F RATIO    PROB. F EXCEEDED
 BETWEEN1940315.0000       2    970157.5000    2.8569         .0607
 WITHIN 8899872.0000     144    339582.4375
 TOTAL  0840176.0000     146
```

```
1TABULATION OF VARIABLE        2 LYCG


          HUDP1        HUD2        HUD3
          ..........+..........+..........+..........+..........+..........+..........
 MIDPOINTS
   77.000)
   70.000)
   63.000)
   56.000)
   49.000)*
   42.000)            *
   35.000)*           *           ****
   28.000)            **          *
   21.000)**          ****        **
   14.000)****        ******      *******
    7.000)*********11 *********11 M********
     .000)M********12 M*********  *********15
   -7.000)*******     *********   *****
  -14.000)*****       ***         *****
  -21;000)****        ****
  -28.000)*
  -35.000)
  -42.000)
  -49.000)            *
  -56.0C )
  -63.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN          .969       2.892       5.635        .000        .000        .000
 S. DEV.      14.084      15.970      12.639        .000        .000        .000
    N         48.000      51.000      48.000        .000        .000        .000
 MAXIMUM      50.500      44.000      35.500        .000        .000        .000
 MINIMUM     -25.500     -48.000     -14.000        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN              3.160
 S. DEV.          14.361
    N            147.
 MAXIMUM          50.500
 MINIMUM         -48.000

        SUM OF SQUARES     DF     MEAN SQUARE   F RATIO    PROB. F EXCEEDED
BETWEEN    528.2605         2       264.1301     1.2857         .2796
WITHIN   29582.4063       144       205.4334
TOTAL    30110.6641       146
```

```
1TABULATION OF VARIABLE        3 LMAXVEQ


          HUDP1       HUD2        HUD3
          .........+.........+.........+.........+.........+.........
 MIDPOINTS
  156.000)
  154.000)                    *
  152.000)
  150.000)
  148.000)
  146.000)*
  144.000)*          **
  142.000)**                  **
  140.000)**         *
  138.000)**         ****       *
  136.000)*****      *******    ***
  134.000)********   ******     *****
  132.000)M********  M*******12 *******
  130.000)******     ********11 M*********
  128.000)******     ***        ****
  126.000)***        **         ********
  124.000)***        **         *****
  122.000)           *          *
  120.000)                      *
  118.000)
  116.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       132.644    132.560    130.458        .000        .000        .000
 S. DEV.       5.060      4.507      5.746        .000        .000        .000
    N         48.000     51.000     48.000        .000        .000        .000
 MAXIMUM     145.530    144.220    153.160        .000        .000        .000
 MINIMUM     123.510    122.310    120.500        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN            131.901
 S. DEV.            5.181
    N            147.
 MAXIMUM         153.160
 MINIMUM         120.500
         SUM OF SQUARES    DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
 BETWEEN    148.6894        2        74.3447    2.8390        .0618
 WITHIN    3770.8674      144        26.1866
 TOTAL     3919.5566      146
```

1TABULATION OF VARIABLE   4 LMAXHDOT

```
          HUDP1      HUD2       HUD3
          ..........+..........+..........+..........+..........+..........
MIDPOINTS
   5.000)
   4.000)
   3.000)
   2.000)
   1.000)
    .000)
  -1.000)***        ****       ***
  -2.000)********11 ********14 ********13
  -3.000)M*******14 M*******11 M*******18
  -4.000)********11 ********12 ********11
  -5.000)****       *********  ***
  -6.000)**         *
  -7.000)
  -8.000)*
  -9.000)*
 -10.000)*
 -11.000)
 -12.000)
 -13.000)
 -14.000)
 -15.000)
```

GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

	HUDP1	HUD2	HUD3			
MEAN	-3.492	-3.225	-2.919	.000	.000	.000
S. DEV.	1.822	1.277	1.044	.000	.000	.000
N	48.000	51.000	48.000	.000	.000	.000
MAXIMUM	-1.100	-1.100	-.600	.000	.000	.000
MINIMUM	-9.900	-6.300	-5.300	.000	.000	.000

0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0

0MEAN	-3.212
S. DEV.	1.426
N	147.
MAXIMUM	-.600
MINIMUM	-9.900

	SUM OF SQUARES	DF	MEAN SQUARE	F RATIO	PROB. F EXCEEDED
BETWEEN	7.8913	2	3.9457	1.9665	.1437
WITHIN	288.9255	144	2.0064		
TOTAL	296.8167	146			

```
1TABULATION OF VARIABLE        2 OMALT


           HUDN1         HUD2         HUD3
          .........+..........+..........+..........+..........+........
 MIDPOINTS
 2040.000)*
 2000.000)*
 1960.000)
 1920.000)*                      *
 1880.000)
 1840.000)            *
 1800.000)                       *
 1760.000)*                      *
 1720.000)
 1680.000)            *
 1640.000)*           **         *
 1600.000)*           **         *
 1560.000)*********   ********11 ****
 1520.000)M*******17  M*******15 M*******18
 1480.000)********19  ********14 ********27
 1440.000)*****       ********   ****
 1400.000)*           ***        **
 1360.000)**          **
 1320.000)
 1280.000)
 1240.000)            *
 1200.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN      1531.573   1508.597   1515.697        .000        .000        .000
 S. DEV.     121.043     83.651     81.542        .000        .000        .000
    N         59.000     60.000     60.000        .000        .000        .000
 MAXIMUM    2026.000   1843.000   1914.000        .000        .000        .000
 MINIMUM    1362.000   1234.000   1404.000        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN            1518.549
 S. DEV.            96.900
    N            179.
 MAXIMUM         2026.000
 MINIMUM         1234.000
         SUM OF SQUARES       DF      MEAN SQUARE   F RATIO   PROB. F EXCEEDED
 BETWEEN   16439.6211          2       8219.8086     .8742          .4190
 WITHIN  1654929.0000        176       9403.0039
 TOTAL   1671368.0000        178
```

```
1TABULATION OF VARIABLE        3 OMYCG


           HUDN1        HUD2        HUD3
          .........+..........+..........+..........+..........+..........+.........
 MIDPOINTS
 1500.000)
 1400.000)
 1300.000)                            *
 1200.000)
 1100.000)
 1000.000)
  900.000)*
  800.000)                            *
  700.000)
  600.000)                            **
  500.000)*                           **
  400.000)                            **
  300.000)**                          ***
  200.000)****       *******          *****
  100.000)********** ********13 M*******12
     .000)M*******20 M*******24 ********16
 -100.000)********** ********13 ********
 -200.000)*****      **         *******
 -300.000)***        *          *
 -400.000)*                     *
 -500.000)*
 -600.000)*
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       -13.119     15.133     77.600       .000       .000       .000
 S. DEV.     220.894    101.572    279.049       .000       .000       .000
    N         59.000     60.000     60.000       .000       .000       .000
 MAXIMUM     886.000    239.000   1345.000       .000       .000       .000
 MINIMUM    -614.000   -256.000   -436.000       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN            26.760
 S. DEV.        215.808
    N           179.
 MAXIMUM       1345.000
 MINIMUM       -614.000

        SUM OF  SQUARES      DF     MEAN SQUARE   F RATIO    PROB. F EXCEEDED
 BETWEEN 257020.0000          2     128510.0000    2.8156         .0626
 WITHIN 8033009.0000        176      45642.0938
 TOTAL  8290029.0000        178
```

```
1TABULATION OF VARIABLE        4 OMVQVR


           HUDN1        HUD2        HUD3
           .........+..........+..........+..........+..........+.........
 MIDPOINTS
   36.000)
   33.000)
   30.000)
   27.000)*                    *
   24.000)
   21.000)***       **         *
   18.000)*         **         *
   15.000)****      ***
   12.000)***       *          ***
    9.000)********11 ********  ****
    6.000)M*******13 ********12 ********12
    3.000)*********  M*******12 M*******19
     .000)********11 ********** ********11
   -3.000)**        *****      *****
   -6.000)*         ***        *
   -9.000)          *          **
  -12.000)
  -15.000)
  -18.000)
  -21.000)          *
  -24.000)
  -27.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN         6.703       4.297       3.880         .000         .000         .000
 S. DEV.       6.531       7.015       6.253         .000         .000         .000
    N         59.000      60.000      60.000         .000         .000         .000
 MAXIMUM      28.400      20.500      27.900         .000         .000         .000
 MINIMUM      -5.400     -19.600      -9.600         .000         .000         .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN              4.950
 S. DEV.           6.687
    N            179.
 MAXIMUM          28.400
 MINIMUM         -19.600

           SUM OF SQUARES    DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
  BETWEEN     275.6931        2       137.8466    3.1570         .0450
  WITHIN     7684.7539      176        43.6634
  TOTAL      7960.4453      178
```

```
1TABULATION OF VARIABLE        2 IALT


          HUDN1       HUD2       HUD3
          ..........+..........+..........+..........+..........+.........
 MIDPOINTS-
 2310.000)*
 2240.000.
 2170.000)
 2100.000)*
 2030.000)                       *
 1960.000)*                      **
 1890.000)
 1820.000)           ***         *
 1750.000)*          *           ***
 1680.000)**         *           *
 1610.000)******     *****       ***
 1540.000)M*******18 M*******17 M*******16
 1470.000)********17 ********14 ********26
 1400.000)**         ******      *
 1330.000)
 1260.000)
 1190.000)
 1120.000)
 1050.000)
  980.000)           *
  910.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN      1566.262   1520.435   1553.719          .000          .000          .000
 S. DEV.     159.623    129.093    136.815          .000          .000          .000
    N         49.000     48.000     54.000          .000          .000          .000
 MAXIMUM    2277.000   1845.000   2034.000          .000          .000          .000
 MINIMUM    1414.000   1010.000   1369.000          .000          .000          .000
)ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
)
)MEAN          1547.208
 S. DEV.        142.661
    N           151.
 MAXIMUM       2277.000
 MINIMUM       1010.000

         SUM OF SQUARES      DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
 BETWEEN  54486.3203          2     27243.1602    1.3447         .2638
 WITHIN 2998348.0000        148     20259.1055
 TOTAL  3052834.0000        150
```

```
TABULATION OF VARIABLE        3 IVQVR


           HUDN1        HUD2         HUD3
           .........+..........+..........+..........+..........+........
MIDPOINTS
  42.000)
  39.000)
  36.000)
  33.000)
  30.000)                            *
  27.000)**          *
  24.000)*                           **
  21.000)            *               ***
  18.000)***                         **
  15.000)*****                       ****
  12.000)***         *******         *****
   9.000)M***        ***             *****
   6.000)********13  M*******14      M*******
   3.000)**********  *********       *********
    .000)******      *****           *********
  -3.000)**          *****           *****
  -6.000)            *
  -9.000)            **              *
 -12.000)
 -15.000)
 -18.000)
GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

 MEAN         7.900       4.760       7.304       .000        .000        .000
S. DEV.       7.348       6.799       8.317       .000        .000        .000
  N          49.000      48.000      54.000       .000        .000        .000
MAXIMUM      27.300      26.900      30.600       .000        .000        .000
MINIMUM      -2.300      -9.900      -7.500       .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN              6.689
S. DEV.            7.617
  N              151.
MAXIMUM           30.600
MINIMUM           -9.900

         SUM OF SQUARES    DF    MEAN SQUARE  F RATIO   PROB. F EXCEEDED
BETWEEN    270.7964         2     135.3982     2.3768        .0964
WITHIN    8430.9336       148      56.9658
TOTAL     8701.7266       150
```

```
1TABULATION OF VARIABLE        4 ALOC


          HUDN1       HUD2        HUD3
          ..........+..........+..........+..........+..........+........
 MIDPOINTS
     .950)
     .900)
     .850)
     .800)*
     .750)
     .700)
     .650)
     .600)
     .550)
     .500)                        *
     .450)*
     .400)
     .350)**
     .300)**                      *
     .250)**         *            *
     .200)**                      **
     .150)M********  *            ***
     .100)********14 ******       *****
     .050)********13 M********27 M********25
     .000)***        ********13  ********16
    -.050)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN         .140        .052        .071        .000        .000        .000
 S. DEV.       .137        .044        .085        .000        .000        .000
    N        49.000      48.000      54.000        .000        .000        .000
 MAXIMUM       .810        .270        .490        .000        .000        .000
 MINIMUM       .010        .010        .010        .000        .000        .000
)ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
)
)MEAN              .087
 S. DEV.           .103
    N           151.
 MAXIMUM           .810
 MINIMUM           .010

          SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
  BETWEEN       .2087         2          .1043   11.2751         .0000
  WITHIN       1.3695       148          .0093
  TOTAL        1.5782       150
```

```
1TABULATION OF VARIABLE        2 AGS


          HUDN1        HUD2         HUD3
          ..........+..........+..........+..........+..........+..........+.........
 MIDPOINTS
    1.400)
    1.330)
    1.260)*
    1.190)*
    1.120)                          *
    1.050)             **
     .980)***
     .910)             **           ****
     .840)             ***          **
     .770)             **           *****
     .700)**           ****         *********
     .630)**                        *********
     .560)****         *****        N
     .490)****         M**          ******
     .420)M***         *****        *
     .350)*******      ********     **********
     .280)*********    **           *****
     .210)********     **********   **
     .140)***          *
     .070)*            *
    -.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN            .427        .476        .574        .000        .000        .000
 S. DEV.          .266        .253        .219        .000        .000        .000
    N           49.000      48.000      54.000        .000        .000        .000
 MAXIMUM         1.240       1.050       1.150        .000        .000        .000
 MINIMUM          .100        .090        .200        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN                .495
 S. DEV.             .252
    N             151.
 MAXIMUM            1.240
 MINIMUM             .090

         SUM OF SQUARES    DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
  BETWEEN      .5764        2          .2882    4.7681        .0098
  WITHIN      8.9455      148          .0604
  TOTAL       9.5219      150
```

```
1TABULATION OF VARIABLE        3 AEASM


          HUDN1      HUD2       HUD3
          .........+..........+..........+..........+..........+..........
 MIDPOINTS
  154.500)
  153.000)**
  151.500)*          **
  150.000)*                    **
  148.500)
  147.000)                     ***
  145.500)***                  *
  144.000)***        *         *
  142.500)*******    ***       ***
  141.000)****       ********  **
  139.500)M********  ******    *******
  138.000)***        M*****    M********
  136.500)****       ********* ********15
  135.000)***        ********11 ********
  133.500)*****      **        *
  132.000)*                    **
  130.500)**
  129.000)
  127.500)
  126.000)*
  124.500)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       139.715    138.537    138.592       .000       .000       .000
 S. DEV.       5.726      3.883      4.128       .000       .000       .000
    N         49.000     48.000     54.000       .000       .000       .000
 MAXIMUM     153.650    152.130    150.400       .000       .000       .000
 MINIMUM     126.100    132.950    131.930       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN            138.939
 S. DEV.           4.640
    N            151.
 MAXIMUM         153.650
 MINIMUM         126.100
         SUM OF SQUARES      DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
 BETWEEN      43.8188         2        21.9094    1.0179         .3639
 WITHIN     3185.5002       148        21.5236
 TOTAL      3229.3188       150
```

```
1TABULATION OF VARIABLE        4 AEASD


         HUDN1         HUD2          HUD3
         ..........+..........+..........+..........+..........+..........
 MIDPOINTS
   15.000)
   14.000)
   13.000)
   12.000)
   11.000)
   10.000)
    9.000)           *           *
    8.000)
    7.000)*
    6.000)**         *           *
    5.000)******     *           *
    4.000)******     *****       ******
    3.000)M***       M*******17  M*******21
    2.000)********17 *******23   ********22
    1.000)*******12              **
     .000)*
   -1.000)
   -2.000)
   -3.000)
   -4.000)
   -5.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN         2.709        2.853       2.849        .000        .000        .000
 S. DEV.       1.640        1.248       1.214        .000        .000        .000
    N         49.000       48.000      54.000        .000        .000        .000
 MAXIMUM       7.120        8.780       8.950        .000        .000        .000
 MINIMUM        .500        1.580       1.210        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN              2.805
 S. DEV.           1.369
    N            151.
 MAXIMUM           8.950
 MINIMUM            .500

        SUM OF SQUARES     DF     MEAN SQUARE   F RATIO   PROB. F EXCEEDED
 BETWEEN      .6689         2          .3344     .1765          .8383
 WITHIN    280.3723       148         1.8944
 TOTAL     281.0410       150
```

```
1TABULATION OF VARIABLE         2 AHDOTMAX


            HUDN1      HUD2       HUD3
            ..........+..........+..........+..........+..........+..........+
 MIDPOINTS
  -15.000)
  -16.500)             **
  -18.000)****         **
  -19.500)******       *****      ****
  -21.000)********     ********   ********12
  -22.500)******       ******     ********15
  -24.000)M*******     M********  M******
  -25.500)***          ***        *******
  -27.000)*****        *****      ****
  -28.500)             **         **
  -30.000)*            ***        **
  -31.500)*                       *
  -33.000)*            *
  -34.500)**
  -36.000)*
  -37.500)
  -39.000)*
  -40.500)**
  -42.000)
  -43.500)             **
  -45.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN      -24.702    -24.214    -23.504         .000         .000         .000
 S. DEV.      5.899      5.453      2.753         .000         .000         .000
    N        49.000     48.000     54.000         .000         .000         .000
 MAXIMUM    -17.610    -16.470    -19.020         .000         .000         .000
 MINIMUM    -40.760    -43.970    -31.520         .000         .000         .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN           -24.118
 S. DEV.          4.835
    N           151.
 MAXIMUM        -16.470
 MINIMUM        -43.970

         SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
 BETWEEN     37.5551         2        18.7776     .8010         .4508
 WITHIN    3469.6978       148        23.4439
 TOTAL     3507.2527       150
```

```
1TABULATION OF VARIABLE        3 AHDOTM



          HUDN1      HUD2       HUD3
          ..........+..........+..........+..........+..........+........
 MIDPOINTS
   -5.000)
   -6.000)
   -7.000)
   -8.000)
   -9.000)           *
  -10.000)
  -11.000)                      *
  -12.000)***        **
  -13.000)*****      *****
  -14.000)***        ********   *****
  -15.000)M*******13 M******    *******
  -16.000)********11 ********12 *********
  -17.000)********** ****       M*******12
  -18.000)**         ********   *****
  -19.000)*          *          ******
  -20.000)*                     *****
  -21.000)                      ***
  -22.000)                      *
  -23.000)
  -24.000)
  -25.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       -15.474    -15.324    -17.038       .000       .000       .000
 S. DEV        1.751      2.007      2.250       .000       .000       .000
    N         49.000     48.000     54.000       .000       .000       .000
 MAXIMUM     -11.860     -8.950    -11.120       .000       .000       .000
 MINIMUM     -19.720    -18.790    -22.200       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN              -15.986
 S. DEV.             2.158
    N              151.
 MAXIMUM            -8.950
 MINIMUM           -22.200

        SUM OF SQUARES      DF      MEAN SQUARE   F RATIO    PROB. F EXCEEDED
BETWEEN      93.5880         2         46.7940    11.4516        .0000
WITHIN      604.7637       148          4.0862
TOTAL       698.3516       150
```

```
1TABULATION OF VARIABLE        4 AHDOTD


           HUDN1       HUD2        HUD3
           .........+..........+..........+..........+..........+.........
 MIDPOINTS
   19.000)
   18.000)
   17.000)
   16.000)           *
   15.000)
   14.000)
   13.000)*
   12.000)
   11.000)           **
   10.000)**                    ***
    9.000)**         **          *
    8.000)*****      **          ***
    7.000)*          *****       **********
    6.000)**         ****        *******
    5.000)M***       M*****      M*******
    4.000)********14 ********11 *****
    3.000)********** ******      *****
    2.000)********   *********   ********
    1.000)                       ****
     .000)
   -1.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN         4.770       5.027       5.000        .000        .000        .000
 S. DEV.       2.635       2.835       2.419        .000        .000        .000
    N         49.000      48.000      54.000        .000        .000        .000
 MAXIMUM      13.460      15.850      10.240        .000        .000        .000
 MINIMUM       1.970       1.550       1.160        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN               4.934
 S. DEV.            2.612
    N             151.
 MAXIMUM           15.850
 MINIMUM            1.160

          SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
  BETWEEN      1.9712         2          .9856     .1428          .8670
  WITHIN    1021.1792       148         6.8999
  TOTAL     1023.1504       150
```

```
1TABULATION OF VARIABLE        2 FALT


          HUD1N      HUD2       HUD3
          ..........+..........+..........+..........+..........+..........
 MIDPOINTS
  147.000)
  140.000)           *
  133.000)
  126.000)
  119.000)*
  112.000)*
  105.000)           **
   98.000)*          **
   91.000)**         *****
   84.000)***        ***        *
   77.000)****       **         **
   70.000)**         M*******13 **
   63.000)M********  ******     ******
   56.000)********   ***        *****
   49.000)******     **         M*******13
   42.000)*********  ******     **********
   35.000)**         ***        *****
   28.000)                      ******
   21.000)*                     **
   14.000)                      **
    7.000)*
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN        60.060     69.437     46.222        .000        .000        .000
 S. DEV.      20.747     21.746     15.462        .000        .000        .000
    N         50.000     48.000     54.000        .000        .000        .000
 MAXIMUM     121.000    142.000     83.000        .000        .000        .000
 MINIMUM      10.000     34.000     13.000        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN              58.105
 S. DEV.           21.526
    N             152.
 MAXIMUM          142.000
 MINIMUM           10.000

         SUM OF SQUARES      DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
 BETWEEN  13980.3867          2      6990.1914   18.6030        .0000
 WITHIN   55987.7891        149       375.7568
 TOTAL    69968.1250        151
```

```
1TABULATION OF VARIABLE        4 FYCG


            HUD1N        HUD2         HUD3
            .........+..........+..........+..........+..........+..........
 MIDPOINTS
   63.000)
   56.000)
   49.000)
   42.000)*                     *
   35.000)          *
   28.000)*         ****        **
   21.000)****      ****        ***
   14.000)**        *******     *****
    7.000)********  ******      ********
     .000)********** M********* M********14
   -7.000)M*****    ****        ********12
  -14.000)*******   ***         *******
  -21.000)****      ***         *
  -28.000)*         **          *
  -35.000)****      **
  -42.000)*         *
  -49.000)
  -56.000)*
  -63.000)          *
  -70.000)
  -77.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN        -5.440        .042        1.407        .000        .000        .000
 S. DEV.      18.815      20.597       12.630        .000        .000        .000
    N         50.000      48.000       54.000        .000        .000        .000
 MAXIMUM      42.000      38.000       43.000        .000        .000        .000
 MINIMUM     -56.000     -63.000      -25.000        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN              -1.276
 S. DEV.           17.658
    N             152.
 MAXIMUM           43.000
 MINIMUM          -63.000

        SUM OF SQUARES     DF      MEAN SQUARE   F RATIO    PROB. F EXCEEDED
BETWEEN    1339.1155        2        669.5576     2.1811          .1165
WITHIN    45741.0703      149        306.9868
TOTAL     47080.1836      151
```

```
1TABULATION OF VARIABLE        2 FVQVR


          HUDN1        HUD2         HUD3
          ..........+..........+..........+..........+..........+..........
 MIDPOINTS
   21.000)
   19.500)
   18.000)           *
   16.500)
   15.000)
   13.500)                      *
   12.000)*          *
   10.500)**         **
    9.000)**         *
    7.500)******     **         ****
    6.000)***        *******    *****
    4.500)******     M*******13 *******
    3.000)M********* ********   M*******
    1.500)********   ******     **********
     .000)******     ****       ********11
   -1.500)*          *          ****
   -3.000)**         *          ***
   -4.500)**         *          *
   -6.000)
   -7.500)*
   -9.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN          3.168       4.252       2.269        .000        .000        .000
 S. DEV.        4.155       3.907       3.441        .000        .000        .000
    N          50.000      48.000      54.000        .000        .000        .000
 MAXIMUM       11.600      18.700      13.300        .000        .000        .000
 MINIMUM       -8.200      -4.200      -4.400        .000        .000        .000
OALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
O
OMEAN              3.191
 S. DEV.           3.895
    N            152.
 MAXIMUM          18.700
 MINIMUM          -8.200

          SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
 BETWEEN     100.0222          2       50.0111    3.4015         .0359
 WITHIN     2190.7109        149       14.7028
 TOTAL      2290.7332        151
```

```
1TABULATION OF VARIABLE        3 FHDOT


          HUDN1      HUD2       HUD3
         ..........+..........+..........+..........+..........+..........
 MIDPOINTS
    3.000)
    1.500)
     .000)
   -1.500)
   -3.000)                      *
   -4.500)                      *
   -6.000)                      **
   -7.500)**                    **
   -9.000)*                     ********
  -10.500)******     *********  ********15
  -12.000)****       ****       M******
  -13.500)********** ********12 *********
  -15.000)M********* M********  *****
  -16.500)*******               ****
  -18.000)****       ******
  -19.500)****       *****
  -21.000)*          ***
  -22.500)*
  -24.000)
  -25.500)
  -27.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       -14.424    -14.762    -11.346       .000       .000       .000
 S. DEV.       3.272      3.291      2.907       .000       .000       .000
    N         50.000     48.000     54.000       .000       .000       .000
 MAXIMUM      -7.300     -9.800     -2.700       .000       .000       .000
 MINIMUM     -22.100    -21.700    -16.800       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN             -13.437
 S. DEV.            3.501
    N             152.
 MAXIMUM           -2.700
 MINIMUM          -22.100
          SUM OF SQUARES     DF     MEAN SQUARE   F RATIO    PROB. F EXCEEDED
 BETWEEN     369.0784        2       184.5392    18.5634          .0000
 WITHIN     1481.2100      149         9.9410
 TOTAL      1850.2883      151
```

```
1TABULATION OF VARIABLE          4 LXCG


           HUDN1        HUD2         HUD3
          ..........+..........+..........+..........+..........+.........
 MIDPOINTS
 3800.000)
 3600.000)
 3400.000)
 3200.000)**         **
 3000.000)           **
 2800.000)**         ***          *
 2600.000)***        ****         *****
 2400.000)******     ****         ***
 2200.000)****       *****        *******
 2000.000)*******    M****        *********
 1800.000)M******    ****         M***
 1600.000)****       ******       ********
 1400.000)***                     ********
 1200.000)****       ****         ******
 1000.000)**         ****         **
  800.000)****       *****        *
  600.000)*
  400.000)
  200.000)*
     .000)
 -200.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN      1815.387   1901.403   1807.034        .000        .000        .000
 S. DEV.     681.858    710.085    487.500        .000        .000        .000
    N         50.000     48.000     54.000        .000        .000        .000
 MAXIMUM    3292.500   3144.000   2727.000        .000        .000        .000
 MINIMUM     234.500    731.500    707.500        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN            1839.582
 S. DEV.          626.911
    N             152.
 MAXIMUM         3292.500
 MINIMUM          234.500

          SUM OF SQUARES     DF     MEAN SQUARE   F RATIO   PROB. F EXCEEDED
 BETWEEN 269924.1875          2    134962.0625     .3404          .7120
 WITHIN 9075792.0000        149    396481.8125
 TOTAL  9345712.0000        151
```

```
1TABULATION OF VARIABLE        2 LYCG


             HUDN1         HUD2          HUD3
             ..........+..........+..........+..........+..........+.........
 MIDPOINTS
   60.000)
   55.000)                          *
   50.000)
   45.000)
   40.000)              *
   35.000)*
   30.000)              **
   25.000)*             *
   20.000)****          *
   15.000)*****         ****          **
   10.000)*******       *****         *******
    5.000)M*****        *******       *********13
     .000)********      M*******      M*******18
   -5.000)**********    ***           *********
  -10.000)****          *********     **
  -15.000)**            **
  -20.000)*             ***
  -25.000)                            *
  -30.000)              *             *
  -35.000)              *
  -40.000)*
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN          3.076          .819        1.935          .000          .000          .000
 S. DEV.       12.916        15.083       10.708          .000          .000          .000
    N          50.000        48.000       54.000          .000          .000          .000
 MAXIMUM       33.000        40.000       53.000          .000          .000          .000
 MINIMUM      -42.000       -35.000      -32.000          .000          .000          .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN               1.958
 S. DEV.           12.885
    N             152.
 MAXIMUM           53.000
 MINIMUM          -42.000
          SUM OF SQUARES      DF     MEAN SQUARE   F RATIO   PROB. F EXCEEDED
 BETWEEN     124.8229          2       62.4114      .3728          .6894
 WITHIN    24942.8984        149      167.4020
 TOTAL     ~5067.7188        151
```

```
1TABULATION OF VARIABLE        3 LMAXVEQ


           HUDN1          HUD2           HUD3
           ..........+..........+..........+..........+..........+.........
 MIDPOINTS
  154.000)
  152.000)
  150.000)                               *
  148.000)                               *
  146.000)
  144.000)
  142.000)*          **
  140.000)***        ****           **
  138.000)*****      ******         **
  136.000)******     *******        ****
  134.000)******     M*********     ****
  132.000)M*****     ********       *******
  130.000)********15 ****           M*********
  128.000)**         ***            ********
  126.000)**         *              *******
  124.000)**         *              *******
  122.000)*          **             *
  120.000)
  118.00
  116.000)*
  114.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN        132.119     133.699     130.470         .000          .000          .000
 S. DEV.        4.832       4.709       5.771         .000          .000          .000
    N          50.000      48.000      54.000         .000          .000          .000
 MAXIMUM      141.820     142.630     150.480         .000          .000          .000
 MINIMUM      116.010     122.150     122.180         .000          .000          .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN              132.032
 S. DEV.             5.285
    N              152.
 MAXIMUM           150.480
 MINIMUM           116.010

