SRDS Report No. RD 68-9

AD 671892

FINAL REPORT

Phase I

Contract No. FA67WA-1700

Project No. 320-212-09N

PILOT FAILURE DETECTION PERFORMANCE WITH THREE LEVELS OF FAULT WARNING INFORMATION

February 1968

Prepared for

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
System Research & Development Service

by

THE BUNKER-RAMO CORPORATION
Canoga Park, California

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PILOT FAILURE DETECTION PERFORMANCE WITH THREE LEVELS OF FAULT WARNING INFORMATION

Prepared by

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This report has been prepared by the Bunker-Ramo Corporation for the System Research and Development Service, Federal Aviation Administration, under Contract No. FA67WA-1700. The contents of this report reflect the views of the contractor, who is responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policies of the FAA. This report does not constitute a standard, specification, or regulation.

THE BUNKER-RAMO CORPORATION
Canoga Park, California

FOREWORD

Contract FA67WA-1700 required a simulation program to determine essential cockpit display characteristics (fault warning, mode progress and flight director display elements) for Category III all-weather approach and landing operations. Contract FA67WA-1700 was a continuation of previous work conducted under Contract FA64WA-5143 which evaluated whole flight director systems. The purpose of these studies was to predict various elements of pilot performance and preference in an envisioned Category III environment so that quantitiative, public data will be available for consideration by procedural and hardware decision makers long before Category III is operational.

The study being reported herein was directed toward fault-warning and mode-progress display, and was conducted between 20 March 1967 and 26 April 1967 as the first of a series of four studies under Contract FA67WA-1700. Two of the remaining three studies on this contract have been planned to further examine fault-warning displays and procedures. Since previous work evaluated whole flight director systems, one study has been planned to evaluate rising runway and expanded localizer features found in modern flight director systems. All four studies are being reported separately in order to facilitate the dissemination of the results.

The conduct of this study required the collective talents of many individuals. Lt. Colonel James R. Nelson, FAA SRDS, served as Contract Technical Monitor. Mr. R. D. Monroe was the Bunker-Ramo Corporation Program Manager. Mr. L. S. Griffin, Mr. D. G. Findley, and Mr. J. L. Streeper performed simulator modification and maintenance. Mr. J. E. Brown, Mr. W. H. Haase, Mrs. G. Y. Sager and Mrs. F. D. Wuestenberg, respectively, conducted data reduction and analysis and assisted in the preparation of this report.

ABSTRACT

The reported study was the first of a series of four studies to examine the feasibility of display and control concepts for commercial subsonic jet transport all-weather (Category III) approach and landing. The study was addressed primarily to fault warning. Pilot detection of autopilot and display system failures was examined with three levels of fault warning display information. Display failure detection and pilot decisions were additionally examined as a function of pilot task load, manual in one axis or automatic. A total of 702 simulated ILS approaches were flown by 18 commercial airline pilots in a Boeing 707-720B research simulator. Pilot/system performance and preference data indicated that the full annunciator display system tested was required in order to attain the best display failure and passive autopilot control failure detection. The failure warning utility of mode progress information below 200 feet of altitude on the approach was found to be inadequate. The data suggested that: (1) mode progress information be de-emphasized, (2) manual control of just one axis causes pilot fault-detection performance to deteriorate compared to monitoring full autopilot operation, (3) second failures following first failures which put the pilot into split-axis control were frequently missed, and (4) there is not enough time from 100 feet to landing to allow any complicated land-or-go-around decision process. Some general characteristics of fault warning displays were discussed.

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INTRODUCTION

If a failure of an airborne sub-system occurs, something or someone (1) must detect the fact that the failure has happened, and (2) process the information in order to (3) take corrective action. Who or what should detect the failure, process the information and take corrective action? The pilot is responsible for the safety of flight, life and property; yet, for some potentially catastrophic failures such as autopilot hardovers, monitor systems can correct the danger almost before the pilot can sense the problem. Conceptually, monitor systems seem to be an ideal solution to the fault detection and warning problem. There are, however, some problems with monitor systems that must be mentioned.

Monitor problem. First, there is the problem of setting error criteria that will detect real system malfunction. Typically, thresholds of allowable error are set. The problem with the threshold approach is that what may be a real error in one case, may be normal operation in another case. If the thresholds are set for the first case, a false alarm occurs in the second. Stated another way, as the error tolerance is decreased in order to increase the probability of detecting system malfunction, the probability that the monitor will false alarm is also increased.

On the surface, it seems conservative to assume that stringent procedures will be followed, and that all "alarms" will be treated as real failures. The realities of human behavior, however, suggest very strongly that if a system false alarms a great deal of the time, the urgency of that warning or action will be attenuated. If the monitor system takes action such as disconnecting an autopilot in order to circumvent human foibles, then a false alarm places the vehicle in manual control. Category III-C manual control at low altitudes may be hazardous. A false alarm, therefore, could place the vehicle in unnecessary jeopardy.

The second problem with monitors has to do with the inherent reliability of monitoring devices. The reliability of the monitoring device must be better than the system it has to monitor. High reliability is suggestive of simplicity; yet, to meet all of the demands of assessing error of the entire system during an entire approach and landing monitors may become complex and expensive.

A dilemma. The fault warning is at present in a state of dilemma. On one hand, monitor systems can be fast, but they have limitations. On the other hand, pilots are comparatively slow acting, but they have extensive memory and can apply much experience to the situation. The solution to this dilemma has to lie in the successful integration (interface) of fault warning equipment and the human pilot.

Approach to the Problem

It is assumed that the equipment should serve the pilot because the pilot is responsible. Wherever possible, the pilot should assess the situation and make decisions. Monitoring equipment should provide the pilot with the information he needs to make good decisions. Where it can be shown that the pilot cannot perform failure detection and make decisions with required accuracy in the time allowed, the equipment will have to assume those critical functions.

The performance limits for Category III-C landings do not allow a great deal of margin for error. Human performance guesses are not precise enough to allow system or procedural design based upon private and unmeasured experience. Precise human fault detection performance measurement within the context of an aircraft instrument approach and landing is needed for the intelligent allocation of function between the pilot and the monitoring systems.

The approach to the problem taken in this experiment was simply to document existing pilot capabilities of detecting and taking action on certain kinds of failures. On the basis of measured pilot performance, system and procedural criteria may be specified. Given human performance expectations, monitoring systems will have to overcome any inherent weakness of the pilot. Hardware requirements may then be based upon what is really needed rather than what would be elegant.

The Study

This study was designed as a first inquiry into how much fault warning information a pilot really needs to detect certain kinds of autopilot and display system failures. The fundamental hypothesis of the approach was that pilot performance should significantly improve as more information is added to his fault warning display. That point at which performance did not significantly improve would represent the minimum amount of information that the pilot needs unless actual measured performance still indicated a potential hazard.

Levels of information. Three levels of fault warning information were constructed. The first level served as experimental control. All first level failures were tested with no monitoring system other than the 28 volt flag logic on the pilot's flight director system and radar altimeter instrument. This level documented basic pilot fault detection capability with minimal monitor system assistance.

The second level of information added a monitor system that illuminated a master caution light. The caution light served only as an alerting cue. One might argue that a monitor system would certainly be able to annunciate a specific failure just as easily as illuminating a caution light. Even though this argument may be valid, the pilot's display panel is premium "real estate." If the pilot can quickly and easily detect a failure once he is alerted to the fact that one has occurred, then additional panel clutter will have been avoided. Since minimum requirements were the subject of the study, this level of failure warning information was examined.

At this master caution level of information, a second light could differentiate between (1) flag type failures and (2) autopilot or display failures that do not cause flags to appear. The utility of such a "Flag" light was also examined within the master caution level of information.

A third level of monitor information was added to the caution light. This level allowed the annunciation of system problems so that the pilot was told what was wrong. In this level the failure detection was done for the pilot (assuming that there were no problems in the presentation of information on the annunciator panel). His job was to correct the situation.

Monitor operation. Control and display system failures were introduced to exercise the three levels of fault warning information. When the monitor was operating during the second and third levels of information, a perfect monitor was assumed. The monitor was assumed to take 5 seconds to integrate enough error during control system failures to trigger the caution and/or annunciator lights. Display system failures were immediately detected by the monitor.

Pilot task load. Previous work (Ref. 4) indicated that failures that were introduced when the pilot was in manual control were hazardous because the failures were not always detected. The amount of failure annunciation information needed by the pilot certainly could be a function of his task load. In this study, pilot task load was varied by asking the pilots to continue in split-axis control (manual in one axis, automatic in the remaining axes) after experiencing a control failure. Pilot performance during display failures was then measured as a function of both the amount of failure annunciation information available and the pilot task load.

Rollout performance. In previous studies (Ref. 4) the approach profile terminated at touchdown. For the present study the simulator was modified to include a simulation of rollout to 60 knots in order to gather baseline rollout performance data. Pilots were asked to rollout using only the horizontal situation indicator raw heading and localizer information to provide these preliminary data for investigating possible display requirements for rollout.

Fault warning information in mode progress displays. Mode progress displays are specified for Category III operations so that the pilot will be informed of the status of his automatic equipment. It is assumed that the pilot will watch mode progress and will notice when mode sequencing does not take place at the proper time. Mode progress displays may have some fault warning utility at the outer marker because there is plenty of time to take remedial action. But, is there enough time at 50 feet for the pilot to notice that the flare mode has or has not engaged? If he does notice non-engagement, does he have enough time to do anything about it? Some systems under development seem to assume that there is enough time for the pilot to take action because they place mode progress displays in prime "real estate" right next to the ADI.

The need for mode progress displays is not being questioned. What is being questioned is the intrinsic failure alerting properties of mode progress information. If mode progress displays can be used only when there is plenty of time, should these displays be placed in an area close to the ADI where the highest priority information is needed? To test the intrinsic fault warning value of mode progress displays, the autopilot flare mode engagement was failed at 50 feet. The only indication of mode non-engagement was the non-illumination of the flare mode annunciator. No other fault warning information was present during these failures.

Effect of shearwinds upon touchdown. Finally, the pilots were requested to continue to touchdown unless a second failure disabled their display in an axis in which an autopilot failure had occurred, thus requiring them to fly that axis manually. The experiment was designed so that touchdowns occurred during three shearwind conditions: (1) tailwind shear, (2) lateral shear, and (3) a combination of tailwind and lateral shear. The effect of these winds upon touchdown was documented.

When examining the data of this experiment, the reader should remember one important point: Each pilot flew thirty-nine approaches for record. Very early in the experiment the subject pilots must have realized that failures were going to occur on every approach. Even though the pilots were constantly looking for failures, performance differences with the various monitor modes were marked.

METHOD

Summary

Three levels of failure warning were compared (see Table M-1). The first level was nothing more than normal instrument flags. The second level assumed a monitor that turned-on a master caution light. The third level was an elaborate system composed of instrument flags, master caution light, and an annunciator panel.

TABLE M-1

STUDY VARIABLES

- Amount of failure warning information
  - No monitor, instrument flags only
  - Master caution + flags
  - Annunciator + master caution + flags
- Type of failure introduced between 450 and 50 feet of altitude
  - Autopilot
    - Passive (fail dead)
    - Softover .25 degrees/second
    - Flare mode engagement
  - Display failures during automatic and split axes control
    - ADI flags
    - HSI flags
    - Radar Altimeter flags
    - Vertical gyro unreliable failure

18 pilots flew 39 approaches for record, totaling 702 recorded approaches which started 12 n.m. out on localizer course.

Two failures per approach were given during 432 of the 702 approaches in this study. Study II, conducted in the STIR facility, revealed that pilots frequently missed the second failure when the first failure put them into split-axis control. The second failure was inserted no sooner than 20 seconds after the first. When the second failure occurred, the pilot was required to make a "land or go-around decision." If the display failure affected the information he was using to manually fly the aircraft, he was required to go-around.

The level of monitor system required was evaluated by counting the number of failures that the pilots did not detect (no detection), the number of incorrect responses, and the number of incorrect decisions to land (manually flying failed information). Other measures were longitudinal range used, lateral displacement, pitch and roll attitude, heading error, lateral drift, indicated airspeed, vertical velocity and pilot response time.

The remaining portions of the method section describe in greater detail how the study was conducted.

Subject Pilots

Four subject pilots participated in preliminary flying for the purpose of de-bugging the experimental procedures, the measurement system, the simulation and the questionnaire; their assistance was invaluable. Eighteen subject pilots flew for record. The average pilot was a commercial Captain (or equivalent), 47 years old, with 16,794 hours of total flight time, 10,345 hours of transport aircraft time, 2,922 hours of jet time, 1,494 hours of instrument time, and 194 hours of simulator time. The pilots represented American Airlines, Continental Airlines, Eastern Airlines, Federal Aviation Administration, Flying Tiger Line, Pan American Airways, Trans World Airlines, United Air Lines, and the United States Air Force.

Apparatus

The study was conducted using the FAA/B-RC Simulator for Transport Instrumentation Research (STIR). STIR is a fixed base, aerodynamic six-degree-of-freedom device that simulates a Boeing 707-720B aircraft. In order to achieve the necessary performance accuracy, the simulator is limited to the low-speed (170 knts.), low-altitude (2,500 ft.), small-angle pertubation (±10 deg.) approach-and-landing flight regime. An ILS final approach course similar to Los Angeles International Airport including glideslope, localizer, and marker beacons is simulated.

The simulator system can be functionally diagrammed into four functional groups shown in Figure M-1. The full system capability within each of the four basic groups (analog computation, program control console, measurement equipment, and control cabin) has been documented elsewhere (Ref. 4). For the purpose of understanding the present study, it is important to specify the control cabin configuration.

Control Cabin. The control cabin exterior is a section of a production 707-720B aircraft with frosted windows to eliminate visual cues. The Captain and First Officer crew stations are mechanized with active controls and instruments as shown in Figure M-2.

Controls. All of the normal aerodynamic surface controls are simulated (operational), and the "feel" is identical to the normal 707-720B aircraft within the performance limitations. Other operational controls include the toe brakes for differential braking, landing gear, spoilers and engine control including thrust reversal. Special controls shown in Figure M-2 are (1) a split-axes autopilot selector, (2) a pushbutton flight director/autopilot mode selector, (3) an autothrottle speed selector/engage panel, and (4) several special-purpose switches. The autopilot is a simulated Bendix PB-20D PALS with added split-axes capability. The autopilot derives its information from sensors which feed into the First Officer's displays

Displays. Standard flight instruments and experimental fault warning/mode progress displays are mounted on the instrument panel as shown in Figure M-2. The standard instruments operate normally. The input signals and flags can be affected by failure insertions. The Captain's flight director system is a Lear-Siegler 4058G (Figure M-3) which was independent of the First Officer's flight director system. Signal flow diagrams appear in Figures M-4 and M-5.