          SUM OF SQUARES       DF       MEAN SQUARE   F RATIO    PROB. F EXCEEDED
BETWEEN     265.6484            2        132.8242     5.0087          .0078
WITHIN     3951.2595          149         26.5185
TOTAL      4216.9063          151
```

```
1TABULATION OF VARIABLE        4 LMAXHDOT


           HUDN1      HUD2       HUD3
          .........+.........+.........+.........+.........+.........
 MIDPOINTS
    5.000)
    4.000)
    3.000)
    2.000)
    1.000)
     .000)                      *
   -1.000)**         ***        ******
   -2.000)*******    ********12 ********19
   -3.000)********17 M*******17 M*******17
   -4.000)M*******12 ********** *********
   -5.000)********11 *****
   -6.000)           *          *
   -7.000)
   -8.000)*
   -9.000)
   10.000)                      *
  -11.000)
  -12.000)
  -13.000)
  -14.000)
  -15.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       -3.534     -3.025     -2.787       .000       .000       .000
 S. DEV.      1.257      1.198      1.399       .000       .000       .000
    N        50.000     48.000     54.000       .000       .000       .000
 MAXIMUM     -1.200      -.700      -.400       .000       .000       .000
 MINIMUM     -8.400     -5.600     -9.700       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN            -3.108
 S. DEV.          1.321
    N           152.
 MAXIMUM          -.400
 MINIMUM         -9.700
         SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
BETWEEN     14.9673          2        7.4837    4.4846        .0128
WITHIN     248.6424        149        1.6687
TOTAL      263.6096        151
```

SUPPLEMENTAL ANALYSIS AND CONSISTENCY TESTS

A sequence of analyses of a data set are subject to many sources of variability, not all of which can be controlled for in an experimental design. The point of this section is to provide two supplemental analyses which deal with such variation.

Thr first problem we consider is that the HUD2 display was slightly different for subject numbered 2, 9, 10, and 11 than it was for other subjects. It is, therefore, of some importance to assess whether this change is liable to make a significant impact on the overall study.

To assess this impact, a one-way ANOVA was done on just the data of subjects 2, 9, 10, and 11. It was impractical to repeat the whole set of 32 possible response variable analyses, so a set of three sensitive variables were chosen for special analysis in both the precision and nonprecision cases. Together with the significance levels obtained those variables are the following:

Variable	Significance Level	
	Precision	Nonprecision
AHDOTMAX	0.0000**	0.0352*
AHDOTM	.2351	.0123**
AHDOTD	.0000**	.0909*

There were several motivations for choosing this group: (1) high significance level in the whole design; (2) middle part of flight scenario data; and (3) basic physical importance of the variable. Needless to say, other variables share these properties, but the conclusion is still likely to be the same. The data for subjects 2, 9, 10, and 11 do not seem to carry a different message from the overall data. Certainly, if one really wishes to assess the differences which do exist in these data, much more analysis is required. If one just wants a quick estimate of the impact of a change in these four subjects, a consideration of the next six histograms should provide tentative assurance.

TABULATION OF VARIABLE   2 AHDOTMAX

```
           HUDP1      HUD2       HUD3
          .........+..........+..........+..........+..........+..........+.........
 MIDPOINTS
   -8.000)
  -10.000)
  -12.000)                       *****
  -14.000)          **           **
  -16.000)***       ********     M****
  -18.000)*         M****        ***
  -20.000)***       *****        **
  -22.000)*         *
  -24.000)M***                   **
  -26.000)**
  -28.000)*
  -30.000)
  -32.000)
  -34.000)
  -36.000)**
  -38.000)
  -40.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE
```

	HUDP1	HUD2	HUD3			
MEAN	-23.104	-17.555	-16.263	.000	.000	.000
S. DEV.	6.108	2.100	3.702	.000	.000	.000
N	17.000	21.000	19.000	.000	.000	.000
MAXIMUM	-15.830	-13.190	-11.940	.000	.000	.000
MINIMUM	-36.680	-21.200	-24.640	.000	.000	.000

0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0

0MEAN	-18.779
S. DEV.	5.003
N	57.
MAXIMUM	-11.940
MINIMUM	-36.680

	SUM OF SQUARES	DF	MEAN SQUARE	F RATIO	PROB. F EXCEEDED
BETWEEN	469.7205	2	234.8602	13.6118	.0000
WITHIN	931.7224	54	17.2541		
TOTAL	1401.4429	56			

```
1TABULATION OF VARIABLE        3 AHDOTM


          HUDP1       HUD2        HUD3
          ..........+..........+..........+..........+..........+..........+.........
 MIDPOINTS
   -5.000)
   -6.000)
   -7.000)
   -8.000)
   -9.000)
  -10.000)**         ***         *
  -11.000)****       *******     ******
  -12.000)*          M**         M**
  -13.000)M**        *******     *******
  -14.000)*****      *
  -15.000)**                     *
  -16.000)
  -17.000)                       *
  -18.000)
  -19.000)
  -20.000)
  -21.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       -12.709    -11.858    -12.324       .000       .000       .000
 S. DEV.       1.675      1.185      1.704       .000       .000       .000
    N         17.000     21.000     19.000       .000       .000       .000
 MAXIMUM     -10.220    -10.100    -10.470       .000       .000       .000
 MINIMUM     -15.320    -13.750    -16.840       .000       .000       .000
)ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
)
)MEAN             -12.267
 S. DEV.            1.536
    N              57.
 MAXIMUM          -10.100
 MTNIMUM          -16.840

          SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
  BETWEEN     6.9008          2       3.4504     1.4873         .2351
  WITHIN    125.2780         54       2.3200
  TOTAL     132.1788         56
```

TABULATION OF VARIABLE 4 AHDOTD

```
          HUDP1      HUD2       HUD3
          .........+..........+..........+..........+..........+..........
MIDPOINTS
  14.000)
  13.000)
  12.000)
  11.000)
  10.000)*
   9.000)
   8.000)*
   7.000)
   6.000)***
   5.000)M***
   4.000)**         **         **
   3.000)*****      M*******12 ***
   2.000)*          *******    M****
   1.000)                      *********
    .000)
  -1.000)
  -2.000)
```

GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

MEAN	4.798	2.763	1.846	.000	.000	.000
S. DEV.	2.153	.630	1.062	.000	.000	.000
N	17.000	21.000	19.000	.000	.000	.000
MAXIMUM	10.320	4.040	4.190	.000	.000	.000
MINIMUM	2.090	1.630	.750	.000	.000	.000

)ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
)

)MEAN	3.064
S. DEV.	1.811
N	57.
MAXIMUM	10.320
MINIMUM	.750

	SUM OF SQUARES	DF	MEAN SQUARE	F RATIO	PROB. F EXCEEDED
BETWEEN	81.2055	2	40.6027	21.4121	.0000
WITHIN	102.3974	54	1.8962		
TOTAL	183.6029	56			

```
1TABULATION OF VARIABLE        2 AHDOTMAX


          HUDN1        HUD2        HUD3
          ..........+..........+..........+..........+..........+..........
 MIDPOINTS
  -14.000)
  -16.000)
  -18.000)*
  -20.000)******                  *
  -22.000)M****      ********     ********11
  -24.000)*****      ****         M****
  -26.000)**         M*           ***
  -28.000)           **           *
  -30.000)           *            *
  -32.000)
  -34.000)*          *
  -36.000)
  -38.000)
  -40.000)
  -42.000)           *
  -44.000)           *
  -46.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       -22.681     -26.229     -23.406       .000        .000        .000
 S. DEV.       3.417       6.687       2.250       .000        .000        .000
    N         20.000      20.000      22.000       .000        .000        .000
 MAXIMUM     -18.380     -21.040     -20.990       .000        .000        .000
 MINIMUM     -33.160     -43.970     -29.420       .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN               -24.083
 S. DEV.              4.651
    N                62.
 MAXIMUM            -18.380
 MINIMUM            -43.970

          SUM OF SQUARES     DF     MEAN SQUARE   F RATIO    PROB. F EXCEEDED
 BETWEEN     141.5063         2        70.7531     3.5442         .0352
 WITHIN     1177.8120        59        19.9629
 TOTAL      1319.3181        61
```

```
1TABULATION OF VARIABLE          3 AHDOTM


          HUDN1        HUD2         HUD3
          ..........+..........+..........+..........+..........+..........
 MIDPOINTS
   -9.000)
  -10.000)
  -11.000)
  -12.000)*
  -13.000)*          **
  -14.000)*          ****         ***
  -15.000)*******    ****         **
  -16.000)M****      M***         *****
  -17.000)**         **           M****
  -18.000)**         ****
  -19.000)*                       ***
  -20.000)                        *
  -21.000)                        **
  -22.000)                        *
  -23.000)
  -24.000)
  -25.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN      -15.560    -15.570    -17.142         .000        .000        .000
 S. DEV.      1.641      1.635      2.365         .000        .000        .000
    N        20.000     20.000     22.000         .000        .000        .000
 MAXIMUM    -11.980    -12.910    -14.080         .000        .000        .000
 MINIMUM    -18.890    -18.340    -22.200         .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN            -16.125
 S. DEV.           2.043
    N             62.
 MAXIMUM         -11.980
 MINIMUM         -22.200

        SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
BETWEEN     35.2761         2       17.6381    4.7427        .0123
WITHIN     219.4201        59        3.7190
TOTAL      254.6962        61
```

```
ABULATION OF VARIABLE        4 AHDOTD



         HUDN1      HUD2       HUD3
         .........+..........+..........+..........+..........+..........
MIDPOINTS
  17.000)
  16.000)           *
  15.000)
  14.000)
  13.000)
  12.000)
  11.000)           **
  10.000)*
   9.000)           **         *
   8.000)*          **         *
   7.000)*          **         ******
   6.000)*          N          ***
   5.000)           **         M**
   4.000)M*****     ***        *
   3.000)*****      **         **
   2.000)*****      ****       **
   1.000)                      ***
GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

 MEAN          4.066      6.082      4.942       .000       .000       .000
 S. DEV.       2.180      3.816      2.352       .000       .000       .000
   N          20.000     20.000     22.000       .000       .000       .000
 MAXIMUM       9.580     15.850      8.560       .000       .000       .000
 MINIMUM       2.180      1.550      1.160       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN              5.027
 S. DEV.           2.931
   N              62.
 MAXIMUM          15.850
 MINIMUM           1.160

            SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
  BETWEEN      40.9099          2       20.4550    2.4978         .0909
  WITHIN      483.1702         59        8.1893
  TOTAL       524.0801         61.
```

The second problem addressed in this section is that of whether one should include the anomaly and missed approach data in the analysis of the APPROACH segment data. To resolve this, and also for another benefit to be discussed in a moment, an analysis of the APPROACH segment (precision and nonprecision) was conducted on all avaliable responses. The list of variables (and levels of significance) are as follows:

SIGNIFICANCE TABLE:
ALTERNATE APPROACH DATA

Variable	Significance Level	
	Precision	Nonprecision
ALOC	0.0762	0.0000**
AGS	.0000**	.0310
AEASM	.1079	.0887
AEASD	.5056	.9204
AHDOTMAX	.0000**	.3804
AHDOTM	.0210*	.0000**
AHDOTD	.0000**	.9616

The histograms and detailed ANOVA for the preceding variables are listed below. The importance of this special analysis for the whole data set is now revealed by comparison with the first table of significance given in the section "Introduction to the Principal Analysis." The pattern of significance is essentially identical in both the data sets. The main implication is that this data set is highly robust to the inclusion/deletion of observations on the basis of the subsequent development of missed approach or anomaly. Although no comparative analysis was made, it is quite likely that a similar conclusion holds for the marker variables and much of the data in the decision segment. In particular, all of the significance levels reported in any of the tables of this report are almost certain to be impervious to deletion (or insertion) of a modest number of observations. This is a very sensible property for a design to possess.

```
1TABULATION OF VARIABLE        4 ALOC


          HUDP1       HUD2        HUD3
          ..........+..........+..........+..........+..........+........
 MIDPOINTS
    1.330)
    1.260)
    1.190)
    1.120)           *
    1.050)                       *
     .980)
     .910)
     .840)
     .770)
     .7(  )
     .630)
     .560)
     .490)*
     .420)*                      *
     .350)*                      *
     .280)**                     *
     .210)****       *
     .140)M*******20 *********   ****
     .070)********24 M*******36 M*******27
    -.000)**         ********11 ********25
    -.070)
    -.140)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN          .129        .087        .077        .000        .000        .000
 S. DEV.        .090        .140        .146        .000        .000        .000
    N         55.000      58.000      60.000        .000        .000        .000
 MAXIMUM        .520       1.090       1.040        .000        .000        .000
 MINIMUM        .030        .010        .010        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN               .097
 S. DEV.            .130
    N           173.
 MAXIMUM           1.090
 MINIMUM            .010


          SUM OF SQUARES    DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
  BETWEEN       .0866        2          .0433    2.6142         .0762
  WITHIN       2.8160      170          .0166
  TOTAL        2.9026      172
```

```
1TABULATION OF VARIABLE       2 AGS


          HUDP1      HUD2       HUD3
          .........+..........+..........+..........+..........+........
 MIDPOINTS
     .600)
     .570)
     .540)
     .510)*
     .480)
     .450)
     .420)
     .390)
     .360)
     .330)                      *
     .300)
     .270)**
     .240)*          *
     .210)**         *          *
     .180)*****                 *
     .150)*                     *
     .120)M*******   *****
     .090)*******19 *********  ****
     .060)*******13 M*******21 M*******16
     .030)***       ********21 ********34
     .000)                      **
    -.030)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN         .112       .065       .051       .000       .000       .000
 S. DEV.       .077       .043       .052       .000       .000       .000
    N        55.000     58.000     60.000       .000       .000       .000
 MAXIMUM       .510       .250       .320       .000       .000       .000
 MINIMUM       .030       .020       .010       .000       .000       .000
 ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)

 MEAN              .075
 S. DEV.           .064
    N          173.
 MAXIMUM           .510
 MINIMUM           .010

          SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
  BETWEEN        .1174        2          .0587   16.9419        .0000
  WITHIN         .5891      170          .0035
  TOTAL          .7065      172
```

```
1TABULATION OF VARIABLE        3 MEASM


          HUDP1        HUD2        HUD3
          ..........+..........+..........+..........+..........+..........+..........
MIDPOINTS
 157.500)
 156.000)
 154.500)*
 153.000)
 151.500)**          *
 150.000)*           *
 148.500)                        *
 147.000)****                    *
 145.500)***         **          *
 144.000)*           **          ****
 142.500)**                      ***
 141.000)*****       ****        ******
 139.500)M**         *********   ****
 138.000)*******     ***         M*****
 136.500)******      M****       *********
 135.000)*********   ********12  *****
 133.500)******      *********   ********11
 132.000)            *********   *******
 130.500)***         *           **
 129.000)**
 127.500)
 126.000)
GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

 MEAN        138.787     136.921     137.294        .000        .000        .000
S. DEV.        5.963       4.478       4.251        .000        .000        .000
   N          55.000      58.000      60.000        .000        .000        .000
MAXIMUM      154.500     151.790     148.320        .000        .000        .000
MINIMUM      128.860     130.540     130.790        .000        .000        .000
ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)

MEAN             137.644
S. DEV.            4.965
   N             173.
MAXIMUM          154.500
MINIMUM          128.860


              SUM OF SQUARES     DF    MEAN SQUARE   F RATIO    PROB. F EXCEEDED
   BETWEEN       109.6192         2      54.8096     2.2563         .1079
   WITHIN       4129.6289       170      24.2919
   TOTAL        4239.2461       172
```

1TABULATION OF VARIABLE   4 AEASD

```
          HUDF1        HUD2        HUD3
          ..........+..........+..........+..........+..........+..........+.........
MIDPOINTS
  16.000)
  15.000)
  14.000)
  13.000)
  12.000)
  11.000)
  10.000)           *
   9.000)
   8.000)*
   7.000)           *           *
   6.000)**         ****        ***
   5.000)****       ****        *
   4.000)*********  ***         ********11
   3.000)M*******19 M*******17  M*******14
   2.000)********16 ********20  ********21
   1.000)****       ********    *********
    .000)
  -1.000)
  -2.000)
  -3.000)
  -4.000)
  -5.000)
```

GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

MEAN	3.075	2.951	2.753	.000	.000	.000
S. DEV.	1.326	1.710	1.403	.000	.000	.000
N	55.000	58.000	60.000	.000	.000	.000
MAXIMUM	8.000	10.140	7.370	.000	.000	.000
MINIMUM	1.170	.740	.540	.000	.000	.000

0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0

0MEAN	2.922
S. DEV.	1.488
N	173.
MAXIMUM	10.140
MINIMUM	.540

	SUM OF SQUARES	DF	MEAN SQUARE	F RATIO	PROB. F EXCEEDED
BETWEEN	3.0433	2	1.5216	.6847	.5056
WITHIN	377.8228	170	2.2225		
TOTAL	380.8660	172			

1TABULATION OF VARIABLE   2 AHDOTMAX

```
          HUDP1      HUD2       HUD3
          .........+.........+.........+.........+.........+.........
 MIDPOINTS
   -9.000)
  -10.500)
  -12.000)                      ********12
  -13.500)           ******     ******
  -15.000)***        *****      ******
  -16.500)*******    ********17 M*******17
  -18.000)*****      M********  **********
  -19.500)******     *******    *****
  -21.000)******     ******
  -22.500)M**        ***
  -24.000)*******    ***        ***
  -25.500)******     *
  -27.000)**
  -28.500)*          *
  -30.000)***
  -31.500)*
  -33.000)**
  -34.500)                      *
  -36.000)**
  -37.500)
  -39.000)
  -40.500)*
```

GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

MEAN	-22.970	-18.157	-16.354	.000	.000	.000
S. DEV.	5.799	3.280	3.762	.000	.000	.000
N	55.000	58.000	60.000	.000	.000	.000
MAXIMUM	-14.740	-12.920	-11.470	.000	.000	.000
MINIMUM	-40.030	-28.720	-34.390	.000	.000	.000

0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0

0MEAN	-19.062
S. DEV.	5.167
N	173.
MAXIMUM	-11.470
MINIMUM	-40.030

	SUM OF SQUARES	DF	MEAN SQUARE	F RATIO	PROB. F EXCEEDED
BETWEEN	1327.2209	2	663.6104	34.5597	.0000
WITHIN	3264.3132	170	19.2018		
TOTAL	4591.5313	172			

```
1TABULATION OF VARIABLE        3 AHDOTM


          HUDP1       HUD2        HUD3
          .........+..........+..........+..........+..........+.........
 MIDPOINTS
   -4.000)
   -5.000)
   -6.000)
   -7.000)
   -8.000)
   -9.000)*          **
  -10.000)****       ********    *****
  -11.000)********15 ********21  ********15
  -12.000)*********  M*********  M*******14
  -13.000)M*****     **********  *******18
  -14.000)*********  ***         ****
  -15.000)********   ***         *
  -16.000)*          *           *
  -17.000)                       *
  -18.000)
  -19.000)*
  -20.000)                       *
  -21.000)*
  -22.000)
  -23.000)
  -24.000)
  -25.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       -12.790    -11.818    -12.310      .000      .000      .000
 S. DEV.       2.188      1.493      1.785      .000      .000      .000
    N         55.000     58.000     60.000      .000      .000      .000
 MAXIMUM      -9.260     -8.810     -9.580      .000      .000      .000
 MINIMUM     -21.030    -16.170    -20.040      .000      .000      .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN             -12.297
 S. DEV.            1.868
    N             173.
 MAXIMUM           -8.810
 MINIMUM          -21.030


        SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
BETWEEN     26.6694         2       13.3347    3.9514        .0210
WITHIN     573.6877       170        3.3746
TOTAL      600.3569       172
```

```
1TABULA   ON OF VARIABLE        4 AHDOTD


          HUDR1         HUD2         HUD3
          .........+..........+..........+..........+..........+........
 MIDPOINTS
   17.000)
   16.000)
   15.000)
   14.000)
   13.000)
   12.000)*
   11.000)
   10.000)**
    9.000)*
    8.000)****
    7.000)*****
    6.000)*****     ***         *
    5.000)M********11 ******
    4.000)********** ******     ***
    3.000)********12 M*******23 ********
    2.000)****      ********18 M*******26
    1.000)          **          ********22
     .000)
   -1.000)
   -2.000)
   -3.000)
   -4.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN        5.069      3.120      1.926       .000       .000       .000
 S. DEV.      2.269      1.179      1.003       .000       .000       .000
    N        55.000     58.000     60.000       .000       .000       .000
 MAXIMUM     12.100      6.220      6.390       .000       .000       .000
 MINIMUM      2.090      1.130       .750       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN             3.326
 S. DEV.          2.023
    N           173.
 MAXIMUM         12.100
 MINIMUM           .750


         SUM OF SQUARES     DF     MEAN SQUARE  F RATIO    PROB. F EXCEEDED
 BETWEEN    287.1079         2       143.5540   58.5556          .0000
 WITHIN     416.7695       170         2.4516
 TOTAL      703.8774       172
```

```
1TABULATION OF VARIABLE        4 ALOC



          HUDN1      HUD2      HUD3
          .........+.........+.........+.........+.........+........
 MIDPOINTS
     .950)
     .900)
     .850)
     .800)*
     .750)
     .700)
     .650)
     .600)*
     .55' )
     .500)                    *
     .450)*
     .400)
     .350)**                  *
     .300)**                  *
     .250)**        *         *
     .200)**                  **
     .150)M*********  *       ***
     .100)********18 ******** *****
     .050)********14 M*******33 M*******27
    -.000)***        ********17 ********18
    -.050)
    -.100)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN         .143       .051       .072       .000       .000       .000
 S. DEV.       .143       .041       .089       .000       .000       .000
    N        56.000     60.000     59.000       .000       .000       .000
 MAXIMUM       .810       .270       .490       .000       .000       .000
 M.NIMUM       .010       .010       .010       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN                .087
 S. DEV.             .106
    N             175.
 MAXIMUM             .810
 MINIMUM             .010


        SUM OF SQUARES    DF    MEAN SQUARE  F RATIO   PROB. F EXCEEDED
 BETWEEN      .2647        2        .1323   13.5402         .0000
 WITHIN      1.6810      172        .0098
 TOTAL       1.9457      174
```

```
1TABULATION OF VARIABLE        2 AGS


          HUDN1          HUD2         HUD3
          .........+..........+..........+..........+..........+..........
 MIDPOINTS
    1.470)
    1.400)
    1.330)
    1.260)*
    1.190)*
    1.120)                            *
    1.050)*          **
     .980)***
     .910)           ***          ****
     .840)*          ***          **
     .770)           ***          *****
     .700)**         ****         *********
     .630)*****      ****         ********11
     .560)****       *****        M
     .490)****       M***         *******
     .420)M***       *******      *
     .350)*******    ********** **********
     .280)********** **           ******
     .210)*********  ********** **
     .140)***        **
     .070)*          *
     .000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN           .451        .486        .569        .000        .000        .000
 S. DEV.         .275        .247        .213        .000        .000        .000
    N          56.000      60.000      59.000        .000        .000        .000
 MAXIMUM        1.240       1.050       1.150        .000        .000        .000
 MINIMUM         .100        .090        .200        .000        .000        .000
0ALL GROUP  COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN               .503
 S. DEV.            .249
    N           175.
 MAXIMUM           1.240
 MINIMUM            .090


          SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
  BETWEEN       .4286         2          .2143    3.5462        .0310
  WITHIN      10.3944       172          .0604
  TOTAL       10.8230       174
```

```
1TABULATION OF VARIABLE        3 AIEASM


          HUDN1        HUD2         HUD3
          ..........+..........+..........+..........+..........+..........
MIDPOINTS
 156.000)
 154.500)
 153.000)**
 151.500)*          **
 150.000)*                    **
 148.500)**
 147.000)                     ***
 145.500)***                  *
 144.000)***        *         *
 142.500)*********  ******    ***
 141.000)*****      ********* **
 139.500)M********  ******    *******
 138.000)***        M*******  M*********
 136.500)*****      ********12 ********16
 135.000)****       ********12 *********
 133.500)*****      ***       ***
 132.000)*          *         **
 130.500)**
 129.000)
 127.500)
 126.000)*
 124.500)
GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

 MEAN       140.001    138.398    138.320       .000       .000       .000
S. DEV.       5.674      3.811      4.086       .000       .000       .000
   N         56.000     60.000     59.000       .000       .000       .000
MAXIMUM     153.650    152.130    150.400       .000       .000       .000
MINIMUM     126.100    132.420    131.930       .000       .000       .000
)ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
)
)MEAN            138.885
S. DEV.            4.611
   N             175.
MAXIMUM          153.650
MINIMUM          126.100

          SUM OF SQUARES    DF     MEAN SQUARE   F RATIO   PROB. F EXCEEDED
 BETWEEN     102.7455        2       51.3727      2.4570        .0887
 WITHIN     3596.2952      172       20.9087
 TOTAL      3699.0405      174
```

```
1TABULATION OF VARIABLE         4 DEASD


          HUDN1        HUD2         HUD3
          ....\.....+..........+..........+..........+..........+..........+.........
MIDPOINTS
  16.000)
  15.000)
  14.000)
  13.000)
  12.000)
  11.000)
  10.000)
   9.000)              *            *
   8.000)
   7.000)*
   6.000)***           *            *
   5.000)*******       ***          *
   4.000)*********     *********    *******
   3.000)M***          M*******18   M*******22
   2.000)********18    *******27    ********24
   1.000)********13    *            ***
    .000)*
  -1.000)
  -2.000)
  -3.000)
  -4.000)
  -5.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE
```

	HUDN1	HUD2	HUD3			
MEAN	2.832	2.914	2.818	.000	.000	.000
S. DEV.	1.653	1.273	1.203	.000	.000	.000
N	56.000	60.000	59.000	.000	.000	.000
MAXIMUM	7.120	8.780	8.950	.000	.000	.000
MINIMUM	.500	1.470	1.210	.000	.000	.000

```
)ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
)
)MEAN          2.855
 S. DEV.       1.377
    N        175.
 MAXIMUM       8.950
 MINIMUM        .500
```

	SUM OF SQUARES	DF	MEAN SQUARE	F RATIO	PROB. F EXCEEDED
BETWEEN	.3183	2	.1592	.0830	.9204
WITHIN	329.8474	172	1.9177		
TOTAL	330.1655	174			

```
1TABULATION OF VARIABLE        2 AHDOTMAX


         HUDN1        HUD2         HUD3
          ..........+..........+..........+..........+..........+..........
 MIDPOINTS
   12.000)
    9.000)
    6.000)
    3.000)
     .000)*
   -3.000)
   -6.000)
   -9.000)
  -12.000)
  -15.000)           *
  -18.000)*****      ******     ***
  -21.000)********14 ********19 ********22
  -24.000)M*******16 M*******16 M*******21
  -27.000)******     *********  *********
  -30.000)***        *****      ***
  -33.000)****       **         *
  -36.000)*
  -39.000)**
  -42.000)**         *
  -45.000)           *
  -48.000)
  -51.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       -24.806    -24.257    -23.456       .000       .000       .000
 S. DEV.       6.882      5.232      2.773       .000       .000       .000
    N         54.000     60.000     59.000       .000       .000       .000
 MAXIMUM        .000    -16.470    -18.900       .000       .000       .000
 MINIMUM     -40.760    -43.970    -31.520       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN            -24.155
 S. DEV.           5.185
    N            173.
 MAXIMUM            .000
 MINIMUM         -43.970


         SUM OF SQUARES    DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
 BETWEEN     52.2779        2       26.1389     .9721         .3804
 WITHIN    4571.2695      170       26.8898
 TOTAL     4623.5469      172
```

```
1TABULATION OF VARIABLE        3 AHDOTM


          HUDN1        HUD2         HUD3
         ..........+..........+..........+..........+..........+.........
 MIDPOINTS
    6.000)
    4.500)
    3.000)
    1.500)
     .000)*
   -1.500)
   -3.000)
   -4.500)
   -6.000)
   -7.500)
   -9.000)           *
  -10.500)           *          *
  -12.000)****       ***
  -13.500)********   ********16 ***
  -15.000)M*******19 M*******18 ********16
  -16.500)********13 ********** M*******14
  -18.000)*******    ********   ********12
  -19.500)**         ***        ********
  -21.000)                      ****
  -22.500)                      *
  -24.000)
  -25.500)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       -15.161    -15.236    -17.022         .000        .000        .000
 S. DEV.       2.756      2.059      2.183         .000        .000        .000
    N         54.000     60.000     59.000         .000        .000        .000
 MAXIMUM        .000     -8.950    -11.120         .000        .000        .000
 MINIMUM     -19.720    -18.900    -22.200         .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN              -15.821
 S. DEV.             2.481
    N             173.
 MAXIMUM              .000
 MINIMUM           -22.200


          SUM OF SQUARES      DF      MEAN SQUARE  F RATIO   PROB. F EXCEEDED
 BETWEEN     129.1640          2        64.5820    11.8127         .0000
 WITHIN      929.4158        170         5.4672
 TOTAL      1058.5796        172
```

```
1TABULATION OF VARIABLE        4 AHDOTD


          HUDN1      HUD2       HUD3
          .........+..........+..........+..........+..........+.........
 MIDPOINTS
   19.000)
   18.000)
   17.000)
   16.000)          *
   15.000)
   14.000)
   13.000)*
   12.000)
   11.000)*         **
   10.000)***       **         ***
    9.000)**        ***        *
    8.000)******    **         ***
    7.000)*         *****      **********
    6.000)****      *****      ********
    5.000)M***      M******    M********
    4.000)********15 ********13 ******
    3.000)********  *******    *******
    2.000)********  ********13 ********
    1.000)                     ****
     .000)*
   -1.000)
   -2.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN        5.074      5.034      4.937      .000      .000      .000
 S. DEV.      2.839      2.837      2.346      .000      .000      .000
    N        54.000     60.000     59.000      .000      .000      .000
 MAXIMUM     13.460     15.850     10.240      .000      .000      .000
 MINIMUM       .000      1.550      1.160      .000      .000      .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN             5.013
 S. DEV.          2.665
    N           173.
 MAXIMUM         15.850
 MINIMUM           .000


        SUM OF SQUARES    DF    MEAN SQUARE  F RATIO   PROB. F EXCEEDED
 BETWEEN      .5620        2        .2810     .0391        .9616
 WITHIN   1221.1746      170       7.1834
 TOTAL    1221.7366      172
```

GENERAL CONCLUSION

The clear conclusion is that from a statistical point of view, there are very real differences in the three displays that have been studied. The tables given allow one quickly to obtain point and interval estimates of many contrasts of interest. These, in turn, are the first steps of any planning or engineering appraisal.

Clearly, there are many questions which are left. This report should help focus those questions, and the designed data set should still be able to help bring about their resolution. This is the highest level to which a shot gun approach can lead. The next questions need to be sharply posed. The data obtained in HUD phase III will remain a tremendous resource in that subsequent investigation.

SUPPLEMENTAL PARAMETER ANALYSIS
FAA/NASA HEAD-UP DISPLAYS - PHASE III

J. Michael Steele
Control Analysis Corp.
May 28, 1980

PURPOSE AND STRUCTURE

This report is intended to supplement the *Experimental Design and Statistical Analysis FAA/NASA Head-up Displays: Final Report.* The principal objective here is to conduct an analysis of variance and provide histograms for nine response variables of secondary interest which were not included in the analyses of the *Final Report.*

As in that report, the analyses here are separated according to precision and nonprecision flight conditions. Each of the two sections is preceded with a list of the parameters studied with an indication of the significance level of the corresponding F-test. This table of significance levels is intended to guide the reader in his consideration of the full data as presented in the histograms which follow the table.

In the second section (Nonprecision), there are three additional analyses made which are given in order to assist the reader in the understanding of the impact of out-liers on the analyses. The point confirmed by these repeated studies is that single out-liers in this data set apparently have a very minor influence on the resulting levels of significance. More details of this observation are made at the end of the section.

After the two analysis sections, there is a brief conclusion. The statements made there confirm the earlier comments of the *Final Report.*

Precision Flights

The levels of significance of the variables studied here under precision conditions are given below. As usual, the symbols * and ** are used to signal significance levels beyond 0.05 and 0.01, respectively. The histograms and ANOVA tables of these variables follow directly in the same order.

Variable	Significance Level
OMHDOT	0.8799
MMALT	.0009**
MMYCG	.0330*
MMVQVR	.2268
MMHDOT	.3170
IMALT	.0011**
IMYCG	.0037**
IMVQVR	.3040
IMHDOT	.9734

```
!TABULATION OF VARIABLE        2 OMHDOT



          HUDP1         HUD2          HUD3
          .........+..........+..........+..........+..........+..........+
 MIDPOINTS
   27.000)
   24.000)
   21.000)             *
   18.000)
   15.000)*
   12.000)             *
    9.000)             *
    6.000)*
    3.000)******       *             *
     .000)***          **            **
   -3.000)*****        ****          ***
   -6.000)***          ******        *******
   -9.000)M*********   M*********13  M*********24
  -12.000)************ **********11  **********11
  -15.000)*********    ****          ********
  -18.000)****         *****         ***
  -21.000)**           *****         *
  -24.000)****         **
  -27.000)*            **
  -30.000)
  -33.000)
  -36.000)*
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       -10.050     -10.469      -9.752       .000        .000        .000
 S. DEV.       9.102       8.776       4.543       .000        .000        .000
    N         58.000      58.000      60.000       .000        .000        .000
 MAXIMUM      13.900      20.800       2.300       .000        .000        .000
 MINIMUM     -34.600     -26.200     -21.600       .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN            -10.086
 S. DEV.           7.689
    N            176.
 MAXIMUM          20.800
 MINIMUM         -34.600

        SUM OF SQUARES     DF      MEAN SQUARE   F RATIO    PROB. F EXCEEDED
BETWEEN     15.2882         2         7.6441      .1280          .8799
WITHIN   10330.6016       173        59.7144
TOTAL    10345.8867       175
```

```
1TABULATION OF VARIABLE        3 MMALT


          HUDP1        HUD2         HUD3
         ..........+..........+..........+..........+..........+..........
 MIDPOINTS
  322.000)
  315.000)
  308.000)*
  301.000)
  294.000)
  287.000)*
  280.000)**
  273.000)
  266.000)          *
  257.000)*****     ***
  252.000)********** *****
  245.000)*******   ******     ****
  238.000)M***      ********14 ********12
  231.000)********13 M*******11 M*******21
  224.000)********** ********11 ********17
  217.000)****      ***        ******
  210.000)*         ***
  203.000)*
  196.000)          *
  189.000)
  182.000)
  175.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN      239.707     234.345     229.733        .000        .000        .000
 S. DEV.     19.210      13.847       7.059        .000        .000        .000
    N        58.000      58.000      60.000        .000        .000        .000
 MAXIMUM    305.000     264.000     246.000        .000        .000        .000
 MINIMUM    204.000     193.000     217.000        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN             234.540
 S. DEV.           14.705
    N             176.
 MAXIMUM          305.000
 MINIMUM          193.000

        SUM OF SQUARES       DF      MEAN SQUARE   F RATIO   PROB. F EXCEEDED
BETWEEN    2936.8435          2       1468.4216     7.2784         .0009
WITHIN    34902.6289        173        201.7493
TOTAL     37839.4688        175
```

```
TABULATION OF VARIABLE          4 MMYCD


            HUDP1        HUD2         HUD3
            ..........+..........+..........+..........+..........+..........
 MIDPOINTS
  165.000)
  150.000)
  135.000)
  120.000)*
  105.000)
   90.000)*
   75.000)
   60.000)
   45.000)*          *
   30.000)*****
   15.000)*****      ****         *****
     .000)*****      M*******36   M*******43
  -15.000)M*******17 ********12   *********
  -30.000)********** *****        *
  -45.000)********
  -60.000)**
  -75.000)**                      *
  -90.000)
 -105.000)*
 -120.000)
 -135.000)
 -150.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S. N'S OTHERWISE

  MEAN      -13.465      -3.845     -3.283        .000       .000       .000
 S. DEV.     37.094      12.233     11.756        .000       .000       .000
    N        58.000      58.000     60.000        .000       .000       .000
 MAXIMUM    126.000      46.000     21.000        .000       .000       .000
 MINIMUM   -111.000     -33.000    -71.000        .000       .000       .000
OALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
O
OMEAN              -6.824
 S. DEV.           23.776
    N             176.
 MAXIMUM          126.000
 MINIMUM         -111.000

          SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
 BETWEEN    3825.2986         2     1912.6492    3.4788         .0330
 WITHIN    95115.1875       173      549.7986
 TOTAL     98940.4375       175
```

```
TABULATION OF VARIABLE        2 MMVQVR


          HUDP1        HUD2         HUD3
          ..........+..........+..........+..........+..........+..........
MIDPOINTS
  24.000)
  22.500)
  21.000)*
  19.500)
  18.000)
  16.500)
  15.000)
  13.500)
  12.000)          *
  10.500)**
   9.000)****      *
   7.500)****      *****        ******
   6.000)********* ******       *******
   4.500)M*******  **********   ********
   3.000)********  M********    M********14
   1.500)*********12 ********14 *********14
    .000)******    ******       *******
  -1.500)**        ***          **
  -3.000)*         ***          **
  -4.500)*
  -6.000)
  -7.500)
GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

 MEAN         3.695       3.050       2.897        .000        .000        .000
S. DEV.       4.104       3.215       2.618        .000        .000        .000
   N         58.000      58.000      60.000        .000        .000        .000
MAXIMUM      21.500      12.400       8.100        .000        .000        .000
MINIMUM      -5.200      -3.500      -3.300        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN              3.276
 S. DEV.           3.370
   N             176.
 MAXIMUM          21.500
 MINIMUM          -5.200

        SUM OF SQUARES    DF    MEAN SQUARE  F RATIO   PROB. F EXCEEDED
BETWEEN     33.8071        2       16.9035    1.4967          .2268
WITHIN    1953.8967      173       11.2942
TOTAL     1987.7036      175
```

```
 ...ULATION OF VARIABLE        3 MMHDOT


          HUDP1        HUD2         HUD3
          ..........+..........+..........+..........+..........+..........+
MIDPOINTS
   4.500)
   3.000)
   1.500)*
    .000)
  -1.500)****
  -3.000)***
  -4.500)*
  -6.000)              *
  -7.500)*******       ****
  -9.000)*****         *********    ***
 -10.500)*********     *********11  ********19
 -12.000)M*******      M*******13   M*******16
 -13.500)****          *******      ********11
 -15.000)******        ****         *********
 -16.500)*****         ****         **
 -18.000)******        ***
 -19.500)*
 -21.000)              *
 -22.500)              *
 -24.000)
 -25.500)
 -27.000)*
GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

 MEAN        -11.252     -12.122     -12.232       .000        .000        .000
S. DEV.        5.456       3.320       1.825       .000        .000        .000
   N          58.000      58.000      60.000       .000        .000        .000
MAXIMUM        1.900      -6.500      -9.100       .000        .000        .000
MINIMUM      -27.100     -22.100     -17.100       .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN             -11.873
 S. DEV             3.821
   N              176.
 MAXIMUM            1.900
 MINIMUM          -27.100

         SUM OF SQUARES     DF     MEAN SQUARE   F RATIO    PROB. F EXCEEDED
BETWEEN     33.7137          2       16.8568      1.1566         .3170
WITHIN    2521.4824        173       14.5750
TOTAL     2555.1960        175
```

```
1TABULATION OF VARIABLE        4 IMALT


          HUDP1        HUD2         HUD3
          .........+..........+..........+..........+..........+..........+
 MIDPOINTS
  252.000)
  245.000)
  238.000)
  231.000)*          *
  224.000)
  217.000)
  210.000)
  203.000)           *
  196.000)****       *          *
  189.000)**         *
  182.000)****       **
  175.000)***        ****       *
  168.000)*******    *****
  161.000)M*******12 M******    *******
  154.000)*********  *******20  M*******20
  147.000)******     ******     ********20
  140.000)*******    ******     **********
  133.000)*          **
  126.000)**         *          *
  119.000)           *
  112.000)
  105.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       161.862    152.086    149.6         .000       .000       .000
 S. DEV.      19.976     18.816      7.5         .000       .000       .000
    N         58.000     58.000     58.000       .000       .000       .000
 MAXIMUM     232.000    234.000    175.000       .000       .000       .000
 MINIMUM     123.000    120.000    129.000       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN              156.750
 S. DEV.           17.268
    N              176.
 MAXIMUM           234.000
 MINIMUM           120.000

        SUM OF SQUARES     DF     MEAN SQUARE   F RATIO   PROB. F EXCEEDED
 BETWEEN   3950.5371        2      1975.2686     7.0852        .0011
 WITHIN   48230.2969      173       278.7878
 TOTAL    52180.8320      175
```

1TABULATION OF VARIABLE   2 IMYCG

```
          HUDP1        HUD2         HUD3
          .........+.........+.........+.........+.........+.........
MIDPOINTS
 120.000)
 105.000)
  90.000)
  75.000)
  60.000)**
  45.000)*                      *
  30.000)*****        **        *
  15.000)***          ********** *******
    .000)*********    M*******21 M******44
 -15.000)M*******16   ********21 *****
 -30.000)********12   ***        *
 -45.000)****         *
 -60.000)***
 -75.000)**
 -90.000)*
-105.000)
 120.000)
-135.000)
-150.000)
-165.000)
-180.000)
-195.000)
GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

 MEAN       -15.328      -3.690       .43         .000        .000        .000
S. DEV.      31.055      14.173       9.6         .000        .000        .000
   N         58.000      58.000      58.000       .000        .000        .000
MAXIMUM      64.000      34.000      38.000       .000        .000        .000
MINIMUM     -89.000     -44.000     -25.000       .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN            -6.943
S. DEV.          23.711
   N            176.
MAXIMUM          64.000
MINIMUM        -144.000

         SUM OF SQUARES     DF     MEAN SQUARE   F RATIO    PROB. F EXCEEDED
BETWEEN    6167.2461         2      3083.6230     5.7850         .0037
WITHIN    92215.8125       173       533.0393
TOTAL     98383.0000       175
```

```
1TABULATION OF VARIABLE        3 IMVQVR


           HUDF1        HUD2         HUD3
           .........+..........+..........+..........+..........+..........+.........
 MIDPOINTS
   24.000)
   22.500)
   21.000)*
   19.500)
   18.000)
   16.500)
   15.000)
   13.500)
   12.000)          **
   10.500)          *
    9.000)**        **          **
    7.500)******    ***         **
    6.000)*******   ******      ****
    4.500)*******   ********    ********11
    3.000)M********11 M********12 M*******
    1.500)*********11 *********   ********13
     .000)*******   *******     ********16
   -1.500)**        ***         **
   -3.000)***       ***
   -4.500)          **
   -6.000)*                     **
   -7.500)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN          3.310        2.988        2.302          .000         .000         .000
 S. DEV.        3.980        3.771        3.062          .000         .000         .000
    N          58.000       58.000       60.000          .000         .000         .000
 MAXIMUM       20.600       12.300        9.600          .000         .000         .000
 MINIMUM       -5.300       -4.900       -6.700          .000         .000         .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN               2.860
 S. DEV.            3.624
    N             176.
 MAXIMUM           20.600
 MINIMUM           -6.700

        SUM OF SQUARES    DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
BETWEEN     31.4165        2       15.7082    1.1989         .3040
WITHIN    2266.6057      173       13.1018
TOTAL     2298.0220      175
```

```
BULATION OF VARIABLE          4 IMHDOT


         HUD-1          HUD2          HUD3
         ..........+..........+..........+..........+..........+..........+..........
MIDPOINTS
   9.000)
   7.500)                              *
   6.000)
   4.500)
   3.000)                              *
   1.500)
    .000)
  -1.500)
  -3.000)**             ***
  -4.500)**             ***            *
  -6.000)*                             *
  -7.500)*****          *
  -9.000)*********11    *******        ***
 -10.500)*********      **********     ********13
 -12.000)M*******       M********15    M*******19
 -13.500)********       *********      ********14
 -15.000)********       ******         *******
 -16.500)**             ***
 -18.000)**
 -19.500)*
 -21.000)               *
 -22.500)
GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

 MEAN        -11.271      -11.348      -11.427          .000          .000          .000
 S. DEV.       3.680        3.491        3.771          .000          .000          .000
    N         58.000       58.000       60.000          .000          .000          .000
 MAXIMUM      -2.600       -3.200        7.800          .000          .000          .000
 MINIMUM     -19.900      -21.400      -15.700          .000          .000          .000
ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)

 MEAN          -11.349
 S. DEV.         3.630
    N          176.
 MAXIMUM         7.800
 MINIMUM       -21.400

          SUM OF SQUARES      DF      MEAN SQUARE   F RATIO    PROB. F EXCEEDED
BETWEEN          .7176          2          .3588     .0269           .9734
WITHIN       2305.7073        173        13.3278
TOTAL        2306.4248        175
```

Nonprecision Flights

Just as in the precision case, we give a list of significance levels of the nine variables under study. The first three variables (OMHDOT, MMALT, and MMYCG) are then reanalyzed with one flight (041209) deleted. There are two good reasons for doing this. In the first place, the extremely high value of MMALT for this flight and the absence of data for MMQVQR through IMHDOT suggest this flight is unrepresentative and should be omitted. In the second place, it is very important and reassuring to see that it is a fact that the omission, even in this extreme case, makes relatively small impact on the significance levels and means in the tables of analysis.

The order of the tables which follow corresponds to the list of significances below.

Variable	Significance Level
OMHDOT	0.7900
MMALT	.0365*
MMYCG	.1928
MMVQVR	.5150
MMHDOT	.7183
IMALT	.0016**
IMYCG	.0282*
IMVQVR	.3584
IMHDOT	.3095
OMHDOT (041209 deleted)	.8149
MMALT (041209 deleted)	.0014*
MMYCG (041209 deleted)	.1864

```
1TABULATION OF VARIABLE        2 OMHDOT


            HUDN1       HUD2        HUD3
            ..........+..........+..........+..........+..........+..........
 MIDPOINTS
   33.000)
   30.000)
   27.000)          *
   24.000)
   21.000)
   18.000)          *
   15.000)*
   12.000)          *           *
    9.000)*****     **
    6.000)*******   *****       **
    3.000)*****     ********    ******
     .000)********13 ********** ********24
   -3.000)M*******  M*******13  M*******12
   -6.000)*****     *******     ****
   -9.000)**        ****        **
  -12.000)****      *           *****
  -15.000)*****     **          *
  -18.000)**        *****       **
  -21.000)*                     *
  -24.000)
  -27.000)*
  -30.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN        -2.749      -1.922      -2.790
 S. DEV.       8.705       8.444       5.985
    N         59.000      60.000      60.000
 MAXIMUM      13.900      25.900      10.800
 MINIMUM     -27.600     -19.000     -19.800
0ALL GROUPS COMBINED (CASES EXCLUDED
0
OMEAN              -2.485
 S. DEV.            7.769
    N             179.
 MAXIMUM           25.900
 MINIMUM          -27.600
          SUM OF SQUARES     DF     MEAN SQUARE   F RATIO   PROB. F EXCEEDED
BETWEEN       28.7387          2       14.3694     .2360          .7900
WITHIN     10714.6523        176       60.8787
TOTAL      10743.3906        178
```

```
1TABULATION OF VARIABLE        3 MMALT


          HUDN1        HUD2         HUD3
          .........+..........+..........+..........+..........+........
 MIDPOINTS
 2000.000)
 1900.000)*
 1800.000)
 1700.000)
 1600.000)
 1500.000)
 1400.000)
 1300.000)
 1200.000)
 1100.000)
 1000.000)
  900.000)
  800.000)          *
  700.000)
  600.000)
  500.000)          **
  400.000)********  *********11 ****
  300:000)M*******41 M*******32 M*******22
  200.000)*********  *********11 ********34
  100.000)          *
     .000)          **
 -100.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       316.708    303.964    253.499        .000        .000        .000
 S. DEV.     211.383    112.041     50.223        .000        .000        .000
    N         59.000     60.000     60.000        .000        .000        .000
 MAXIMUM    1866.000    835.000    436.000        .000        .000        .000
 MINIMUM     184.000     25.000    175.000        .000        .000        .000
OALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
O
OMEAN            291.249
 S. DEV.         142.500
    N            179.
 MAXIMUM        1866.000
 MINIMUM          25.000

       SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
BETWEEN 133443.3125        2     66721.6250    3.3734         .0365
WITHIN 3481059.0000      176     19778.7422
TOTAL  3614502.0000      178
```

```
TABULATION OF VARIABLE        4 MMYCG


           HUDN1       HUD2        HUD3
           .........+.........+.........+.........+.........+.........
MIDPOINTS
 300.000)
 280.000)
 260.000)              *
 240.000)
 220.000)
 200.000)
 180.000)              **
 160.000)*             *
 140.000)              **          *
 120.000)
 100.000)*             ***         *
  80.000)**            **          *
  60.000)***           ***         ***
  40.000)*********     ***         *****
  20.000)***           M*******12  ****
    .000)M*********    ********    M*******30
 -20.000)*********     *****       *********
 -40.000)*******       ****        ***
 -60.000)******        ****        **
 -80.000)*****         ****        *
-100.000)              ****
-120.000)***           **
GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

 MEAN        -9.034     10.333      4.700       .000       .000       .000
 S. DEV.     54.727     80.371     34.282       .000       .000       .000
   N         59.000     60.000     60.000       .000       .000       .000
 MAXIMUM    164.000    268.000    136.000       .000       .000       .000
 MINIMUM   -114.000   -125.000    -74.000       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN              2.061
 S. DEV.          59.773
   N             179.
 MAXIMUM         268.000
 MINIMUM        -125.000

        SUM OF SQUARES     DF     MEAN SQUARE   F RATIO    PROB. F EXCEEDED
BETWEEN  11786.3008         2      5893.1484    1.6617          .1928
WITHIN  624164.3125       176      3546.3879
TOTAL   635950.5625       178
```

TABULATION OF VARIABLE   2 MMVQVR

```
           HUDN1       HUD2        HUD3
           ..........+..........+..........+..........+..........+..........
MIDPOINTS
  22.500)
  21.000)
  19.500)
  18.000)                          *
  16.500)
  15.000)
  13.500)*                         **
  12.000)**           *            *
  10.500)             ***          **
   9.000)****         ****         ****
   7.500)**********   *********    *******
   6.000)******       ********     *****
   4.500)M********    M*******12   M********
   3.000)*****        *******      ********
   1.500)******       ******       *******12
    .000)******       *****        *****
  -1.500)****         **           **
  -3.000)***                       *
  -4.500)*            *
  -6.000)**                        *
  -7.500)
  -9.000)
```

GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

	HUDN1	HUD2	HUD3			
MEAN	3.784	4.629	4.335	.000	.000	.000
S. DEV.	4.381	3.352	4.235	.000	.000	.000
N	58.000	59.000	60.000	.000	.000	.000
MAXIMUM	13.200	11.300	17.700	.000	.000	.000
MINIMUM	-5.900	-3.800	-6.300	.000	.000	.000

0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)

0

0MEAN	4.253
S. DEV.	4.007
N	177.
MAXIMUM	17.700
MINIMUM	-6.300

	SUM OF SQUARES	DF	MEAN SQUARE	F RATIO	PROB. F EXCEEDED
BETWEEN	21.4677	2	10.7339	.6661	.5150
WITHIN	2803.9753	174	16.1148		
TOTAL	2825.4429	176			

```
1TABULATION OF VARIABLE        3 MMHDOT


          HUDN1       HUD2        HUD3
          .........+..........+..........+..........+..........+..........+.........
 MIDPOINTS
   44.000)
   40.000)
   36.000)
   32.000)           **
   28.000)
   24.000)
   20.000)
   16.000)           *
   12.000)
    8.000)
    4.000)                      *
     .000)*          *          *
   -4.000)****
   -8.000)********12 ********   ******
  -12.000)M*******13 M*******17 M*******39
  -16.000)********20 ********16 *********
  -20.000)****       *******11  **
  -24.000)***        ***        *
  -28.000)
  -32.000)*
  -36.000)
  -40.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       -13.224    -12.195    -12.420       .000       .000       .000
 S. DEV.       5.417     10.471      4.004       .000       .000       .000
    N         58.000     59.000     60.000       .000       .000       .000
 MAXIMUM       -.800     33.900      5.200       .000       .000       .000
 MINIMUM     -30.900    -25.000    -22.100       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN            -12.608
 S. DEV.           7.156
    N            177.
 MAXIMUM          33.900
 MINIMUM         -30.900

        SUM OF SQUARES    DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
BETWEEN     34.2149        2       17.1075     .3316         .7183
WITHIN    8977.9414      174       51.5974
TOTAL     9012.1563      176
```

```
1TABULATION OF VARIABLE        4 IMALT


          HUDN1      HUD2       HUD3
          ..........+..........+..........+..........+..........+..........+..........+
 MIDPOINTS
  880.000)
  840.000)
  800.000)          *
  760.000)
  720.000)
  680.000)
  640.000)
  600.000)
  560.000)
  520.000)          *
  480.000)                     *
  440.000)                     *
  400.000)
  360.000)*
  320.000)          ***
  280.000)***       *****
  240.000)********  M********  ***
  200.000)M*******25 ********23 ********12
  160.000)********18 ********15 M*******29
  120.000)**        **         ********14
   80.000)*
   40.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       195.758    220.712    172.716       .000       .000       .000
 S. DEV.      42.810     99.611     60.598       .000       .000       .000
    N         58.000     59.000     60.000       .000       .000       .000
 MAXIMUM     356.000    804.000    468.000       .000       .000       .000
 MINIMUM      92.000    128.000    106.000       .000       .000       .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN            196.265
 S. DEV.          74.053
    N            177.
 MAXIMUM         804.000
 MINIMUM          92.000

        SUM OF SQUARES     DF     MEAN SQUARE   F RATIO   PROB. F EXCEEDED
 BETWEEN  68547.5625        2     34273.7813    6.6513        .0016
 WITHIN  896609.3125      174      5152.9258
 TOTAL   965156.8750      176
```

```
TABULATION OF VARIABLE        2 IMYCG


             HUDN1         HUD2          HUD3
            ..........+..........+..........+..........+..........+.........
MIDPOINTS
 420.000)
 390.000)
 360.000)
 330.000)
 300.000)                  *
 270.000)
 240.000)
 210.000)
 180.000)
 150.000)                  *
 120.000)                  *
  90.000)**                ******
  60.000)*****             *********     ***
  30.000)*******           *****         *********11
    .000)M*******17        M*******16    M*******36
 -30.000)********17        ********11    *********
 -60.000)********          ******
 -90.000)*                 **
-120.000)*                 *
-150.000)
-180.000)
-210.000)
GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

 MEAN         -8.845      14.390       4.717        .000        .000        .000
 S. DEV.      41.812      65.641      22.789        .000        .000        .000
   N          58.000      59.000      60.000        .000        .000        .000
 MAXIMUM      86.000     296.000      73.000        .000        .000        .000
 MINIMUM    -107.000    -106.000     -39.000        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
OMEAN               3.497
 S. DEV            47.441
   N              177.
 MAXIMUM          296.000
 MINIMUM         -107.000

          SUM OF SQUARES     DF     MEAN SQUARE  F RATIO   PROB. F EXCEEDED
BETWEEN   15924.2500          2      7962.1250    3.6439        .0282
WITHIN   380195.4375        174      2185.0313
TOTAL    396119.6875        176
```

```
...ULATION OF VARIABLE        3 IMVOVR


          HUDN1        HUD2         HUD3
          ..........+..........+..........+..........+..........+.........
MIDPOINTS
  21.000)
  19.500)
  18.000)              *
  16.500)                           *
  15.000)
  13.500)*             *
  12.000)              *            ****
  10.500)***           **
   9.000)*****         *****        ***
   7.500)********      ******       ***
   6.000)******        ********     *******
   4.500)M*******      M********    **********
   3.000)*********11   **********   M****
   1.500)********      ********11   **********
    .000)****          ***          ********11
  -1.500)**            *            ***
  -3.000)*             *            **
  -4.500)                           *
  -6.000)              *
  -7.500)
  -9.000)*
 -10.500)
GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

 MEAN         4.347      4.663      3.615        .000        .000        .000
S. DEV.       3.978      4.053      4.210        .000        .000        .000
   N         58.000     59.000     60.000        .000        .000        .000
MAXIMUM      13.900     17.800     16.400        .000        .000        .000
MINIMUM      -9.300     -5.800     -4.900        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN            4.204
 S. DEV.         4.084
   N            177.
 MAXIMUM        17.800
 MINIMUM        -9.300

       SUM OF SQUARES     DF      MEAN SQUARE   F RATIO    PROB. F EXCEEDED
BETWEEN    34.4086         2       17.2043      1.0321        .3584
WITHIN   2900.5803       174       16.6700
TOTAL    2934.9888       176
```

```
1TABULATION OF VARIABLE        4 IMHDOT


          HUDN1          HUD2          HUD3
              ..........+..........+..........+..........+..........+..........
MIDPOINTS
   30.000)
   27.000)            *
   24.000)
   21.000)
   18.000)            *             *
   15.000)            **            *
   12.000)*
    9.000)
    6.000)
    3.000)
     .000)
   -3.000)
   -6.000)**          **            *
   -9.000)*****       *********     *****
  -12.000)********16  M******       M********18
  -15.000)M*******12  *********16   ********22
  -18.000)********12  **********    **********
  -21.000)******      ***           *
  -24.000)***         **            *
  -27.000)*           **
  -30.000)            **
  -33.000)
 GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

  MEAN       -14.853     -13.034     -12.933        .000        .000        .000
 S. DEV.       5.684      10.061       6.325        .000        .000        .000
    N         58.000      59.000      60.000        .000        .000        .000
 MAXIMUM      10.800      25.900      19.500        .000        .000        .000
 MINIMUM     -26.900     -29.600     -23.200        .000        .000        .000
0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN             -13.596
 S. DEV.            7.616
    N             177.
 MAXIMUM           25.900
 MINIMUM          -29.600

          SUM OF SQUARES     DF      MEAN SQUARE   F RATIO    PROB. F EXCEEDED
BETWEEN      136.6967         2        68.3484     1.1806          .3095
WITHIN     10072.9570       174        57.8905
TOTAL      10209.6523       176
```