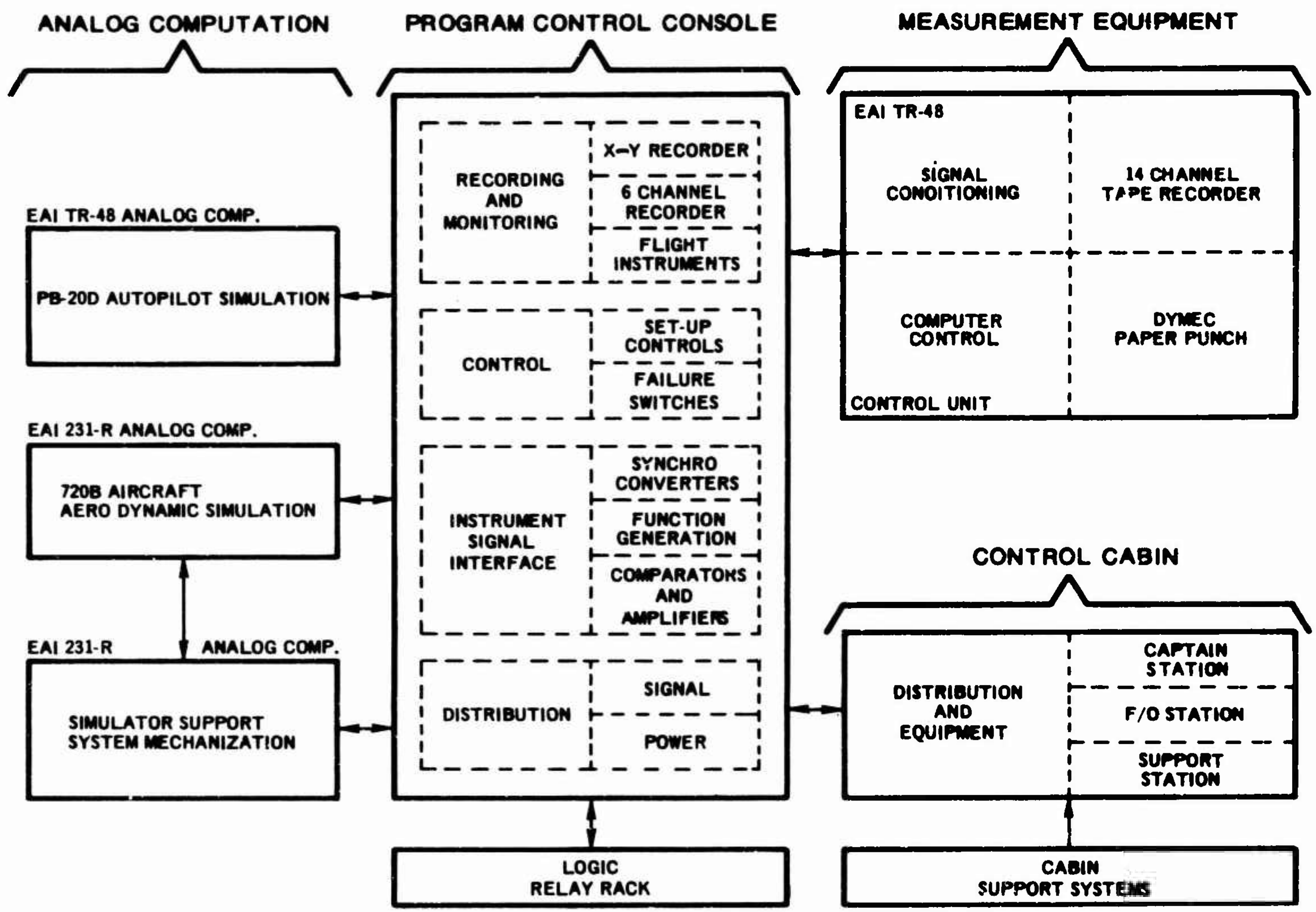

FIGURE M-1 - Simulator Block Diagram

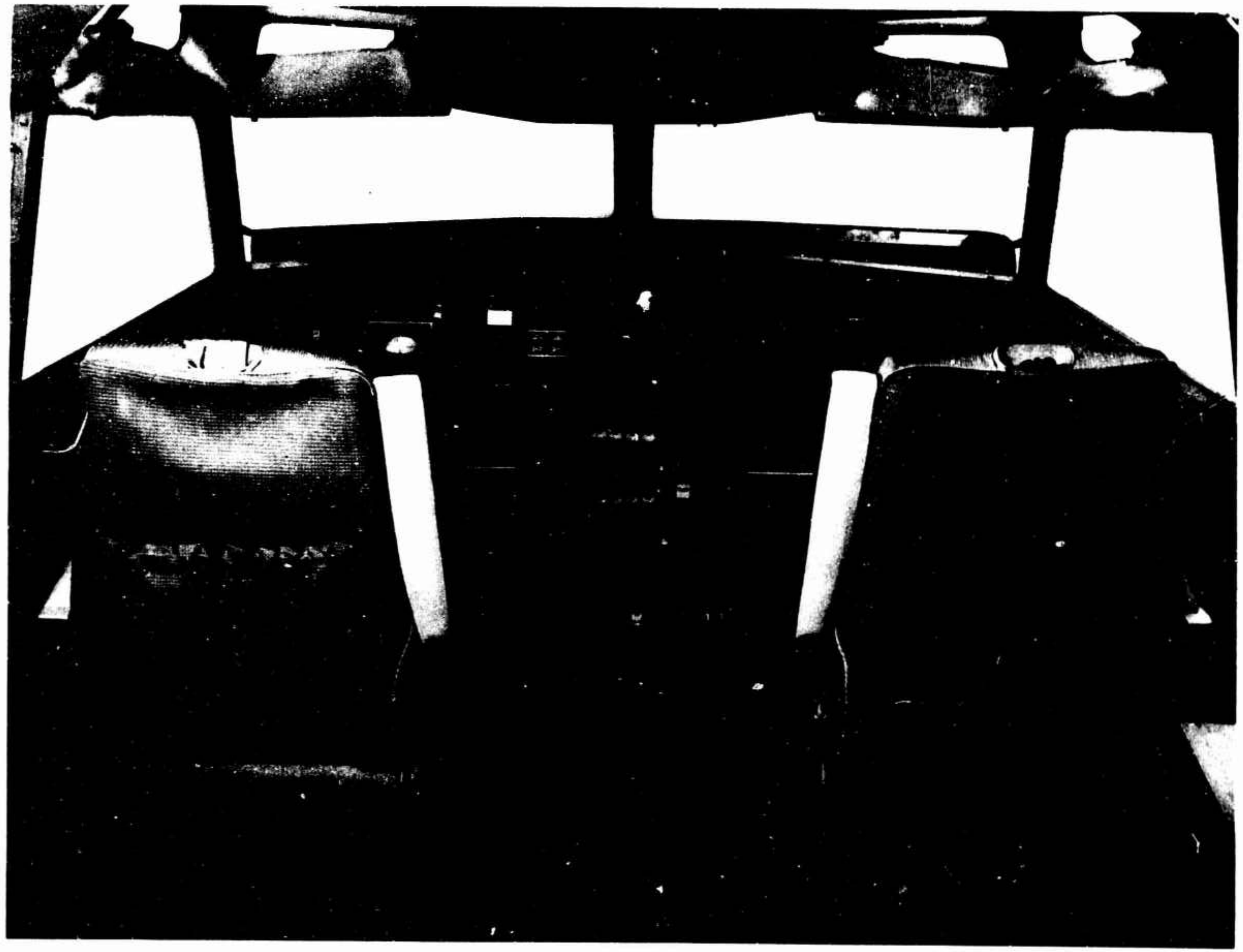

FIGURE M-2 - Control Cabin

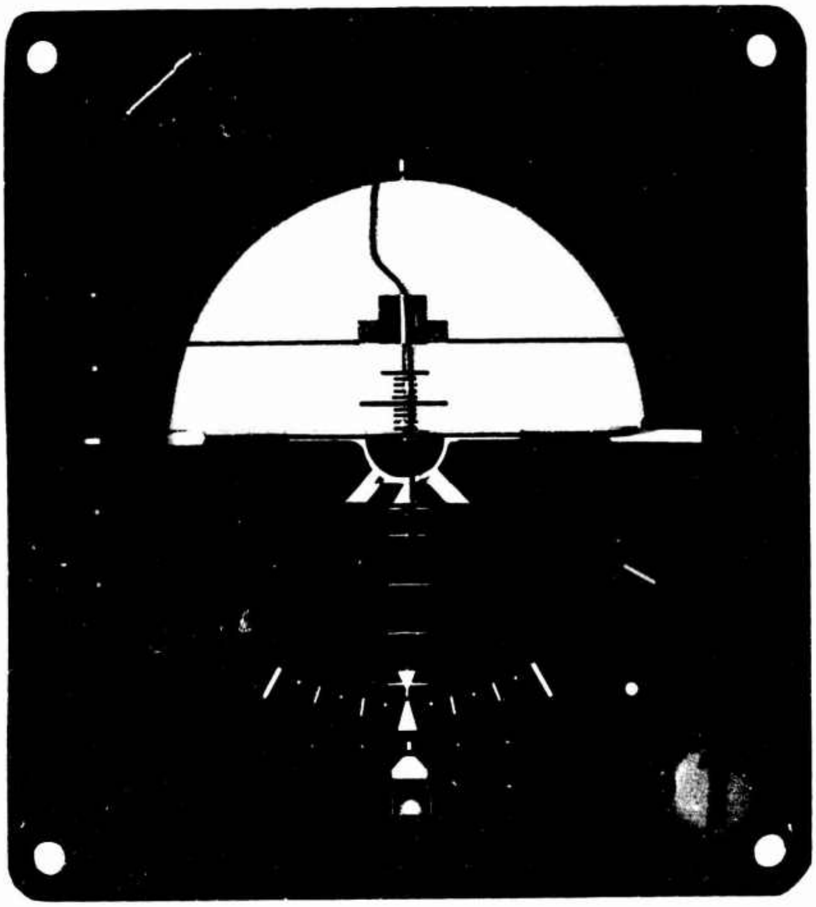

FIGURE M-3 - Lear Siegler 4058

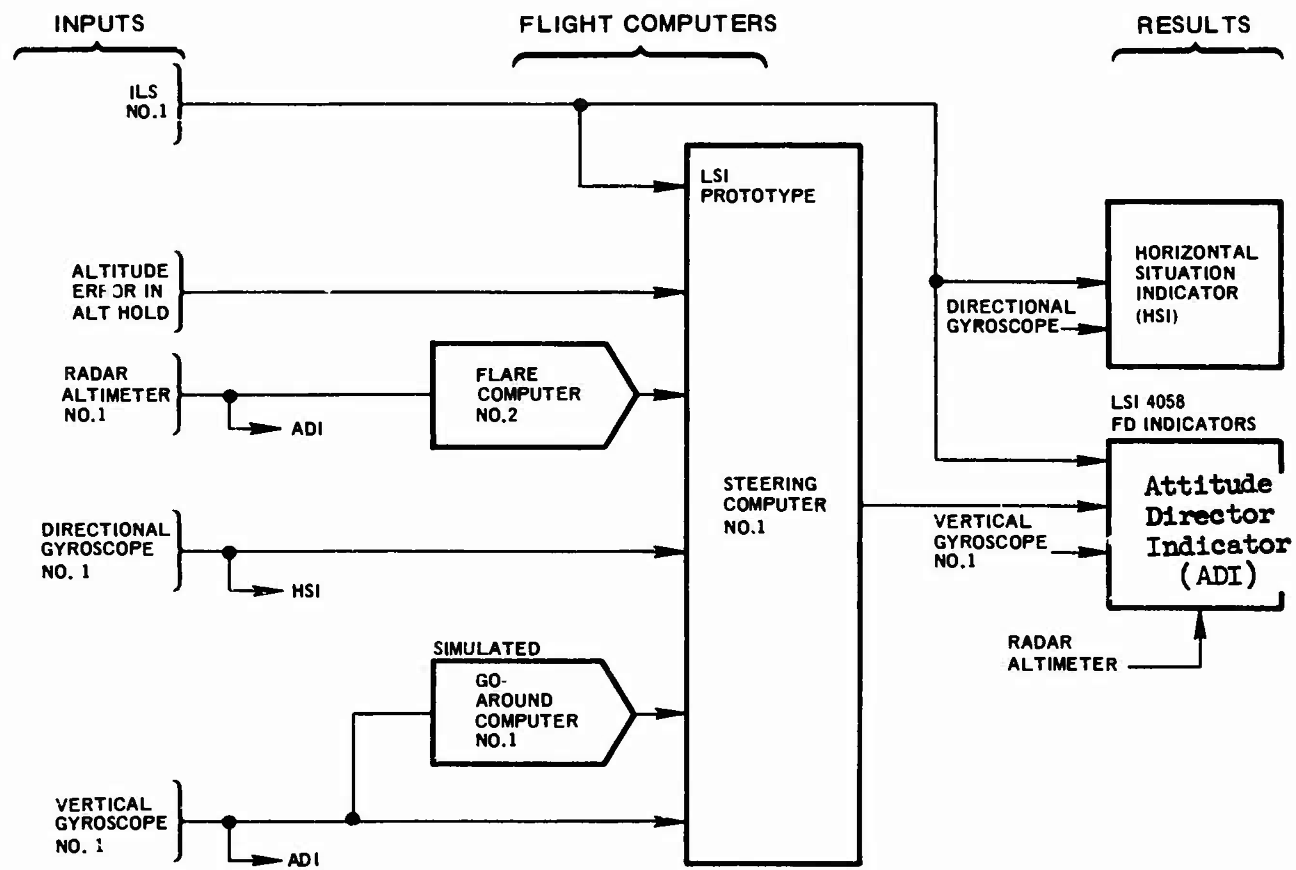

FIGURE M-4 - Logic Flow for Captain's Side

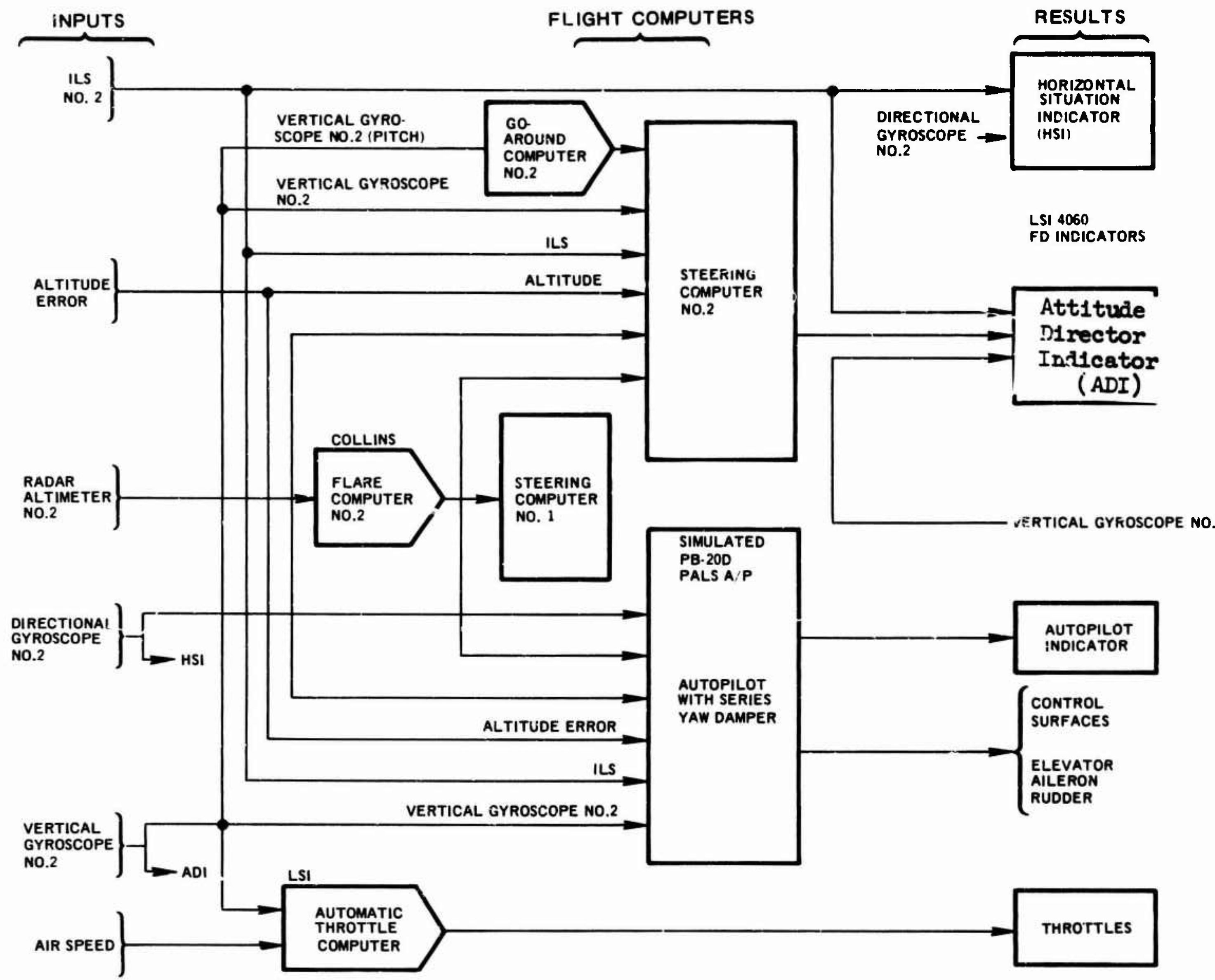

FIGURE M-5 - Logic Flow for First Officer's Side

The fault warning/mode progress displays consisted of three panels. In addition, a series of four green lights indicated the engaged automatic control equipment. The operation of the individual indicators follows:

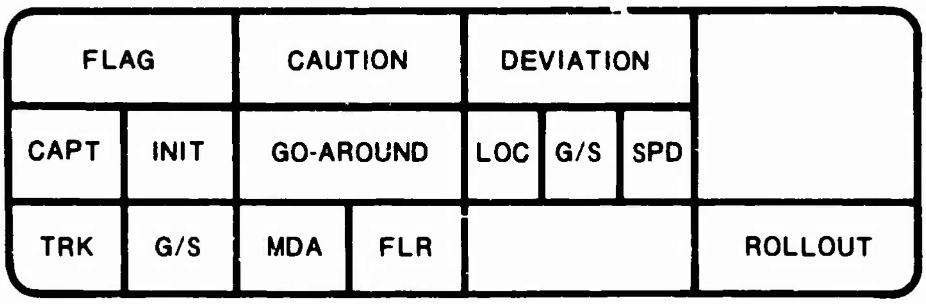

FIGURE M-6 - Master Fault Warning /Mode Progress Display.

(1) The master fault warning/mode progress display (Figure M-6) was located above the Captain's flight director. The panel face was opaque so that the pilot could only see the illuminated elements which are listed below:

*FLAG - A master warning light used to indicate that an instrument flag was in view.

*CAUTION - A master warning light used to indicate the presence of a failure.

*DEVIATION - A master warning light used with LOC, G/S, SPD lights.

*LOC. Indicated excessive deviation ($\pm\frac{1}{2}$ dot)
*G/S. Indicated excessive deviation ($\pm\frac{1}{2}$ dot)
*SPD. Indicated excessive deviation (± 5 knts.)

CAPT. and INIT. - Indicated localizer engaged.

TRK and G/S - Indicated G/S engaged .

MDA - Indicated 100 ft. altitude (wheel height).

FLR - Indicated flare mode engagement.

ROLLOUT - Indicated mode engagement.

(*) Denotes that the indicator usage was a study variable.

(2) The automatic control annunciator panel (Figure M-7) consisted of four lighted pushbutton switches. If a pitch or roll control failure occurred, the top portion of the switch would light up (red). If that axis was disconnected, the bottom portion would light (amber) and the top portion would extinguish. The pushbutton was used to disconnect the fault axis. The autothrottle and yaw units were not used.

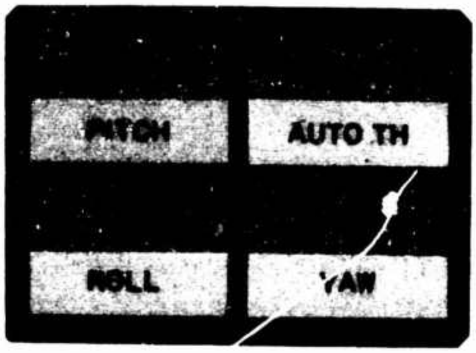

FIGURE M-7 - Automatic Control Annunciator Panel

(3) The system annunciator panel (Figure M-8) unit indications (amber) were used if either the unit or one of its primary inputs failed. The logic sequence is also presented in the system diagrams (Figure M-3 and M-4).

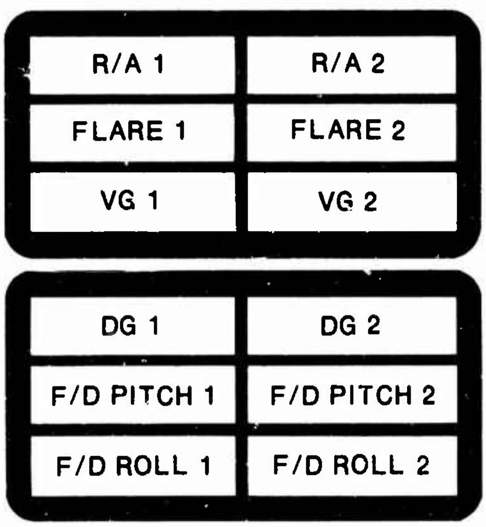

FIGURE M-8 - System Annunciator Panel

Flight Profile

The flight profile was a simulated ILS approach to runway 25L at Los Angeles International Airport. The 2.75-degree glideslope projected from a point 1,000 feet inside the runway threshold; the ± 0.7-degree beam width indicated ± 2 dots of glideslope deviation on the ADI. The ± 2-degree localizer terminated 1,000 feet beyond the departure end of the runway; 150-microamp beam width was equal to two dots of localizer error on the HSI.

Initial conditions. Prior to the start of the problem the simulator was set into a trim condition without autopilot coupling approximately 12.5 miles from the glideslope shack at an absolute altitude of 2,500 feet (2,628 feet barometric altitude) and inbound on the localizer course. In this position, the simulator was two dots below the glideslope, the heading was 248 degrees, thrust was set for 147 KIAS and flaps were set to 30 degrees. As an initial wind was inserted, the aircraft heading was altered so that lateral drift was zero. The steady-state wind was 10 knots lateral, 10 knots longitudinal, or a combination thereof in the horizontal plane. Wind gusts were random movements with a maximum amplitude of 2 knots and a one-CPS band width.

Profile execution. When the approach was started, the autopilot was engaged in the altitude hold and localizer track modes. Airspeed was reduced to 132 KIAS and the autothrottle system was engaged. The autopilot automatically captured the glideslope and trimmed the aircraft for the approach. At 50 feet of absolute altitude, the flare mode was engaged. At 20 feet, the autothrottle system began a programmed linear power reduction to engine idle at touchdown. A flare computer controlled pitch. Touchdown necessitated manual (1) disengagement of the autopilot and the autothrottle system, (2) deployment of spoilers, (3) application of reverse thrust and braking, and (4) use of differential brakes and/or rudder control until 60 KIAS reset the simulator to the initial conditions.

The execution of a missed-approach was also a manual function. When go-around mode was selected, the flight director commanded eight degrees of pitch attitude and wings level. The simulator reset to the initial conditions when the aircraft passed 500 feet of altitude.

System Failures

In order to exercise the fault warning system, autopilot control failures, Captain's display failures and flare mode engagement failures were inserted during the approaches. The procedures sub-section explains the experimental rules for failure insertion. A description of each failure follows:

Control failures. Three types of control system failures were investigated:

(1) Passive (dead) control failure. During passive autopilot failures, the autopilot failed to respond to its input signals in either pitch or roll.

(2) Softover control failures. During softover autopilot failures, the autopilot failed to respond to its input signals in either pitch or roll, and produced aileron or elevator control movement. In pitch, the column moved fore or aft 0.5 inches/second, which was approximately equal to 1.0 degree of elevator; 1.0 constant elevator was equivalent to 0.25 degrees/second of pitch attitude rate. In roll, the wheel moved right or left 1.0 degree/second. One degree of constant wheel change was approximately equal to 0.3 degrees/second roll attitude rate.

(3) Flare mode engagement failure. At 50 feet of absolute altitude, the flare mode failed to engage. During this failure, the autopilot continued to track in the glideslope mode. The simulator failed to flare, pitch attitude decreased very slightly as ground effect increased, the autothrottle system failed to reduce thrust at 20 feet of absolute altitude, and the flare mode engagement light failed to illuminate.

Display failures. Six Captain's display failures were inserted.

(1) Glideslope receiver output opened, causing a glideslope flag to appear and the raw glideslope indicator and the pitch command bars to drive to their center positions.

(2) Localizer receiver output opened, causing the raw localizer course deviation indicator and the expanded localizer indicator to return to their center positions. The bank steering bar biased out of view. Localizer and roll flight director flags appeared.

(3) Directional gyro failure caused the horizontal situation indicator (HSI) compass card to freeze and the OFF flag to appear.

(4) Vertical gyro dead failures caused the vertical gyro to freeze in position in both pitch and roll axes. The vertical gyro OFF flag appeared on the ADI.

(5) Vertical gyro unreliable failure caused the vertical gyro to slew to a slight offset (about 3-6 degrees of pitch and roll) and thereafter operate in a non-linear and erratic manner. There was no flag representation of this failure.

(6) Radar altimeter input opened, causing the radar altimeter display to freeze in position. Since flare mode engagement at 50 feet was triggered by the radar altimeter, the flare mode did not engage. The radar flag appeared on the radar altitude instrument.

The display flag-type failures were grouped according to location and formed principal display failure variables. Glideslope and vertical gyro dead failures were "ADI failures." Localizer and directional gyro failures were "HSI failures." The radar altimeter failure represented a flag failure outside the flight director system displays. The vertical gyro unreliable failure represented an insidious failure that did not have an associated instrument flag. It was assumed that the pilot's ability to detect flags within any one of these three locations (ADI, HSI, and RA) would be similar. The main purpose of creating different failures within each location was to vary the problem.

Failure Monitor Modes

The amount of failure monitor information presented to the pilot was varied by creating three failure monitor modes: (1) no monitor, (2) caution, and (3) caution plus annunciator.

No monitor. Basic pilot failure detection capability was determined by pilot performance in this mode. In this mode only existing warning flags on the Captain's display operated during those failures that had flag representations. The vertical gyro unreliable failure did not cause a flag to appear. Control system failures could only be detected by inappropriate column or wheel actions, excessive flight director command errors, or an attitude and path/course following discrepancy.

Caution. The second failure monitor mode was divided into two categories in order to test the utility of the FLAG light on the fault warning mode progress display. One half of the subject pilots (Group I) received a flag light for flag failures and a master caution light for vertical gyro unreliable and passive and softover autopilot control failures. Group II received a caution light for all display and control failures.

Caution plus annunciator. The third failure mode brought the full monitor and annunciator system into operation. Control system failures were annunciated by the automatic control annunciator panel (Figure M-7) in addition to the master caution light. Display system failures were annunciated by the system annunciator panel (Figure M-8), master caution light and instrument warning flags (except vertical gyro unreliable, which had no flag representation).

Table M-2 shows the system operation during each failure mode.

TABLE M-2

Display Warning Information as a Function of Monitor Mode

Experimental Failure Condition	Failure	Effect on Information or System	No Monitor	Caution (Lights) Group I	Caution (Lights) Group II	Caution + Annunciator
Passive Control	Pitch or Roll Autopilot	Pitch/Roll Axis Dead		Caution	Caution	Pitch or Roll Annunciator Red, When disconnect, Amber
Softover Control	Pitch or Roll Autopilot	Pitch Column $\frac{1}{2}$"/sec. Roll Wheel 1^{o}/sec.		Caution	Caution	Pitch or Roll Annunciator Red, When Disconnect, Amber
Flare Mode Engagement	No Mode Change	System Flies Attitude to Ground	Mode Engagement Light does not Illuminate, All Modes.			
ADI Display Failure	G/S	Raw G/S - 0 Pitch Command - 0	G/S Flag	Flag	Caution	Caution FD Pitch #1
	VG Dead	ADI Freezes	VG Flag Roll FD Flag	Flag	Caution	Caution FD Pitch #1 FD Roll #1 VG #1
HSI Display Failure	LOC	Raw Loc - 0 Exp. Loc - 0 Roll Command Bar out of View	Loc Flag FD Flag	Flag	Caution	Caution FD Roll #1
	DG	DG Freezes	HSI OFF Flag Roll FD Flag	Flag	Caution	Caution DG #1 FD #1
Radar Altimeter Failure	RA	No Flare Mode RA Freezes	RA Flag	Flag	Caution	Caution RA #1 Flare #1 FD Pitch #2
VGU	Vertical Gyro	VG Slews and Becomes Non-Linear		Caution	Caution	VG #1 Roll FD #1 Pitch FD #1

Winds

In addition to turbulent air, three windshear conditions were simulated. The three winds were a tailwind shear, a lateral shear, and quartering windshear composed of both tailwind shear and lateral shear components. The tailwind shear was a 10-knot steady-state headwind which sheared to calm from 100 feet to touchdown. The lateral shear was a 10-knot steady-state 90-degree crosswind that sheared to calm from 100 feet to the ground. The quartering windshear was a vector composed of both tailwind and lateral shear conditions that resulted in calm winds at touchdown.