```
ITABULATION OF VARIABLE        2 OMHDOT


            HUDN1         HUD2          HUD3
            ..........+..........+..........+..........+..........+..........
  MIDPOINTS
    33.000)
    30.000)
    27.000)           *
    24.000)
    21.000)
    18.000)           *
    15.000)*
    12.000)           *             *
     9.000)*****      **
     6.000)*******    *****         **
     3.000)*****      *********     ******
      .000)********13 ***********   ********24
    -3.000)M********  M*******13    M*******12
    -6.000)*****      *******       ****
    -9.000)**         ****          **
   -12.000)***        *             *****
   -15.000)*****      **            *
   -18.000)**         *****         **
   -21.000)*                        *
   -24.000)
   -27.000)*
   -30.000)
  GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

   MEAN       -2.598     -1.922     -2.790        .000        .000        .000
  S. DEV.      8.702      8.444      5.985        .000        .000        .000
     N        58.000     60.000     60.000        .000        .000        .000
  MAXIMUM     13.900     25.900     10.800        .000        .000        .000
  MINIMUM    -27.600    -19.000    -19.800        .000        .000        .000
 0ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
 0
 0MEAN           -2.435
  S. DEV.         7.761
     N          178.
  MAXIMUM        25.900
  MINIMUM       -27.600

           SUM OF SQUARES    DF     MEAN SQUARE   F RATIO    PROB. F EXCEEDED
 BETWEEN       24.9182         2       12.4591      .2050          .8149
 WITHIN     10636.7578       175       60.7815
 TOTAL      10661.6758       177
```

```
TABULATION OF VARIABLE        3 MMALT


          HUDN1        HUD2         HUD3
          .........+.........+..........+..........+..........+..........+..........
MIDPOINTS
1000.000)
 950.000)
 900.000)
 850.000)              *
 800.000)
 750.000)
 700.000)
 650.000)
 600.000)
 550.000)
 500.000)
 450.000)              ******       *
 400.000)****          *****        *
 350.000)*********11   ****         ***
 300.000)M********16   M*******25   ********
 250.000)*********20   ********12   M*******28
 200.000)*******       ****         ********18
 150.000)                           *
 100.000)
  50.000)              **
    .000)              *
 -50.000)
GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

 MEAN       289.997    303.964    253.499        .000        .000        .000
 S. DEV.     51.290    112.041     50.223        .000        .000        .000
    N        58.000     60.000     60.000        .000        .000        .000
 MAXIMUM    403.000    835.000    436.000        .000        .000        .000
 MINIMUM    184.000     25.000    175.000        .000        .000        .000
ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
0MEAN            282.402
 S. DEV.          79.574
    N            178.
 MAXIMUM         835.000
 MINIMUM          25.000

        SUM OF SQUARES     DF     MEAN SQUARE   F RATIO    PROB. F EXCEEDED
BETWEEN  81362.0625         2     40681.0313     6.8493         .0014
WITHIN 1039410.1250       175      5939.4844
TOTAL  1120772.0000       177
```

TABULATION OF VARIABLE 4 MMYCG

```
            HUDN1        HUD2         HUD3
            .........+..........+..........+..........+..........+..........+..........
MIDPOINTS
 300.000)
 280.000)
 260.000)               *
 240.000)
 220.000)
 200.000)
 180.000)               **
 160.000)*              *
 140.000)               **           *
 120.000)
 100.000)*              ***          *
  80.000)**             **           *
  60.000)***            ***          ***
  40.000)**********     ***          *****
  20.000 ***            M********12  ****
    .000)M*********     *********    M*********30
 -20.000)**********     *****        **********
 -40.000)********       ****         ***
 -60.000)*******        ****         **
 -80.000)*****          ****         *
-100.000)               ****
-120.000)***            **
GROUP MEANS ARE DENOTED BY M'S IF THEY COINCIDE WITH *'S, N'S OTHERWISE

 MEAN          -9.362     10.333      4.700        .000        .000        .000
 S. DEV.       55.146     80.371     34.282        .000        .000        .000
    N          58.000     60.000     60.000        .000        .000        .000
 MAXIMUM      164.000    268.000    136.000        .000        .000        .000
 MINIMUM     -114.000   -125.000    -74.000        .000        .000        .000
ALL GROUPS COMBINED (CASES EXCLUDED IF SPECIAL CODES FOR EITHER VARIABLE)
0
 MEAN                2.017
 S. DEV             59.938
    N              178.
 MAXIMUM           268.000
 MINIMUM          -125.000