Pilot Task

The pilot's task was to fly the aircraft to a successful touchdown using the autopilot and flight director as tools to accomplish this objective. Display and control system failures could be expected. Whenever a failure was detected, the pilot was to call out the failure and take corrective action. If a control failure was detected, the pilot was to disconnect the autopilot axis that had failed and continue the approach by flying in a split-axis mode. If a display failure occurred, the pilot was to continue on autopilot and signify his decision by hitting the response bar. If both the autopilot and Captain's display failed in the same axis, the pilot was to execute a missed approach himself or relinquish control to the First Officer as the situation demanded. At the initiation of a missed approach, the pilot was to engage the go-around mode of the flight director system.

Requesting the pilots to continue the approach after experiencing one failure was for the purpose of documenting pilot fault detection capability as the pilot's task load was increased.

For those approaches that ended in touchdown, the pilot had to manually disengage the autopilot at touchdown, deploy the spoilers, reverse thrust (the F/O would usually help by signifying reverse thrust limit), brake, and steer the aircraft down the runway using heading and raw localizer on the HSI.

Experimental Designs

The primary purpose of this study was to document pilot performance with three levels of failure warning information during control and display system failures. Following any one of these failures, or combinations thereof, the pilots either executed a missed approach or landed. When they landed, they did so under different split-axis conditions and different winds. Pilot/system performance during each of these four events required different experimental designs which follow:

Control failures. Three levels of fault warning information (monitor modes) were tested with passive and softover control failures in pitch and roll for each of the nine subjects in each of two experimental groups. The design is diagrammed in Figure M-9. The experimental design is a Lindquist Type VI (Ref. 5). The analysis of variance source tables for all designs are shown in Appendix A.

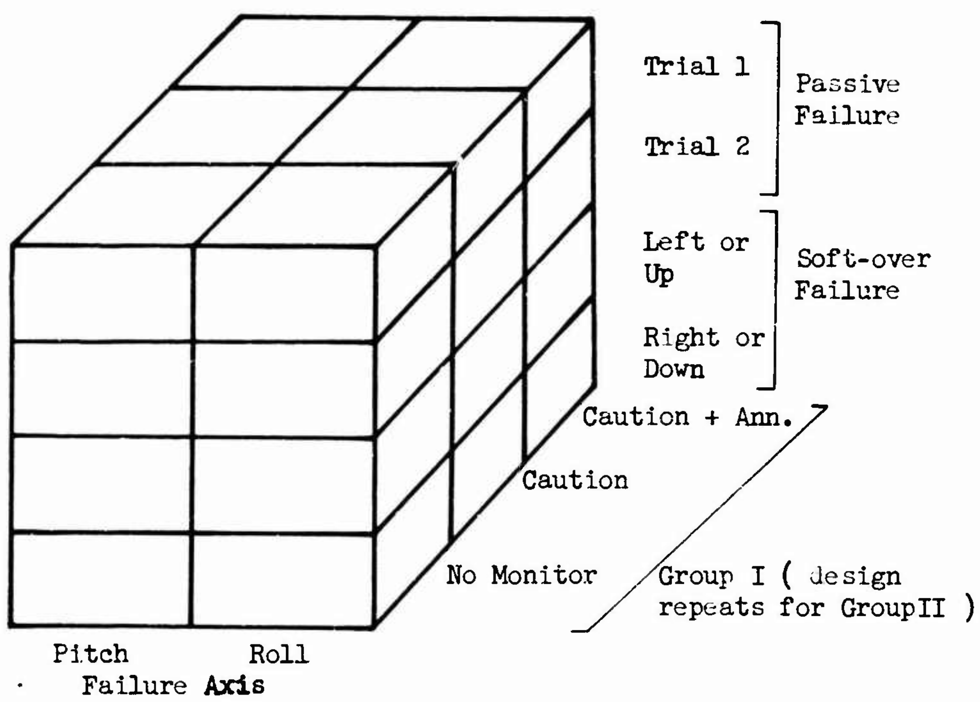

FIGURE M-9 - Experimental Design for Control Failures

Display Failures. The pilot was asked to assume split-axis control following a control system failure so that the effect of pilot task load upon display failure detection could be examined. Three monitor modes were then tested with four display failures for each of the nine subjects in each group. The Lindquist Type VI experimental design for display failures is diagrammed in Figure M-10. Note that there were no control system failures prior to display failures in the automatic control mode. Control system failures were assumed to put the pilot into split-axis pitch manual and split-axis roll manual control prior to the display failure during pitch manual and roll manual split-axis conditions. All display failures during split-axes control were, therefore, second failures.

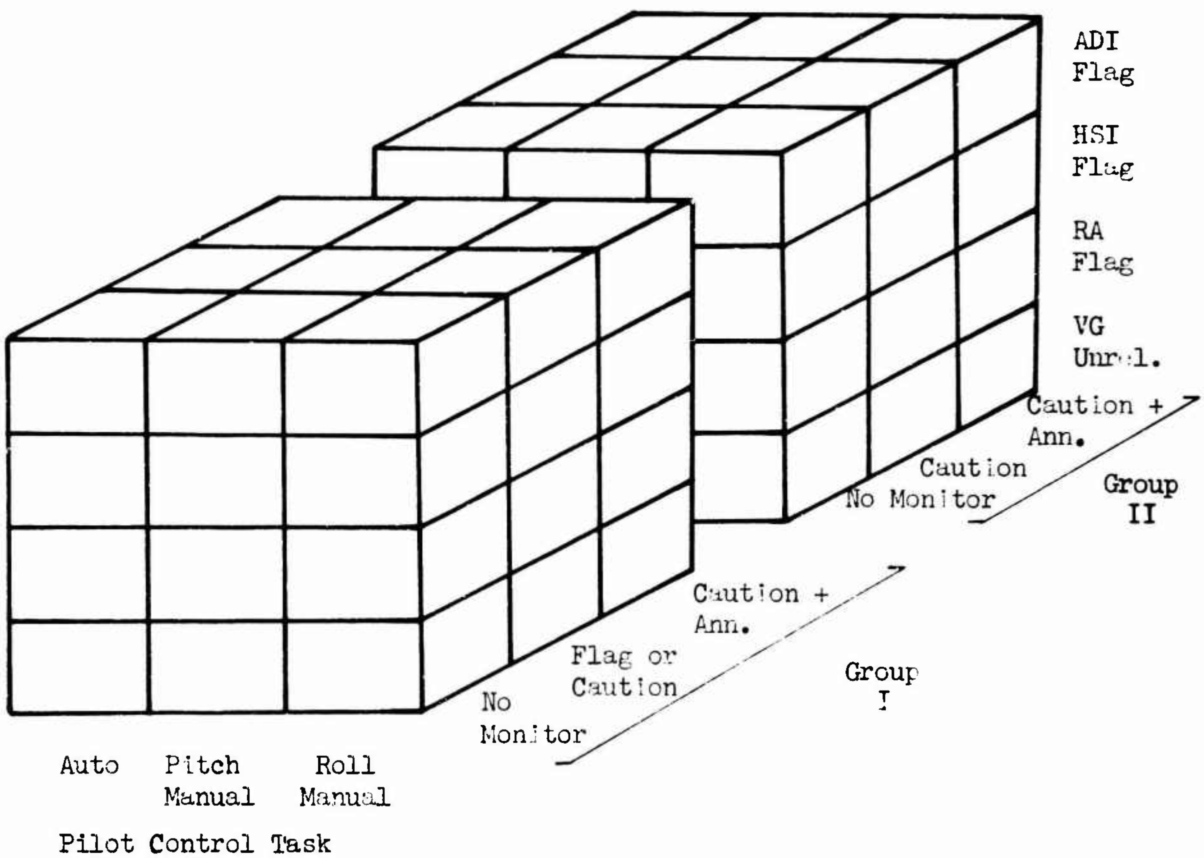

FIGURE M-10 - Experimental Design for Display Failures

Go-around performance. Go-around performance was placed into a smaller experimental design as a function of the three monitor modes and the two split-axis control conditions prior to the display failure that caused the pilot to execute a missed approach. Because missed approach did not occur an equal number of times within each condition, a randomized block design and analysis of variance was used. Data from all missed approaches that occurred under the conditions defined by each cell in Figure M-11 were placed into that cell and formed the residual error term.

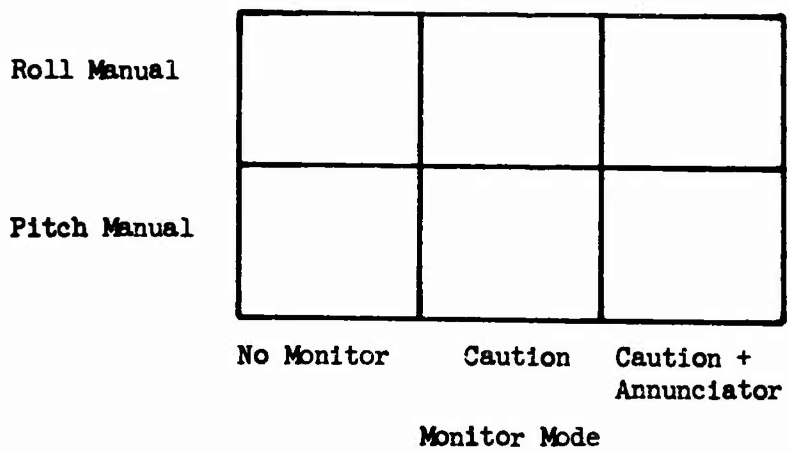

FIGURE M-11 - Experimental Design for Go-Around performance

The effect of wind upon touchdown. For those approaches that proceeded to touchdown, three wind conditions were confounded with failure monitor modes. The effect of wind upon touchdown performance as a function of automatic, pitch manual split-axis, and roll manual split-axis control was of interest. It was assumed that the pilots would have responded to all control and display system failures prior to reaching the altitude at which the shearwind started taking effect (100 feet). The three winds were a tailwind shear, a lateral shear and a quartering shear composed of both tailwind and lateral shear components. The three winds and three control conditions formed the randomized blocks design shown in Figure M-12. There was an unequal number of scores in each cell of the design because pilots were not forced to continue to touchdown; the decision to land remained the prerogative of the pilot.

	Automatic	Pitch Manual	Roll Manual
Tailwind Shear			
Lateral Shear			
Tailwind & Lateral Shear			

FIGURE M-12 - Experimental Design for the Effect of Wind upon Touchdown Performance

Because each approach was flown under carefully controlled experimental conditions, measured changes in pilot performance can be attributed to the experimental conditions. The measures which were placed into each experimental design for analysis appear next.

Measurement

Three general classes of measures were recorded in this study: pilot preference measures, pilot detection performance measures and pilot/system performance measures.

Pilot preference measures. The source of pilot preference data was the questionnaire. After all flights were completed, the pilots filled out a questionnaire which interrogated their opinions of the primary features of the fault warning system in terms of utility, color coding, location and modes of operation. Comments on the procedures and system improvement were also solicited. The pilots were also asked to scale the difficulty of detecting passive autopilot failures during each of the three monitor modes.

Pilot detection performance. Each time a failure was not seen by a subject pilot within 30 seconds, the experimenter serving as First Officer scored a no detection for that condition. An incorrect response was scored when the pilot called out the wrong failure or identified the correct failure, but his action was not consistent with what he said. (For example, an incorrect response would be scored if the pilot identified a pitch axis control failure, then proceeded to disconnect the roll axis.) A false alarm was scored when the pilot called out a failure when none had been inserted. The pilot was never penalized for executing a go-around when he could have continued to landing under the decision logic that he was requested to use; however, an incorrect decision to land was scored when the pilots continued manually to touchdown when there was a display failure in the axis that they were controlling manually.

Pilot/system performance. The basic data consisted of 10 channels shown in Table M-3. These data were acquired at (1) failure insertion, (2) pilot response and (3) touchdown or (4) every 1.5 seconds during go-around. These basic data were further treated in different ways to describe pilot/system performance (1) during control and display failures, (2) at touchdown and (3) during go-around.

Failure data treatment. Four data treatments were used to describe pilot/system performance during control and display failures. The first treatment shown in Table M-3 was simply the value of the indicated parameter at pilot response. The second was the absolute value (sign ignored) of the data at pilot response. Describing performance using absolute values is most important in lateral plane measures because the system tended to accrue error to one side or the other as a function of the steady-state winds which were randomly from the right or left. The absolute value describes the amount of error accrued, independent of direction.

The third way of treating the basic data was to find the change in system performance between failure insertion and pilot response. The change in

TABLE M-3

Pilot/System Performance Measures

Basic Data Channels	Measurement Accurate to	Failure Data Treatments				
		Pilot Response	Absolute at Response	Average Change	Absolute Change	Touchdown Data
Longitudinal Range*	1.0 feet			X		X
Lateral Displacement	0.5 feet			X	X	X
Pitch Attitude	0.02 degrees	X	X	X	X	X
Roll Attitude	0.02 degrees	X	X	X	X	X
Heading Error**	0.02 degrees			X	X	X
Lateral Drift	0.05 feet/sec.	X	X	X	X	X
Absolute Altitude	0.5 feet			X		
Indicated Airspeed	0.2 knots			X		X
Vertical Velocity	2.0 feet/min.			X		X
Response Time	0.02 sec.			X		

*From Glideslope transmitter.
** Heading error about nominal 248° runway compass heading.

performance was generated by subtracting the values of the indicated channels at pilot response from the value at failure insertion. The fourth data treatment subtracted the absolute value of the indicated channels at pilot response from the absolute value at failure insertion in order to assess the amount of change of system error independent of direction.

Touchdown data treatment. The values of the eight touchdown parameters were treated with regard to sign (AE, average error) and without regard to sign (AAE, average absolute error).

Go-around. Go-around was considered to start at the pilot response to the second failure. When go-around mode was triggered by the pilot, data were scanned every 1.5 seconds until the simulator reset. The scan that contained lowest altitude was used in conjunction with response scans and, in one case, the failure insertion scan to generate go-around data. These data treatments are listed in Tables R-52 and R-56 in the Go-around performance section.

Procedures

Pilot briefing and training. Upon arrival at 0800 hours, each pilot was given a standardized briefing on the program, the specific purpose of the study, a detailed explanation of the entire system operation and procedures to be followed. Each subject pilot was then seated in the left-hand seat in the simulator cabin and was briefed again by the experimenter/First Officer. Four familiarization approaches were conducted. All system failures were exercised to provide pilot practice. Two approaches terminated in touchdowns and two approaches terminated in go-arounds. After practice, 39 approaches for record were flown (see order of presentation, below). A 45-minute lunch break was taken at a logical point. Experimental flying continued after a short re-briefing and warm-up approach. Experimental flying nominally concluded at 1530 hours. Following the flights for record, the subject pilot completed the questionnaire, was de-briefed and departed the facility at approximately 1645 hours.

Order of presentation. The 39 approaches were divided into three blocks of 13 approaches each. The first block was flown with no monitor. The second block was flown alternately with caution light failure mode for one subject, and caution plus annunciator for the next subject. The last block of approaches was flown using the untested monitor mode.

Within each block of 13 approaches, one trial was flown automatic until the occurrence of a flare mode failure at 50 feet; the flare mode failure approach was randomly placed with the remaining 12 approaches. These remaining 12 approaches consisted of all possible combinations of four display failure locations and three pilot control tasks, randomly ordered for each block. The pilot control tasks at the display failure determined the control failure axis (pitch or roll); no control failures preceded display failures during "automatic" pilot control task. Pitch axis control failures preceded pitch manual split-axis display failures (there were four in each block of 13). Two pitch axis control failures were passive and two were softover failures; therefore, two trials of each failure type were possible. The direction of the softover failures (up or down) was equally distributed. The four possibilities (2 failure types x 2 trials) within the axis of control failure were randomly assigned. Four roll axis failures leading to roll manual split-axis control during display failures were similarly treated.

Failure altitudes. Failure altitudes were randomly assigned within an altitude band of 450 feet to 100 feet (except the flare mode failure which had to occur at 50 feet). When two failures were given on one approach, the second failure had to be programmed to occur no lower than 100 feet, and had to occur no sooner than 20 seconds after the preceding control failure. These restrictions were imposed because we wanted the pilot to have ample time to detect and act upon the first failure before experiencing the second. We also wanted the second failure to be inserted prior to the windshear at 100 feet. Previous experience indicated that 20 seconds would be more than adequate.

Wind conditions. Windshear was confounded with monitor mode. The windshear magnitude and type (tailwind, lateral, or quartering) were constant for each block of 13 approaches. The direction of the wind was randomly assigned for each approach. Having assigned the wind direction, the windshear was set to shear to near calm on the ground so that there would not be a requirement to decrab the aircraft. The console operator, acting as Los Angeles approach control, reported the ground winds which were derived by subtracting the shearwind magnitude and vector from the initial condition lateral, longitudinal and quartering winds. Turbulent air was always used.

RESULTS AND DISCUSSION

Introductory Comment

General organization of this section. The purpose of this study was to determine pilot fault detection capability as a function of the amount of failure monitor information that was present. The performance data were quite dependent upon the particular failures that were introduced. Therefore, a major portion of this results section was organized according to the types of failures. Control failures, display failures and flare mode failures, go-around performance, the effects of winds upon touchdown, roll-out performance, and a general discussion of fault-warning and mode-progress devices are discussed in this section.

Sub-section organization. Each major sub-section starts with the easiest data form to interpret and proceeds to the more difficult. The number of times that the pilots did not detect a failure is an example of a data form that appears first. Next, pilot response times and aircraft parameters provide a more complex look at pilot/system performance. Preference (pilot opinion) data will appear as applicable within each sub-section. Each sub-section, therefore, presents a summarized version of all data that bears upon the topic of that sub-section.

Method of presenting summarized data. Within each problem-oriented sub-section, some data are shown according to the level of failure monitor; other data are shown as a function of levels of control, and still other data are reported as over-all averages and standard deviations. The decision to summarize or break-out (report one number or many numbers) performance data is based upon the results of an analysis-of-variance test where one was conducted. If a difference between means is shown to be reliable by the analysis-of-variance "decision tool," then the means are independently reported. For example, if pilot response times to softover control failures were different from their response times to passive control failures, AND this apparent difference was shown to be reliable by the analysis of variance, then both means would be shown. If, however, the statistical tool could not confirm a significant difference (i.e., the difference could have occurred by chance alone) then the data would simply be shown as one average response time to control failures. An analysis-of-variance summary table is placed within each section.

Finally, it is quite possible for a source of variance (e.g., monitor mode) to be significant in the analysis of variance, yet some of the means within that particular source may not be significantly different from each other. For example, monitor modes may be a significant source of variance in the analysis of variance. There are three means associated with this source, one for each level (no monitor, caution light only, and the full system). The distributions of scores underlying each of these three means can be such that there is no significant difference between two of the three means even though the source of variance was significant. When a source of variance is significant, the Duncan's New Multiple Range Test (Ref. 1) is used to find out which means are significantly different. Duncan's test results are indicated either by footnotes to the tables of means and standard deviations or by placing boxes around the means which are not significantly different. Since the tables of means also contain standard deviations, the boxes are placed around means and standard deviations even though the box refers to the means. The interpretation to be used is that numbers within the same box are not significantly different.

Control Failures

Detection. Out of 216 passive control failures that were administered, 39 were undetected. Five out of 216 softover control failures were undetected. Table R-1 shows that the number of times that failures were undetected reduced as the amount of monitor system information increased. Softover failures did not seem to present a detection problem, but passive failures were difficult to detect. The full monitor system with caution light and annunciator panel

TABLE R-1
Control Failure Detection as a Function of Monitor Modes

	Softover Failure			Passive Failure		
Measure	No Monitor	With Caution	Caution + Annun.	No Monitor	With Caution	Caution + Annun.
Number of times failure not detected	2	2	1	21	16	2
%	2.8%	2.8%	1.4%	29.2%	22.2%	2.8%
Number of incorrect responses*	2	1	0	3	4	2
%	2.8%	1.4%	0.0%	4.2%	5.6%	2.8%
Number of false alarms**	1	1	0	2	4	1
%	1.4%	1.4%	0.0%	2.8%	5.6%	1.4%

*Incorrect responses include incorrect identification of failure.
**A false alarm was scored when a pilot called out a failure that didn't exist. Note that most false alarms were thought to be passive autopilot failures.

was necessary to reduce the non-detections of passive failures to two times out of 72 failures. Table R-2 shows that the pitch axis passive failure was most difficult to detect. Contrary to what was seen in passive failures, the roll axis softover failure appeared more difficult to detect than the pitch axis softover failure.

Incorrect responses. An incorrect response was scored when the pilot either (1) called out a pitch failure instead of a roll failure (or the reverse), or (2) correctly identified the failed axis but disengaged the wrong axis, or (3) disengaged the whole autopilot. Table R-1 shows that the number of incorrect responses reduced when the full monitor system was used. Passive failures again were the problem. The two incorrect responses shown (Table R-1) for passive failures with the caution plus annunciator were due to incorrect identifications of the failure even though the responses were, in fact, correct. Table R-2 indicates that the roll axis passive failure accounted for most of the incorrect responses: These incorrect responses were largely caused by confusion between the passive autopilot failure and the vertical gyro unreliable failure.

TABLE R-2

Control Failure Detection as a Function of Failed Axis

	Softover Failure		Passive Failure	
Measure	Pitch Manual	Roll Manual	Pitch Manual	Roll Manual
Number of times failure not detected	1	4	22	17
%	0.9%	3.7%	20.4%	15.8%
Number of incorrect responses*	1	2	1	8
%	0.9%	1.9%	0.9%	7.4%
Number of false alarms	1	1	7	0
%	0.9%	0.9%	6.5%	0.0%

*Incorrect responses include incorrect identification of failure.

False alarms. Although the numbers were not high, more false alarms appeared in the monitor-with-caution-conditions (Table R-1) than without any monitor or with the caution light and annunciator panel. Table R-2 shows that the false alarms were thought to be pitch passive failures.

Summary of detection, incorrect responses and false alarms. Passive failure non-detections, incorrect responses and false alarms together (Table R-1) indicated classic human operator signal detection behavior in the presence of uncertainty and noise. The number of non-detections decreased when the caution light was added; but, the number of incorrect responses and the false alarms tended to increase. One suspects, therefore, that guessing was going on--the pilots were catching more failures in the process of guessing, but introducing "failures" of their own by either incorrectly responding or calling-out a failure that did not exist. On the basis of these data and criteria, the passive control failure was shown to be the detection problem during no monitor and caution conditions. When the annunciator was added, there was a marked improvement in fault detection and response performance.