          SUM OF SQUARES    DF    MEAN SQUARE  F RATIO   PROB. F EXCEEDED
BETWEEN    12091.4609        2     6045.7305    1.6961        .1864
WITHIN    623795.6250      175     3564.5464
TOTAL     635887.0625      177
```

Concluding Remarks

These supplemental analyses confirm the earlier observations of the *Final Report,* and the most forceful conclusion of this second study rests in echoing the sentiments of that earlier *Report.*

The data studied here show clearly that in a statistical sense there are real differences in several parameters of physical importance for the displays under consideration. By considering the means and their associated confidence intervals one can proceed to draw legitimate engineering and policy conclusions.

The data obtained under HUD-phase III is a valuable resource, and as subsequent questions are raised about flight displays, it will continue to be one of the steadiest guides available.

APPENDIX E

COPILOT/OBSERVER CHECKLIST AND DATA SHEET

Date ______________________ Observer ______________________

Subject ______________________ Run No. ______________________

Landing data card and briefing

Pre-run checklist:

Flaps: 15	Speed bug : set	Autopilot: as required
Gear: up	Alt bug: set	F.D. panel: set
Power: set	Heading bug: set	

Final descent checklist:

No smoking - Antiskid -Flight and nav inst
Landing gear - Flaps - Hydraulic and brake pressure

Captain's callouts (check yes or no):

Target speed ______________________ Minimums ______________________

OM altitude ______________________ 1000 ft ______________________

100 ft above ______________________ Ground contact ______________________

Comments:

APPENDIX F

ATC SCRIPT

1. ATC 1 (1500 ft initial altitude)

   At operate,

   "NASA 710, maintain present heading with radar vectors to final approach at Moffett."

   At operate + 30 sec,

   "Turn (R or L) to heading (125° or 55°). This is your intercept heading, you're cleared for a(n) (localizer front course, ILS) approach to runway 9. Report at the outer marker inbound."

2. ATC 2 (2500 ft initial altitude)

   At operate,

   Same as ATC 1.

   At operate + 15 sec,

   "You're cleared to descent and maintain 1500 ft."

   At operate + 30 sec,

   Same as ATC 1.

3. ATC 3 (4000 ft initial altitude)

   At operate,

   Same as ATC 1.

   At operate + 15 sec,

   "You're cleared to descend and maintain 1500 ft."

   At operate + 30 sec,

   Same as ATC 1.

4. For all scenarios, after aircraft passes outer marker -

   "The ceiling is reported at XXX ft, visibility is XX miles, winds are XXX deg at XX knots. You're cleared to land."

   "We've got one on the runway for departure; continue your approach, we'll keep you advised."

   Followed in 20 sec by,

   "Ceilings reported at XXX ft, RVR is XXX, winds from XXX at XX knots. Cleared to land."

APPENDIX G

TEST PILOT QUESTIONAIRES AND INSTRUCTIONS

NASA-Ames Research Center | Head-up Display

Test Pilot Questionnaire

> Note: This study is designed to assess the advantages and disadvantages of the headup display concept for possible use in commercial aviation. All information you give on this form will be kept confidential and will be summarized statistically.

Leave blank
Subj. assigned code:
Exp. No.: ______
BOT: ______
EOT: ______
Vis. Tests: ______
Form Compl. ______

[Please print all answers]

Name: ______

Address: ______ zip ______

Phone (office pref.) [ ] ______ Birthdate: ______

Do you wear spectacles while flying? yes no (circle)
If you have no military experience skip questions 1a. – 1d.

1a. Military Background: Branch ______

b. Did you receive military pilot training? yes no (circle)

c. List aircraft types in which you trained (if applicable – otherwise leave blank):

1st. ______ 2nd. ______

3rd. ______ 4th. ______

d. List all aviation-related (specialized) training: ______

(continue on opposite side if necessary)

---

2. List all pilot associations in which you are *now* a member: ______

3. List all airlines and military commands you have ever flown for beginning with the most recent:

(Insert in brackets the approximate starting date for each)

(continue on opposite side if necessary)

[ ] ______
[ ] ______
[ ] ______
[ ] ______
[ ] ______
[ ] ______

4a. Total hours flown (approx.) not including Flight Engr.: ______

4b. Years flying since solo: ______

5. Flight Experience Breakdown by Aircraft Type/Model:

Using your log book as necessary, try to be as complete as possible on this question. Include your Civil (non-commercial-private), Airline, and Military flight experience in this table following the sample given. Place a check in the small box for those aircraft for which you hold a 'type' rating.

SAMPLE

Aircraft Type/Model				Crew Position				
				Pilot	Copilot	Instr.	Flt. Engr.	Other
B 707	c		Hrs.	300	2850		1200	
	a	✓						
✓	m		Dates	2-73 / 5-77	4-68 / 3-73	/	2-66 / 4 63	/

Check here if 'type' rated

Check one for
c = civil
a = airline
m = military

From/To

Insert total hrs. at top of box

-1-

LM 26

Test Pilot Questionnaire

5. Flight Experience Breakdown by Aircraft Type/Model: (continued)

Aircraft Type/Model			Crew Position				
			Pilot	Copilot	Instr.	Flt. Engr.	Other
1. ☐	c	Hrs.					
	a						
	m	Dates	/	/	/	/	/
2. ☐	c	Hrs.					
	a						
	m	Dates	/	/	/	/	/
3. ☐	c	Hrs.					
	a						
	m	Dates	/	/	/	/	/
4. ☐	c	Hrs.					
	a						
	m	Dates	/	/	/	/	/
5. ☐	c	Hrs.					
	a						
	m	Dates	/	/	/	/	/
6. ☐	c	Hrs.					
	a						
	m	Dates	/	/	/	/	/
7. ☐	c	Hrs.					
	a						
	m	Dates	/	/	/	/	/
8. ☐	c	Hrs.					
	a						
	m	Dates	/	/	/	/	/
9. ☐	c	Hrs.					
	a						
	m	Dates	/	/	/	/	/
10. ☐	c	Hrs.					
	a						
	m	Dates	/	/	/	/	/
11. ☐	c	Hrs.					
	a						
	m	Dates	/	/	/	/	/
12. ☐	c	Hrs.					
	a						
	m	Dates	/	/	/	/	/

6a. Are you Cat. II rated? yes no (circle)

b. If "yes" specify type(s) of aircraft: (1) __________ (2) __________
(3) __________ (4) __________

7a. Are you Cat. III qualified? yes no (circle)

b. If "yes" specify type(s) of aircraft: (1) __________ (2) __________
(3) __________ (4) __________

8. Summary of Reduced Visibility Landing Experience:

Insert in each appropriate box the *number of landings* you have made in the weather conditions noted in the table on following page.

8. Summary of Reduced Visibility Landing Experience: (continued)

	Cumulatively within the past	Weather Condition			
		Category I		Category II	
		Manual	Coupled	Manual	Coupled
DAY	6 months				
TIME	12 months				
ONLY	2 years				
NIGHT	6 months				
TIME	12 months				
ONLY	2 years				

9. Head-up Display Experience:

For purposes of this questionnaire, a head-up display is defined as a visual display of flight information located in the field of view when looking outside through the forward windshield. It may be electro-mechanical or cathode-ray driven.

9a. Have you ever flown an aircraft(s) that had a head-up display? yes no

b. If "yes" specify type of aircraft and approx. number of hours for each one in brackets:
(1)__________ [ ] (2)__________ [ ] (3)__________ [ ]

c. If "yes" place an asterisk (*) in all those spaces of question 9b. if the head-up display you used presented IFR information suitable for making a "*landing*" as opposed to weapons delivery type of display.

d. Have you ever made instrument approaches using a head-up display? yes no

e. If "yes" specify approximate number of such approaches: __________

10. What is your professional opinion of head-up displays for commercial aviation? __________

11. What is your professional opinion of the autoland concept for commercial aviation? __________

12. Based upon what you now know about head-up displays, list below the benefits (advantages) and limitations (disadvantages) which you think apply to its use in commercial aviation operations?

a. Benefits (advantages)

Most important: __________
Next most important: __________
Next most important: __________
Next most important: __________
Next most important: __________
Next most important: __________

(continue on opposite side if necessary)

Test Pilot Questionnaire

12b. Limitations (disadvantages)

Most important: ______________________________
Next most important: ______________________________
Next most important: ______________________________
Next most important: ______________________________
Next most important: ______________________________
Next most important: ______________________________

(continue on opposite side if necessary)

13. Narrative Description of the Most Extreme Landing Conditions you have ever Encountered.

Please describe, using as much detail as you desire, the most extreme landing conditions (environmental, procedural inside the cockpit, etc.) with regard to the following basic categories: (continue on opposite side as necessary)

a. Headwind: ______________________________

b. Tailwind: ______________________________

c. Wind Shear: ______________________________

d. Other Unusual Weather (e.g., precipitation): ______________________________

e. Nighttime Visual Illusions: ______________________________

f. Daytime Visual Illusions: ______________________________

g. Intermittent Visual Conditions (including unexpected visual range reductions): ______________________________

h. Others: ______________________________

Thank you for providing us with this useful information

HUD DEBRIEFING QUESTIONNAIRE

To help us understand the results we get from this study, please answer the following questions:

1. How confident do you feel in your understanding and ability to effectively and safely use the HUD?

Much less confidence than with conventional instruments	-10	0	+10	Much more confidence than with conventional instruments

2. Using the conventional instrument panel as a reference, rate the HUD on each of the following characteristics by placing a mark on the line. You may explain your ratings in item 3.

HUD very much more difficult than panel (-10) — HUD very much easier than panel (+10)

Lateral Flightpath Control LOCALIZER

-10 0 +10

Vertical Flightpath Control GLIDE SLOPE

-10 0 +10

Vertical Flightpath Control NONPRECISION

-10 0 +10

Speed Control and Thrust Management

-10 0 +10

3. General comments about ratings in item 2.

4. During the "Radar Vectoring" part of the scenarios you flew, rate the HUD with regard to general "situation awareness." Did you always know where you were? Where the Localizer and Glide Slope were? Use the conventional instrument panel (ADI and Flight Director, HSI, and RMI) as a reference.

HUD very much worse than instrument panel	-10	0	+10	HUD very much better than instrument panel

5. Did you find the information on the HUD to be sufficient? Did you desire more information? Please be specific.

6. Did you ever refer to the instrument panel when flying using the HUD?__________. If yes, what did you look at? Why? Explain.

7. Using the conventional instrument panel as a reference, rate the HUD on the following characteristics. You may explain your reasons in item 8.

HUD very much worse than instrument panel | HUD very much better than instrument panel

Ability to detect wind shears

-10 | 0 | +10

High crosswind landings

-10 | 0 | +10

Initiation of missed approach

-10 | 0 | +10

Detection of runway obstructions

-10 | 0 | +10

8. General Comments about ratings in item 7.

9. Do you believe the HUD provides any advantages with reference to the conventional instrument panel?__________. If so, what? Please be specific.

10. Do you believe the HUD provides any disadvantages with reference to the conventional instrument panel?__________. If so, what? Please be specific.

11. All things considered, rate the HUD on the following scale. Base your answer on as many factors as you can – safety, economics, passenger comfort, etc.

I strongly prefer the conventional panel | In strongly prefer the HUD

-10 | 0 | +10

12. List the factors you considered for rating in item 10 in order of importance, starting with the most important.

13. General comments about the HUD.

THE TRAINING PROGRAM

This section is designed to help us evaluate the effectiveness of the training program used in this study. Your input will be most helpful in designing better training programs.

The training package consisted of four basic components, the handout material, the classroom session, the video tapes, and simulator training. Please evaluate each of these using the scale below. Note that each scale has an "overrun." If you feel the material was overdone or misleading, please place your mark in the appropriate space.

1. Handout material

Misleading "negative training"	0 ⊢—|—|—|—|—|—|—|—|—|—⊣ 10	Overdone
	Contributed nothing ... Completely effective	

Comments:

2. Classroom lecture

Misleading "negative training"	0 ⊢—|—|—|—|—|—|—|—|—|—⊣ 10	Overdone
	Contributed nothing ... Completely effective	

Comments:

3. Video tapes

Misleading "negative training"	0 ⊢—|—|—|—|—|—|—|—|—|—⊣ 10	Overdone
	Contributed nothing ... Completely effective	

Comments:

4. Simulator training

Misleading "negative training"	0 ⊢—|—|—|—|—|—|—|—|—|—⊣ 10	Overdone
	Contributed nothing ... Completely effective	

Comments:

5. Please indicate your assessment of the overall effectiveness of the training program.

0 |—|—|—|—|—|—|—|—|—|—| 10

Contributed nothing — Completely effective

Comments:

6. How would you change the training program? Please be specific.

7. Considering all of the above, if this study were to be updated using improved training programs, would the results and conclusions be:

Probably very different — 0 |—|—|—|—|—|—|—|—|—|—| 10 — Probably the same

8. General comments about the training program.

SUBJECT PILOT DEBRIEFING QUESTIONNAIRE

Introduction

In order to obtain as much information as possible from your participation in this study, we would appreciate it if you would take some time to complete the following questionnaire. Please attempt to be concise and specific, but try to give us as much information and insight as you can. As with all other data obtained in this study, your name will not be used in connection with your responses to these questions.

The Simulation

This section of the questionnaire is designed to help us to evaluate the quality of the simulation used to conduct the evaluation.

1. On the scale below, please place a mark at the spot you believe best represents the *flying characteristics* or *handling qualities* of the aircraft simulated in this study.

Totally unlike the B-727	0 —————————— 10	Exactly like the B-727

2. How did the flying characteristics differ from the B-727? Please be specific.

3. How realistic were the low visibility effects you saw in this study?

Totally unlike similar real world conditions	0 —————————— 10	Exactly like similar real world conditions

4. How did the low visibility effects differ from real world conditions? Please be specific.

5. How realistically were the wind and turbulence conditions simulated?

Not at all like real world wind and turbulence	0 —————————— 10	Exactly like real world wind and turbulence

6. How were the winds and turbulence different from real world conditions? Please be specific.

7. How realistic were the runway obstruction situations used in this study?

Very unreal	0 —————————— 10	Very realistic

8. Considering all of the above, if this study were repeated using an actual B-727 airplane flying in the same conditions simulated would the results and conclusions reached be:

Probably very different	0										10	Probably the same

9. General comments about the simulator and test conditions.

CREW PROCEDURES AND CALLOUTS

Each air carrier uses somewhat different crew procedures and callouts. Furthermore, the use of HUD would require the development of specific procedures and callouts. To assist in the evaluation of the procedures used in this evaluation, please answer the following questions:

1. In this study, we asked you, the flying pilot, to make most routine callouts. Does your company use this procedure?

2. With regard to routine callouts, were there too many?________.

   Just right?________.
   Too few?________.

3. Did you find the deviation callouts by the copilot useful?________.

4. How would you change the procedures and callouts? Please be specific.

5. Given a single HUD in the cockpit, would you, the Captain:

   ______ (a) Prefer to fly the approach yourself with the HUD.

   ______ (b) Monitor the approach through the HUD while the First Officer flies the approach on panel instruments.

   ______ (c) Monitor the panel instruments while the First Officer flies the approach using the HUD.

   ______ (d) Prefer to fly the approach yourself using panel instruments.

6. Given two HUDS in the cockpit, how would you manage the approach?

   ______ (a) Both pilots head-up, captain flying.

   ______ (b) Captain head-up and flying, first officer head-down.

   ______ (c) First officer head-down and flying, captain monitoring through HUD.

   ______ (d) First officer head-up and flying, captain monitoring head-down.

   ______ (e) Captain head-down and flying, first officer monitoring HUD.

   ______ (f) Other (please specify).

7. Considering all the above, if this study was repeated using different cockpit procedures and callouts, would the results and conclusions reached be:

Probably very different 0 |__|__|__|__|__|__|__|__|__|__| 10 Probably the same

General Comments

Please feel free to comment on any aspect of this study. How could we do a better job? What have we forgotten to ask about?

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4. Jenney, L. L.; Malone, T. B.; and Schwackert, G. A.: Head-Up Displays: A Study of Their Applicability in Civil Aviation. NASA CR-117135, 1971.

5. Naish, J. M.: A Review of Some Head-Up Display Formats. NASA TP-1499, 1979.

6. Shrager, J. J.: Head-Up Displays: A Literature Review and Analysis with an Annotated Bibliography. FAA-RD-78-31. 1978.

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TABLE 1.– FSAA MOTION LIMITS

Axis (parameter)		Displacement[a]	Velocity[b]	Acceleration[c]
Roll	(ϕ)	±0.663 rad	±1.75 rad/sec	±2.09 rad/sec^2
Pitch	(θ)	±0.349 rad	±1.01 rad/sec	±2.62 rad/sec^2
Yaw	(ψ)	±0.436 rad	±0.90 rad/sec	±1.68 rad/sec^2
Longitudinal	(X)	±1.0 m	±2.1 m/sec	±2.4 m/sec^2
Lateral	(Y)	±12.2 m	±8.7 m/sec	±2.4 m/sec^2
Vertical	(Z)	±1.3 m	±2.6 m/sec	±3.7 m/sec^2

[a]Maximum displacement allowed by the parabolic limiter.

[b]Maximum velocity reached under a maximum acceleration starting from rest at one end of the available travel and driving into the parabolic limiter at the other end.

[c]Maximum instantaneous acceleration.

TABLE 2.– SUBJECT PILOT INFORMATION

Pilot	Age	Airline	Hr/yr	HUD experience
A[a]	44	A	9.2K/22	No
B[a]	42	B	10.0K/19	Yes
C[a]	43	C	10.6K/22	No
D[a]	43	D	13.0K/24	Yes
E	36	E	9.5K/16	No
F[a]	42	F	13.5K/20	No
G	41	G	12.0K/20	No
H[a]	45	A	10.2K/25	No
I[a]	47	H	12.0K/25	No
J[a]	43	I	8.5K/21	No

[a]Also possesses military flight experience.

TABLE 3.– CEILING AND VISIBILITY CONDITIONS

Approach type		Ceiling, ft	Visibility, ft
Precision	1	250	3000
	2	400	6000
Nonprecision	1	500	7000
	2	800	12000

TABLE 4.– WIND AND TURBULENCE

Case	Wind		Turbulence, rms ft/sec
	Speed, knots	Direction, deg	
Headwind	10	20° off localizer course	1.0
Quartering tailwind	20	135° off localizer course	2.0
Crosswind	20	80° off localizer course	3.0

TABLE 5.– SUMMARY OF CORE EXPERIMENTAL DESIGN

Winds	Ceiling and visibility			
	Well above minimums		Near minimums	
	40 ⊕ 1 ILS	80 ⊕ 2 NPA	25 ⊕ 3000 ILS	50 ⊕ 1 NPA
Headwind, 10 knots				
Crosswind, 20 knots				
Quartering tailwind, 8 knots				

TABLE 6.– INTERCEPT SEGMENT DATA

Variable		ILS			NPA		
		No HUD	FD HUD	FP HUD	No HUD	FD HUD	FP HUD
OMALT	M	1479.	1429.	1429.	1532.	1509.	1516.
	SD	92.	43.	79.	121.	84.	82.
	MAX	2041.	1541.	1853.	2026.	1843.	1914.
	MIN	1374.	1349.	1359.	1362.	1234.	1404.
OMYCG	M	9.2	0	23.0	-13.1	15.1	77.6
	SD	225.	300.	399	221	102	279
	MAX	519	1035	2053	886	239	1345
	MIN	-827	-1825	-1058	-614	-256	-436
OMVQVR	M	5.2	4.9	5.7	6.7	4.3	3.9
	SD	6.9	5.6	7.0	6.5	7.0	6.3
	MAX	28.4	20.2	29.6	28.4	20.5	27.9
	MIN	-11.5	-5.1	-9.1	-5.4	-19.6	-9.6
IALT	M	1568	1566	1542	1566	1520	1554
	SD	140	208	121	150	129	137
	MAX	2218	2902	2027	2277	1845	2034
	MIN	1436	1396	1431	1414	1010	1369
IVQVR	M	7.6	4.9	8.0	7.9	4.8	7.3
	SD	6.1	8.2	9.1	7.3	6.8	8.3
	MAX	23.7	22.9	30.0	27.3	26.9	30.6
	MIN	-.9	-30.5	-10.9	-2.3	-9.9	-7.5

TABLE 7.– OUTLIERS GREATER THAN ONE DOT LOCALIZER ERROR AT OUTER MARKER

Display	Subject	Case	Wind	OMYCG	Altitude
No HUD	4	8	315° @ 15	886	1500
	8	6	170° @ 20	-827	1500
FD HUD	3	2	315° @ 15	1035	1500
	5	5	225° @ 15	-1825	2500
FP HUD	5	8	315° @ 15	1345	4000
	8	8	315° @ 15	782	1500
	9	2	315° @ 15	1026	4000
	9	5	225° @ 15	-1058	2500
	10	3	010° @ 20	948	4000
	11	2	315° @ 15	2053	4000

TABLE 8.– APPROACH SEGMENT DATA

Variable		ILS			NPA		
		No HUD	FD HUD	FP HUD	No HUD	FD HUD	FP HUD
ALOC	M	0.13	0.09	0.06	0.14	0.05	0.07
	SD	.10	.15	.08	.14	.04	.09
	MAX	.52	1.09	.39	.81	.27	.49
	MIN	.03	.01	.01	.01	.01	.01
AGS	M	.11	.07	.05	.43	.48	.57
	SD	.08	.04	.06	.27	.25	.22
	MAX	.51	.25	.32	1.24	1.05	1.15
	MIN	.03	.02	.01	.10	.09	.20
AEASM	M	138.2	136.7	137.0	139.7	138.5	138.6
	SD	5.4	4.1	4.2	5.7	3.9	4.1
	MAX	151.8	149.3	148.3	153.7	152.1	150.4
	MIN	128.9	130.5	130.9	126.1	133.0	131.9
AEASD	M	3.00	3.04	2.78	2.71	2.85	2.85
	SD	1.18	1.79	1.41	1.64	1.25	1.21
	MAX	6.41	10.14	7.37	7.12	8.78	8.95
	MIN	1.27	.74	.54	.50	1.58	1.21
AHDOTMAX	M	-22.7	-18.3	-16.3	-24.7	-24.2	-23.5
	SD	5.4	3.4	4.0	5.9	5.5	2.8
	MAX	-14.7	-12.9	-11.9	-17.6	-16.5	-19.0
	MIN	-36.7	-28.7	-34.4	-40.8	-44.0	-31.5
AHDOTM	M	-12.8	-11.9	-12.3	-15.5	-15.3	-17.0
	SD	2.0	1.4	1.8	1.8	2.0	2.3
	MAX	-9.3	-10.1	-10.4	-11.9	-9.0	-11.1
	MIN	-21.0	-16.2	-20.0	-19.7	-18.8	-22.2
AHDOTD	M	4.96	3.17	1.90	4.77	5.03	5.00
	SD	2.20	1.21	1.06	2.64	2.84	2.42
	MAX	12.10	6.22	6.39	13.46	15.85	10.24
	MIN	2.09	1.13	.75	1.97	1.55	1.16

TABLE 9.– SUMMARY OF TOTAL NUMBER OF APPROACHES AND GO-AROUNDS

	ILS			NPA		
	No HUD	FD HUD	FP HUD	No HUD	FD HUD	FP HUD
Total approaches	58	57	60	59	60	60
Go-arounds due to anomalies	2	5	5	1	6	4
Other go-arounds	0	0	0	4	3	0

TABLE 10.– SUMMARY OF MIDDLE MARKER DATA

Variable		ILS			NPA		
		No HUD	FD HUD	FP HUD	No HUD	FD HUD	FP HUD
MMALT	M	239.7	234.3	229.7	290.0	302.6	249.0
	SD	19.2	13.8	7.1	51.3	61.4	43.6
	MAX	305.0	264.0	246.0	403.0	459.0	405.0
	MIN	204.0	193.0	217.0	184.0	199.0	175.0
MMYCG	M	-13.5	-3.8	-3.3	-9.4	12.1	4.9
	SD	37.1	12.2	11.8	55.1	85.2	34.8
	MAX	126.0	46.0	21.0	164.0	268.0	136.0
	MIN	-111.0	-33.0	-71.0	-114.0	-125.0	-74.0
MMVQVR	M	3.9	3.1	2.9	3.8	4.1	4.2
	SD	4.1	3.2	2.6	4.4	3.3	4.3
	MAX	21.5	12.4	8.1	13.2	11.3	17.7
	MIN	-5.2	-3.5	-3.3	-5.9	-3.8	-6.3
MMHDOT	M	-11.3	-12.1	-12.2	-13.2	-13.9	-12.9
	SD	5.5	3.3	1.8	5.4	4.5	2.9
	MAX	1.9	-6.5	-9.1	-.8	-.3	-8.0
	MIN	-27.1	-22.1	-17.1	-30.9	-25.0	-22.1

TABLE 11.– SUMMARY OF DATA AT RUNWAY THRESHOLD

Variable		ILS			NPA		
		No HUD	FD HUD	FP HUD	No HUD	FD HUD	FP HUD
FALT	M	47.5	52.3	44.9	60.1	69.4	46.2
	SD	14.6	18.2	7.0	20.7	21.7	15.5
	MAX	100.0	100.0	63.0	121.0	142.0	83.0
	MIN	19.0	22.0	25.0	10.0	34.0	13.0
FYCG	M	-2.3	3.1	4.1	-5.4	0	1.4
	SD	22.7	22.1	18.0	18.8	20.6	12.6
	MAX	57.0	59.0	90.0	42.0	38.0	43.0
	MIN	-50.0	-46.0	-33.0	-56.0	-63.0	-25.0
FVQVR	M	3.3	3.3	2.2	3.2	4.3	2.3
	SD	3.8	3.9	2.9	4.2	3.9	3.4
	MAX	18.2	17.8	8.5	11.6	18.7	13.3
	MIN	-2.9	-3.7	-2.9	-8.2	-4.2	-4.4
FHDOT	M	-12.6	-11.6	-11.0	-14.4	-14.8	-11.3
	SD	2.9	2.5	1.9	3.3	3.3	2.9
	MAX	-6.9	-6.8	-7.3	-7.3	-9.8	-2.7
	MIN	-19.0	-18.2	-15.4	-22.1	-21.7	-16.8

TABLE 12.– SUMMARY OF LANDING DATA

Variable		ILS			NPA		
		No HUD	FD HUD	FP HUD	No HUD	FD HUD	FP HUD
LXCG	M	1492	1720	1751	1815	1901	1807
	SD	626	692	372	682	710	487
	MAX	3120	3253	2570	3292	3144	2727
	MIN	510	531	864	235	731	708
LYCG	M	1.0	2.9	5.6	3.1	.8	1.9
	SD	14.1	16.0	12.6	12.9	15.1	10.7
	MAX	50.5	44.0	35.5	33.0	40.0	53.0
	MIN	-25.5	-48.0	-14.0	-42.0	-35.0	-32.0
LMAXVEQ	M	132.6	132.6	130.5	132.1	133.7	130.5
	SD	5.1	4.5	5.7	4.8	4.7	5.8
	MAX	145.5	144.2	153.2	141.8	142.6	150.5
	MIN	123.5	122.3	120.5	116.0	122.2	122.2
LMAXHDOT	M	-3.5	-3.2	-2.9	-3.5	-3.0	-2.8
	SD	1.8	1.3	1.0	1.3	1.2	1.4
	MAX	-1.1	-1.1	-.6	-1.2	-.7	-.4
	MIN	-9.9	-6.3	-5.3	-8.4	-5.6	-9.7

TABLE 13.– SUMMARY OF LANDINGS AND MISSED APPROACHES FOR ANOMALY CASES

Anomaly	No HUD		FD HUD		FP HUD	
	Landing	M. A.	Landing	M. A.	Landing	M.A.
Wind shear	5	0	3	2	2	0
Variable visibility	4	1	0	1	3	3
Low visibility	3	0	1	1	3	0
Runway obstruction	0	2	0	5	0	6

TABLE 14.– SUMMARY OF DATA FOR RUNWAY OBSTRUCTION ANOMALY CASES

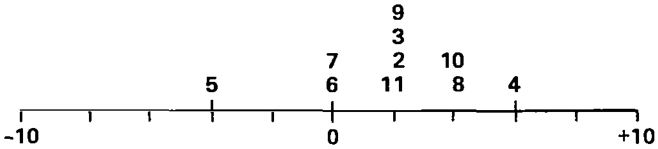
HUD	ILS/NPA	Ceiling, ft	Visibility	Altitude at go-around initiation, ft	Distance from runway at G.A. initiation, ft	Lowest altitude, ft
No HUD	ILS	250	3,000	168	1,700	110
No HUD	NPA	800	12,000	345	3,580	335
FD HUD	ILS	250	3,000	185	700	140
FD HUD	ILS	250	3,000	135	1,250	65
FD HUD	ILS	250	3,000	140	1,390	120
FD HUD	NPA	500	7,000	N/A	N/A	N/A
FD HUD	NPA	800	12,000	250	2,100	155
FP HUD	ILS	250	3,000	115	1,800	75
FP HUD	ILS	400	6,000	195	2,929	162
FP HUD	ILS	400	6,000	155	1,900	105
FP HUD	ILS	400	6,000	110	1,250	65
FP HUD	ILS	400	6,000	130	1,500	120
FP HUD	NPA	500	7,000	75	450	45

TABLE 15. SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE NO. 1

HUD TYPE 1. How confident do you feel in your understanding and ability to effectively and safely use the HUD?

FLIGHT DIRECTOR

Much less confidence than with conventional instruments

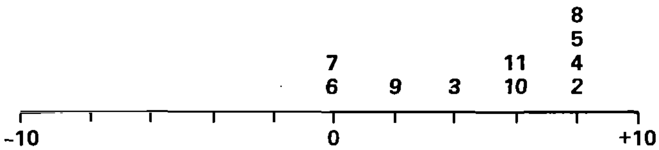


Much more confidence than with conventional instruments

$\bar{x} = 5.9$
$\sigma = 1.37$

FLIGHT PATH

Much less confidence than with conventional instruments



Much more confidence than with conventional instruments

$\bar{x} = 7.5$
$\sigma = 1.65$

FLIGHT DIRECTOR There was a general feeling among most pilots that the FD HUD was equal to, or slightly better than, head down in their ability to use it, but this feeling was not strong enough to be statistically significant (t-test for one sample case).
"t" = 2.07, "p" = not sig.

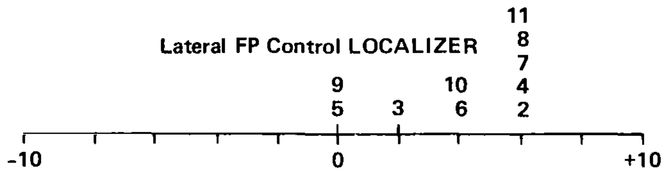
FLIGHT PATH Eighty percent of the pilots felt that the FP HUD could be used more effectively and safely than head down instruments (significant at 0.001 level for one sample t-test).
"t" = 4.79, "p" = 0.99 sig.

TABLE 16. SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE NO. 2a.

HUD TYPE 2a. Using the conventional instrument panel as a reference, rate the HUD on each of the following characteristics by placing a mark on the line. You may explain your ratings in item 3.

FLIGHT DIRECTOR

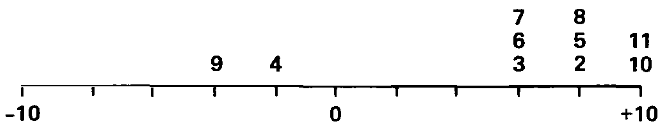
HUD very much more difficult than panel



HUD very much easier than panel

$\bar{x} = 7.0$
$\sigma = 1.25$

FLIGHT PATH



$\bar{x} = 7.8$
$\sigma = 2.39$

FLIGHT DIRECTOR A significant preference was found for the FD HUD over head down in lateral flightpath control.
"t" = 5.07, "p" = 0.99 sig.

FLIGHT PATH A significant preference was found for the FP HUD over head down in lateral flightpath control.
"t" = 3.69, "p" = 0.99 sig.

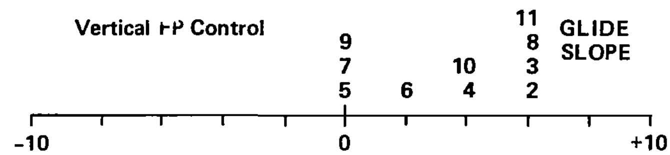
TABLE 17. SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE NO. 2b.

HUD TYPE

2b. Using the conventional instrument panel as a reference, rate the HUD on each of the following characteristics by placing a mark on the line. You may explain your ratings in item 3.

FLIGHT DIRECTOR

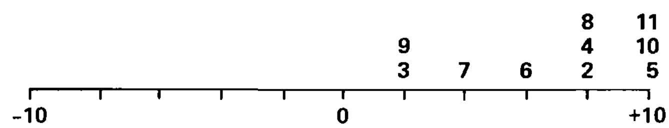
HUD very much more difficult than panel



HUD very much easier than panel

x̄ = 6.7
σ = 1.34

FLIGHT PATH



x̄ = 8.4
σ = 1.58

FLIGHT DIRECTOR — A significant preference was found for the FD HUD over head down in vertical flightpath control.
"t" = 4.02, "p" = 0.99 sig.

FLIGHT PATH — A significant preference was found for the FP HUD over head down in vertical flightpath control.
"t" = 6.81, "p" = 0.99 sig.

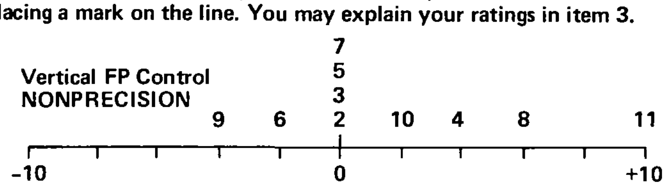
TABLE 18. SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE NO. 2c.

HUD TYPE

2c. Using the conventional instrument panel as a reference, rate the HUD on each of the following characteristics by placing a mark on the line. You may explain your ratings in item 3.

FLIGHT DIRECTOR

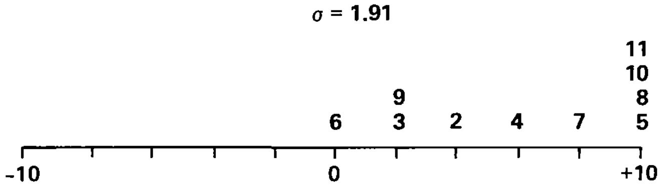
HUD very much more difficult than panel



HUD very much easier than panel

x̄ = 5.9
σ = 1.91

FLIGHT PATH



x̄ = 8.1
σ = 1.97

FLIGHT DIRECTOR — No significant preference was found for the FD HUD over head down in vertical flightpath control for nonprecision approaches.
"t" = 1.48, "p" = not sig.

FLIGHT PATH — A significant preference was found for the FP HUD over head down in vertical flightpath control for nonprecision approaches.
"t" = 4.97, "p" = 0.99 sig.

TABLE 19. SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE NO. 2d.

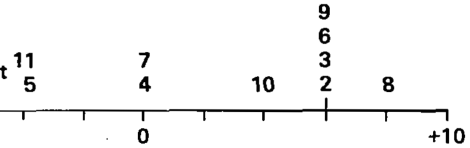
HUD TYPE

2d. Using the conventional instrument panel as a reference, rate the HUD on each of the following characteristics by placing a mark on the line. You may explain your ratings in item 3.

FLIGHT DIRECTOR

HUD very much more difficult than panel

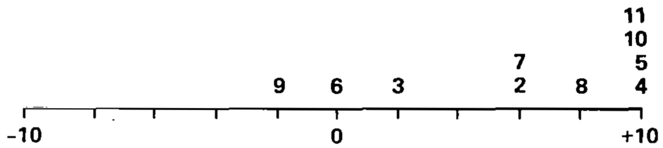
Speed Control and Thrust Management



HUD very much easier than panel

$\bar{x} = 6.4$
$\sigma = 2.22$

FLIGHT PATH



$\bar{x} = 8.0$
$\sigma = 2.26$

FLIGHT DIRECTOR	No significant preference was found for the FD HUD over head down in speed and thrust management. "t" = 1.96, "p" = not sig.
FLIGHT PATH	A significant preference was found for the FP HUD over head down in speed and thrust management. "t" = 4.19, "p" = 0.99 sig.

TABLE 20(a).– SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE – FD HUD

Question 3. General comments about ratings in item 2.

Subject	Pilot Comments
2	No comments
3	On NPA, I would feel better if I had IVSI.
4	No comments
5	I find no advantage to HUD while IFR. When VFR, it is helpful to have instrument data overlaying the runway especially on NPA.
6	Donut seems too large for good altitude control in level flight, but it is very good for glide path control. Could be made smaller.
7	Lateral control with large crosswind is excellent. I found myself not really aware of a large heading correction. Glide slope was about the same as conventional except it would be easier if "contrast" of glide slope and localizer bugs were enhanced. A little harder to pick up trends with digital airspeed. Airspeed worm is good but needs to be more visible. Thrust display good except I would like all three engines. I could make small adjustments with center engine only.
8	HUD appeared easier on localizer approach once established on localizer. I was more aware of airspeed and altitude. It eliminated a lot of items not needed in scan. On NPA, once runway came into view, HI-LO was useful. Would eliminate a lot of short landings especially at night.
9	Harder for me to use fixed depression line and delta gamma than just eyeball. Symbols tend to confuse and block out vision during final phases of approaches.
10	Vertical and lateral flightpath better than conventional because of increased scale and reduced scan. Only slightly better than on nonprecision. Speed and thrust better, but only because the display is integrated.
11	General approach parameters much easier with HUD. Thrust control easier with EPR within scan of HUD. Airspeed without the standard needle a little harder because of rate that needle moves sometimes determines amount of thrust needed to stop needle.

TABLE 20(b).– SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE – FD HUD

Question 3. General comments about ratings in Item 2.

Subject	Pilot Comments
2	The big improvement over head down is the expanded size of the display. Vertical direction of aircraft is not as great an improvement in the HUD because the VG display head down is fairly large and easy to maintain a pitch attitude.
3	With more time, I think my ratings would all be much higher on the plus side.
4	Had some problems with lead-in when turning to intercept localizer. The presentation heads down seems easier to use to line up. Once lined up, HUD does better maintaining.
5	Localizer was better than flight director, but not as much better as glide slope, speed and thrust management. NPA on a scale of 1 to 10 is a 20.
6	Once established on localizer, I feel much better with the HUD. Descending turns to intercept localizer prove to be more disorienting than head down.