Response time. Response time indicated the time that it took the pilots to detect a control failure, call out the problem axis and disengage the autopilot in the failed axis. Table R-3 shows average pilot response times that resulted from softover and passive control failures for each of the monitor modes.

TABLE R-3
Pilot Response Time to Control Failures

	Monitor Mode			
Failure Intensity	No Monitor	With Caution	Caution + Annunciator	Across Monitor Mode
Passive	15.68* (3.31)**	14.34 (4.40)	8.43 (0.68)	12.82 (4.48)
Softover	7.15 (2.08)	6.82 (1.98)	7.18 (1.32)	7.05 (1.82)
Across Failure Intensity	11.41 (5.10)	10.58 (5.08)	7.81 (1.22)	9.93 (4.47)

* Mean response time in seconds.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

It took much longer for the pilots to respond to passive failures than to softover failures when no monitor was present (15.68 sec. vs. 7.15 sec.). The addition of a monitor with a caution light did not significantly change response time from the no-monitor condition. When the annunciator panel was operating, pilot response time to passive failures reduced to 8.43 sec., which was not significantly different from their response times to softover failures.

Disregarding monitor modes, pilot responses to passive failures took longer than responses to softover failures (Table R-3) and it took an equivalent amount of time to respond to either pitch axis or roll axis passive failures. Softover failures, on the other hand, were axis dependent. Pilots responded to pitch softover failures (5.94 sec.) more quickly than they responded to roll softover failures (8.16 sec.).

TABLE R-4
Pilot Response Time to Control Failures

Failure Intensity	Failed Axis: Pitch	Failed Axis: Roll	Across Axis Failed
Passive	12.63* (4.44)**	13.01 (4.56)	12.82 (4.58)
Softover	5.94 (1.27)	8.16 (1.59)	7.05 (1.82)
Across Failure Intensity	9.28 (4.67)	10.58 (4.18)	9.93 (4.47)

* Mean response time in seconds.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

<u>Summary of response time</u>. Passive failures appeared to be more difficult to detect in the no-monitor and monitor-with-caution-light-only conditions. It took just as long for pilots to detect either pitch or roll passive failures. Pitch softover failures were detected more readily than roll softover failures. With the monitor and annunciator panel

operating, passive and active failures were equally detected, but the pilot response time was still about 7.0 sec. Under the conditions of the study, the monitor took 5.0 seconds to detect the failure. One could thus assume the pilot response time to the monitor to be 2.0 seconds.

Altitude used. Altitude used measured the amount of altitude consumed from failure insertion until pilot response. This measure indicated the altitude consequences of the response times just presented.

Essentially the same pattern indicated in response time measures emerged. Table R-5 shows the altitude that was consumed as a consequence of each combination of monitor mode and failure intensity. The monitor levels examined had no effect upon the amount of altitude used during softover failures. The monitor-with-caution-light did not alter the altitude used during passive failures when compared to the altitude used when there was no-monitor at all. In fact, the addition of the caution light increased the variability (in terms of one standard deviation) of altitude used during passive failures. The monitor with annunciator panel reduced the passive failure altitude consumption to the softover failure level. When the monitor with caution and annunciator operated, there was an average altitude consumption of 74 feet with a 13.7-foot standard deviation.

TABLE R-5
Altitude Used During Control Failures

Failure Intensity	Monitor Mode: No Monitor	With Caution	Caution + Annunciator	Across Monitor Mode
Passive	146.40* (30.94)**	144.44 (47.96)	80.26 (10.71)	123.70 (45.34)
Softover	68.47 (18.61)	69.86 (21.89)	68.26 (13.85)	68.86 (18.26)
Across Failure Intensity	107.43 (46.72)	107.15 (52.73)	74.26 (13.70)	96.28 (44.10)

*Mean altitude used in feet.
**One standard deviation.
Note: Means contained within the same box are not significantly different.

There was a difference in the amount of altitude used as a function of failure axis (Table R-6). More altitude was used during roll axis failures, probably because the pilot response time to roll failures was longer than response time to pitch failures. Although the previous pilot response time measures indicated a difference between pitch and roll axis failures as a function of failure intensity (softover or passive--Table R-4), the time differences reported had no reliable effect upon the altitude consumed.

TABLE R-6
Altitude Used During Control Failures

Measure	Failed Axis: Pitch	Failed Axis: Roll	Across Failed Axis
Average	89.64*	102.92	96.28
Standard Deviation	44.74**	42.62	44.10

* Feet.
** One standard deviation.

Changes in the amount of altitude used can be related to pitch attitude changes and vertical velocity changes as well as response time. As aircraft parameters that result in altitude change, pitch attitude and vertical velocity will be examined next.

Pitch attitude. The actual data treatment being reported here took the absolute value (signs ignored) of pitch attitude at failure insertion and subtracted from it the absolute value of the pitch attitude at pilot response. Since pitch attitude normally was about 2.0° at failure insertion, a larger (i.e., 3°) pitch attitude at response shows as a negative number in these data. This data treatment was chosen to represent pitch attitude because it was the most sensitive.

Table R-7 indicates that during pitch softover failures a 1.32-degree pitch-up tendency occurred. Since pitch-up and pitch-down softover failures occurred an equal number of times, it is likely that the pilots were more sensitive to the occurrence of a pitch-down than a pitch-up, and tended to restrain the column pitch-down.

TABLE R-7
Pitch Attitude Change During Control Failure

Failure Intensity	Failed Axis: Pitch	Failed Axis: Roll	Across Axis Failed
Passive	-0.24* (0.82)**	-0.03 (0.42)	-0.14 (0.66)
Softover	-1.32 (1.80)	0.18 (0.57)	-0.57 (1.53)
Across Failure Intensity	-0.78 (1.49)	0.08 (0.51)	-0.35 (1.19)

* Mean pitch attitude change in degrees. Note that a negative implies response value larger than failure insertion (pitch-up).
** One standard deviation.
Note: Means contained within the same box are not significantly different.

It is evident that pitch attitude simply did not change as a function of monitor mode (Table R-8) as did the response time or altitude used. The altitude consumed that was previously shown cannot be due to any changes in pitch attitude as a function of monitor mode. Finally, there was no evidence of roll control failure getting so far out of hand as to cross-couple into pitch.

TABLE R-8
Pitch Attitude Change During Control Failure

	Monitor Mode			
Failure Intensity	No Monitor	With Caution	Caution + Annunciator	Across Monitor Mode
Passive	0.06 * (0.73)**	-0.36 (0.68)	-0.11 (0.49)	-0.14 (0.66)
Softover	-0.62 (1.37)	-0.36 (1.25)	-0.72 (1.91)	-0.57 (1.53)
Across Failure Intensity	-0.28 (1.14)	-0.36 (1.00)	-0.42 (1.42)	-0.35 (1.19)

* Mean pitch attitude change in degrees; negative implies pitch-up.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

<u>Vertical velocity change</u>. This measure was the amount of change between vertical velocity at failure insertion and vertical velocity when the pilot responded to the control failure. Unlike the attitude change measure, vertical velocity retained the original signs attached to the values. Since vertical velocity at failure insertion was nominally -640 feet per minute, a decrease in vertical velocity at pilot response (e.g., -440 fpm.) would show as a negative number [e.g., -640-(-440) = -200]. Therefore, negative vertical velocity change values show a lessening of sink rate.

Table R-9 shows that vertical velocity tended to have increased by the time pilots responded to pitch failures with no monitor. Vertical velocity had decreased at pilot response during pitch failures in the monitor with caution-light-only approaches. The tendency of the pilots to decrease vertical velocity during the caution-light-only pitch failures was interesting. Apparently, the pilots were holding a slight pitch-up bias while they were diagnosing the failure. This tendency was not seen during other conditions, and was not clearly evident in the pitch attitude measure. The value, -77.3 feet per minute of change between failure insertion and pilot response, was rather small; the effect, therefore, was not profound. Finally, when the full monitor system with caution light and annunciator panel was operating, there were no differences in vertical velocity as a function of pitch or roll control failures. Vertical velocity data variability was twice as high during pitch failures as during roll failures, as would be expected.

TABLE R-9
Vertical Velocity Change During Control Failures

	Monitor Mode			
Axis Failed	No Monitor	With Caution	Caution + Annunciator	Across Monitor Mode
Pitch	62.3* (181.3)**	-77.3 (183.5)	19.1 (192.6)	1.4 (193.2)
Roll	-8.5 (96.3)	0.0 (87.1)	-14.3 (79.2)	-7.6 (87.2)
Across Axis Failed	26.9 (148.5)	-38.7 (147.5)	2.4 (147.2)	-3.1 (149.6)

* Mean vertical velocity change in feet per minute; negative implies pitch-up.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

Disregarding monitor mode, Table R-10 shows that vertical velocity at pilot response during passive failures had decreased, while vertical velocity at pilot response for softover failures was not significantly different from the vertical velocity change during roll failures. In this case the data were felt to be quite sensitive to a mechanization problem.

There was a slight bias in the pitch axis trim mechanization of the autopilot in the simulator. Pitch trim follow-up was designed to aerodynamically trim servo load. As in any feedback control system, the system seeks equilibrium, but cannot achieve perfect equilibrium. The mechanization was such that a very slight pitch-up aerodynamic trim remained that was well within the requirements for the autopilot to leave the aircraft in a trim condition upon disconnect. When the autopilot was failed passive, the servo released the elevator and the trim bias that existed produced a pitch-up tendency which resulted in an average 50-foot-per-minute change in vertical velocity at the end of an average 12 seconds of time. Since the softover control failure did not release the elevator from the servo until the moment of pilot response, this effect was not seen.

TABLE R-10
Vertical Velocity Change During Control Failures

Axis Failed	Failure Intensity: Passive	Failure Intensity: Softover	Across Failure Intensity
Pitch	-56.5* (174.9)**	59.2 (194.8)	1.4 (193.2)
Roll	-6.2 (90.4)	-9.0 (84.6)	-7.6 (87.2)
Across Failed Axis	-34.0 (140.9)	25.1 (153.4)	-3.1 (149.6)

* Mean vertical velocity change in feet per minute; negative implies pitch-up.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

__Longitudinal range__. The change between longitudinal range at failure insertion and longitudinal range at pilot response showed the distance that the vehicle traveled while the pilot was detecting and acting on the failure. Table R-11 shows that distance traveled varied with monitor mode and failure intensity in the same way that response time and altitude used did. About 3,127 feet were traveled during an average passive failure with no monitor and monitor with caution light. Since the remaining means were not significantly different, the average of these scores, 1,521 feet, describes range consumed during all other conditions.

TABLE R-11
Longitudinal Range Consumed During Control Failures

	Monitor Mode			
Failure Intensity	No Monitor	With Caution	Caution + Annunciator	Across Monitor Mode
Passive	3133* (610)**	3121 (968)	1680 (183)	2645 (953)
Softover	1439 (438)	1480 (425)	1485 (253)	1451 (378)
Across Failure Intensity	2286 (1003)	2300 (1111)	1557 (252)	2048 (939)

* Mean longitudinal range in feet.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

Table R-12 showing distance traveled as a function of failure intensity and failed axis corroborates the response time values of the same interaction (axis failed by failure intensity) shown in Table R-4.

TABLE R-12
Longitudinal Range Consumed During Control Failures

Failure Intensity	Axis Failed: Pitch	Axis Failed: Roll	Across Axis Failed
Passive	2607* (939)**	2682 (974)	2645 (953)
Softover	1221 (244)	1681 (349)	1451 (378)
Across Failure Intensity	1914 (975)	2181 (885)	2048 (939)

* Mean longitudinal range in feet.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

Indicated airspeed. The average change in indicated airspeed from failure insertion until pilot response was homogeneous for all failures. On the average, 0.85 knot was lost with a standard deviation of 2.19 knots. The autothrottle system installed in the simulator held airspeed constant through the control failures that were inserted.

Lateral displacement. The change in absolute lateral displacement was determined by subtracting the absolute value of lateral displacement at pilot response from the absolute value of lateral displacement at failure insertion. Negative values indicate that displacement was larger at pilot response than at failure insertion. The amount of lateral displacement was dependent upon each combination of failure intensity, monitor mode, and axis. During pitch axis failures, there were no differences in lateral displacement as a function of monitor mode or failure intensity as one might expect. The average lateral displacement change during all pitch axis failures was 1.28 feet with a standard deviation of 5.17 feet. Table R-13 shows the lateral displacement changes which occurred during roll failures.

TABLE R-13
Lateral Displacement Change During Roll Control Failures

Failure Intensity	Monitor Mode: No Monitor	Monitor Mode: With Caution	Monitor Mode: Caution + Annunciator	Across Monitor Mode
Passive	-29.92* (28.45)**	-21.61 (22.46)	-1.10 (7.55)	-17.55 (24.28)
Softover	-15.10 (17.35)	-16.62 (21.09)	-9.33 (20.20)	-13.69 (19.50)
Across Failure Intensity	-22.52 (24.41)	-19.12 (21.62)	-5.22 (15.60)	-15.62 (22.00)

* Mean lateral displacement in feet.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

In the no-monitor case, lateral displacement during passive failures changed almost 30 feet, whereas during softover failures, the lateral displacement changed only 15 feet. Note the variability underlying these means in Table R-13. With no monitor during a passive failure, 68% of the scores were between zero and sixty feet. When the monitor-with-caution-light was operating, the difference between passive and softover failures became non-significant. Average lateral displacement during the caution light monitor mode was, therefore, 19.12 feet with a standard deviation of 21.62 feet.

When the monitor with caution and annunciator panel operated, performance improved considerably. Again, since there was no significant difference between the means indicated, the average lateral displacement change with the full system was 5.22 feet.

Considering the softover failures by themselves, monitor mode did not influence the amount of lateral displacement change from failure insertion until pilot response.

Before concluding the discussion of lateral displacement, it would be well to examine roll attitude, heading error and drift rates that lead to the lateral displacements that were found.

<u>Roll attitude</u>. This measure indicated the absolute amount of roll change from failure insertion to pilot response in a manner similar to lateral displacement. The amount of roll attitude change was a function of either (1) monitor mode, or (2) failure intensity for roll failures. Failure intensity did not interact with monitor mode as in the lateral displacement measure.

The amount of roll attitude change from failure insertion until pilot response was constant until the caution light and annunciator panel were in operation (Table R-14). When the full system was in operation, there was a reduction in roll attitude change.

TABLE R-14
Roll Attitude Change During Control Failures

	Monitor Mode			
Measure	No Monitor	With Caution	Caution + Annunciator	Across Monitor Mode
Mean	-3.23*	-3.26	-2.54	-3.01
Standard Deviation	4.24**	4.21	3.74	4.06

* Mean roll attitude in degrees.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

Independent of monitor mode, passive roll failures yielded an average of 3.17 degrees of roll attitude change at pilot response whereas softover failures led to an average 8.8 degrees of roll change (Table R-15). Even though pilot response times to softover failures were quite faster than response times to passive failures, higher roll attitudes prevailed as a consequence of the softover failures. These higher roll attitudes did not regularly lead to greater lateral displacement (refer again to Table R-13), because softover failures resulted in generally lower lateral displacements than did passive failures. Neither did the roll attitude changes during passive failures lead to more heading error.

TABLE R-15
Roll Attitude Change During Control Failures

Failure Intensity	Failed Axis: Pitch	Failed Axis: Roll	Across Failed Axis
Passive	-0.01* (0.37)**	-3.17 (2.77)	-1.59 (4.81)
Softover	-0.06 (0.12)	-8.80 (2.61)	-4.43 (2.43)
Across Failure Intensity	-0.03 (0.28)	-5.99 (3.89)	-3.01 (4.06)

* Mean roll altitude change in degrees.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

Heading error. Heading error was the difference between the aircraft heading and the runway heading of 248 degrees. The measure reported here was the absolute change in heading error between failure insertion and pilot response. Roll axis failures (Table R-16) created heading error changes until the full monitor system with annunciator panel was operating. With the full system in operation, there were no differences between heading error change shown for roll failures and for pitch failures.

TABLE R-16

Heading Error Changes During Control Failures

Failed Axis	Monitor Mode: No Monitor	With Caution	Caution + Annunciator	Across Monitor Mode
Pitch	-0.06* (0.54)**	0.04 (0.50)	-0.08 (0.53)	-0.04 (0.52)
Roll	-0.83 (1.32)	-0.45 (1.29)	-0.09 (0.84)	-0.46 (1.20)
Across Axis Failed	-0.44 (1.07)	-0.21 (1.00)	-0.09 (0.70)	-0.25 (0.94)

* Mean heading error change in degrees.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

Contrary to what was shown for roll attitude (Table R-15), heading error indicated in Table R-17 was greater as a consequence of passive failures. Even though roll attitude changes at pilot response were high during softover failures, pilot response time was faster which resulted in less change in heading error and, consequently, less lateral displacement.

TABLE R-17
Heading Error Change During Control Failures

Failure Intensity	Failed Axis: Pitch	Failed Axis: Roll	Across Axis Failed
Passive	-0.07* (0.57)**	-0.74 (1.34)	-0.40 (1.08)
Softover	-0.00 (0.47)	-0.18 (0.96)	-0.09 (0.76)
Across Failure Intensity	-0.04 (0.52)	-0.46 (1.20)	-0.25 (0.94)

* Mean heading error change in degrees.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

Lateral drift. Lateral drift difference was treated the same as the previous measures. The change in lateral drift was greater during roll failures than during pitch failures, as expected. During roll failures, adding a caution light to the system did not significantly change lateral drift (Table R-18). When the caution light and annunciator panel were both operating, the change in lateral drift reduced to 6.47 feet per second. Previous measures of heading error, roll attitude and lateral displacement indicated that pitch and roll axis failures were equivalent in the caution plus annunciator panel monitor mode. This was not the case for lateral drift, because roll axis failures produced lateral drift values that were significantly different from those attained during pitch axis failures in the caution plus annunciator mode.

TABLE R-18
Lateral Drift Change During Control Failures

Failed Axis	Monitor Mode: No Monitor	With Caution	Caution + Annunciator	Across Monitor Mode
Pitch	-0.04* (0.68)**	-0.21 (1.08)	-0.18 (0.92)	-0.14 (0.90)
Roll	-10.39 (6.49)	-9.81 (5.73)	-6.47 (5.16)	-8.89 (6.02)
Across Axis Failed	-5.21 (6.94)	-5.01 (6.34)	-3.32 (4.85)	-4.51 (6.14)

* Mean lateral drift in feet per second.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

Looking further into the caution plus annunciator mode, it was found that lateral drift was also a function of failure intensity in that mode. Table R-19 shows that softover failures produce the higher drift in the caution plus annunciator mode.

TABLE R-19
Lateral Drift Change During
Control Failures in the Caution + Annunciator Monitor Mode

Failure Intensity	Mean	Standard Deviation
Passive	-1.41*	2.46
Softover	-5.24	5.85

* Feet per second.

Disregarding monitor mode, roll axis softovers (Table R-20) created lateral rates of 11.04 feet per second, whereas passive failures showed 6.74 feet per second lateral rates at pilot response. These lateral drift changes verify the consequence of roll attitude changes seen earlier.

TABLE R-20
Lateral Drift Change During Control Failures

Failure Intensity	Failed Axis: Pitch	Failed Axis: Roll	Across Axis Failed
Passive	-0.34* (0.90)**	-6.74 (5.73)	-3.54 (5.20)
Softover	-0.06 (0.86)	-11.04 (5.55)	-5.49 (6.83)
Across Failure Intensity	-0.14 (0.90)	-8.89 (6.02)	-4.51 (6.14)

* Mean lateral drift in feet per second.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

Summary of lateral displacement changes. The effect of failure monitor mode upon lateral plane performance was generally the same as the vertical plane. Generally, there were no differences between the no monitor and the caution light only; but, performance improved with the addition of the annunciator panel. Softover failures led to high roll attitude and lateral drift at pilot response; but, possibly because response times to softover failures were considerably faster than response times to passive failures, these larger attitudes and drifts did not result in larger heading errors or larger lateral displacements. The softover failures appeared to be easy to detect and act upon.

<u>Summary of pilot performance during control failures</u>. Table R-21 shows that where there were differences in pilot/system performance as a function or monitor mode, the addition of a monitor with only a caution light did not change performance from the no-monitor case. During passive failures, the aircraft displacement parameters, altitude used, longitudinal range consumed, and lateral displacement accrued were all considerably reduced by the monitor with caution light and annunciator panel. With the full monitor system in operation, there were no differences between softover failures and passive failures.

Pitch attitude, vertical velocity, roll attitude, heading, and lateral drift parameters were unaffected by the monitor modes during passive failures. When these parameters were examined across both passive and softover failures, the monitor mode effect noted in the displacement parameters emerged.

TABLE R-21
Summary of Performance During Control Failures

Axis Failed	Measure	Passive Failures: No Monitor	Passive Failures: With Caution	Passive Failures: Caution + Annunciator	Passive Failures: Mean	Mean Softover Failure	Mean Across Passive & Softover Failures: No Monitor	Mean Across Passive & Softover Failures: With Caution	Mean Across Passive & Softover Failures: Caution + Annunciator	Mean Across Passive & Softover Failures: Mean
Both Pitch & Roll	Response Time (sec.)	15.68* (3.30)**	14.34 (4.40)	8.43 (0.68)		7.05 (1.82)				
	Altitude Used (ft.)	146.40 (30.94)	144.04 (47.96)	80.76 (10.71)		68.86 (18.26)				
	Longitudinal Range (ft.)	3133 (610)	3121 (968)	1680 (183)		1451 (378)				
Pitch	Attitude (deg.)				-0.24 (0.82)	-1.32 (1.80)				
	Vertical Velocity (fpm.)				-56.5 (174.9)	59.2 (194.8)	62.3 (181.3)	-77.3 (183.5)	19.1 (192.6)	
	Longitudinal nge (ft.)				2607 (939)	1221 (244)				
	Altitude Used (ft.)									89.64 (44.74)
Roll	Attitude (deg.)				-3.17 (2.61)	-8.80 (2.77)	-3.23 (4.24)	-3.26 (4.21)	2.54 (3.74)	
	Heading Error(deg.)				-0.74 (1.37)	-0.18 (0.96)	-0.83 (1.32)	-0.45 (1.29)	-0.09 (0.84)	
	Lateral Drift (fps.)				6.74 (5.73)	-11.04 (5.55)	-10.39 (6.49)	-9.81 (5.73)	-6.47 (5.16)	
	Lateral Displacement(ft.)	-29.94 (28.45)	-21.61 (22.46)	-1.10 (7.55)		-13.69 (19.50)			-5.22 (15.60)	
	Longitudinal Range (ft.)				2682 (974)	1687 (349)				
	Altitude Used (ft.)									102.92 (42.62)

* Means.
** Standard deviations.
Note: Means within the same box not significantly different.

<u>Amount of change required for pilot fault detection</u>. When slightly rearranged, these data can provide <u>some</u> information about the amount of instrument display change that takes place before a pilot detects a failure in the system and takes action on that failure (without a monitor to help him). Since pilot monitoring capabilities are in question, the data shown in the next two tables (Table R-22 and R-23) were gathered with special rules. Where a reliable difference in the data was indicated, the values were taker from pilot responses during no-monitor approaches for failures in the axis of concern and of the indicated failure intensity. Where monitor modes were not significantly different, the data were taken from means across monitor modes for the failure intensity indicated and failures in the axis of concern.

Of the pitch axis measures taken, Table R-22 indicates that when the pilots detected pitch failures, attitude had changed 0.6 degrees and vertical velocity had changed 62.3 feet per minute. These small values suggest that the pilots were deriving their cues from other sources of information; 0.6 degrees of attitude change and 62 feet per minute vertical velocity change over a 7 to-15-second time do not seem to be enough of an average discrepancy to alert the pilot.

TABLE R-22
Pitch Axis Conditions When Pilot Responded to a Failure

	Measures		
Failure Intensity	Attitude Difference	Vertical Velocity Change	Response Time
Passive	0.60 deg. * (0.73 deg.)**	62.3 fpm. (181.3 fpm.)	15.68 sec. (3.31)sec.)
Softover	0.63 deg. (1.37 deg.)	62.3 fpm. (181.3 fpm.)	7.15 sec. (2.08 sec.)

* Means, see text for explanation of how these data were selected.
** One standard deviation.

Roll Axis measures shown in Table R-23 did indicate more differences than pitch. The lateral displacement and heading error build-up seemed to trigger pilot response during the passive roll control failures. Roll attitude and rate of departure from the localizer seemed to trigger pilot responses to softover failures. Although the roll attitudes and lateral drifts were larger during softover failures, heading error had not yet accrued and the resulting lateral displacement was lower during softover failures at pilot response.

TABLE R-23
Roll Axis Conditions When Pilot Responded to a Failure

	Measures				
Failure Intensity	Attitude Difference	Drift Rate Difference	Lateral Displacement Difference	Heading Error Difference	Response Time
Passive	3.17 deg.* (2.61 deg.)**	6.74 fps. (5.73 fps.)	29.94 ft. (28.45 ft.)	0.74 deg. (1.37 deg.)	15.68 sec. (3.31 sec.)
Softover	8.80 deg. (2.77 deg.)	11.04 fps. (5.55 fps.)	15.10 ft. (17.35 ft.)	0.18 deg. (0.96 deg.)	7.15 sec. (2.08 sec.)

* Means, see text for explanation of how these data were selected.
** One standard deviation.

In the questionnaire, the pilots were asked to indicate the first cue that they used to detect a control system failure when there was no monitor operating. Forty percent (40%) of the pilots indicated glideslope and localizer deviation and 25% indicated that flight director commands triggered their decision. Thirty-five percent (35%) of the responses were varied; "wandering off," "aircraft flight path as related by instruments," and "failure of the aircraft to track properly" were typical responses in this category. The data shown in Tables R-22 and R-23 provide some measures of this error tolerance that the pilots were verbally indicating.

The difficulty of detecting a passive failure. The difficulty of detecting the passive failure was indicated by pilot responses to a scale in the questionnaire. The median responses shown in Table R-24 show a slight but non-significant difference between the no-monitor and caution-light-only monitor mode. Pilots indicated that it was hard to detect a passive failure in these modes. With the caution light and annunciator panel in operation, pilots reported the detection of passive failures to be easy.

TABLE R-24
Passive Failure Detection Difficulty

Monitor Mode	Difficulty Scale Categories						
	Very Hard	Hard	Slightly Hard	Neither Hard Nor Easy	Slightly Easy	Easy	Very Easy
No Monitor		X*					
Caution			X				
Caution + Annunciator						X	

* Median response.

TABLE R-25

Control Failure Analysis of Variance Summary

Channel	Treat	Group	Inten	Cont	Fail	IC	IF	CF	IG	CG	FG	ICG	IFG	CFG	ICF	ICFG
Longitudinal	AE	.05*	.01	.01	.01	.01	.01									
Airspeed	AE															
Altitude	AE	.05	.01	.01	.01		.01									
Response Time	AE		.01	.01	.01	.01	.01									
Pitch	AAE		.05	.01		.01	.05									
Roll	AAE		.01	.01	.05	.01										
Lateral Displacement	AAE			.01	.01			.01								
Lateral Drift	AAE		.01	.01	.01	.01	.05	.01							.05	
Heading Error	AAE		.01	.01	.05	.05		.05								

* Source of variance significant at the indicated level of confidence. Blank spaces indicate non-significant differences.

Note: Analyses shown are for the difference between failure insertion and response. AE means average with respect to signs; AAE indicates absolute averages. Analysis of variance sources are listed across the top. Main effects (Inten, Cont, and Fail) are followed by interactions of Intensity, Cont, and Failure.

Concluding remarks on control failures. Pilot detection, incorrect response, false alarm scores together with the performance data and opinion data all repeatedly indicate the same story--the detection of passive autopilot control failure is a problem for the pilot.

With no monitor system operating, it seems unlikely that any single aircraft performance parameter would provide enough information for the pilot to detect a failure. If a single parameter would have provided the right information, certainly the pilots all would have indicated it in their questionnaire responses, and that parameter would have "stood out" in the performance measurement at pilot response. The data support a common sense notion that it must be a combination of events that would lead to the detection of error in this circumstance.

In the aircraft cockpit it is probably a complex interaction of the amount of error in several different parameters combined with the rate-of-error accrual in each parameter that leads to pilot detection of a failure. Undoubtedly, the particular parameters that might be used are different from pilot to pilot. Unfortunately, the problem gets even more complicated.

As a monitor, the pilot must detect the presence of an error signal in noise that is created by the environment, turbulence and normal autopilot corrective control actions. The reality of this problem was indicated by one pilot when he wrote, "The failure had to show enough indication to assure that it was not just an error in synchronization of F/D and autopilot since they may not compensate at the same rate." An error in synchronization of the flight director or other performance and attitude instruments may be caused by either an abnormal control action or no control action where one should be required. Pilots have to look for the former, abnormal control action during softover control failures, and the latter, no control action during passive failures. The difference in reported difficulty shows that the detection of no control action where one is required is much more difficult a problem than the detection of an abnormal control action. The tone of the remarks made by all subject pilots was summarized nicely by one subject when he indicated that the no-monitor condition was "... a very dangerous situation."

When the caution light operated, there was no meaningful improvement in detection, incorrect response, false alarms, the 10 performance measures, and in the difficulty scale. It was felt that there were two reasons for this lack of improvement. First, when the caution light turned-on, the pilots still had to find the problem; in effect, the light simply told them to "worry." They had to try to differentiate between a control system failure and a display system failure. Locating the problem took time. Second, it was felt that the mode progress/fault warning system that was in the simulator did not present an optimum environment for the caution light. Normal mode progress lights were turning on to indicate the "normal" events along the bottom of the mode progress/fault warning display. The caution light turning on would indicate an "abnormal" event. Such information should be separated on the panel so that if a light comes on in the fault warning location, it definitely and unequivocally means trouble.

Finally, performance on the caution light plus annunciator panel approaches showed a dramatic improvement. There were, again, two reasons for this improvement. First, the annunciator panel in this case was four trans-illuminated switchlights which illuminated red in the appropriate axis when a failure occurred. At the right-hand side of the Captain's instrument display panel, the presence of a red light meant trouble in the indicated axis. Secondly, and more importantly, the pilot corrective action was to push the switchlight to disengage the failed axis. The red light served as a command, "push me." No pilots questioned this command; most pilots reacted quite favorably to it. This test, therefore, suggests that fault warning devices should tell the pilot <u>what to do</u> in addition to <u>what is wrong</u>. If the pilot has time, the fault warning system should allow the pilot to diagnose the problem. More is said about the characteristics of fault warning systems in the last subsection of the results section.

<u>Display Failures</u>

Display failures occurred either (1) when the autopilot was fully engaged and there had been no previous failure, or (2) when a previous control system failure had caused the pilot to disconnect an axis and manually control the failed axis. Display failures, therefore, occurred during three different piloting tasks: (1) while flying pitch manually with the roll autopilot engaged, (2) while flying roll manually with the pitch autopilot engaged, and (3) while monitoring the fully engaged autopilot. Pilot detection of display failures was quite dependent upon the piloting task for each of the principle display variables (failure mode and failure location).

<u>The effect of monitor mode and control task upon detection</u>. Table R-26 shows that the number of times that pilots did not detect display failures decreased as the caution light was added, then further decreased as the full monitor system was in operation. Out of 60 times that display failures were undetected (out of 648 approaches), nine failures were missed with the full monitor system in operation. Only two failures were undetected when the autopilot was fully operating and the pilots were required only to monitor automatic system performance.

Failure detection during split-axis control did not fare as well. Thirty-four (34) display failures went undetected when the pilots were manually controlling pitch. The worst condition (18 no-detections) occurred during roll manual approaches with no monitor in operation.

TABLE R-26
No Detection, Incorrect Response and Incorrect Decision to Land During Display Failures

Measure	Pilot Control Task	Monitor Mode: No Monitor	With Caution	Caution Annunciator	Totals
No Detection	Pitch Manual	11* 15.3%	10 13.9%	3 4.2%	24 11.1%
	Roll Manual	18 25.0%	10 13.9%	6 8.3%	34 15.7%
	Automatic	1 1.4%	1 1.4%	0 0.0%	2 0.9%
	Totals	30 13.9%	21 9.7%	9 4.2%	60 9.3%
Incorrect Response	Pitch Manual	18 25.0%	14 19.4%	14 19.4%	46 21.3%
	Roll Manual	27 37.5%	16 22.2%	10 13.9%	53 24.5%
	Automatic	10 13.9%	12 16.7%	5 6.9%	27 12.5%
	Totals	55 25.5%	42 19.4%	29 13.4%	126 19.4%
Incorrect Decision to Land	Pitch Manual	13 18.1%	10 13.9%	11 15.3%	34 15.7%
	Roll Manual	19 26.4%	11 15.3%	6 8.3%	36 16.7%
	Automatic**	7 9.7%	4 5.6%	2 2.8%	13 6.0%
	Totals	39 18.1%	25 11.6%	19 8.8%	83 12.8%

* Number of cases. Percent shown is percent of occurrance of no detection, incorrect response, or incorrect decisions to land out of the total number of display failures given during the indicated pilot task and monitor mode.

** In these cases, the pilots had not detected a previous passive control failure and thought that they were "automatic." Since they were operating as system monitors, their "incorrect decisions to land" were scored in this category.

Incorrect responses. An incorrect response was scored when a pilot did not correctly identify the display failure. Contrary to the incorrect response performance during control system failures, the number of incorrect responses reduced when the caution light was added. The 55 incorrect responses during no-monitor approaches reduced to 42 with the addition of a caution light. When the annunciator panel operated, the number of incorrect responses further reduced to 29. Again, roll manual produced more incorrect responses (53) overall, and the roll-manual, no-monitor situation was the worst case with 27 incorrect responses. Although only two failures were undetected when the pilots were monitoring the operation of the automatic system, the pilots made 27 incorrect responses to display failures while automatic. Overall, the severity of the experimental fault detection task was reflected by a 20% error rate. As a consequence of this high error rate, over two-thirds of the 126 incorrect responses led to a touchdown when the pilots should have gone around.

Incorrect decision to land. Eighty-three (83) times the pilots landed when the information upon which they were depending to manually fly the simulator had failed. Table R-26 shows that roll manual, no-monitor, was again the worst case. With the full monitor system in operation, however, pitch manual resulted in more incorrect decisions than roll manual control. The full monitor system reduced the number of times that incorrect decisions to continue were made to 19 out of 216, or about 9% of the time.

The incorrect decisions to land when the pilot was "automatic" needs further explanation. In no case was it necessary for the pilot go-around because of a display failure when the full autopilot was operational. For example, a Captain's glideslope failure did not affect the autopilot and did not require a go-around under the decision rules set for this experiment. There were, however, 13 times that the pilots had not detected a previous passive control system failure by the time that the second failure (the display failure--inserted no sooner than 20 seconds after the insertion of the previous control failure) was inserted in the same axis as the control failure. Since the pilots were not in manual control (even though they should have been), they were operating as monitors of what they thought was autopilot performance. These 13 incorrect decisions to land were placed in the "automatic" pilot control task category in Tables R-26 and R-34.

Typically, two types of responses occurred during these 13 incorrect decisions to land while the pilots were "automatic." The pilots either (1) responded correctly to the display failure but failed to realize that the autopilot was not fully operational and continued to "automatic" landing, or (2) they responded to the previous passive control failure after the display failure had occurred and ignored the display failure. Since they had made a response to the second failure, they were apparently satisfied, and continued manually in the failed axis to landing with the flag in full view. Putting this second type of response in different terms, two failures occurred. The pilots did not see the first failure. When the second failure occurred, they responded to the first and did not take further action on the second failure.

Tables R-27 through R-33 present summaries of touchdown parameters during 75 of the 83 accidental landings. The data of eight accidental landings were lost because the touchdowns occurred too rapidly for the measurement system control logic in the simulator to adequately respond. The tables show the data according to the actual conditions (pitch manual, roll manual) that existed, independent of whether or not the pilot knew that the control system failure had occurred. The principle result was that lateral plane parameters indicated some unsuccessful landings during roll axis failure and vertical plane parameters showed some unsuccessful landings during pitch failures. As will be seen, some of these accidental landings would have been successful by criteria applied to the analysis of normal touchdowns.

TABLE R-27

Pitch Attitude at Accidental Touchdown

Pitch Attitude in 2° Intervals	Pitch Manual			Roll Manual			Across Control Task			
	No Monitor	Caution	Caution + Annun.	No Monitor	Caution	Caution + Annun.	No Monitor	Caution	Caution + Annun.	Totals
-4°- 2°(down)	1*		1			1	1		2	3
-2°- 0°	5	2	2				5	2	2	9
0°- 2°	6	9	6	4	2	1	10	11	7	28
2°- 4°	4		2	10	8	3	14	8	5	27
4°- 6°				2	1		2	1		3
6°- 8°	2	1		1			3	1		4
8°- 10°										
10°- 12°										
12°- 14°(up)						1			1	1
Totals	18	12	11	17	11	6	35	23	17	75

* Number of landings when score was within the defined intervals.

TABLE R-28

Vertical Velocity at Accidental Touchdown

Rate of Descent in 500 fpm. Int.	Pitch Manual			Roll Manual			Across Control Task			
	No Monitor	Caution	Caution + Annun.	No Monitor	Caution	Caution + Annun.	No Monitor	Caution	Caution + Annun.	Totals
2000-1500	1*		1			1	1		2	3
1500-1000										
1000- 500	12	4	5	2			14	4	5	23
500- 0	5	8	5	15	11	5	20	19	10	49
Totals	18	12	11	17	11	6	35	23	17	75

TABLE R-29
Longitudinal Range from Glide Slope Transmitter
at Accidental Touchdown

Longitudinal Range in 500' Intervals	Pitch Manual: No Monitor	Pitch Manual: Caution	Pitch Manual: Caution + Annun.	Roll Manual: No Monitor	Roll Manual: Caution	Roll Manual: Caution + Annun.	Across Control Task: No Monitor	Across Control Task: Caution	Across Control Task: Caution + Annun.	Totals
4500-4000(before)	1*						1			1
4000-3500										
3500-3000										
3000-2500		1				1		1	1	2
2500-2000				1			1			1
2000-1500	1		1			1	1		2	3
1500-1000	1	1	2	1		1	2	1	3	6
(Threshold)										
1000- 500	5	3	1	1			6	3	1	10
500- 0 (G/S shack)	6	6	6	7	2	2	13	8	8	29
0- 500	3			6	5		9	5		14
500-1000	1			1	4	1	2	4	1	7
1000-1500		1						1		1
1500-2000										
2000-2500										
2500-3000(after)			1						1	1
Totals	18	12	11	17	11	6	35	23	17	75

* Number of landings when score was within the defined intervals.

TABLE R-30

Lateral Displacement at Accidental Touchdown

Lateral Displacement in 60' Inter.	Pitch Manual			Roll Manual			Across Control Task			Totals
	No Monitor	Caution	Caution + Annun.	No Monitor	Caution	Caution + Annun.	No Monitor	Caution	Caution + Annun.	
600-540(left)					1*			1		1
540-480				2		1	2		1	3
480-420										
420-360										
360-300										
300-240				1			1			1
240-180					3			3		3
180-120				1		1	1		1	2
120- 60				1			1			1
60- 0	6	6	3	2			8	6	3	17
0- 60	11	6	7	4	2	1	15	8	8	31
60-120	1		1	1	2	1	2	2	2	6
120-180										
180-240				1	1		1	1		2
240-300				1	1		1	1		2
300-360										
360-420				1	1		1	1		2
420-480						1			1	1
480-540(right)				2		1	2		1	3
Totals	18	12	11	17	11	6	35	23	17	75

* Number of landings when score was in the defined intervals.

TABLE R-31
Roll Attitude at Accidental Touchdown

Roll Attitude in 2-Degree Intervals	Pitch Manual			Roll Manual			Across Control Task			Totals
	No Monitor	Caution	Caution + Annun.	No Monitor	Caution	Caution +Annun.	No Monitor	Caution	Caution Annun.	
16° - 14° (left)				1*	1		1	1		2
14° - 12°										
12° - 10°				1			1			1
10° - 8°										
8° - 6°				2	1	1	2	1	1	4
6° - 4°					1			1		1
4° - 2°			1	2		1	2		2	4
2° - 0°	9	5	3	2	2		11	7	3	21
0° - 2°	9	7	7	4	2	3	13	9	10	32
2° - 4°					2			2		2
4° - 6°				1			1			1
6° - 8°				2			2			2
8° - 10°					2			2		2
10° - 12°										
12° - 14°										
14° - 16°				2			2			2
16° - 18°										
18° - 20°										
20° - 22° (right)						1			1	1
Totals	18	12	11	17	11	6	35	23	17	75

* Number of landings when score was within the defined interval.

TABLE R-32
Lateral Drift at Accidental Touchdown

Lateral Drift in 9Ft. Per Sec. Int.	Pitch Manual			Roll Manual			Across Control Task			Totals
	No Monitor	Caution	Caution +Annun.	No Monitor	Caution	Caution +Annun.	No Monitor	Caution	Caution + Annun.	
54 - 45(left)				1*			1			1
45 - 36										
36 - 27				1	1		1	1		2
27 - 18				1	1		1	1		2
18 - 9		1		2	1		2	2		4
9 - 0	11	7	5	2			13	7	5	25
0 - 9	7	2	4	5	1	2	12	3	6	21
9 - 18		1	1	2	2	1	2	3	2	7
18 - 27		1	1	1	2	1	1	3	2	6
27 - 36										
36 - 45				1	2		1	2		3
45 - 54(right)				1	1	2	1	1	2	4
Totals	18	12	11	17	11	6	35	23	17	75

* Number of landings when the score was within the defined interval.

TABLE R-33
Heading Error at Accidental Touchdown

Heading Error in 4-Degree Intervals	Pitch Manual			Roll Manual			Across Control Task			
	No Monitor	Caution	Caution + Annun.	No Monitor	Caution	Caution + Annun.	No Monitor	Caution	Caution Annun.	Totals
24° - 20° (left)				1*			1			1
20° - 16°				1			1			1
16° - 12°										
12° - 8°					2			2		2
8° - 4°				3			3			3
4° - 0°	9	8	5	5	2		14	10	5	29
0° - 4°	9	2	4	3	2		12	4	4	20
4° - 8°		2	2	2	2	4	2	4	6	12
8° - 12°					1			1		1
12° - 16°				2	1		2	1		3
16° - 20°					1			1		1
20° - 24° (right)						2			2	2
Totals	18	12	11	17	11	6	35	23	17	75

* Number of landings when the score was within the defined interval.

Other incorrect responses. Thirty-three of the remaining forty-three incorrect responses had two principle causes. First, there were 19 times that the pilots disengaged the autopilot completely at the sight of the second failure when it was unnecessary to do so. Second, during an additional 14 of the incorrect responses, the pilots conservatively elected to go-around when they could have continued. In a very real sense, this was hardly an error, but it was an incorrect response according to the decision rule set for this study.

Summary of the effect of monitor mode and control task upon detection. With the full monitor system, therefore, nine display failures were undetected during split-axes approaches. All display failures were detected when the pilots were, or thought that they were, automatic. Detection performance was spoiled by the number of incorrect responses. During pitch manual control with the full monitor system in operation, 14 incorrect responses resulted in 11 incorrect decisions to land. During roll manual control, 10 incorrect responses resulted in six incorrect landings. This resulting pilot/system performance with the full monitor system in operation was not felt to be good enough, even though the test was quite severe.

The effect of display failure location and control task upon detection. Flag failures occurred in three locations: (1) in the ADI, (2) in the HSI, and (3) in the radar altimeter (RA) instrument immediately to the right of the ADI. A fourth display failure, vertical gyro unreliable, was presented to examine an insidious failure that was not associated with flag events. Table R-34 shows pilot detection performance as a function of display failure location and pilot control task.