7	In general, once established on ILS, HUD is much easier to fly especially on high crosswind approaches. It is extremely valuable when making transition and continuing descent, especially on NPA and on ILS when weather is marginal.
8	Once established on localizer, very easy to maintain localizer with HUD. Same for glide slope. On NPA, I thought the HUD takes the uncertainty out of knowing when to leave MDA by using the 3° line. Also, the MDA line is useful in approaching and maintaining MDA. With reference to speed worm and potential flightpath, I was able to fly a more stable approach by not having to jockey power levers.
9	Localizer moves too fast. In capture mode, if in a turn and descending, cannot see localizer bar. OK once established on approach. With HUD, easier to see glide path deviation and gives better picture of aircraft position. Speed control somewhat distracting. Airspeed changes are rapid and worm sometimes gives impression of being very far out of airspeed envelopes. No power presentation available. Need some reference for power settings to prevent loss of control due to very large windshears.
10	The much expanded scale of reference and fine line precision simply make the whole task easier. The caret showing almost instantaneous speed trend is a big plus. In wind shear, particularly in poor visibility, flight path vector seems to give a real jump on short landing threat.
11	Much less scan time involved. Speed and thrust control info is excellent.

TABLE 21. SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE NO. 4

HUD TYPE

4. During the "Radar Vectoring" part of the scenarios you flew, rate the HUD with regard to general "situation awareness." Did you always know where you were? Where the localizer and glide slope were? Use the conventional instrument panel (ADI and Flight Director, HSI, and RMI) as a reference.

FLIGHT DIRECTOR

HUD very much worse than instrument panel (-10) … HUD very much better than instrument panel (+10)

-10	-8	-6	-4	-2	0	+2	+4	+6	+8	+10
		6	7, 5	10, 9, 8	11, 3		4, 2			

$\bar{x} = 4.4$
$\sigma = 1.65$

FLIGHT PATH

HUD very much worse than instrument panel (-10) … HUD very much better than instrument panel (+10)

-10	-8	-6	-4	-2	0	+2	+4	+6	+8	+10
		9	10	7, 6, 3	11, 5			8, 4, 2		

$\bar{x} = 5.1$
$\sigma = 2.18$

FLIGHT DIRECTOR

Eight out of the ten pilots rated the FD HUD as slightly lower in terms of position awareness, however, while highly consistent it was not statistically significant in strength (t-test for one sample case).
"t" = 1.15, "p" = not sig.

FLIGHT PATH

Three of ten pilots said the FP HUD was better than head down for general position and situation awareness. Two pilots felt there was some benefit, and the other five pilots felt head down gave better awareness. No significant differences were found statistically.
"t" = 0.144, "p" = not sig.

TABLE 22(a).– SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE - FD HUD

Question 5. *Did you find the information on the HUD to be sufficient? Did you desire more information?*

Subject	Pilot Comments
2	No comments
3	I would like to see pitch lines like on the other display.
4	Yes - No
5	I find HUD deficient in presentation of pitch and roll. Digital readouts more distracting than airspeed and altitude needles. I do not find it necessary to fly precisely to the digit.
6	The information was good for approach but for go-around and vectoring you need more of an HSI type display in order to have a better situation awareness. The heading display leaves something to be desired. My objection is that it just gives you a heading without relating it to your position on the approach.
7	Need better pitch info, especially during go-arounds. This would also help in level flight especially in turns. Digital readout of altitude makes it more difficult to pick up immediate deviations.
8	HUD is excellent in approach but clutters scan during vectoring and turning and gives you a moment of uncertainty about your position.
9	Need some pitch reference. Horizon line is of no use as it represents nothing. Very difficult to maintain altitude on instruments. Altitude hold feature always overshot and we had tendency to go below specified altitude.
10	I distinctly feel that DME should be a part of this display for situation awareness.
11	Yes, sufficient info is available. However, a better system for pitch management upon capture or heading change could be incorporated.

TABLE 22(b).- SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE - FP HUD

Question 5. Did you find the information on the HUD to be sufficient? Did you desire more information?

Subject	Pilot Comments
2	How about flashing the altitude numbers to indicate OM crossing altitude.
3	Yes, except the OM helps me to know where I am at all times.
4	Yes - No
5	Yes - No. I think altitude and airspeed on a declutter mode would be helpful. Below the 5° nose down line there is no descent reference either in body angle or descent rate.
6	Pitch up and pitch down should be marked in 5° increments. It was possible to pitch down so far you could lose heading information. Localizer bar should be out of view completely until loc capture, then it should appear centered in FPS and then "pull" you toward loc center. When you declutter you should still have pitch attitude in case of go-around.
7	I would like to have vertical speed information and some way to more precisely determine wings level and bank angle. Also it might be valuable to know what your power setting is in addition to the thrust vector.
8	Occasionally when descending below 1500 fpm you would lose the heading scale and you would have to lessen your rate of descent. Also need a heading reminder.
9	Info OK. Course line sometimes confusing. Need to rearrange my thinking in relation to course line. Don't think course line of that prominence necessary. I confused it with localizer as they crossed during capture of localizer. Distracts from localizer.
10	I would like vertical speed information.
11	Yes. Heading information at steep rates of descent.

TABLE 23. SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE NO. 7a.

HUD TYPE

7a. Using the conventional instrument panel as a reference, rate the HUD on the following characteristics. You may explain your reasons in item 8.

Ability to Detect Wind Shears

HUD very much worse than instrument panel ← → HUD very much better than instrument panel

HUD TYPE	-10					0					+10	
FLIGHT DIRECTOR			11		3	6, 5	10	9, 7, 2	8, 4			$\bar{x}$ = 5.9, σ = 1.91
FLIGHT PATH							9, 3	6	7, 5, 4	2	11, 10, 8	$\bar{x}$ = 8.2, σ = 1.55

FLIGHT DIRECTOR No significant difference was found between the FD HUD and head down.
"t" = 1.49, "p" = 0.83 not sig.

FLIGHT PATH Significant agreement was found between pilots (100 percent) that the FP HUD was superior to head down in coping with wind shears.
"t" = 6.53, "p" = 0.99 sig.

TABLE 24. SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE NO. 7b.

HUD TYPE

7b. Using the conventional instrument panel as a reference, rate the HUD on the following characteristics. You may explain your reasons in item 8.

High Crosswind Landings

HUD very much worse than instrument panel ← → HUD very much better than instrument panel

HUD TYPE	-10					0					+10	
FLIGHT DIRECTOR				6	2	7	10, 8, 3	9	11, 5, 4			$\bar{x}$ = 6.1, σ = 1.73
FLIGHT PATH					3	9, 7, 6	2		5	8, 4	11, 10	$\bar{x}$ = 7.1, σ = 2.33

FLIGHT DIRECTOR No significant difference was found between the FD HUD and head down.
"t" = 2.01, "p" = 0.92 not sig.

FLIGHT PATH Significant agreement was found between pilots (90 percent) that the FP HUD was superior to head down in coping with crosswinds.
"t" = 2.84, "p" = 0.98 sig.

TABLE 25. SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE NO. 7c.

HUD TYPE

7c. Using the conventional instrument panel as a reference, rate the HUD on the following characteristics. You may explain your reasons in item 8.

FLIGHT DIRECTOR

Initiation of Missed Approach

HUD very much worse than instrument panel ← → HUD very much better than instrument panel

-10					0					+10
5	6	11		7 2	10 3	8	9	4		

$\bar{x} = 4.2$
$\sigma = 2.57$

FLIGHT PATH

-10					0					+10
		6			11 7 3 2	9	10 5	8	4	

$\bar{x} = 5.9$
$\sigma = 1.97$

FLIGHT DIRECTOR No significant difference was found between the FD HUD and head down, in fact, a slightly negative relationship was found.
"t" = 0.98, "p" = 0.65 not sig.

FLIGHT PATH No significant difference was found between the FP HUD and head down in coping with a missed approach.
"t" = 1.44, "p" = 0.81 not sig.

TABLE 26. SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE NO. 7d.

HUD TYPE

7d. Using the conventional instrument panel as a reference, rate the HUD on the following characteristics. You may explain your reasons in item 8.

FLIGHT DIRECTOR

Detection of Runway Obstructions

HUD very much worse than instrument panel ← → HUD very much better than instrument panel

-10					0					+10
			5	2	10 7 3	9		8	4	11 6

$\bar{x} = 6.5$
$\sigma = 2.55$

FLIGHT PATH

-10					0					+10
				4 2	10 3		7 6	9		11 8 5

$\bar{x} = 6.67$
$\sigma = 2.35$

FLIGHT DIRECTOR No significant difference was found between the FD HUD and head down.
"t" = 2.26, "p" = 0.94 not sig.

FLIGHT PATH Significant agreement was found between pilots (80 percent) that the FP HUD was superior to head down in coping with runway obstructions.
"t" = 2.58, "p" = 0.97 sig.

TABLE 27(b).- SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE - FP HUD

Question 8. General comments about ratings in item 7.

Subject	Pilot Comments
2	HUD symbols can mask or distract from an object ahead such as an aircraft on runway.
3	No comment.
4	No comment.
5	The tape worm and flashing symbol was great for speed excursions but I don't feel that is necessarily a shear detection device. Flightpath info relative to heading is great thus allowing interpolation of crosswind.
6	No attitude information during missed approach if you are in declutter mode. If it weren't for that I would say it was equal to conventional instruments on missed approach.
7	The main advantage is in recognition of windshears.
8	You have an instant knowledge of any windshear with the instantaneous readout of airspeed and speed worm. The same with crosswind landings. On missed approaches, for a moment there is just a little confusion with the HUD but then you settle down and just fly the HUD. As you are already looking out of the window, you can detect any obstruction on the runway immediately.
9	Able to pick up windshears faster due to 1 knot increments on airspeed indicator. Missed approach easier because you have pitch reference available plus visual awareness. Because you are not dividing time between cockpit and outside, obstruction becomes apparent much faster.
10	On missed approach, display seems very busy at rotation but had I decluttered it may have been much better. At any rate, the flightpath vector symbol is super here. On obstructions, this is a simulator environment and pretty tough to relate to real world reality.
11	No comment.

TABLE 27(a).- SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE - FD HUD

Question 8. General comments about ratings in item 7.

Subject	Pilot Comments
2	No comments.
3	No comments.
4.	No comments.
5	I followed "command" on HUD, not looking at the runway. Having heading indications above command dot helps pick up the crosswind easier. Having no pitch info derogates the proper attitude and thus the performance of the missed approach. Looking at HUD while visual distracts from fully viewing the outside world when VFR.
6	I am much more likely to recognize a shear if I see an airspeed indicator jump than to see a number change. IFR, I would recognize a shear sooner with conventional instruments. VFR, I think I would recognize a shear with the HUD sooner.
7	Good for shears because you can integrate visual cues with the display to detect changes. I would like a major declutter capability.
8	Can detect windshear very rapidly with HUD. On high crosswinds, you have to divide time between HUD and watching the runway. On initial missed approach, it was difficult but once into missed approach, it was easier. No problems on runway obstructions.
9	The HUD gives better indications of windshear because of its airspeed and heading information. Pick up objects on runway better because you are focussing down runway.
10	Quite helpful in windshear if you are in delta-gamma mode; not much otherwise. Quite good in crosswind if you remain in localizer mode but if you do that, you lose the windshear protection. OK for missed approach but not a dramatic improvement. For runway obstruction, the plus of early runway detection and minus of view clutter rate a wash here.
11	Airspeed needle movement is much easier to catch for windshears. Installation of go-around button for initial pitch attitude for go-around would make HUD better. Runway obstructions with heads up comes into view sooner, hence safer.

TABLE 28. SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE NO. 11

HUD TYPE

11. All things considered, rate the HUD on the following scale. Base your answer on as many factors as you can — safety, economics, passenger comfort, etc.

FLIGHT DIRECTOR

I strongly prefer the conventional panel ← → I strongly prefer the HUD

-10					0					+10
			5		7, 3	6	10, 9, 2	11, 8, 4		

$\bar{x} = 6.4$
$\sigma = 1.65$

FLIGHT PATH

I strongly prefer the conventional panel ← → I strongly prefer the HUD

-10					0					+10
			6			3	9	7	10, 8, 5, 2	11, 4

$\bar{x} = 8.0$
$\sigma = 2.16$

FLIGHT DIRECTOR — A significant difference was found between the FD HUD and head down, in that nine of ten pilots felt the HUD was equal to or better than head down. However, the ratings were not particularly high (t-test for one sample case).
"t" = 2.69, "p" = 0.98 sig.

FLIGHT PATH — A significant difference was found between the FP HUD and head down (0.001 level of significance for single sample t-test). Nine out of ten pilots preferred the FP HUD to head down.
"t" = 4.39, "p" = 0.99 sig.

TABLE 29(a).- SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE - FD HUD

Question 12. List the factors you considered for rating in item 10 in order of importance, starting with the most important.

Subject	Pilots Comments
2	Safety, passenger comfort.
3	Something new; something in front of your eyes.
4	Safety, windshear protection.
5	Pitch and roll info. Command info too sensitive in display movement but too much tolerance in correction. HUD requires too many aircraft corrections to fly a comfortable approach for passengers.
6	Referencing yourself in relation to runway. Altitude control in level flight. Localizer capture (dot takes off abruptly and sometimes hidden behind similar dot on side of display). HI-LO bar off to side of runway during large crosswinds.
7	If used for low visibility approaches only and with declutter capability and more visible airspeed, glide slope, and localizer info, it would be excellent. However, for maneuvering and VFR, at this point I prefer conventional instruments.
8	Localizer, glide slope, airspeed indicator, altitude, engine instruments, raw data.
9	Outside visibility. Longer time to prepare for landing. Good information without scan of complete instrument panel.
10	As an approach tool, it's good, but because of scale and display integration, not because of any leap forward in logic or philosophy. As a maneuvering tool, I believe it to be less than present conventional display.
11	Safety, simplicity, and better display for nonprecision approach.

TABLE 29(b).- SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE - FP HUD

Question 12. List the factors you considered for rating in item 10 in order of importance, starting with the most important.

Subject	Pilot Comments
2	The HUD can provide a means to reduce or eliminate large control and/or power changes. Therefore, smaller deltas mean passenger comfort is improved, less stress on airframe and engines, better fuel economy (less excursions from intended flightpath = less fuel) and lower hand flown mimimums equals less diversions to alternate airport.
3	I like a clear view. It's a new ballgame. With more time, I would give the HUD a higher rating.