No detections. Table R-34 shows that the two no-detections during automatic control occurred during an HSI flag and a RA flag failure. When the pilots were roll manual, they missed fewer HSI flags than all other flags. When pitch manual, the pilots missed more HSI flags. The data seem to suggest that the pilots pay more attention to the radar altimeter when pitch manual (two no-detections) than when roll manual (10 no-detections). The vertical gyro unreliable failure was detected more frequently when pitch manual. Quite likely, the pilots adopted different scan patterns for the different control tasks. Over all control tasks, the ADI and HSI flags were missed more frequently (17 each) than the radar altimeter flag (13) and the vertical gyro unreliable (13).

TABLE R-34
No Detection, Incorrect Response and Incorrect Decision to Land During Display Failures

Measure	Pilot Control Task	Failure Location ADI Flag	HSI Flag	RA Flag	VG Unreliable	Total
No Detection	Pitch Manual	7* 13.0%	10 18.5%	2 3.7%	5 9.3%	24 11.1%
	Roll Manual	10 18.5%	6 11.1%	10 18.5%	8 14.8%	34 15.7%
	Automatic	0 0.0%	1 1.9%	1 1.9%	0 0.0%	2 0.9%
	Total	17 10.5%	17 10.5%	13 8.0%	13 8.0%	60 9.3%
Incorrect Response	Pitch Manual	13 24.0%	8 14.8%	16 29.7%	9 16.7%	46 21.3%
	Roll Manual	8 14.8%	18 33.3%	12 22.2%	15 27.8%	53 24.5%
	Automatic	14 25.9%	3 5.6%	3 5.6%	7 13.0%	27 12.5%
	Total	35 21.6%	29 17.9%	31 19.1%	31 19.1%	126 19.4%
Incorrect Decision to Land	Pitch Manual	12 22.2%	0 0.0%	15 27.8%	7 13.0%	34 15.7%
	Roll Manual	5 9.3%	17 31.5%	0 0.0%	14 25.9%	36 16.7%
	Automatic**	9 16.8%	1 1.9%	1 1.9%	2 3.7%	13 6.0%
	Total	26 16.1%	18 11.1%	16 9.9%	23 14.2%	83 12.9%

* Number of cases. Percent shown is percent of occurrence of no detection, incorrect response, or incorrect decision to land out of the total number of display failures given during the indicated pilot task and failure location.

** See footnote on Table R-26.

Incorrect responses. Curiously, 18 of the HSI flags during roll manual situations led to incorrect responses and 13 of the pitch manual ADI flags led to incorrect responses. Note that the HSI flags during roll manual and the ADI flags during pitch manual were the best detection conditions during split-axis control; these same conditions were the worst in terms of incorrect responses. Fewer ADI flags led to incorrect responses during roll manual control (8) than during pitch manual control (13). Fewer HSI flags led to incorrect responses during pitch manual control (8) than during roll manual control (18). Only two RA flags were missed during pitch manual control, yet there were incorrect responses to 16 of the RA failures during pitch manual control. All ADI flags were detected during automatic control; yet, 14 responses to ADI flags were incorrect while the pilot was monitoring the autopilot. Most incorrect responses were incorrect identifications of the flags.

These data reflect that it is not enough to just see the problem; the pilot must be able to correctly respond to what he sees. These data are a clear case for the necessity of labeling instrument flags and having the flags cover the functions that are failed.

Incorrect decisions to land. During pitch manual control, all ADI flags, RA flags and vertical gyro failures required a go-around. For these failures, almost all incorrect responses resulted in an incorrect decision to land. While pitch manual (roll auto), an HSI flag was not a go-around situation and, therefore, resulted in no incorrect decisions to land. The same was true of the radar flag during roll manual approaches. During roll manual, all HSI flags, vertical gyro unreliable and the ADI vertical gyro flags required a go-around. Incorrect responses to these failures almost always led to an incorrect decision to land.

Summary. During pitch manual control, most non-detections occurred on the HSI although seven ADI flags were missed. During roll manual control, most non-detections occurred on the ADI and radar altimeter (10 each). Eight (8) vertical gyro unreliable failures were missed and six (6) HSI flags were undetected. ADI and HSI flags were missed more than radar flags and the vertical gyro unreliable failures. Most incorrect responses occurred to ADI flags (35) although HSI (29), radar (31), and vertical gyro unreliable failures (31) were not far behind. The largest number of incorrect responses (18) occurred to HSI flags during roll manual control. Curiously, as the probability of detection increased, the number of incorrect responses also increased for a particular control task.

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[1]A vertical gyro failure while split-axes required the pilot to relinquish control to the First Officer in this experiment. This failure was, therefore, not well received by the pilots, who confessed operational reluctance to transfer control at the critical moment of go-around during these low altitude failures.

As previously noted, a pilot's ability to detect failures and respond correctly is seriously degraded when he is actively in control of one or more axes. When he is only monitoring a fully automatic system, his ability to detect failures is good, but his ability to respond correctly is not as good as desired. Perhaps the responses seen in this study would be better with more extensive training.

Having shown pilot detection, non-detection and incorrect responses during display failures, pilot/system performance changes during display failures will next be examined. Pilot response time, pitch attitude, vertical velocity, altitude used, longitudinal range consumed, indicated airspeed change, lateral displacement, lateral drift, heading error and, finally, roll attitude comprise the system performance measurement set.

Pilot response time. Response time indicated the amount of time consumed between display failure insertion and pilot response to that failure. Table R-35 shows that pilot responses to ADI flags were faster (5.56 sec.) than responses to HSI and radar altimeter flags (RA) and the vertical gyro unreliable (VGU) failure (average 7.36 sec. to HSI, RA, and VGU). The failure monitor mode did not influence pilot response time to display failures. Neither was pilot response time affected by pilot control task (split-axes or automatic).

TABLE R-35

Pilot Response Time During Display Failures

Measure	Display Failures: ADI	HSI	RA	VGU
Mean	5.56*	7.30	7.64	7.15
Standard Deviation	3.46	4.79	5.03	5.06

* Seconds.

Pitch attitude. The change in pitch attitude between failure insertion and pilot response was high (pitch-up) and more variable (1) during pitch manual control when the radar altimeter had failed and (2) during roll manual control when the vertical gyro unreliable failure occurred (Table R-36). The pitch manual radar altimeter failures and roll manual vertical gyro failures were go-around conditions. These data suggest that pilots had started to execute go-around prior to triggering the response measurement by engaging the flight director go-around mode or disengaging the autopilot during these conditions. No such pitch-up action was evidenced during other go-around situations (ADI and VGU failures during pitch manual and HSI failures during roll manual). The apparent initiation of go-around prior to triggering response was also seen in the vertical velocity data.

TABLE R-36

Pitch Attitude Change During Display Failures

Pilot Control Task	Display Failures				Across Display Failure
	ADI	HSI	RA	VGU	
Pitch Manual	-0.45 * (2.12)***	-0.23 (1.56)	-2.20** (4.57)	-0.63 (2.41)	-0.88 (2.98)
Roll Manual	0.00 (0.62)	-0.63 (2.49)	-0.06 (0.93)	-1.46** (4.31)	-0.51 (2.61)
Automatic	0.20 (0.99)	-0.11 (0.72)	0.03 (0.39)	0.24 (0.24)	0.09 (0.75)
Across Control Task	-0.08 (1.41)	-0.32 (1.75)	-0.71 (2.89)	-0.61 (2.95)	-0.43 (2.36)

* Mean difference in degrees between failure insertion and response.

** These two scores significantly different from all the rest, but not from each other. Remaining scores are not significantly different.

*** One standard deviation.

Vertical velocity. Vertical velocity during display failures changed as a complex interaction of (1) monitor mode, (2) the particular display failure, (3) pilot control task, and (4) pilot group differences.[1] These data are presented by failure monitor mode, starting with no monitor approaches.

No monitor. During no monitor approaches, the two pilot groups had exactly the same conditions. Vertical velocity decreased during the pitch manual, radar altimeter failure for both groups (Table R-37). The decrease

[1]As indicated in the method section, the pilots were placed into two groups; one group had a "Flag" light for flag failures during the "caution" monitor mode and the other group had the caution light. During "no monitor" conditions both pilot groups had equivalent conditions. The analysis of variance results, however, indicated group differences during the no monitor condition. These two pilot groups were not equivalent during equivalent conditions; therefore, the flag light variable was confounded with pilot group differences.

in vertical velocity was evidence that a go-around had already been initiated when the pilots responded by disengaging the autopilot or engaging the go-around flight director mode. Group differences were apparent during the vertical gyro unreliable failure. Group II roll manual had little vertical velocity change; yet, Group I pilots during the same conditions had initiated a go-around. When the monitor "with caution light" was added, vertical velocity change was quite different.

TABLE R-37

Vertical Velocity Change During No Monitor Display Failures

Group	Manual Axis	Display Failure ADI	HSI	RA	VGU	Across Display Failures
I	Pitch	-54* (309)**	-157 (363)	-394 (982)	-39 (287)	-161 (558)
	Roll	98 (225)	-85 (214)	-148 (250)	-319 (914)	-113 (500)
II	Pitch	-169 (290)	-21 (351)	-512 (1045)	-258 (529)	-240 (628)
	Roll	60 (202)	-129 (431)	-143 (192)	-56 (182)	-671 (273)

* Mean difference in feet per minute between failure insertion and response.
** One standard deviation.

With caution. This monitor mode has been called "with caution" for brevity. Actually, this mode contained the caution light, flag light and deviation light variables. Group I had a caution and deviation light operating. Group II had a flag light for flag failures or a caution light for vertical gyro unreliable failures. Table R-38 shows what happened.

With caution and deviation light (Group I) operating, go-around appeared in progress during pitch manual ADI flags and during roll manual vertical gyro unreliable failures. Whereas Group I pilots were executing go-arounds to radar altimeter flags during pitch manual with no monitor (Table R-37), they stopped doing this when the caution and deviation light operated (Table R-38). Group II pilots further decreased their vertical velocity during radar altimeter failures while pitch manual. Since the nominal vertical velocity during the approach was -640 feet per minute, the -704 feet per minute average value of vertical velocity change (difference between failure insertion and pilot response) indicated that a positive climb rate was established prior to engaging the go-around mode or disengaging the roll autopilot. Pilots in Group II were responding to the roll manual HSI flags in the same way. Further comment will be deferred until the final part of this interaction, the caution plus annunciator monitor mode, has been presented.

TABLE R-38

Vertical Velocity Change During "Caution" Mode Display Failures

Group		Manual Axis	Display Failure: ADI	HSI	RA	VGU	Across Display Failures
I:	Caution + Deviation	Pitch	-415* (997)**	71 (271)	-173 (679)	162 (301)	-87 (649)
		Roll	-26 (174)	-46 (241)	19 (206)	-372 (975)	-106 (522)
II:	Flag or Caution	Pitch	-300 (445)	-268 (589)	-704 (862)	-212 (465)	-307 (619)
		Roll	-56 (218)	-520 (822)	-65 (319)	-30 (153)	-138 (486)

* Difference in feet per minute between failure insertion and response.

** One standard deviation.

Caution plus annunciator. When the full monitor system was operating, both groups again had the same conditions. More evidence of executing go-arounds prior to engaging the go-around mode was seen. Table R-39 shows both groups executing go-around during pitch manual radar altimeter flags and vertical gyro unreliable failures. Whereas Group I executed go-arounds in this fashion during "caution light," pitch manual ADI failures (see Table R-38), their vertical velocity was increasing by 266 feet per minute (sinking more rapidly) during the same conditions with full monitor plus annunciator panel in operation (Table R-39). Group I showed a similar reversal of strategy during vertical gyro unreliable failures while roll manual; in the "caution light" mode (Table R-38), Group I pilots had started go-around, but exhibited less tendency to go-around under the same conditions with the full system in operation (Table R-39).

Group II strategy also changed. During roll manual HSI flags with a flag light (Table R-38), Group II was clearly executing go-around prior to response (average velocity change of -520). During the same conditions with the full monitor system (Table R-39) there was only an average 12 foot per minute change in vertical velocity at response.

TABLE R-39

Vertical Velocity Change During Display Failures With The Full Monitor

Group	Manual Axis	Display Failure				Across Display Failures
		ADI	HSI	RA	VGU	
I	Pitch	266* (542)**	-60 (225)	-548 (1072)	-598 (1193)	-235 (893)
	Roll	9 (227)	-402 (902)	-12 (103)	171 (457)	-59 (542)
II	Pitch	-515 (589)	38 (412)	-479 (1096)	-323 (749)	-320 (755)
	Roll	12 (195)	122 (295)	-6 (170)	-513 (901)	-96 (531)

* Mean difference in feet per minute between failure insertion and response.

** One standard deviation.

Discussion. During no-monitor approaches with vertical gyro unreliable failures, basic group differences were evident. These group differences verified our subjective judgment that the pilot groups were not equivalent. One group seemed to have more difficulty adopting the required decision logic and executing their decisions in the short time required. Out of all the performance data taken, only vertical velocity change showed group differences.

The flag light may have had some value when the annunciator panel was not operating. Seven out of nine pilots who saw the flag light (78%) reported it to be of significant value in their questionnaires. Vertical velocity showed more go-arounds in progress when response was triggered during the flag light operation than during caution light operation for the same failures. The basic group differences, however, could have contributed to the performance seen during flag light only conditions, and thus confounded these data. Since overall performance was more consistent during the full monitor system operation, it must be concluded that the flag light <u>may</u> have had some benefit, but the full system with the annunciator was better.

At one time or another, the pilots initiated go-around before triggering "response" measurement by engaging the go-around flight director mode, disengaging the autopilot or pushing the response bar. Their strategy seemed to be a simple matter of priority: FIRST, act to initiate a positive climb rate, THEN, engage go-around, disconnect the autopilot and clean-up the aircraft as time permitted. Unfortunately, this pilot strategy desensitized the response measures taken during display failures, along with some of the go-around measurement.

"Response" was not always triggered at the same point in the detection-decision-response sequence of events. Where a go-around was required, more go-arounds were in progress at response during the full caution-plus-annunciator monitor mode than during the with-caution monitor mode; the with-caution mode elicited more go-arounds in progress at "response" than during the no-monitor mode. If pilots had triggered response measurement prior to taking their go-around action in all cases, then the response time measures may have shown proportionally shorter response times to the monitor-with-caution and the monitor-with-caution-and-annunciator modes. As it was, response time was not sensitive to any monitor mode differences. For the same reason, all display failure response measurement was desensitized during the caution and caution-plus-annunciator modes. These data, however, do reflect the time and parameter changes from failure insertion until the pilot had the first opportunity to hit the response bar, disconnect the autopilot, or engage go-around, which is certainly valuable information.

Altitude used. An average 62.95 feet was consumed between failure insertion and pilot response during all display failures. The standard deviation shows that 68% of the time altitude consumed was within ± 53.33 feet of that mean. Failure monitor modes, pilot control task and failure location did not systematically affect the amount of altitude used.

Longitudinal range. The differences between longitudinal range at failure insertion and pilot response indicated the distance traveled while the pilot was detecting and acting upon the failure. Similar to response time, monitor mode did not influence distance traveled, but display failure location did. Table R-40 shows that the average distance traveled during ADI failures was 1,133 feet, while the distance traveled during all other display failures was about 1,515 feet on the average. As the range increased, so did the variability.

TABLE R-40

Longitudinal Range Traveled During Display Failures

Measure	Display Failure ADI	HSI	RA	VGU
Mean	1133*	1496	1584	1465
1 Standard Deviation	727	1004	1031	1026

* Distance in feet.
Note: Means contained within the box are not significantly different.

Indicated airspeed. Airspeed did vary slightly as a function of failure monitor mode (Table R-41). When there was no monitor at all, airspeed increased only 0.1 knots on the average. When the monitor operated in both the caution light and annunciator panel modes, airspeed increased an average 1.7 knots between failure insertion and pilot response. Practically, this small average change in airspeed may seem meaningless; but, note the standard deviations.

TABLE R-41

Indicated Airspeed Change During Display Failures

	Monitor Mode		
Measure	No Monitor	With Caution	Caution + Annunciator
Mean	-0.11*	-1.53	-1.87
1 Standard Deviation	4.77	6.70	7.76

* IAS change in knots

Note: Means contained within the box are not significantly different.

In the two modes of monitor operation, airspeed change at pilot response varied around the indicated means ± approximately 7 knots 68% of the time. Therefore, 32% of the time airspeed deviated in excess of ± 7 knots about the mean. Since the vertical velocity and pitch attitude measures revealed that the pilots had initiated go-around prior to triggering the response measurement, the variability of airspeed with the monitor system in operation also must have been due to thrust application prior to triggering response during go-around decisions.

Lateral displacement. The average change in lateral displacement from display failure insertion until pilot response varied as a function of pilot control task, display failure and monitor mode during roll manual approaches. Disregarding monitor mode for the moment, Table R-42 indicates that average lateral displacement changed most during radar altimeter failures when the pilots were roll manual (62.29 feet).

The next largest change was 29.13 feet during HSI failures when roll manual and, finally, an average 7.86 feet during HSI failures when pitch manual. Note that the variability of these data was quite high, indicating a great deal of lateral displacement change during roll manual display failures.

Table R-43 shows that under no monitor, roll manual conditions, lateral displacement changed an average 154 feet when radar altimeter failures occurred. Especially note that one standard deviation during this condition was

271 feet. Sixteen percent (16%) of the time, lateral displacement changed more than 271 plus 154, or 425 feet.

TABLE R-42

Lateral Displacement Change During Display Failures***

Pilot Control Task	Display Failure				Across Display Failures
	ADI	HSI	RA	VGU	
Pitch Manual	-0.06* (19.74)**	7.86 (49.15)	0.22 (25.79)	-5.99 (46.88)	0.61 (37.69)
Roll Manual	-10.94 (81.68)	29.13 (140.11)	62.29 (192.06)	-6.17 (143.50)	18.58 (146.74)
Automatic	2.19 (38.85)	-0.35 (5.71)	1.42 (13.99)	-5.59 (26.12)	-0.59 (24.61)
Across Control Task	-2.94 (53.43)	12.21 (86.16)	21.31 (115.20)	-5.78 (87.90)	6.20 (88.91)

* Mean difference in feet between failure insertion and response.

** One standard deviation.

*** An interaction of roll manual control with monitor modes underlies these data: See also Table R-43.

Note: Means contained within the box are not significantly different.

The addition of the caution light drastically reduced average lateral displacement change during radar altimeter failures when roll was manual (from no monitor 154 feet to 1.97 feet), but created a large average change in lateral displacement during HSI failures (from no monitor 2.75 feet to 87 feet). The magnitude of lateral displacement changes during these worst case conditions deserves some diagnosis.

Table R-44 shows the roll manual, radar altimeter, no monitor and caution light, HSI failure data two ways. First, the average change data treatment repeats what was previously shown in Table R-43. The change in absolute lateral displacement (signs ignored) for the same conditions represent the second treatment.

In review, the average change subtracts the lateral displacement at pilot response from the lateral displacement at failure insertion. If Y = lateral displacement in feet, the + Y would occur right of the centerline, -Y would occur left of the centerline, and $\Delta Y = Y$ failure -Y response. Any

TABLE R-43

Lateral Displacement Change During Display Failures

Display Failure	No Monitor			With Caution			Caution + Annunciator			Across Monitor Modes and Pilot Control Tasks
	Pitch Manual	Roll Manual	Auto	Pitch Manual	Roll Manual	Auto	Pitch Manual	Roll Manual	Auto	
ADI	2.56*	-6.89	11.94	0.36	-14.92	-2.69	-3.08	-11.00	-2.69	-2.94
HSI	28.56	2.75	0.50	-9.17	87.44**	-1.14	4.19	-2.81	-0.42	12.21
RA	-0.22	154.28**	-0.31	-1.06	1.97	4.75	1.94	30.61	-0.19	21.31
VGU	-2.67	-26.42	-9.97	-4.33	-19.42	-6.67	-9.78	27.33	-0.14	-5.78
Across Display Failures	7.06	30.93	0.54	-3.55	13.77	-1.44	-1.68	11.03	-0.86	6.20
Standard Deviations:										
ADI	10.23	77.21	58.19	29.20	72.70	32.37	15.51	97.58	10.92	53.43
HSI	73.95	113.44	3.96	26.82	189.51	8.98	23.83	83.69	1.43	86.16
RA	39.96	271.80	9.59	12.58	108.91	21.72	17.72	124.04	5.37	115.20
VGU	6.71	177.79	35.29	22.71	141.65	28.18	79.13	103.52	5.83	87.90
Across Display Failures	43.44	187.14	34.58	23.48	139.31	24.30	42.39	102.68	6.75	89.91

* Mean difference in feet between failure insertion and response.
** These two scores are significantly different from each other and all the remaining scores.
Remaining scores are not significantly different.

positive value of Δ Y would therefore represent aircraft movement from right to left whether or not it crossed the centerline. Negative values of Δ Y represent movement from left to right.

TABLE R-44

Lateral Displacement Change During Two Display Failure Conditions

Roll Manual Worst Conditions	Data Treatments: Average Change	Absolute Change
No Monitor with RA failure	+ 154 *	- 3
Caution with HSI failure	+ 67	- 43

* Feet.

In both roll manual cases shown in Table R-44, the change indicated aircraft movement to the left; but, what we really want to know is, were the pilots making their lateral situation better or worse? They could have been laterally displaced at the failure insertions and have been converging on the centerline of the localizer; or, they could have been on the beam at failure insertion and have been diverging at response. Since the absolute average changes ($|\Delta Y| = |Y_f| - |Y_r|$) were negative, the absolute values of lateral displacement at response were larger than the absolute values at failure insertion. Therefore, the amount of lateral displacement during roll manual radar altimeter failures with no monitor, and HSI failures with caution light actually changed from an error on the right side of the course to a larger error on the left side of the course as shown in Figure R-1. If lateral drift was building at the response, the lateral displacement could result in a marginal situation below 200 feet of altitude.

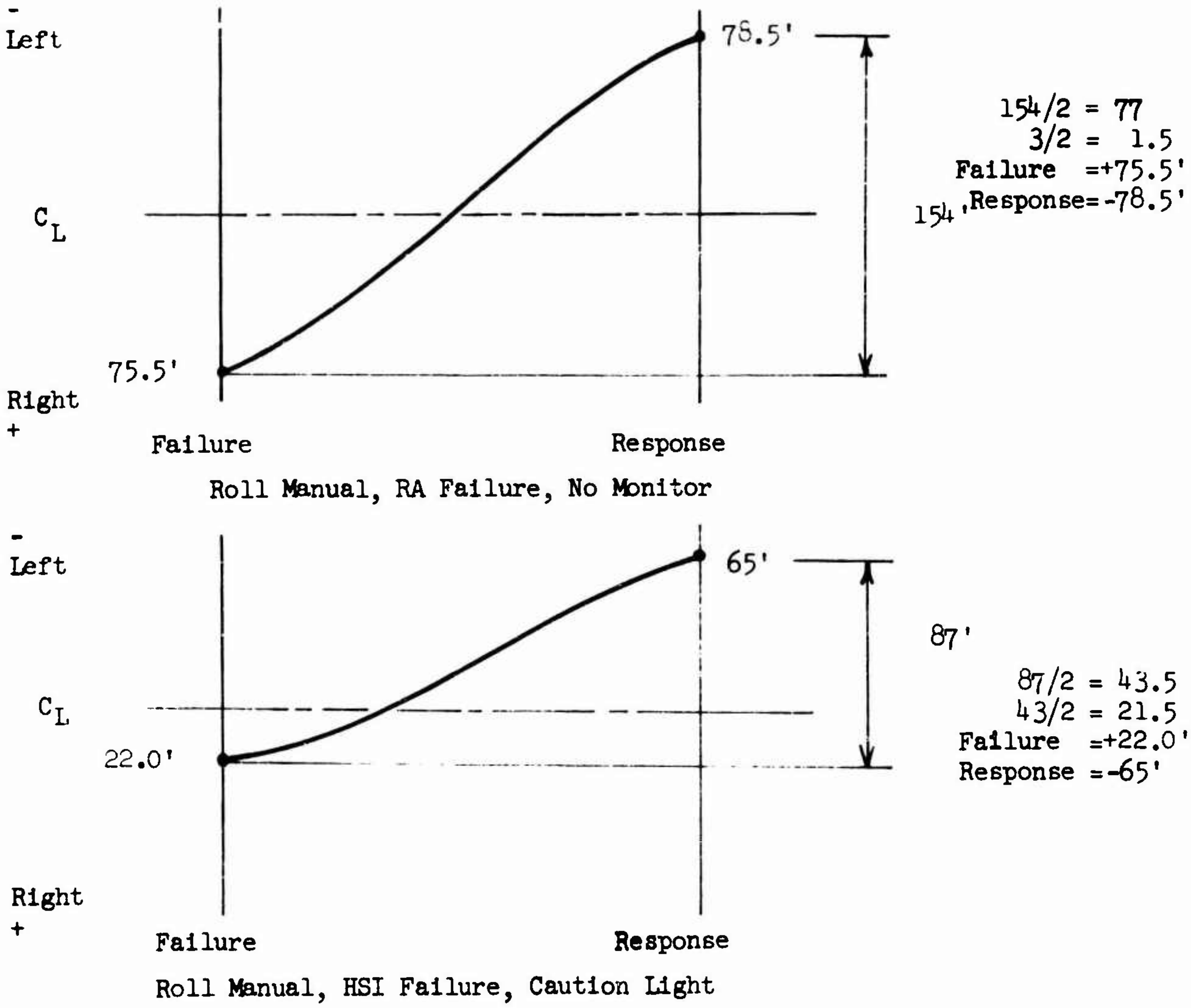

FIGURE R-1 - Lateral Displacement During Two Roll Manual Conditions

Lateral Drift. The monitor mode by pilot control task by display failure interactions shown in lateral displacement data was not significant in the lateral drift data. We must, therefore, examine the available evidence as a function of two data treatments by monitor mode and control task in order to determine the seriousness of the lateral displacement data just presented.

First, Table R-45 shows that the average lateral drift at pilot response was lower durin the no-monitor approaches (-1.52 feet per sec.) than during the caution-plus-annunciator mode (2.22 feet per sec.). The change in lateral drift followed the same pattern, but indicated that the monitor-with-caution and no-monitor approaches were not significantly different; very small values resulted. The lateral drift at failure insertion was, therefore, the same as the lateral drift at pilot response for the no-monitor and with-caution conditions. Note, however, that the variability of these data was rather high--one standard deviation was better than 10 feet per second in all cases.

TABLE R-45

Lateral Drift During Display Failures

	Monitor Mode		
Measure	No Monitor	With Caution	Caution + Annunciator
At Pilot Response	-1.52* (12.45)**	0.11 (13.60)	2.22 (11.98)
Change During Failure	0.76 (11.01)	-0.64 (10.38)	-2.66 (10.55)

* Feet per second.
** One standard deviation.
Note: Means contained within boxes are not significantly different.

Returning now to the roll manual lateral problem, Table R-46 shows an absolute average lateral drift at pilot response of 21 feet per second. The change in absolute lateral drift during the failures was positive (2.91 feet per second), indicating that drift was smaller in absolute magnitude at pilot response than at failure insertion. Again, the standard deviations were large enough to take notice of them.

TABLE R-46
Lateral Drift During Display Failure

	Pilot Control Task		
Measure	Roll Roll Manual	Pitch Manual	Automatic
At Pilot Response	21.36* (15.43)**	5.35 (4.75)	2.36 (2.11)
Change During Failure	2.91 (11.61)	-1.11 (4.35)	-0.33 (1.84)

* Absolute average in feet per second.
** One standard deviation.
Note: Means contained within boxes are not significantly different.

Summary. Thus far it appears that the roll manual lateral displacement during HSI and radar altimeter failures was not getting any worse, i.e., Lateral drift was high, but was getting smaller at pilot response. Pitch manual and automatic approaches show much better lateral performance, as would be expected. Finally, the caution light monitor mode reduced lateral displacement during radar altimeter flag failures, quite likely by bringing the radar altimeter failure to the attention of the pilot. During roll manual display failures, an HSI flag was a go-around situation, and the presence of the caution light seemed to create a lateral displacement problem. Since this was a go-around, it is possible that the pilots concentrated on executing the go-around in pitch, giving lateral displacement performance a secondary priority. This hypothesis was somewhat verified by heading error data showing a similar effect.

Heading error. As in lateral displacement and lateral drift, the absolute heading error change (Table R-47) showed an average increase in heading error of -1.75 degrees during roll manual HSI failures. An increase in heading error was also seen during vertical gyro failures while roll-manual (-1.19 degrees). Both of these conditions were go-around situations out of roll manual control, and seem to suggest that the roll axis was at least momentarily disregarded while executing go-arounds. Also evident was a reduction in heading error while roll manual with ADI flags (not a go-around). The variability of heading error was in the 4-degree region during roll manual failures.

TABLE R-47
Heading Error Change During Display Failures

Pilot Control Task	Display Failure				Across Display Failures
	ADI	HSI	RA	VGU	
Pitch Manual	0.03* (1.42)**	-0.04 (1.08)	0.19 (1.38)	0.07 (1.43)	0.06 (1.36)
Roll Manual	0.59*** (4.71)	-1.75*** (4.94)	0.26 (4.28)	-1.19*** (3.89)	0.10 (4.54)
Automatic	-0.24 (1.21)	-0.05 (1.11)	-0.05 (0.98)	-0.34 (1.25)	-0.71 (1.14)
Across Control Task	0.13 (2.93)	-0.67 (3.08)	0.13 (2.64)	-0.49 (2.55)	-0.21 (2.82)

* Mean difference in degrees between failure insertion and response.
** One standard deviation.
*** These scores are significantly different from each other and all the rest. Remaining scores are not significantly different.

Roll attitude. The only roll attitude data treatment that revealed a performance difference as a function of the experimental variables was the absolute roll attitude at pilot response shown in Table R-48. When roll was manually controlled, there was an average 4.6-degree roll attitude at pilot response. The change in roll attitude from failure insertion to pilot response was -0.36 degrees on the average, with a 4.65-degree standard deviation. The change in absolute roll attitude was -0.21 degrees on the average with a 2.99-degree standard deviation. Roll attitude at pilot response was high in magnitude and in the opposite direction from roll attitude at failure insertion.

TABLE R-48
Absolute Roll Attitude at Pilot Response
to Display Failures

Roll Manual	Pitch Manual	Automatic
4.60*	0.86	0.42
(4.95)**	(1.39)	(0.91)

* Absolute average in degrees.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

Summary of performance data. The full monitor system yielded the best performance for all pilot control tasks (split-axes and automatic) and for all display failures that were given. Vertical velocity change showed the flag light to be of some benefit when the annunciator was not in operation, but performance with the annunciator panel and caution light was better. The roll manual pilot task yielded large lateral displacement changes during radar altimeter and HSI failures with no monitor, and during the caution light monitor mode approaches. Although the full monitor system significantly reduced these large lateral displacement changes (See Table R-49), the best performance while roll manual showed an average 11-foot change with a 102-foot standard deviation during display failures. The possibility of a 102-foot lateral displacement change at low altitude was therefore quite high.

Pitch attitude change and vertical velocity change revealed that the pilots were initiating go-around prior to engaging go-around mode or disconnecting the autopilot. Lateral displacement change during display failures suggested that the pilots disregarded the lateral axis momentarily during the initial part of the go-around. Lateral displacement changed from error on the right side of the course to larger error on the left, quite possibly because of left-handed pilot wheel/column operation and right-handed thrust application during go-around.

Concluding, the full monitor system was necessary to stabilize performance, but it did not yield extremely precise (especially, lateral) performance when the pilot was distracted by a manual control task. The touchdown performance measures (in a following section) show that the pilot did not always recover the lateral axis prior to touchdown. Go-around performance, also presented in a following section, shows lateral displacement also.

TABLE R-49
Selected Performance During Display Failures

Measure	Display Failure: ADI	HSI	RA	VGU	Average Over Display Failures
Pilot Response Time	5.56 sec.* (3.35 sec.)**	7.30 sec. (4.79 sec.)	7.64 sec. (5.03 sec.)	7.15 sec. (5.06 sec.)	
Altitude Used					62.95 ft. (53.33 ft.)
Distance Traveled	1133 ft. (727 ft.)	1496 ft. (1004 ft.)	1584 ft. (1031 ft.)	1465 ft. (1026 ft.)	
Lateral Displacement:					
Pitch Manual (All Monitor Modes)	-0.06 ft. (19.74 ft.)	7.86 ft. (49.15 ft.)	0.22 ft. (25.79 ft.)	-5.59 ft. (46.88 ft.)	
Roll Manual (All Monitor Modes)	-10.94 ft. (81.68 ft.)	29.13 ft. (140.11 ft.)	62.29 ft. (192.66 ft.)	-6.17 ft. (143.50 ft.)	
No Monitor	-6.89 ft. (77.21 ft.)	2.75 ft. (113.44 ft.)	154.24 ft. (271.28 ft.)	-26.42 ft. (177.79 ft.)	30.93 ft. (187.14 ft.)
Caution	-14.92 ft. (72.70 ft.)	87.44 ft. (189.51 ft.)	1.97 ft. (108.91 ft.)	-19.42 ft. (141.65 ft.)	13.77 ft. (139.31 ft.)
Caution + Annunciator	-11.00 ft. (97.58 ft.)	-2.81 ft. (83.69 ft.)	30.61 ft. (124.04 ft.)	27.33 ft. (103.52 ft.)	11.03 ft. (102.60 ft.)

* Mean.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

TABLE R-50

Display Failure Analysis of Variance Summary

Channel	Measure	Treat	G.	Error	Disp	Cont	Fail	DC	DF	CF	DG	CG	FG	DCG	DFG	DCF	DCFG
Pitch	TC[4]	AE[6]						.01									
Pitch	TC	AAE[7]				.01 *		.01									
Roll	TC	AE															
Roll	TC	AAE				.01											
Y Drift[1]	TC	AE					.01										
Y Drift	TC	AAE				.01											
Pitch	IC-TC[5]	AE				.01		.01									
Sink	IC-TC	AE				.01		.01									.01
Roll	IC-TC	AE															
Y Displ[2]	IC-TC	AE			.01			.01								.01	
Y Drift	IC-TC	AE					.01										
Head	IC-TC	AE															
X Range[3]	IC-TC	AE			.01												
IAS	IC-TC	AE					.01										
Alt	IC-TC	AE															
R/T	IC-TC	AE			.01												
Pitch	IC-TC	AAE				.01		.01									
Roll	IC-TC	AAE	.05														
Y Displ	IC-TC	AAE															
Y Drift	IC-TC	AAE				.01											
Head	IC-TC	AAE						.01									

1. Lateral drift.
2. Lateral displacement.
3. Longitudinal range.
4. Measure at pilot response.
5. Difference between failure insertion and response.
6. Average error with respect to sign.
7. Average absolute error.

* Source of variance significant at the indicated level of confidence.

Flare Mode Failure

During three approaches for each subject (54 approaches total) the autopilot flare mode failed to engage at 50 feet. When this happened, the only cue the pilot had was that the mode engagement light on the mode progress display failed to turn on. The pilots did not detect the flare mode engagement failure 37 times (69%). Resulting touchdown performance is shown in Table R-51.

TABLE R-51

Flare Mode Failure Touchdown Performance

Measure	Mean	Standard Deviation
Distance Down Runway	1025.0 ft.	297.0 ft.
Vertical Velocity	464.0 ft./min.	160.0 ft./min.
Pitch Attitude	1.9 deg.	1.1 deg.
Roll Attitude *	0.5 deg.	1.0 deg.
Heading Error *	1.5 deg.	1.6 deg.
Lateral Displacement *	16.4 ft.	19.7 ft.
Lateral Drift *	2.2 ft./sec.	4.6 ft./sec.
Airspeed	127.8 kts.	2.8 kts.

* Absolute average (signs ignored).

Note in Table R-51 that the only serious consequence of the flare mode failure was that the vertical velocity on touchdown was high, as would be expected. The pilots generally thought that failure of a light to turn on was a poor way to alert the pilot to a problem, especially in this portion of the profile approach, where vision is narrowing down to essential performance parameters on the pilot's display panel.

Go-Around Performance

Go-around performance measurement was taken at the lowest altitude attained during the go-around execution. Data were also generated that described the change in performance between the time the pilot responded to the failure (pilot response) and the time that the lowest altitude was attained. The analysis of variance summary is shown in Table R-56.

Vertical plane performance. The failure monitor mode did not influence vertical plane performance during go-around; but pilot task prior to the second failure that created the go-around requirement did influence performance. The lowest altitude was attained (1) more quickly, (2) in less longitudinal distance, and (3) with less altitude consumed when the pilot was pitch manual split-axis compared to roll manual split-axis (Table R-52). Of the 203 go-arounds that occurred, there were only three cases during which the simulator descended below the glideslope at the lowest altitude. The worst case was a 1.23 foot loss. In no case was this altitude lost during go-arounds with the full monitor system in operation. In fact, Table R-53 shows that the aircraft was 19.0 feet above the glideslope at the lowest altitude on the average during go-arounds with the full monitor system in operation. There were, however, some cases of smaller altitude gains as reflected by the 11.3 foot standard deviation of the scores underlying that 19.0 foot performance mean.

Curiously, the altitude consumed between response and the lowest altitude attained seemed to be only a function of the amount of altitude remaining. A scatter plot of the altitude consumed between pilot response and the lowest altitude attained and the altitude at which response occurred is shown as Figure R-2. Note that there is no real clustering of the data except on the zero altitude consumed line which is a data artifact.[1] Non-clustering of the data suggests that the pilots employed a strategy of using the available altitude to execute their go-around rather than always going around as quickly and smoothly as possible. This strategy is alarming, for it will be absolutely safe only if the pilot correctly interprets the amount of altitude he has available to perform the maneuver. Note that two go-around attempts struck the ground. These were cases where the pilot decided to go-around at 20 feet of altitude and didn't make it. Six go-arounds came within 10 feet of the ground, and a total of 19 go-arounds came within 20 feet of the ground. Since an altitude loss below the glideslope occurred only three times, most approaches would have been within obstacle clearance limits, PROVIDED that their lateral deviation was not excessive when they were close to the ground. Lateral performance, however, shows lateral error accrual during go-around under certain conditions that could be serious when coupled with the vertical plane go-around strategy employed.

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1. The 37 cases of zero altitude consumed was a data artifact because the measurement system required that the pilot (1) disconnect the autopilot, (2) trigger go-around mode or (3) engage the "response" bar to indicate response to a failure. In 37 cases, the pilots had already attained positive vertical velocity before they exerted any of the actions above to call "response".

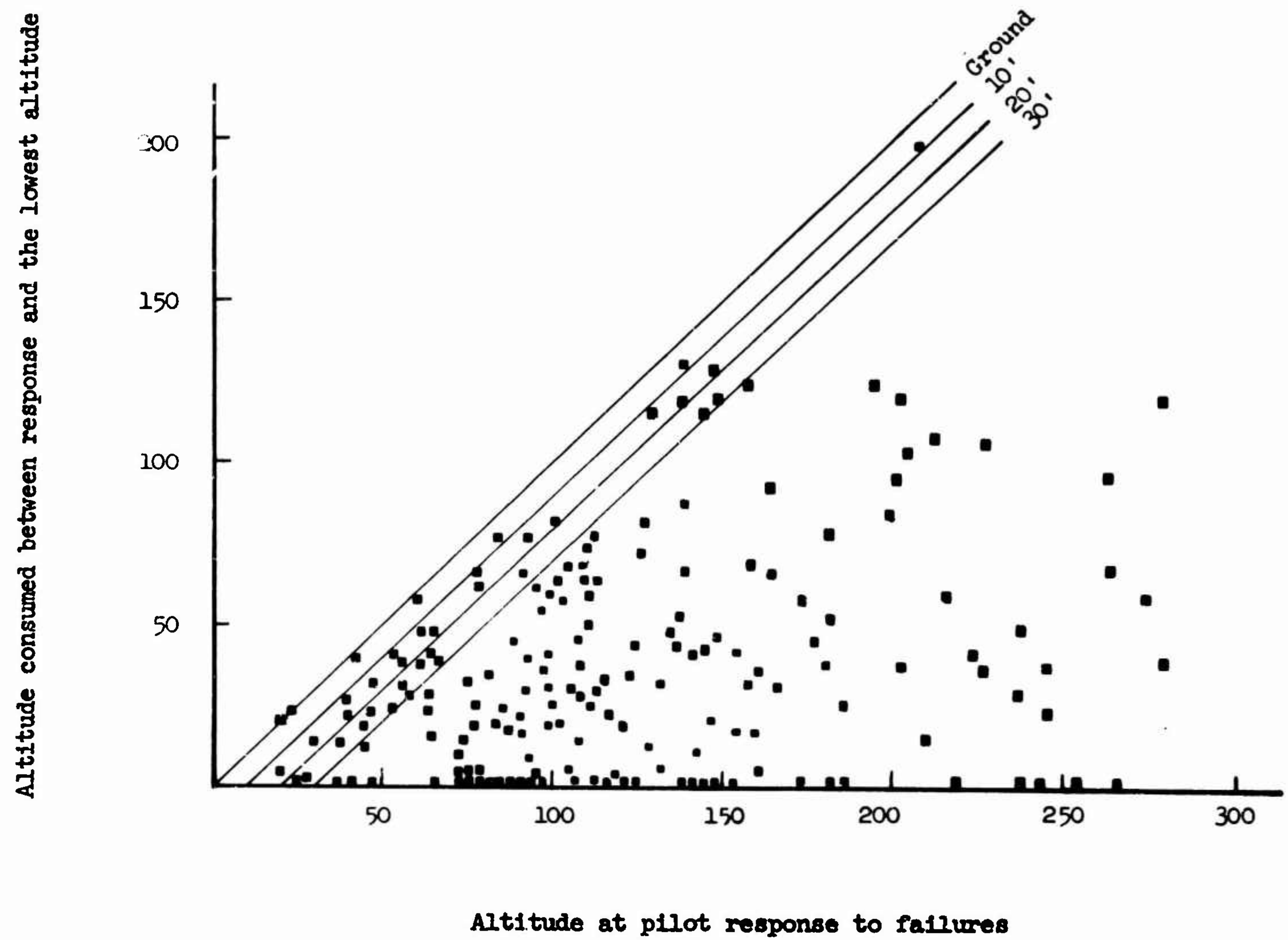

FIGURE R-2 - Scatter Plot of Altitude at Failure Insertion Versus Altitude Consumed between Failure Insertion and Lowest Altitude Attained during Go-Around

TABLE R-52

Go-Around Performance as a Function of Pilot Task Prior to Second Failure

Measure at Lowest Altitude	Pilot Task: Pitch Manual	Pilot Task: Roll Manual	Across Pilot Task
Time from Pilot Response	3.9 sec. * (2.0 sec.) **	4.5 sec. (2.0 sec.)	4.1 sec. (2.0 sec.)
Distance from G/S Transmitter	n.s. ***	n.s.	1608.0 ft. (1341.0 ft.)
Distance from Pilot Response	785.0 ft. (661.0 ft.)	1063.0 ft. (905.0 ft.)	905.0 ft. (734.0 ft.)
Average Lowest Altitude	n.s.	n.s.	88.8 ft. (74.1 ft.)
Altitude Consumed from Pilot Response	31.7 ft. (33.1 ft.)	43.9 ft. (37.7 ft.)	37.0 ft. (35.6 ft.)
Altitude Consumed from Failure Insertion	n.s.	n.s.	125.8 ft. (74.7 ft.)
Pitch Attitude	n.s.	n.s.	7.7 deg. (3.9 deg.)
Indicated Airspeed	133.4 kts. (6.0 kts.)	136.3 kts. (11.3 kts.)	134.7 kts. (8.9 kts.)
Roll Attitude	1.7 deg. (2.1 deg.)	6.9 deg. (5.8 deg.)	4.0 deg. (5.8 deg.)
Lateral Drift	3.5 fps. (6.1 fps.)	23.2 fps. (17.6 fps.)	12.0 fps. (15.8 fps.)

* Average performance.
** One standard deviation.
*** No significant difference between pitch and roll manual scores.

TABLE R-53

Altitude Gain

Monitor Mode			Across Monitor Mode
No Monitor	Caution	Caution + Annunciator	
13.7 *	16.1	19.0	16.4
(9.3) **	(10.6)	(11.3)	(16.5)

* Average in feet.
** One standard deviation.