4	Easier to fly. Safety - quicker interpretation of factors to complete safe landing or go-around. Better windshear detection and correction. Direct reference for landing points.
5	Flightpath info now. Thrust and speed control is precise. Speed worm and stickshaker line are very helpful in shear situations.
6	Outside interference.
7	Transition to ground contact. Maintaining proper glide slope during last part of descent. Recognizing windshear.
8	I feel that by using the HUD you will be able to get in when the ceiling is marginal on both the precision and nonprecision approaches. Also where fields have no ILS. This would save money by not having to divert to alternate, bussing passengers, hotels, etc. Also save fuel by making it on first approach.
9	More time spent looking out. Simpler scan of heading, airspeed, altitude and flightpath.
10	Economics. For final approach work, this thing is incomparable. For terminal area maneuvering involving major pitch, speed and particularly altitude changes, I found it a bit less so.
11	The basic fact that the pilot has guidance for touchdown and minimums on nonprecision approaches plus the fact that the approach is more accurate makes HUD much more valuable than standard instruments.

TABLE 30(a).- SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE -FD HUD

Question 13. General comments about the HUD.

Subject	Pilot Comments
2	No comment.
3	I like it very much. With more use I would feel more at ease.
4	I would like to see this used from FAF to landing. There is some problem with large wind corrections when runway appears. Harder to bring runway into scan than with conformal HUD. Much better than head down.
5	I believe taking a conventional VG presentation of pitch and roll and super-imposing crosshairs for command info and giving the peripheral info such as raw data glide slope and localizer, heading, EPR, airspeed and placing it further from the pilot (closer to windshield) would be better.
6	Overall, I am very impressed with the system, and it is certainly a step in the right direction. With some improvements I think it will be a very workable system, and one that any instrument pilot could readily adapt to. With passengers in the back of the aircraft, the system should encourage smoothness which it does not at this time.
7	With changes I suggested, if HUD was used during instrument approaches much like we use our conventional flight director, it would be an excellent step forward in the art of instrument approaches.
8	I enjoyed using the HUD. More aware of altitude and airspeed. Confusing on vectoring and turning and initiating go-around. I like HI-LO once I learned the switching.
9	Since this HUD is still just a flight director, pilot must change from instruments to visual just as in head down flying. Much more difficult to fly than other HUD. The system is better than nothing however. Real world one to one is better.
10	More accurate for approaches than conventional instruments. Altitude hold is too sloppy. At localizer capture, the steering dot goes zipping right across into the dot ladder at other side and gets lost. EPR is of some help but a speed trend display would beat that one in my book. Once again, DME. Speed control could be more demanding. In delta gamma with a crosswind, I decrabbed too early, I think due to the nature of the presentation. I like vertical speed reference.
11	In my opinion, HUD has a future and is needed.

TABLE 30(b).- SUMMARY OF HUD DEBRIEFING QUESTIONNAIRE -FP HUD

Question 13. General comments about the HUD.

Subject	Pilot Comments
2	I like it.
3	I like it very much.
4	I like it very much. I think it would enable pilots to do a better and safer job flying the aircraft in low visibility and windshear situations. I feel that lower minimums would be possible with the HUD.
5	The HUD is very easy to learn and to operate by using it or having a demonstration. I found it difficult to learn by reading about it. I wish I could use it for a few months in airline flying. It is smooth and comfortable. Except for descent rate, it has all the info needed for making a CAT I/II instrument approach. A system warning light would be necessary close by to warn of malfunctions.
6	I think HUD should enhance rather than replace conventional systems. It will never work 100 percent of the time for all approaches. The conventional instruments do, however.
7	In general, I feel it is an excellent display for making approaches, especially in the areas of transition, crosswind tracking, final descent tracking, and in recognizing windshears.
8	I enjoyed flying this HUD very much. I felt very comfortable and at ease in flying it. When returning to flight instruments head down, I was rough on controls and had difficulty holding 100 ft whereas with HUD I held the altitude within 20 ft.
9	The course line kind of snowed me, at least at first. I disliked the way almost all reference info disappears when pitch exceeds about -4½°. The level wing portion of the flightpath symbol may possibly give better roll reference at flare if they were longer.
10	I was very much impressed with the number of items HUD was able to display. After a few runs I had no problems understanding what was presented. I like having information available to me during last 300 ft of descent in a CAT II approach. At present, we must rely on copilot to read and relay G/S, LOC, airspeed and altitude to us. The system was very difficult to use during an intercept of over 30°. Localizer moves too fast to catch it. I don't like the course line presentation. System excellent once established on final. During approach, hard to determine aircraft actual position relative to glide slope. Somewhat confusing to me. Flare command seem to make for landings past the desired 1000 ft point. Suggest flare command disappear at -3° indication.
11	Hopefully HUD will be adopted in the future.

TABLE 31. SUMMARY OF HUD TRAINING QUESTIONNAIRE NO. 1

HUD TYPE	1. Handout material	Mean	"t"	"p"
FLIGHT DIRECTOR	Misleading "negative training" / Over-done 11; 6; 10 9 5; 0 7 2 3 4 Contributed nothing — $\bar{x} = 8.1$, $\sigma = 2.15$ — Completely effective		4.35	0.99
FLIGHT PATH	10 6; 7 4; 0 5 9 2 3 11 Contributed nothing — $\bar{x} = 7.2$, $\sigma = 1.86$ — Completely effective Pilots felt both FD and FP HUD handout materials were effective.		3.59	0.99

TABLE 32. SUMMARY OF HUD TRAINING QUESTIONNAIRE NO. 2

HUD TYPE	2. Classroom Lecture	Mean	"t"	"p"
FLIGHT DIRECTOR	Misleading "negative training" / Over-done 11; 10; 6; 9 5; 0 2 7 3 4 Contributed nothing — $\bar{x} = 9.22$, $\sigma = 1.09$ — Completely effective		11.59	0.99
FLIGHT PATH	7; 6 3 11; 0 5 9 4 2 10 Contributed nothing — $\bar{x} = 8.1$, $\sigma = 1.83$ — Completely effective Pilots felt that classroom lectures for both HUDs were effective.		5.09	0.99

TABLE 33. SUMMARY OF HUD TRAINING QUESTIONNAIRE NO. 3

HUD TYPE	3. Video tapes	Mean	"t"	"p"
FLIGHT DIRECTOR	Misleading "negative training"; Over-done Scale: 0 ... 2, 5, 7/3, 11/10/9/6/4 Contributed nothing — Completely effective $\bar{x} = 9.0$ $\sigma = 1.5$		8.00	0.99
FLIGHT PATH	Scale: 0 ... 9, 6, 7/2, 11/10/5/4/3 Contributed nothing — Completely effective $\bar{x} = 9.22$ $\sigma = 1.09$ Pilots felt that video tapes for both HUDs were effective.		8.85	0.99

TABLE 34. SUMMARY OF HUD TRAINING QUESTIONNAIRE NO. 4

HUD TYPE	4. Simulator training	Mean	"t"	"p"
FLIGHT DIRECTOR	Misleading "negative training"; Over-done Scale: 0 ... 4, 7/3/2, 11/10/9/6/5 Contributed nothing — Completely effective $\bar{x} = 9.4$ $\sigma = 0.73$		18.35	0.99
FLIGHT PATH	Scale: 0 ... 4, 9/7/2, 11/10/6/5/3 Contributed nothing — Completely effective $\bar{x} = 9.22$ $\sigma = 1.30$ Pilots felt that simulator training for both HUDs was effective.		8.73	0.99

TABLE 35. SUMMARY OF HUD TRAINING QUESTIONNAIRE NO. 5

HUD TYPE	5. Please indicate your assessment of the overall effectiveness of the training program.	Mean	"t"	"p"
FLIGHT DIRECTOR	0 … 10 … 7, 2 … 3 … 9, 6, 5, 4 Contributed nothing — $\bar{x} = 9.0$, $\sigma = 1.19$ — Completely effective		10.57	0.99
FLIGHT PATH	0 … 10 … 7, 6, 4 … 3, 2 … 11, 5 Contributed nothing — $\bar{x} = 8.5$, $\sigma = 1.01$ — 9 — Completely effective *Pilots felt overall effectiveness of both HUD training procedures was effective.*		8.22	0.99

TABLE 36. SUMMARY OF HUD TRAINING QUESTIONNAIRE NO. 7

HUD TYPE	7. Considering all of the above, if this study were to be updated using improved training programs, would the results and conclusions be:	Mean	"t"	"p"
FLIGHT DIRECTOR	Probably very different — 0 … 2 … 5 … 7, 3 … 10 … 9, 6, 4, 11 — Probably the same $\bar{x} = 7.55$ $\sigma = 2.65$		2.89	0.97
FLIGHT PATH	0 … 7 … 4 … 10, 2 … 6, 3 … 11, 9, 5 $\bar{x} = 8.55$ $\sigma = 1.42$ Pilots felt improved training programs would have little impact on results and conclusions. (It should be noted that even though the relationship was statistically significant, $\alpha = 0.03$, the distribution of ratings on the flight director training was very scattered. This probably reflects a lack of personal preference for the display, rather than a limitation in the training package. Even though subjects tended to have more questions during *the flightpath training, their overall opinions tended to rate the flightpath display higher* in training.) While all subjects' responses to the training questionnaire were positive and significantly different from pure chance, it does not appear that the training questionnaire discriminated very well.		8.33	0.99

TABLE 37.– DESIGN STRUCTURE

	HUD1		HUD2		HUD3	
	C1	C2	C1	C2	C1	C2
Precision						
W1	1	1	2	3	1	3
W2	3	2	1	1	2	1
W3	2	3	3	2	2	3
Nonprecision						
W1	1	3	2	2	3	2
W2	3	2	3	1	3	1
W3	2	1	1	3	2	1

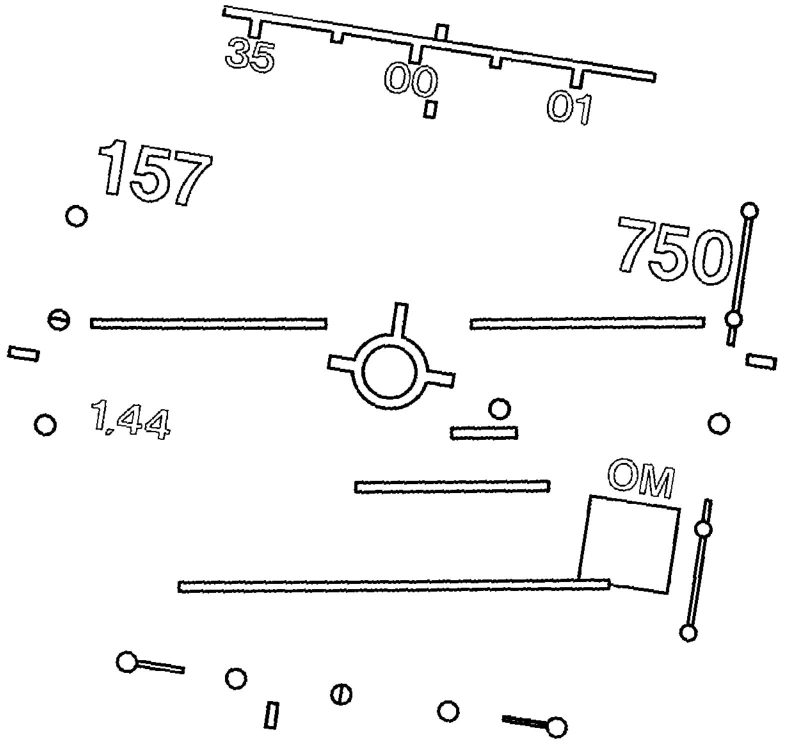


Figure 1.– FD HUD; ILS mode.

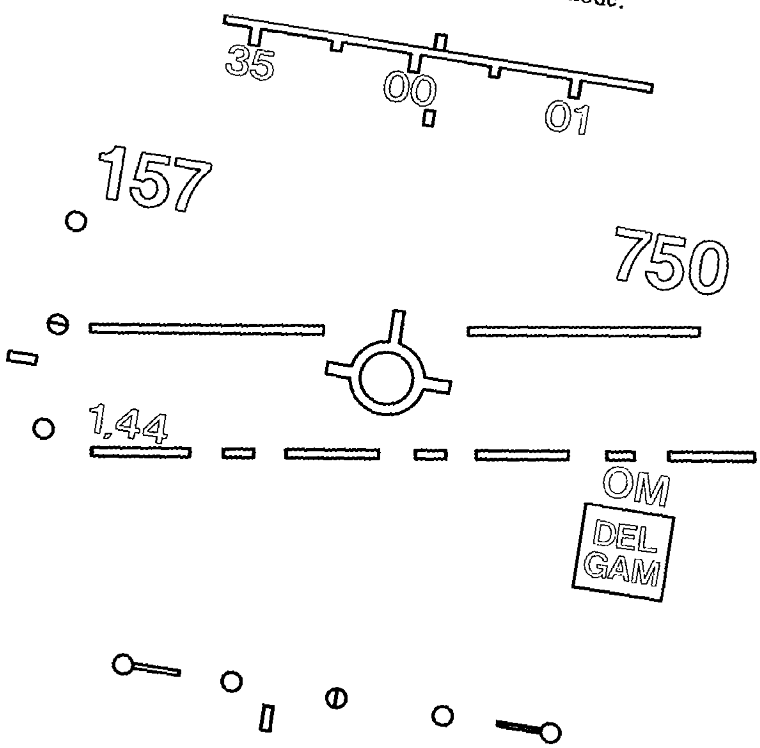


Figure 2.– FD HUD; nonprecision mode.

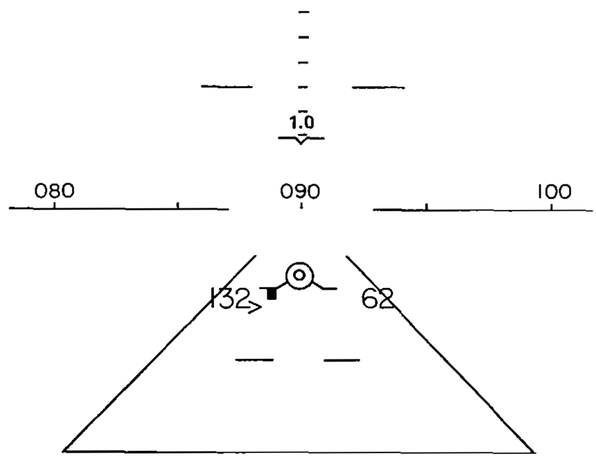


Figure 3.– FP HUD symbology.

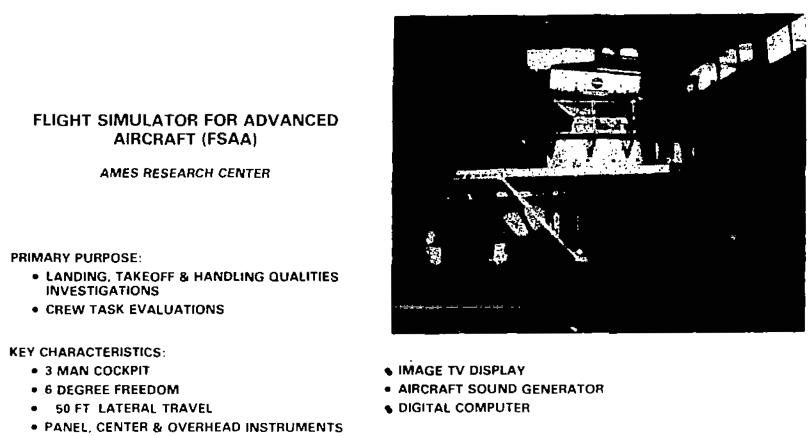


Figure 4.– Simulator area.

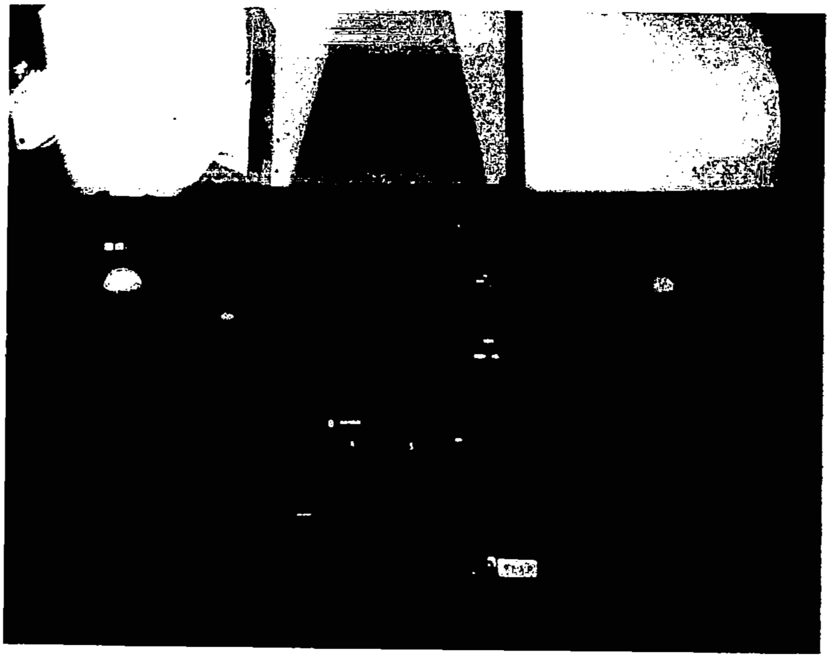


Figure 5.– FSAA cockpit layout.

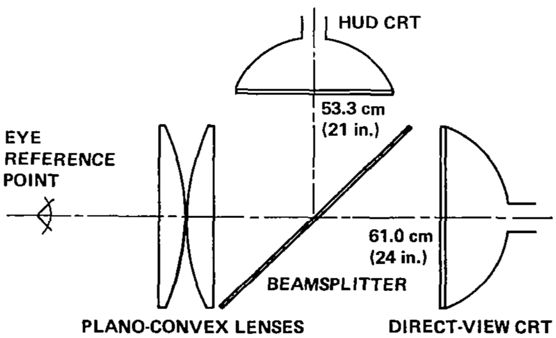


Figure 6.– Schematic view of the HUD lenses and beamsplitter.

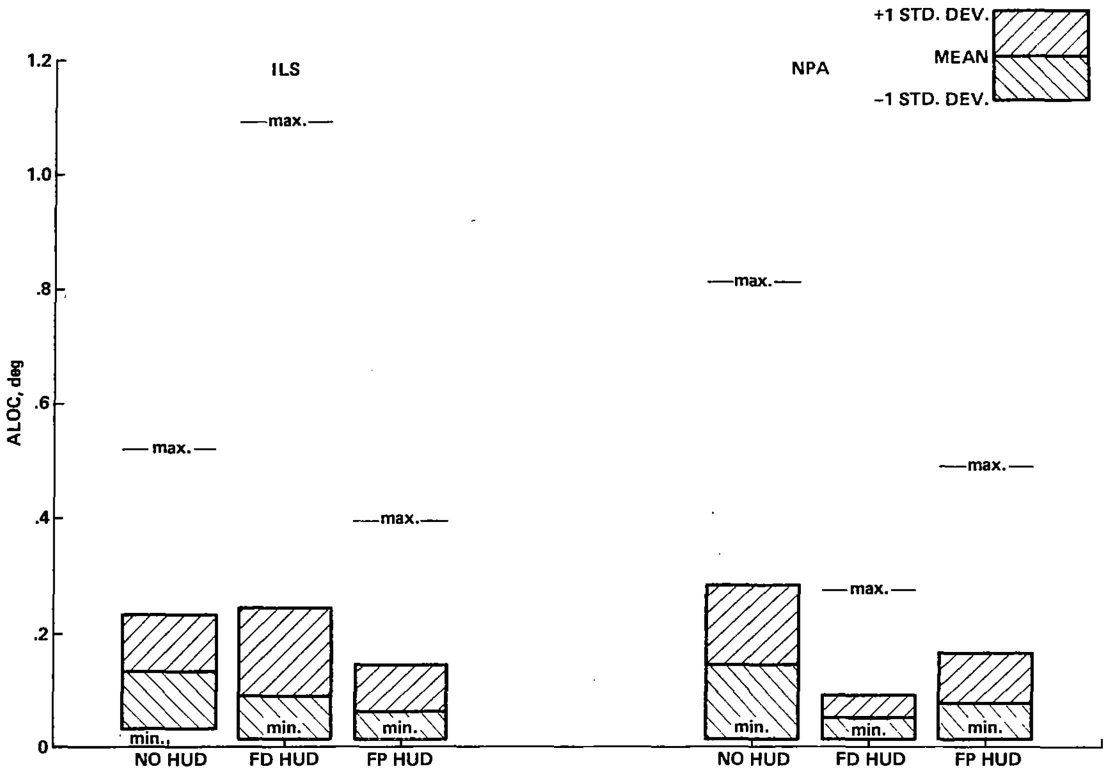


Figure 7.– RMS localizer error – approach segment.

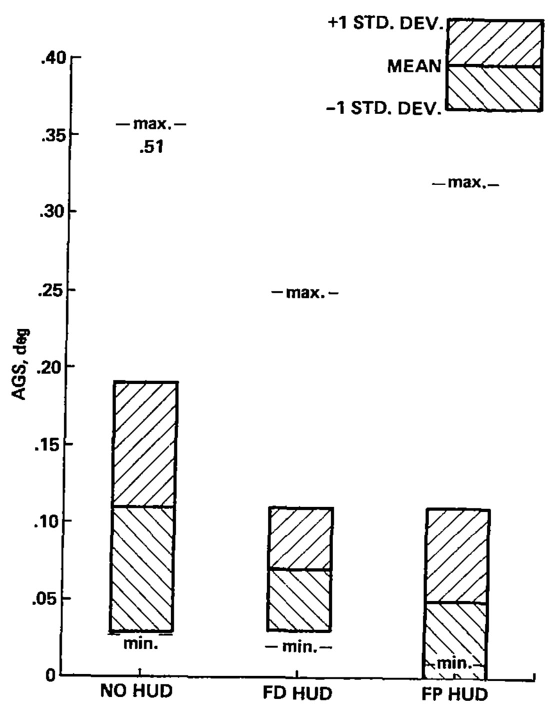


Figure 8.– RMS glide-slope error – approach segment.

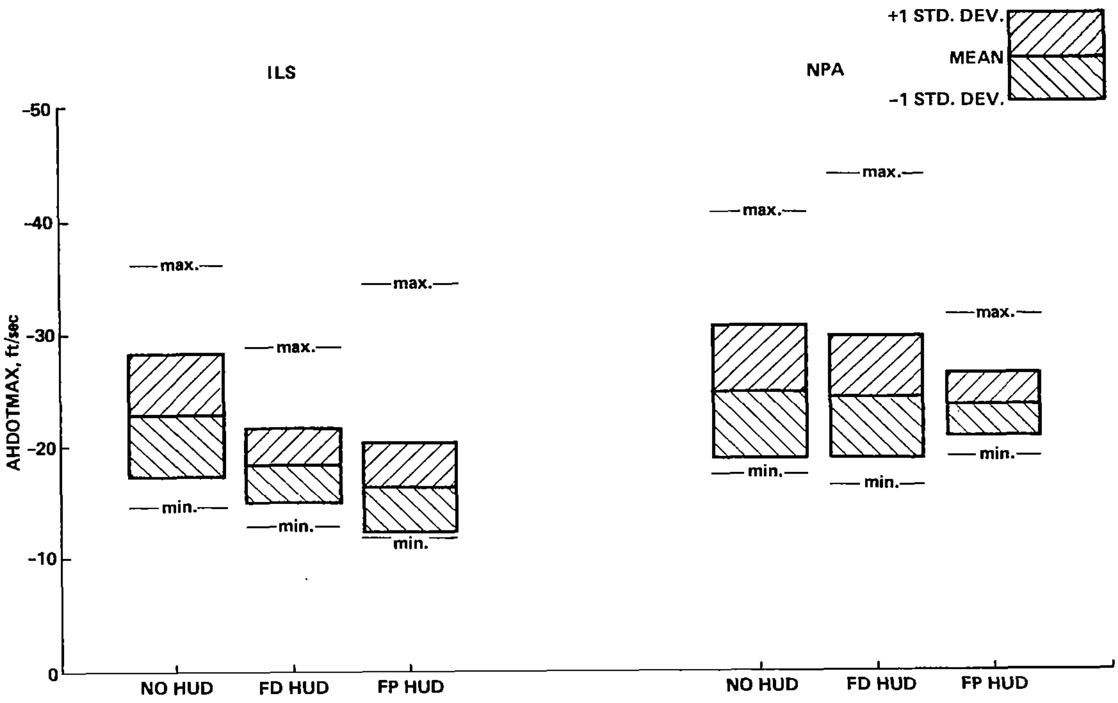


Figure 9.– Maximum sink rate – approach segment.

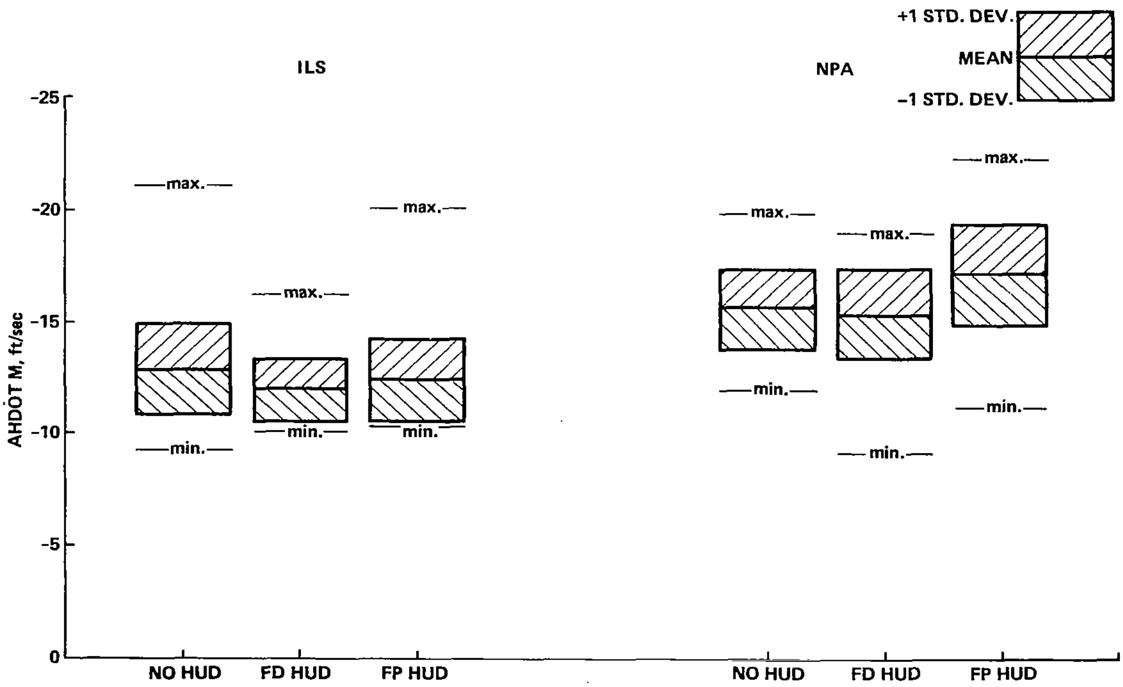


Figure 10.– Mean sink rate – approach segment.

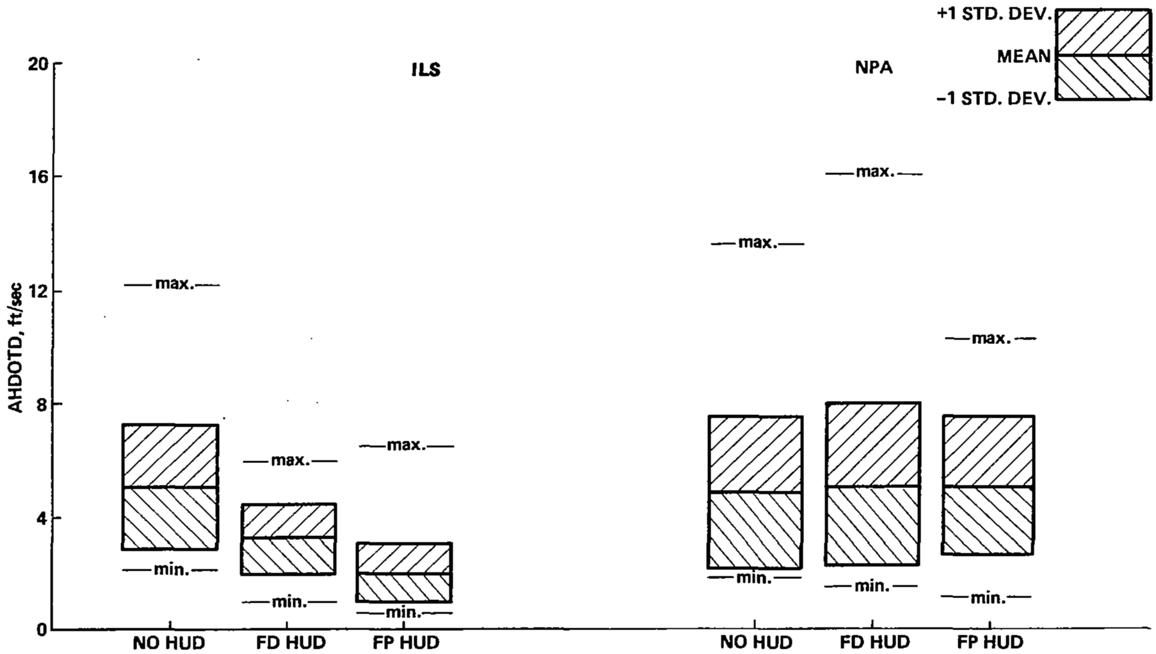


Figure 11.– RMS division of sink rate from mean sink rate – approach segment.

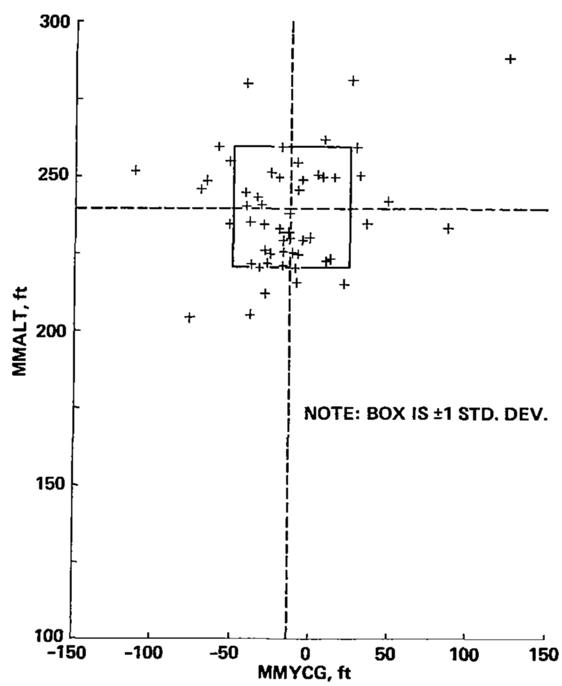


Figure 12.– ILS approach – lateral displacement and altitude at middle marker for NO HUD case.

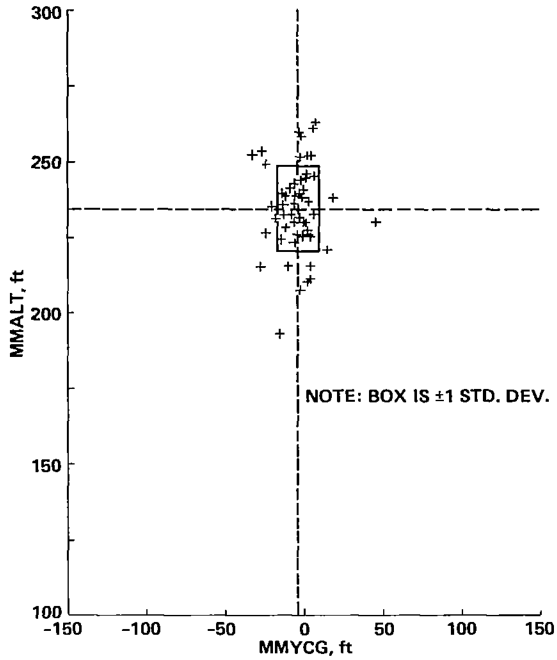


Figure 13.– ILS approach – lateral displacement and altitude at middle marker for FD HUD case.

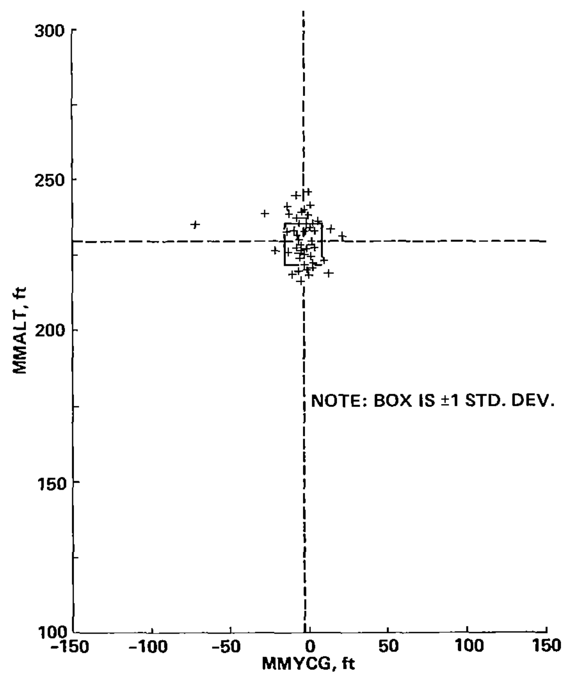


Figure 14.– ILS approach – lateral displacement and altitude at middle marker for FP HUD case.

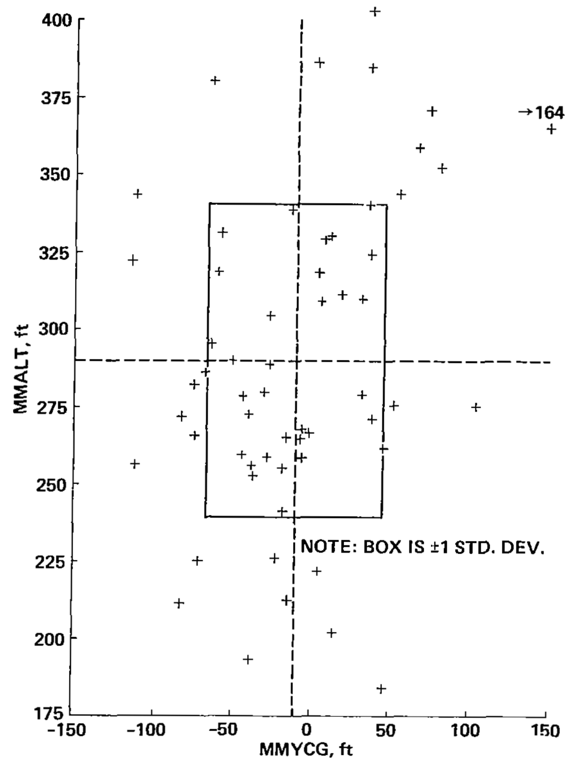


Figure 15.– Nonprecision approach – lateral displacement and altitude at middle marker for NO HUD case.

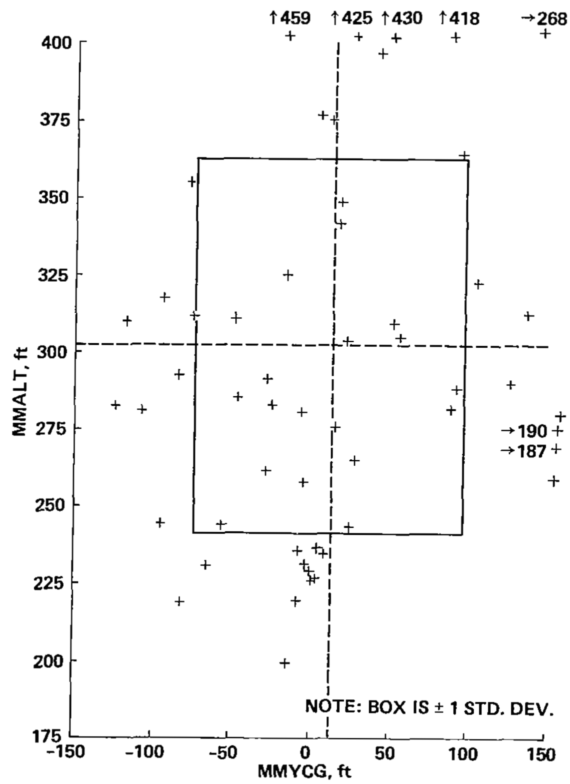


Figure 16.– Nonprecision approach – lateral displacement and altitude at middle marker for FD HUD case.

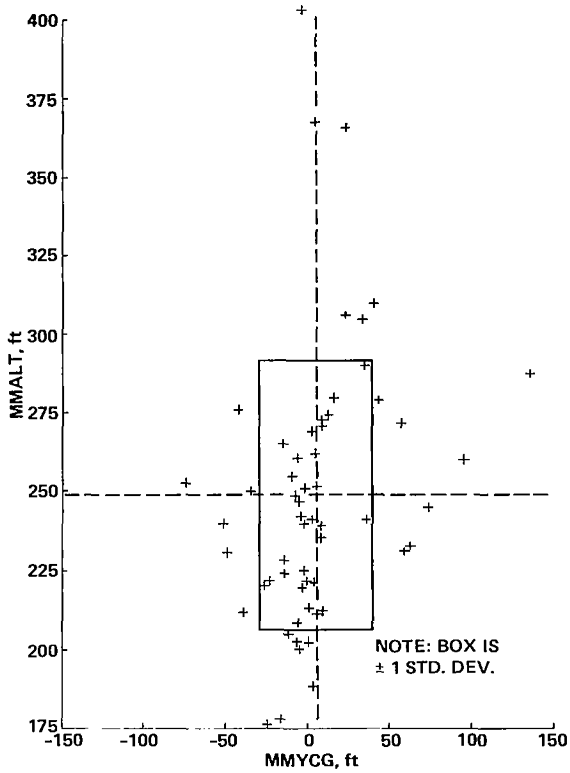


Figure 17.– Nonprecision approach – lateral displacement and altitude at middle marker for FP HUD case.

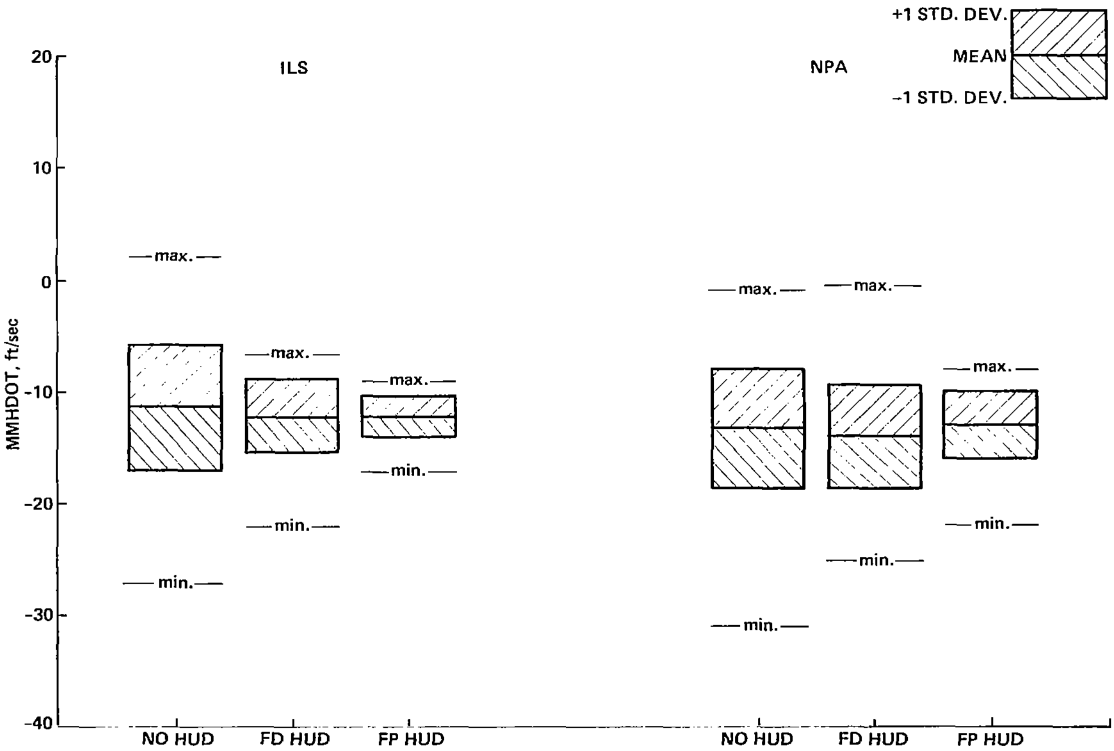


Figure 18.– Sink rate data at middle marker.

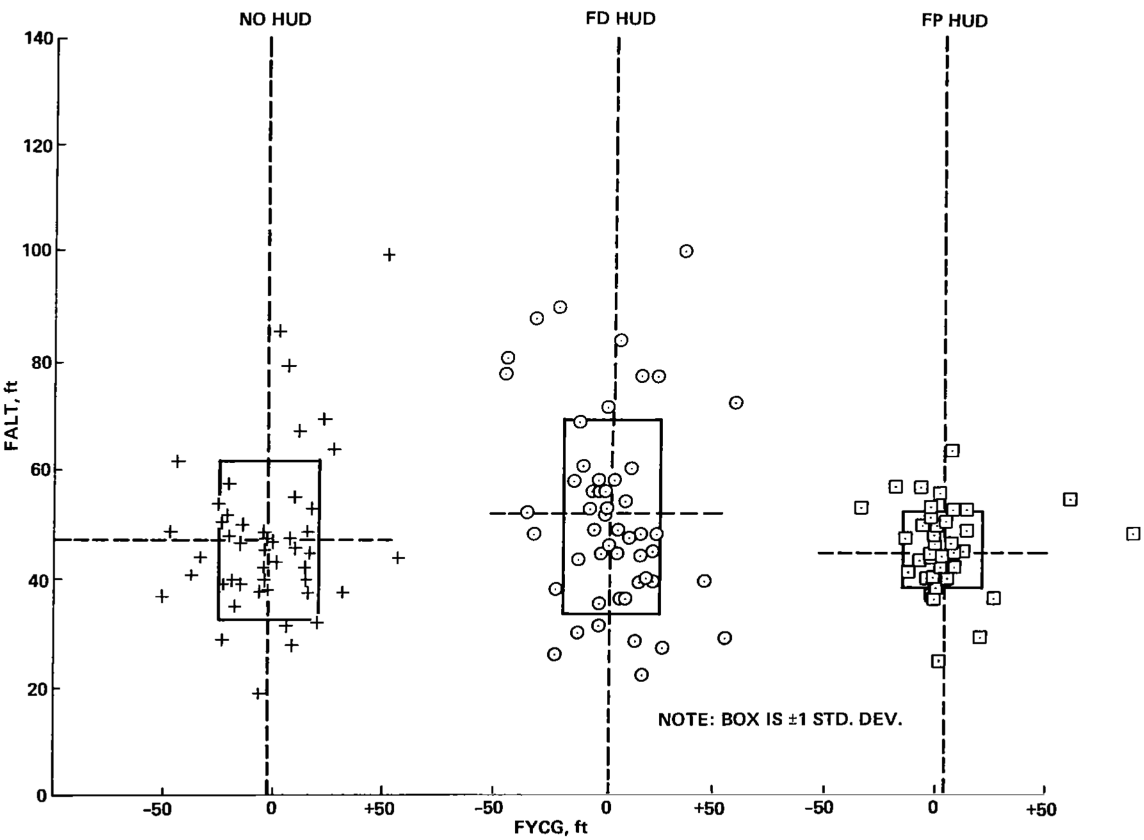


Figure 19.– ILS approach – lateral displacement and altitude at runway threshold.

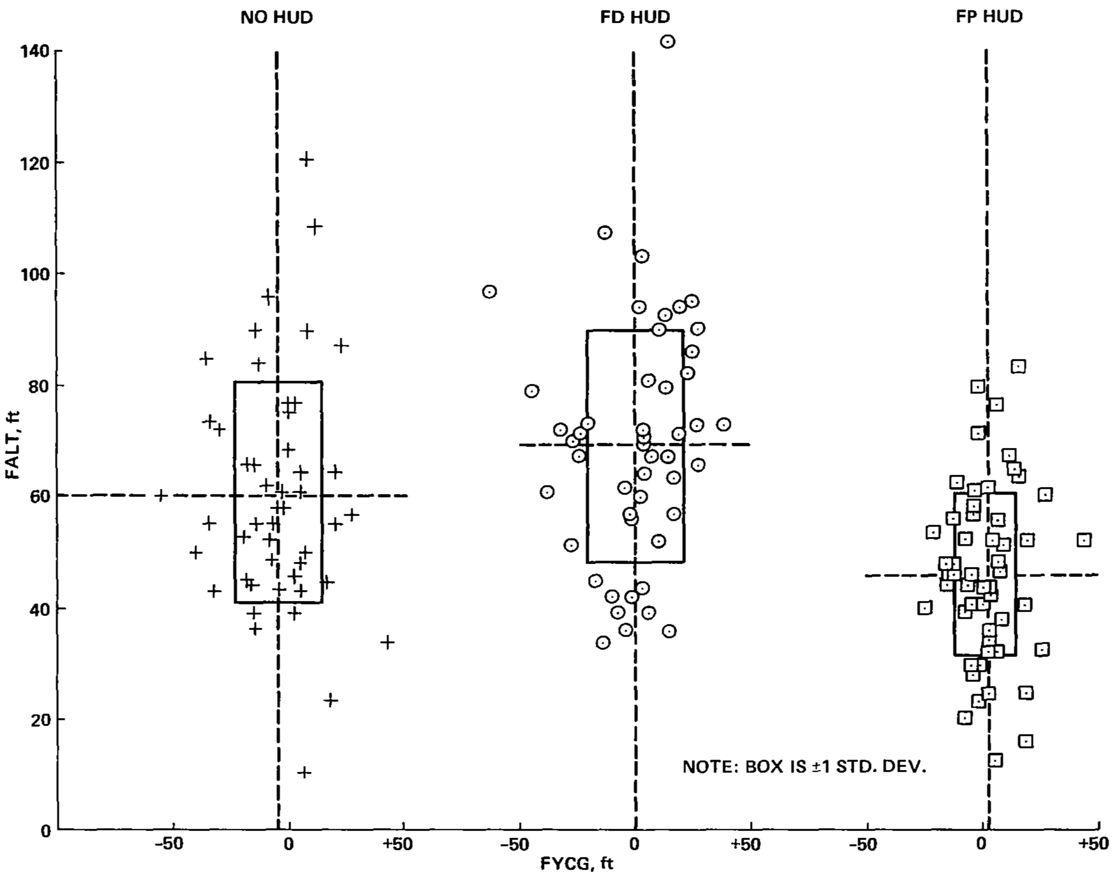


Figure 20.– Nonprecision approach – lateral displacement and altitude at runway threshold.

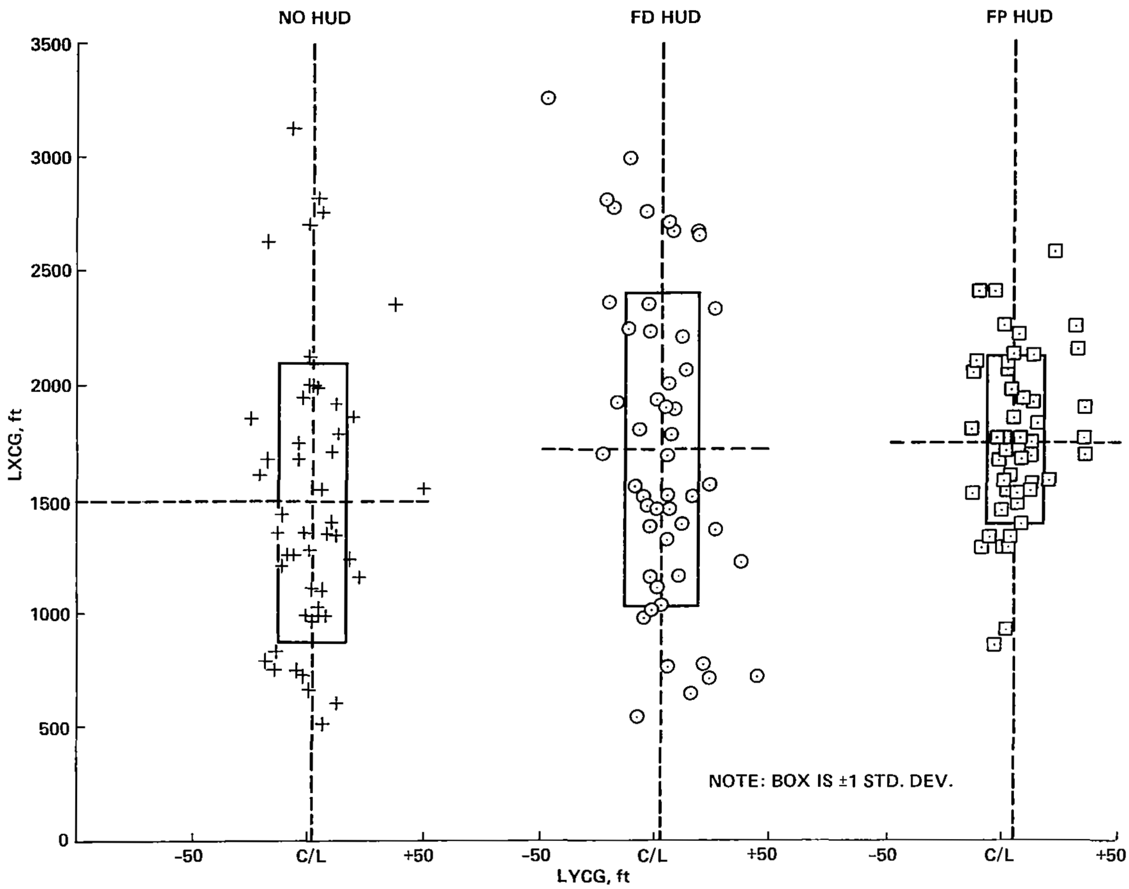


Figure 21.– ILS approach – landing footprint data.

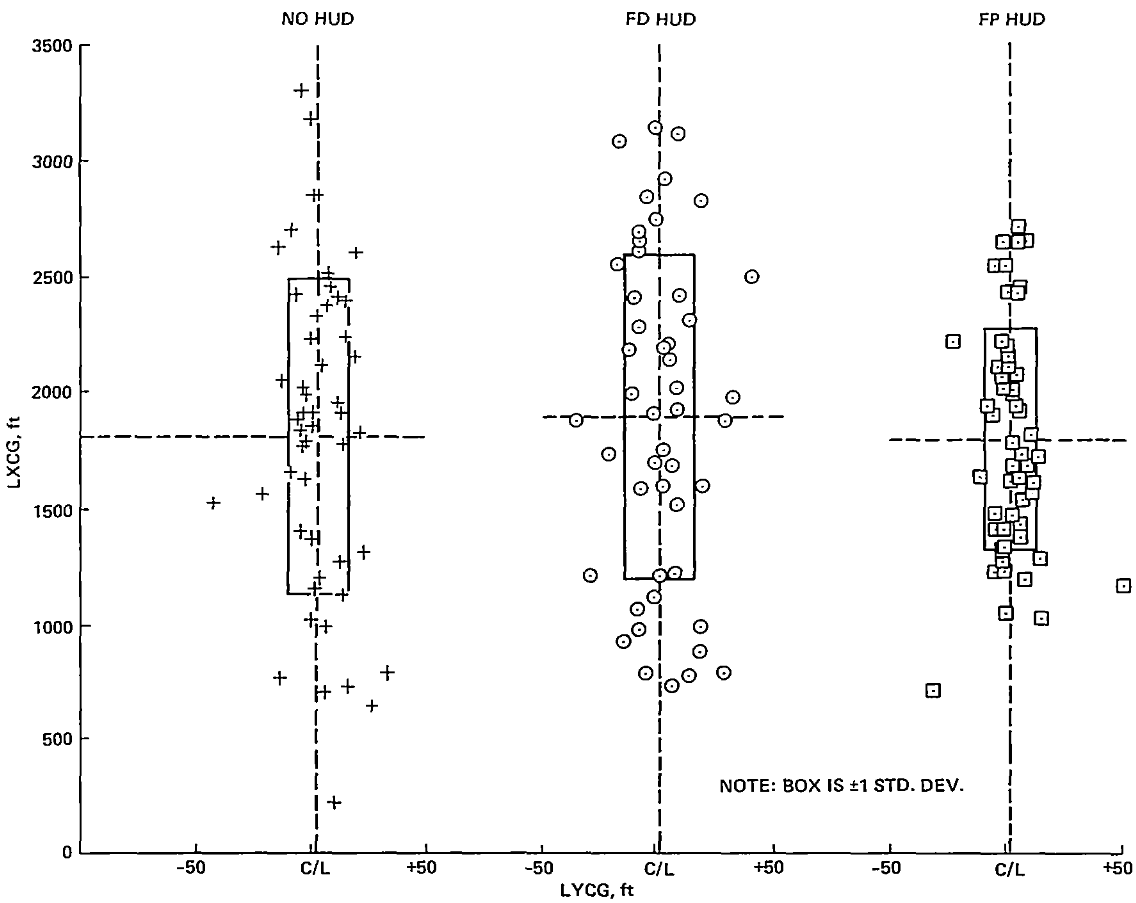


Figure 22.– Nonprecision approach – landing footprint data.

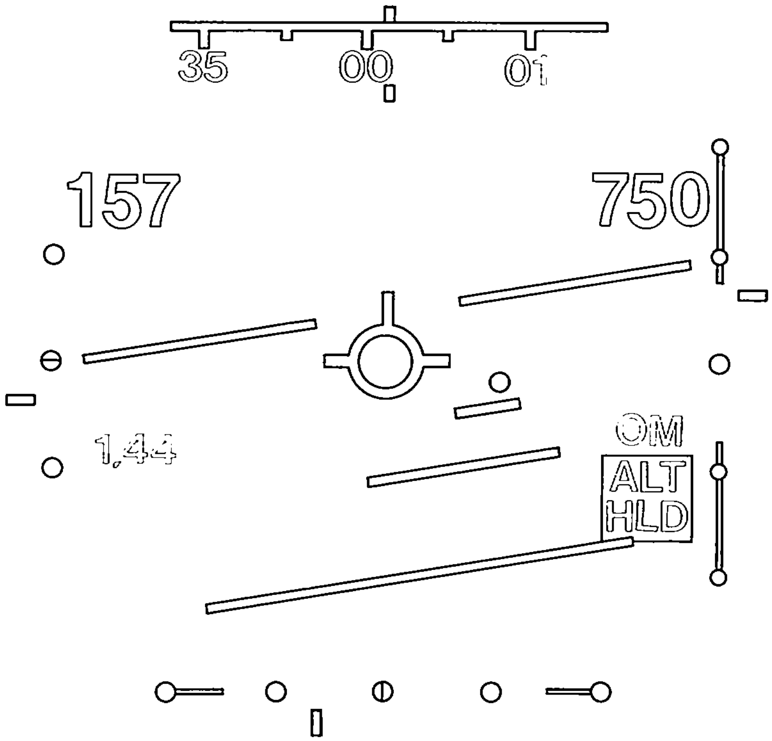


Figure 23.– Flight director HUD.

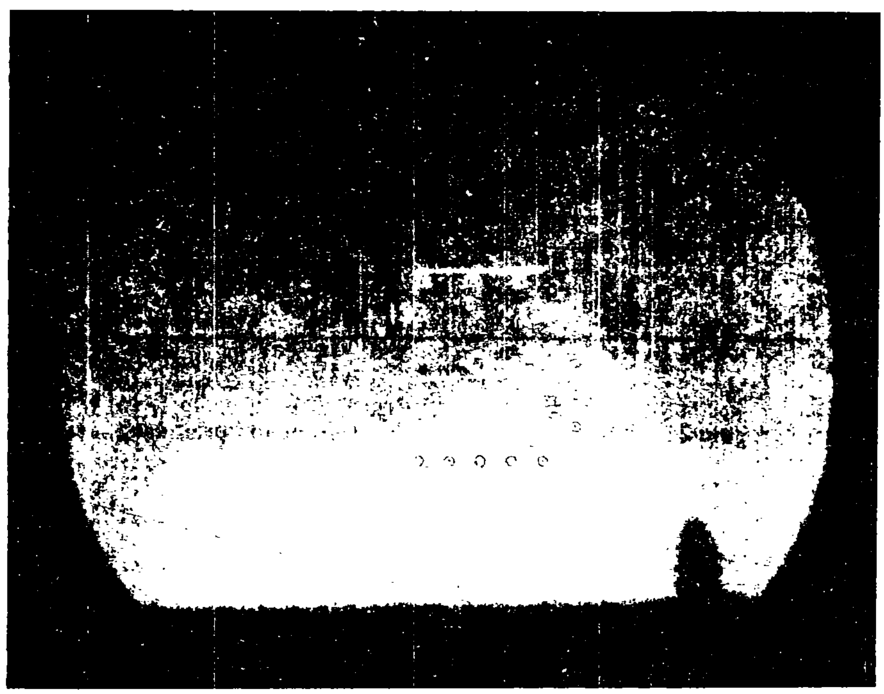


Figure 24.– Situation A.

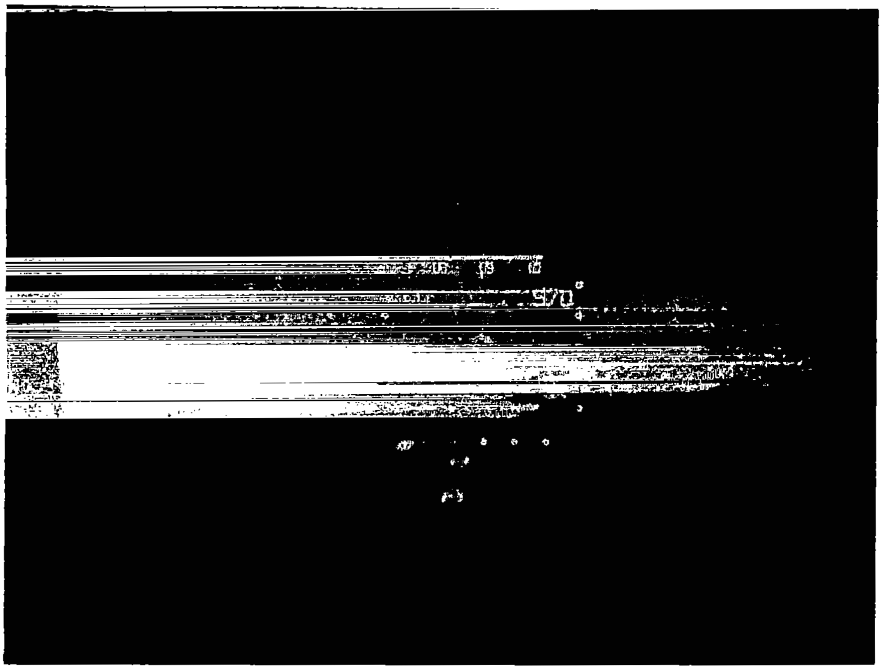


Figure 25.– Situation B.

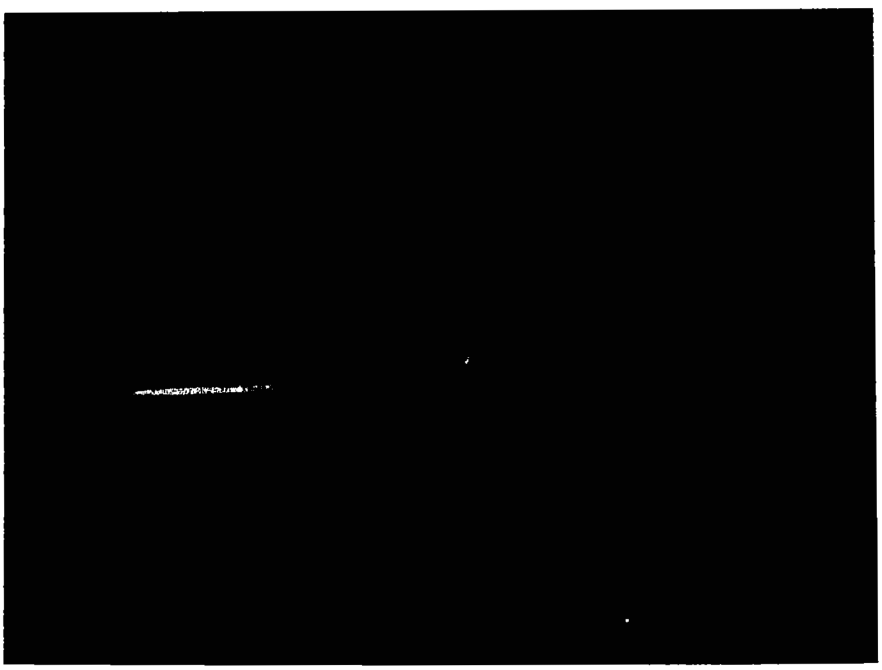


Figure 26.– Situation C.

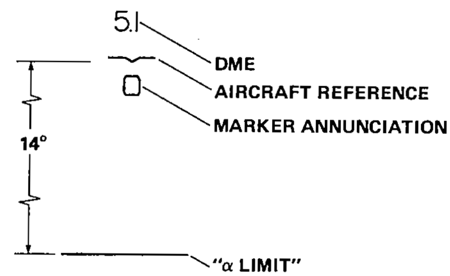


Figure 27.– Fixed display elements.

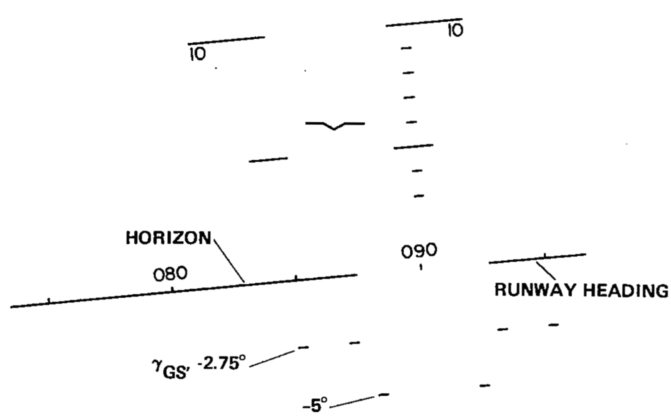


Figure 28.– Aircraft attitude presentation.

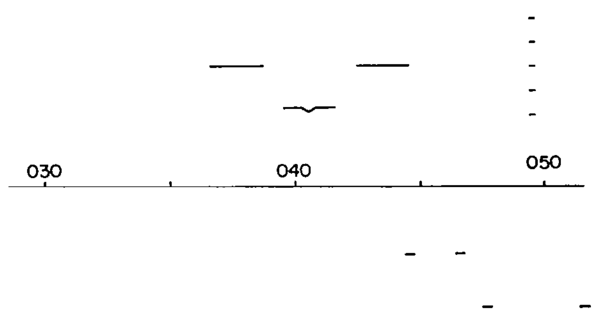


Figure 29.– Difference between aircraft and runway heading greater than 9°.

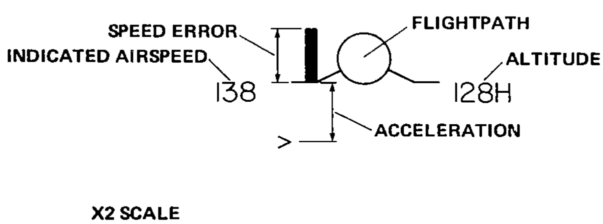


Figure 30.– Flightpath symbol and related elements.

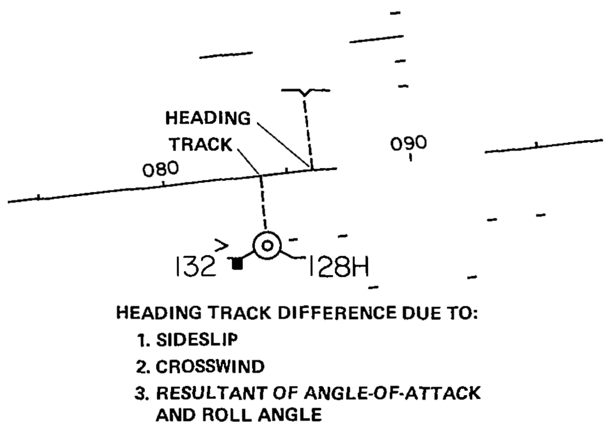


Figure 31.– Flightpath symbol and related elements shown in context of aircraft attitude.

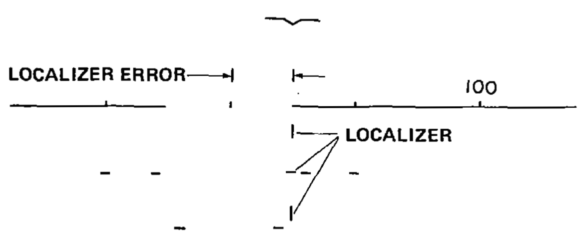


Figure 32.– Aircraft position relative to approach course.

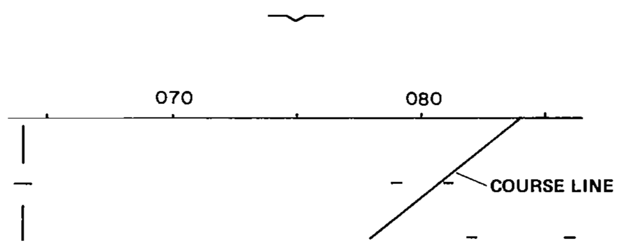


Figure 33.– Course-line symbol.

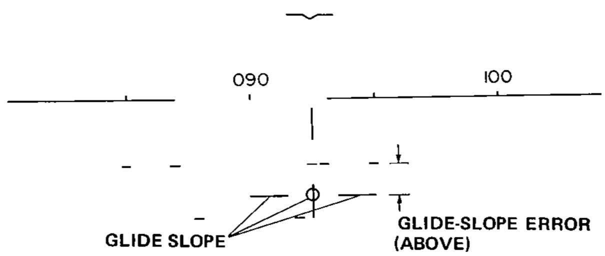


Figure 34.– ILS glide-slope error indications.

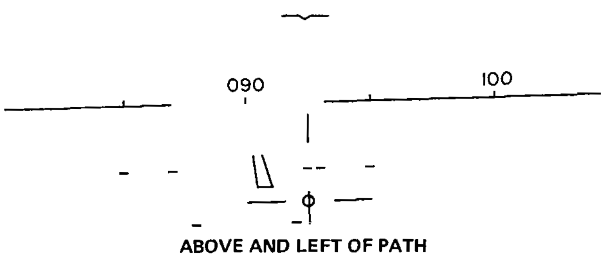


Figure 35.– Aircraft above and left of ILS.

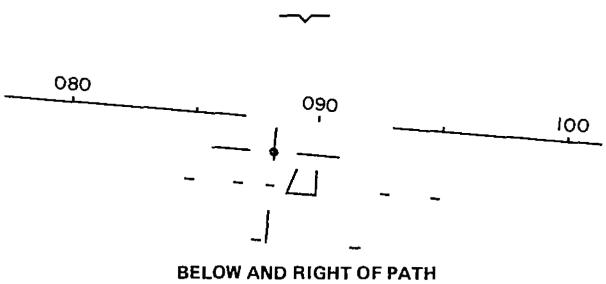


Figure 36.– Aircraft below and right of ILS.

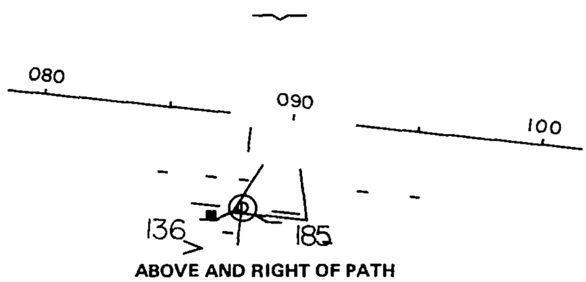


Figure 37.– Aircraft above and right of ILS.

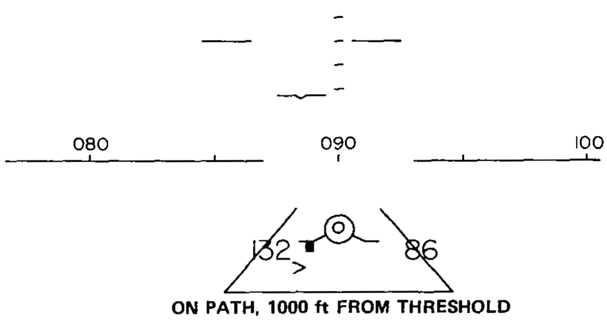


Figure 38.– Aircraft on path, 1000 ft from threshold.

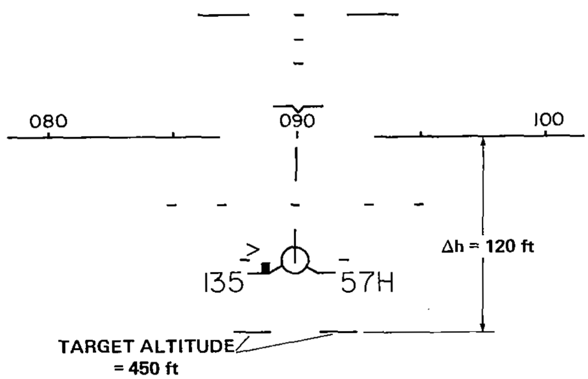


Figure 39.– Symbol for annunciating and capturing preselected target altitude.

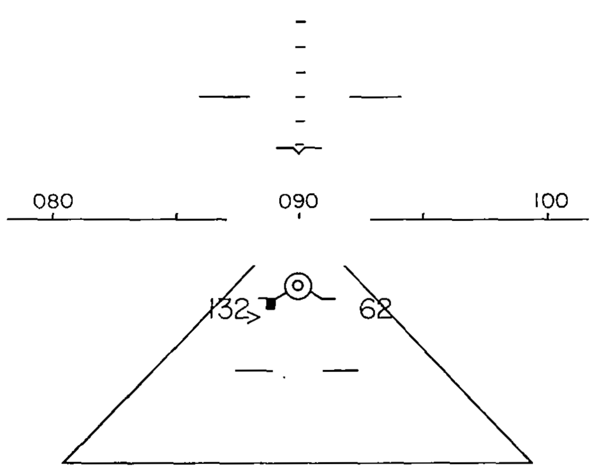


Figure 40.– Ground-proximity symbol rising as flare altitude is approached.

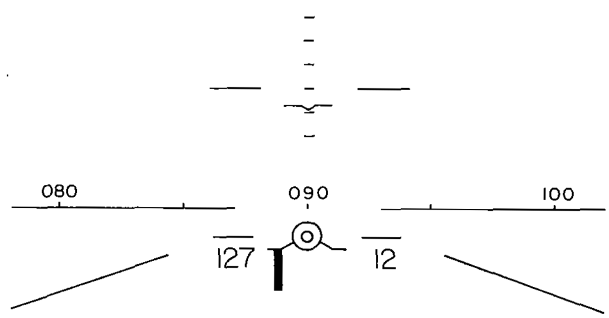
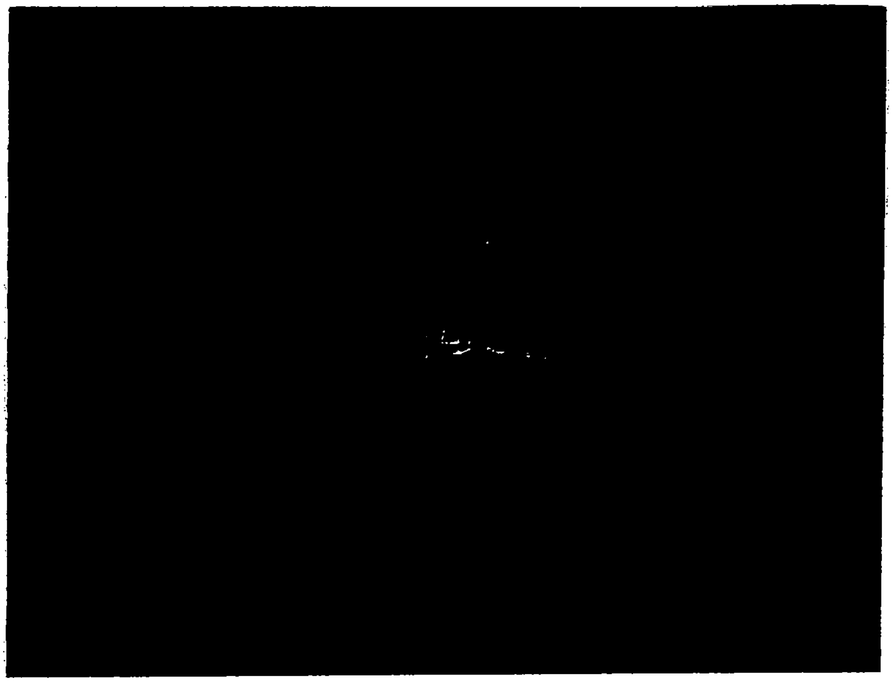
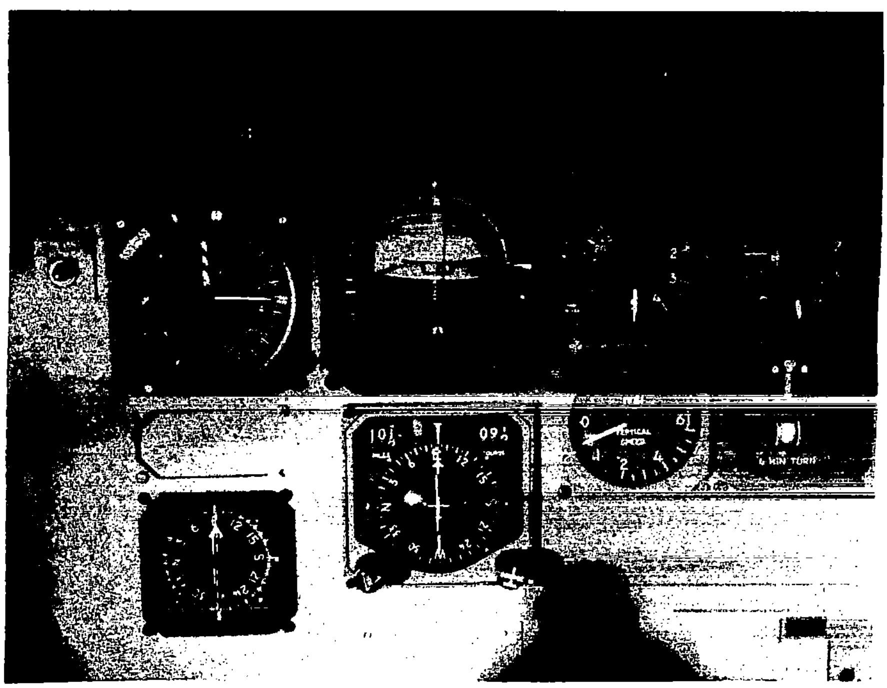


Figure 41.– Ground-proximity symbol shortly before touchdown.

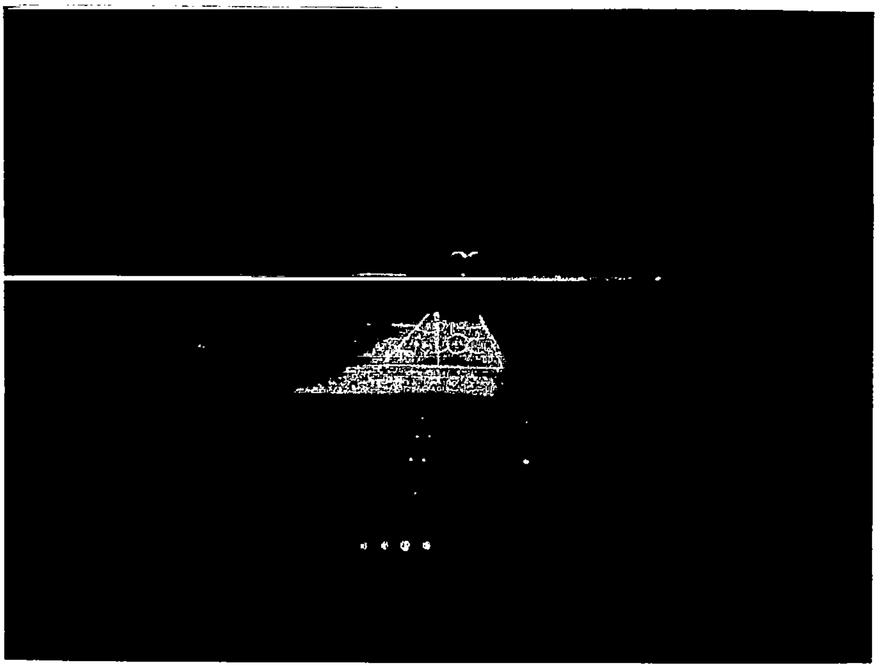


(a) Head-up presentation.

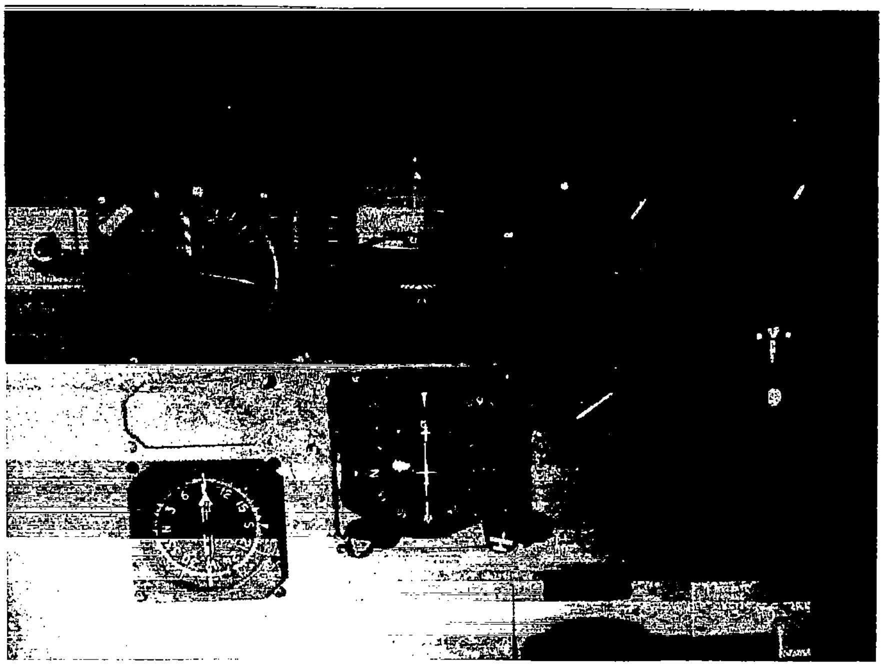


(b) Head-down presentation.

Figure 42.– Comparison of head-up and head-down information, aircraft on approach.

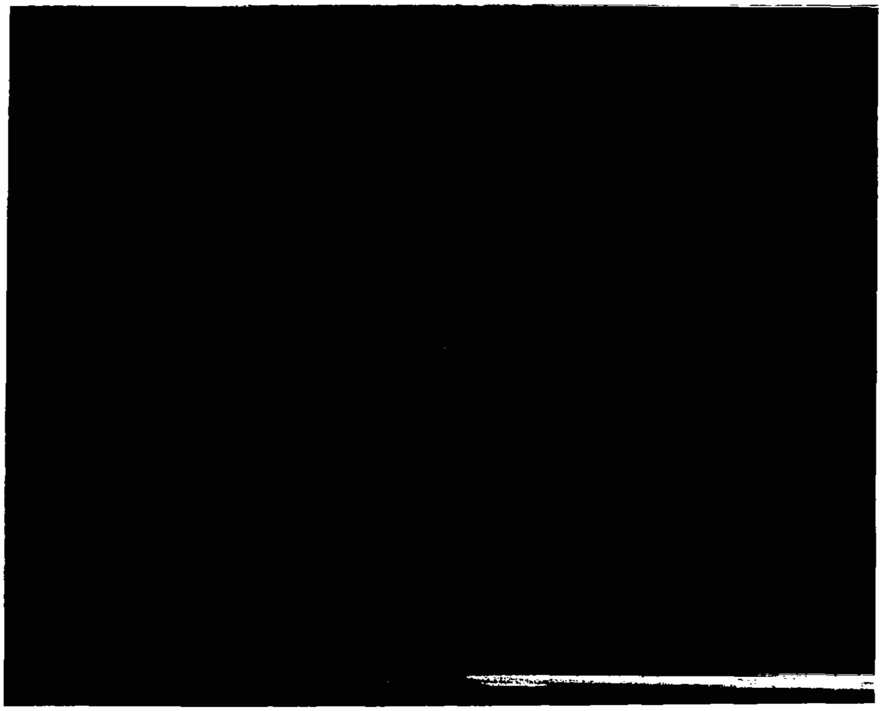


(a) Head-up presentation.

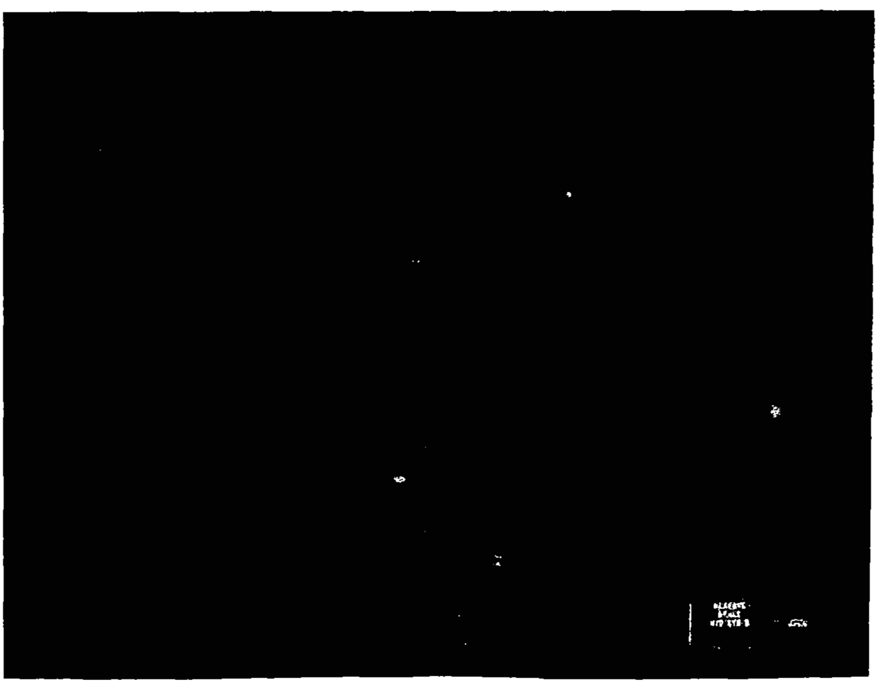


(b) Head-down presentation.

Figure 43.– Comparison of head-up and head-down information, aircraft approaching flare.



(a) Head-up presentation.



(b) Head-down presentation.

Figure 44.– Comparison of head-up and head-down information at touchdown.

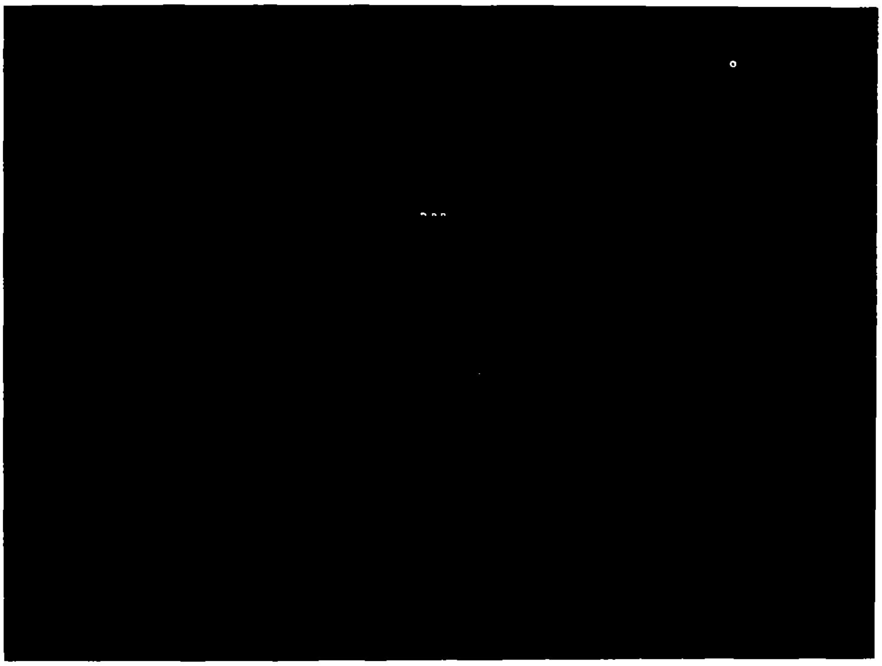


Figure 45.— Situation A.

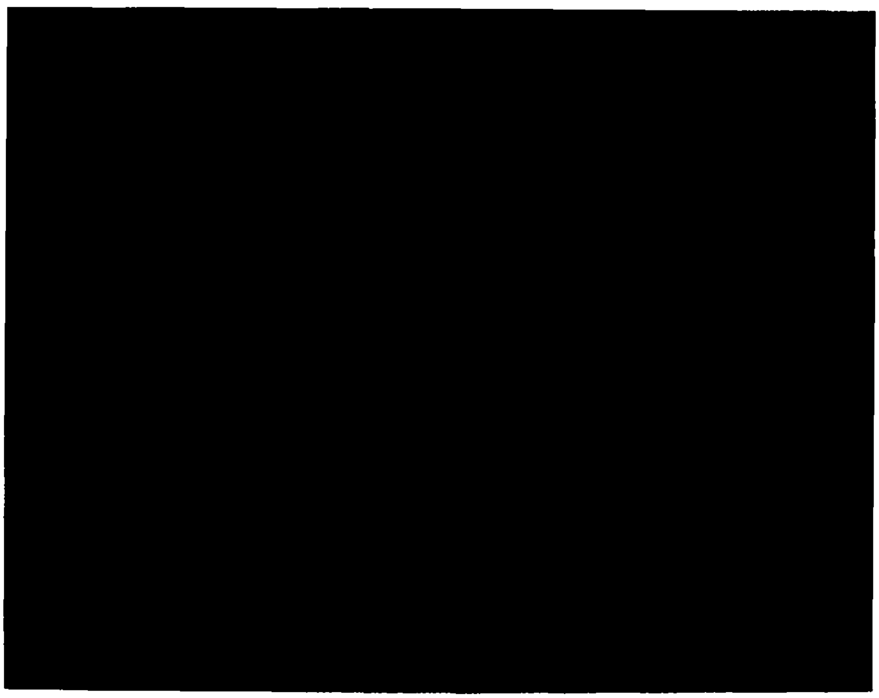


Figure 46.— Situation B.

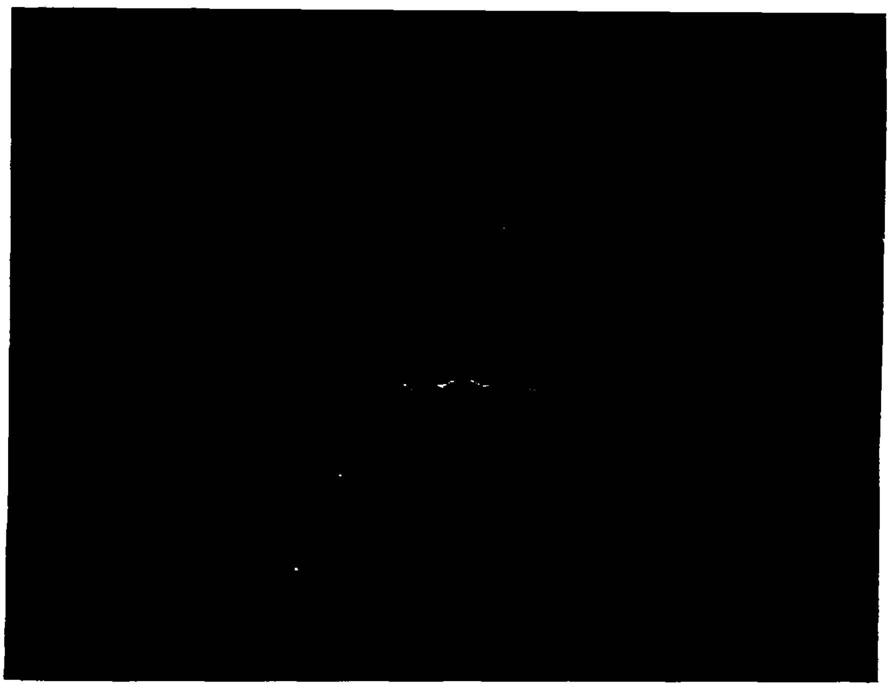


Figure 47.– Situation C.

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15. Supplementary Notes

*This Head-Up Display (HUD) report is number 16 in a series.

**Federal Aviation Administration, Moffett Field, California

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16. Abstract

The experiment reported here is the culmination of a series of studies conducted under a joint agreement between the Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA). The objectives of the overall program were to evaluate the advantages and disadvantages of head-up displays (HUDs) in commercial-jet-transport approach and landing operations.

In this experiment, ten airline captains currently qualified in the B-727 aircraft flew a series of instrument-landing system (ILS) and nonprecision approaches in a motion base simulator using both a flight-director HUD concept and a flightpath HUD concept as well as conventional head-down instruments under a variety of environmental and operational conditions to assess: (a) the potential benefits of these HUDs in airline operations; (b) problems which might be associated with their use; and (c) flight-crew training requirements and flight-crew operating procedures suitable for use with the HUDs. Results are presented in terms of objective simulator-based performance measures, subject-pilot-opinion and rating data, and observer data.

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