Lateral plane performance. Lateral displacement during pitch manual split-axis approaches was no particular problem, but lateral displacement (Table R-54), heading error (Table R-55) and lateral drift (Table R-52) show that the aircraft was off of the localizer course, and departing at a high (23 feet per second) rate at the lowest altitude when roll manual split-axis conditions existed prior to the second failure. These data corroborate the lateral performance data seen earlier during display failures; the pilots tend to disregard roll in favor of pitch during go-arounds. In and of itself, this strategy is not alarming. When one couples the roll performance and strategy with the pitch axis strategy of using the available altitude to execute the go-around, a potential hazard is indicated.

TABLE R-54

Lateral Displacement at Lowest Altitude During Go-around

	Monitor Mode			Across Monitor Mode
Pilot Task	No Monitor	Caution	Caution + Annunciator	
Pitch Manual	18.28 * (30.20) **	14.87 (19.37)	23.54 (48.34)	18.89 (34.76)
Roll Manual	257.52 (176.12)	206.67 (194.42)	126.21 (125.89)	187.96 (171.96)
Across Pilot Task	114.82 (163.54)	95.91 (158.02)	71.45 (105.70)	92.18 (143.08)

* Mean lateral displacement in feet.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

If the pilot simultaneously allows the aircraft to go low and at the same time drift off course laterally, he could depart the obstacle clearance zone. One may scoff at the alarm, but remember that the pilot could be just a few feet above the glideslope, a few feet above the ground during go-around, and conceivably strike the glideslope antenna in the two-three standard deviation case of roll manual lateral displacement shown.

TABLE R-55

Heading Error at Lowest Altitude During Go-Around

Pilot Task	Monitor Mode: No Monitor	Monitor Mode: Caution	Monitor Mode: Caution + Annunciator	Across Monitor Mode
Pitch Manual	1.03 * (0.85) **	3.66 (1.93)	3.60 (1.83)	2.86 (2.02)
Roll Manual	8.68 (7.52)	8.14 (6.99)	6.86 (5.88)	7.77 (6.69)
Across Pilot Task	4.11 (6.08)	5.56 (5.23)	5.12 (4.51)	4.99 (5.25)

* Mean heading error in degrees.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

<u>Summary of go-around performance</u>. The vertical and lateral plane go-around strategy of the pilots seen in this study needs to be verified when pilots go-around out of automatic approaches (Phase III upcoming) and in real aircraft under adequately controlled experimental conditions. At the present time one must conclude on the basis of these data that pitch manual split-axis control leads to safer go-around performance than roll manual split-axis control, and that the full monitor system yielded better lateral performance than no monitor during the roll manual split-axis conditions prior to go-around (the worst case).

TABLE R-56

Go-Around Performance Analysis of Variance Summary

Measure at Lowest Altitude	Source of variance: Pilot Task (P)	Failure Mode (F)	PxF
Time from Pilot Response	.05*	**	
Distance from G/S Transmitter			
Altitude Loss (or Gain)		.05	
Lowest Altitude			
Altitude Consumed from Pilot Response	.05		
Altitude Consumed from Failure Insertion			
Distance Consumed from Pilot Response	.05		
Pitch Attitude			
Indicated Airspeed	.05		
Roll Attitude	.01		
Lateral Drift	.01		
Heading Error			.01
Lateral Displacement	.01		.01

* Source of variance significant beyond the level of confidence indicated.
** Blank spaces indicate non-significant source of variance.

Touchdown Performance

Windshears were confounded with failure modes in the experimental design because it was assumed that all failures would have been detected and acted upon prior to the aircraft entering the shearwinds below 100 feet of altitude. Unfortunately, many failures were not detected in the no monitor and caution light monitor modes. No-monitor was confounded with the pure tailwind shear; caution was confounded with the lateral shear; and, caution-plus-annunciator was confounded with the combination tailwind and lateral shears. The effects of windshears upon touchdown may be influenced, in part, by the monitor mode performance. This is the first problem of touchdown performance interpretation.

A second problem of touchdown data interpretation arose because there were unequal numbers of landings under all experimental conditions.[1] Roll manual data is based upon only 32 actual landings. Pitch manual data is based upon 52 actual landings. The autopilot, on the other hand, was responsible for 162 landings. From a statistical standpoint, performance estimates based upon 162 scores are far more reliable than those based upon 32 scores.

The following analysis and interpretation of touchdown performance, therefore, must be tempered (qualified) by a knowledge of these two problems.

Touchdown performance shown in Table R-57 did not look promising. Overall, 50.4% of the 246 scoreable touchdowns were within the allowable tolerances indicated in Table R-58. Out of 32 roll manual landings, 6.2% were successful; 17.3% of the pitch manual landings were successful; 69.8% of the automatic landings were successful. A breakdown of percent successful landings by individual parameter is included in Table R-59. Also shown is the percent successful touchdowns (1) when six out of the seven criteria were met and (2) when five out of the seven criteria were met on each touchdown.

1. A larger number of touchdowns was planned in the experimental design. At least one failure always occurred prior to touchdown. Many subjects, however, conservatively executed missed-approaches when they could have continued under the decision rules set forth for this experiment. It was near impossible to achieve the number of touchdowns that were planned.

TABLE R-57

Percent Successful Touchdowns

	Pilot Task			
Windshears	Pitch Manual	Roll Manual	Automatic	Across Pilot Task
Tailwind	17.6% (17) *	9.1% (11)	85.2% (54)	61.0% (82)
Tailwind & Lateral	11.1% (18)	9.1% (11)	66.7% (54)	47.0% (83)
Lateral	23.5% (17)	0.0% (10)	57.4% (54)	43.0% (81)
Across Windshears	17.3% (52)	6.2% (32)	69.8% (162)	50.4% (246)

* Number of actual .ouchdowns under these conditions that could be scored.

TABLE R-58

Criteria for Successful Touchdowns

Measure	Tolerance Band	Percent of Time Within Tolerance
Distance Down Runway	0-3000 ft.	94.3
Lateral Displacement	± 60 ft.	82.5
Pitch Attitude	0-5 deg.	96.3
Roll Attitude	± 5 deg.	94.7
Heading Error	± 4 deg.	80.9
Lateral Drift	± 9 fps.	83.7
Vertical Velocity	0-360 fpm.	78.5

TABLE R-59

Successful Touchdown by Channel

Pilot Task	Channel	Windshears: Tail	Windshears: Lateral	Windshears: T & L	Across Winds
Pitch Manual	X Range	76.5 *	76.5	100.0	84.6
	Y Displ	82.4	88.2	88.9	86.5
	Pitch	82.4	100.0	88.9	90.4
	Roll	100.0	100.0	100.0	100.0
	Heading	88.2	70.6	72.2	76.9
	Y Drift	88.2	76.5	88.9	84.6
	Altitude	41.2	64.7	27.8	44.2
2 criteria not met		82.4	88.2	94.4	88.5
1 criterion not met		64.7	64.7	61.1	63.5
All criteria met		17.6	23.5	11.1	17.3
Roll Manual	X Range	90.9	100.0	81.8	90.6
	Y Displ	54.5	30.0	27.3	37.5
	Pitch	100.0	100.0	90.9	96.9
	Roll	81.8	50.0	81.8	71.9
	Heading	45.5	40.0	45.5	43.8
	Y Drift	27.3	10.0	45.5	28.1
	Altitude	63.6	70.0	90.9	75.0
2 criteria not met		45.5	30.0	54.5	43.8
1 criterion not met		27.3	20.0	27.3	25.0
All criteria met		9.1	0.0	9.1	6.2
Automatic	X Range	100.0	96.3	98.1	98.1
	Y Displ	96.3	81.5	92.6	90.1
	Pitch	96.3	98.1	100.0	98.1
	Roll	98.1	94.4	100.0	97.5
	Heading	100.0	83.3	85.2	89.5
	Y Drift	96.3	92.6	94.4	94.4
	Altitude	96.3	87.0	87.0	90.1
2 criteria not met		100.0	94.4	98.1	97.5
1 criterion not met		98.1	87.0	92.6	92.6
All criteria met		85.2	57.4	66.7	69.8
Winds Over Pilot Task	X Range	93.9	92.6	96.4	94.3
	Y Displ	87.8	76.5	83.1	82.5
	Pitch	93.9	98.8	96.4	96.3
	Roll	96.3	90.1	97.6	94.7
	Heading	90.2	75.3	77.1	80.9
	Y Drift	85.4	79.0	86.7	83.7
	Altitude	80.5	80.2	74.7	78.5
2 criteria not met		89.0	85.2	91.6	88.6
1 criterion not met		81.7	74.1	77.1	77.6
All criteria met		61.0	43.2	47.0	50.4

*Percent of landings that are within tolerance.

An analysis of individual performance measures (Table R-60) revealed that pilot task (manual roll, manual pitch, or automatic) was a significant variable for all measures. Significant wind conditions occurred next most often and there were two measures in which a significant wind by pilot task interaction occurred. An examination of these data follows:

TABLE R-60

Touchdown Performance Analysis of Variance Summary

Touchdown Performance Measure	Source of Variance		
	Pilot Task(P)	Wind (W)	PxW
Distance from G/S Transmitter	.01*	.01	
Indicated Airspeed	.01		
Pitch Attitude	.01	.05	
Vertical Velocity	.01		.05
Roll Attitude	.01	.01	.01
Heading Error	.01	.01	
Lateral Drift	.01		
Lateral Displacement	.01		

* Source of variance significant beyond the level of confidence indicated.

Note: Blank spaces indicate non-significant sources of variance.

Tailwind shear. This condition started with a 10-knot headwind shearing to calm from 100 feet to the ground. The tailwind shear created pitch manual control problems during the flare. An average 1.1-degree pitch attitude at touchdown (Table R-61), 25 feet ahead of the glideslope shack with a vertical velocity (Table R-62) in excess of 450 feet per minute suggest that the pilot was unable to flare the aircraft. Under these conditions the flare computation was difficult to follow because the pitch steering bar did not command a noticeable change until below 20 feet. By the time the pilot recognized the command it was too late to take effective control action.

TABLE R-61

Vertical and Longitudinal Touchdown Performance

Touchdown Performance Measure	Pilot Task: Pitch Manual	Pilot Task: Roll Manual	Pilot Task: Auto	Winds: Tailwind Shear	Winds: TW/Lat. Shear	Winds: Lateral Shear	Overall Average
Distance Down Runway in Ft.	975* (1395)**	1132 (1324)	1397 (543)	1140 (822)	1155 (865)	1530 (1030)	1273 (923)
Indicated Airspeed in Knots	127.7 (4.0)	128.1 (11.0)	125.6 (2.8)		n.s.		126.4 (5.0)
Pitch Attitude in Degrees	1.1 (1.8)	3.5 (2.0)	3.8 (1.2)	3.1 (1.7)	3.1 (1.8)	2.6 (1.5)	2.9 (1.7)

* Means.

** One standard deviation.

***Winds did not significantly influence indicated airspeed.

Note: Means contained within the same box are not significantly different.

TABLE R-62

Vertical Velocity at Touchdown

Windshears	Pilot Task: Pitch Manual	Pilot Task: Roll Manual	Pilot Task: Automatic	Across Pilot Task
Tailwind	-498* (444)**	-327 (226)	-206 (106)	-283 (258)
Tailwind & Lateral	-474 (290)	-182 (142)	-223 (127)	-272 (205)
Lateral	-271 (330)	-261 (194)	-228 (170)	-241 (213)
Across Windshears	-415 (317)	-256 (194)	-219 (136)	-265 (226)

* Mean vertical velocity in feet per minute.

** One standard deviation.

Note: Means contained within the same box are not significantly different.

Lateral shear. The lateral shear was created by shearing a 10 knot 90 degree crosswind to calm as the aircraft descended from 100 feet to touchdown. Lateral shear mainly affected the lateral measures, especially during roll manual, split-axis control.

Roll attitude at touchdown was the highest (6.3 degrees) during roll manual landings with the lateral windshear (Table R-64). Heading error in Table R-63 was greater during lateral shears than during tailwind shears as would be expected. Curiously, the shearwinds did not significantly influence lateral drift or lateral displacement. Lateral drift and displacement were systematically influenced by pilot control tasks. The excessive lateral deviation (175 feet) and lateral drift (21.8 feet per second) during roll manual touchdowns apparently obscured any small deviations created by the windshear. These data serve as further evidence that the lateral control problem during manual instrument landings is severe.

TABLE R-63

Lateral Touchdown Performance

	Pilot Task			Winds			
Performance Measure	Roll Manual	Pitch Manual	Auto	Tailwind Shear	TW/Lat. Shear	Lateral Shear	Overall Average
Heading Error in Degrees	7.5 * (6.7)**	2.2 (1.9)	1.7 (2.3)	1.6 (3.0)	2.7 (3.7)	3.2 (4.1)	2.5 (3.7)
Lateral Drift in ft. per sec.	21.8 (16.9)	4.6 (5.8)	2.4 (5.1)		n.s ***		5.4 (10.1)
Lateral Displacement	175.0 (186.2)	32.0 (63.3)	25.6 (53.4)		n.s		46.4 (97.9)

* Mean

** One standard deviation.

*** Winds did not significantly influence lateral drift and lateral displacement.

Note: Means contained within the same box are not significantly different.

TABLE R-64

Roll Attitude at Touchdown

Windshears	Pilot Task: Roll Manual	Pilot Task: Pitch Manual	Pilot Task: Automatic	Across Pilot Task
Tailwind	2.7 (2.0)	0.3 (0.4)	0.6 (1.1)	0.8 (1.4)
Tailwind & Lateral	2.0 (2.6)	0.5 (0.6)	0.7 (0.9)	0.8 (1.3)
Lateral	6.3 * (4.6) **	0.2 (0.4)	1.2 (2.4)	1.6 (3.1)
Across Windshear	3.6 (3.6)	0.3 (0.5)	0.8 (1.6)	1.1 (2.1)

* Average (absolute) roll attitude in degrees.
** One standard deviation.
Note: Means contained within the same box are not significantly different.

Tailwind shear plus lateral shear. The combination of tailwind and lateral shear did not significantly change vertical plane performance from the pure tailwind shear condition. Neither did the combination significantly alter lateral plane performance from the pure lateral shear condition.

Final comment on touchdown performance. This study was a severe test. Pilots were asked to continue in manual control after they had experienced one control failure. Not all of the control failures were detected during approaches that had less than the full monitor system in operation. Even with one control failure having occurred, display failures were apt to occur. After 39 approaches under these conditions the pilots were so geared to looking for failures that their manual control capability suffered when (and if) they arrived at the flare. Under these stressed conditions the tested flight director and computers did not make the man effective.

The flight director system and human pilot could not handle the tailwind shear. In roll, the flight director/pilot combination could not successfully handle the lateral plane. Since human pilots have been visually landing aircraft for many years, it can only be concluded that either the proper information for the human pilot to land the aircraft is not yet on the instrument panel, or the information that is available is not being used effectively.

The next study being undertaken by the STIR project will more carefully analyze the manual flare in an attempt to diagnose the manual flare and touchdown problem. Completely removing the human pilot from the control loop is one solution to the problem. An alternative solution could well come from an understanding of why the pilot cannot adequately control the flare (vertically and laterally) with existing information.

Rollout

Following each touchdown, the pilot had to deploy the spoilers, push the column full forward (the First Officer held it there once it had been positioned), reverse thrust, apply brakes, and steer the simulator down the runway using raw heading and localizer information on the horizontal situation indicator. During the execution of the study, it became obvious that the task was unreasonable in the simulator. The rollout data were dropped from the analysis for the following reasons:

The task was difficult in and of itself. The pilot's view of the HSI was partially blocked by the wheel hub when the column was held full forward; the pilots had to look around the wheel hub while reversing thrust and braking. If the pilot looked over the top of the wheel hub, the upper lip of the HSI case would obscure the heading index and the top portion of the compass card. Adding to the difficulty of this task, the rollout dynamics of the simulator became suspect after the first few subject pilots were run; the pilots were consistently going divergently unstable and leaving the runway. It was decided, therefore, to drop the rollout data from consideration until a more satisfactory simulation of rollout could be achieved. The simulator rollout dynamics were worked on for the remainder of the study.

General Characteristics of Fault Warning Systems

Although only one fault warning system was installed in the simulator for this study, various modes of operation were employed that allow some inquiry into general features of fault warning systems. In addition to the performance data already presented, there was a wealth of pilot opinion that evolved. This section will examine some fault warning system characteristics within the guidelines of this study, and offer pilot comment.

Caution light. When asked if it was necessary to have both the caution light and the mechanical flags during display failures, 50% of the pilots said yes, 50% said no. Thirty percent of the pilots thought that the flags were too small. Thirty-five percent of the pilots thought that the radar altimeter flag needed to be backed up by the caution light. Generally, flags outside of the ADI were difficult to see.

Flag light. Seven out of nine pilots who saw the flag light thought that it was of significant value. It was generally agreed that such a light should indicate flags down on both sides of the cockpit. Five pilots thought the flag light should be above the ADI, and four thought it ought to be in a central location.

Annunciator panel. Forty-five percent of the pilots thought that it was necessary for the annunciator panel to be redundant with mechanical flags with the present system. Given a flight director system and radar altimeter display with larger flags, 30% of the pilots could classify this feature as "necessary."

Discussion. The performance data showed significantly better performance in the caution plus annunciator mode. Flags and annunciator without the caution light were not investigated. At this time it is not known whether the annunciator caused better performance, or whether better performance was due to the combination of caution and annunciator. The small flags on the ADI itself could have contributed to the problem. A study (Phase III) is being designed to more fully look at the necessity of redundancy between the display flags and the annunciator panel.

This study did not look into the possibility of a comparator monitor across the two sides of the cockpit. Given only a comparator, the comparison function may need annunciation. For example, it is possible for two vertical gyros to disagree even though neither one shows a flag. With self-monitors, the self-monitor could assess signal quality and just as easily trip a mechanical flag as illuminate a light. The saving would be in panel space and some increase in warning mechanism reliability (a light is not as reliable as a flag). This saving would be substantial IF FLAGS WERE SHOWN TO BE AS EFFECTIVE AS LIGHTS.

Deviation light. The general consensus of the pilots was that the deviation light was more of a nuisance than a help. It illuminated when excessive deviation was detected. This was just the time when the pilots were usually quite busy trying to recover the course. At this critical time, the presence of a new light on the panel forced them to stop paying attention to what they were doing in order to read the new light. It compounded the problem. Most pilots knew that they were excessively deviating and were trying their best to do something about it.

Abort command. An abort command was not incorporated into the fault warning system exercised, but decision rules were given to the pilots. The rule was to execute go-around if a display failure occurred in a manually controlled axis. When asked if they developed any general rules of thumb for executing decision in this study, six of the 22 pilots (including pre-experimental) said "no." Five pilots said that they would go-around if they were not positive. Seven pilots cited a great deal of confusion generated by the system and the failures, but pointed out that further training on the system would certainly help. Four pilot responses are quoted in the following paragraph; words in parentheses are added by the authors:

"After flying 11-12 hours non-stop from London-LAX, I'm too tired to correctly apply any rule of thumb. Even subtle failures must be unmistakeable and instantly displayed with the information that the approach can or cannot be continued." Another responded, "I do not believe that our crews today making, say one Cat III actual per year, and say two practice approaches can maintain proficiency in making last minute decisions whether to continue or go-around. By this I mean, roll axis out, (pitch) autopilot O.K. Now DG out, should I continue? Any functions inoperative would be enough for me (to go-around)." Yet another said, "I made several incorrect decisions based on the information presented, usually due to too-hasty action. I found it difficult to 'take my time' when a failure occurred at 100 feet." A fourth pilot said, "Any failure below 200 feet would require a go-around as far as I'm concerned. From this point to touchdown (there) is not time to have to analyze a problem."

The responses in the preceding paragraph seem to suggest that a go-around or abort advisory function is needed. Yet, when asked directly if they would rather have a decision made for them or be told only the specific failures, 12 pilots wanted the decisions left up to them. The principal reason was that decisions would have to be pre-programmed and there are too many variables to cover all situations. Some pilots suggested that the seriousness of the failure be indicated. The responses of four pilots are quoted in the next paragraph. These four pilots seemed to clarify the problem.

One pilot said, "Up to some minimum altitude I would rather have the prerogative. If a failure occurs below that altitude, I would rather have a simple 'abort' light and a fault warning system to help analyze the situation at a safe altitude after missed approach." A second pilot said, "Certain failures at 100 feet or less must be made evident to the pilot in such a way that the decision to abort or continue is made for him. I include flare capability, runway alignment, and excessive roll or pitch." A third pilot said, "If the command is reliable it would be invaluable. Especially from 200 feet to touchdown. Any malfunction in this portion of the approach does not leave enough time for ground school prior to runway contact." A fourth pilot said, "If failures progress to a point where approach is hazardous, then some method of advising decision to abort (should be incorporated) instead of correlating several failures to determine what decisions to make."

It is clear that the question should have been limited to below 200 feet; it is the time factor that creates the interpretation problem. It seems reasonable that pilot acceptance of a well-programmed abort advisory below 200 feet would be good. Such an advisory would not be without problem, however, because one can think of an exception to every rule. For example, with loss of glideslope at 55 feet of altitude, the aircraft would be into the flare mode and not need the glideslope before the pilot could even respond to the failure.

Fault warning and mode progress display design. Including the pre-experimental subject pilots, 16 of the 22 pilots did not like the present system. The overwhelming response was that the display was too complex, confusing, had too many lights and the flags were too small. Some very constructive suggestions emerged, the most significant being the suggestion to separate the mode progress from fault warning information. (See pages 9, 13, 14.)

Mode progress information. Twelve pilots responded to a request for suggestions to improve mode progress display. In general terms, they said de-emphasize or eliminate the display. It was very clearly pointed out that the mode progress function caused lights to illuminate to indicate normal sequencing of the autopilot in the same location that the FLAG, CAUTION and DEVIATION lights were located. Thus, lights illuminating in the area above the ADI meant either normal or emergency events.

A composite of the best responses indicated that the mode progress display should be (1) moved to the left side of the Captain's display panel, (2) be vertical in orientation, and (3) that the modes should be legible prior to illumination. One pilot suggested an amber armed condition and a green engagement condition. The reason for legibility without illumination is so that the pilots can learn where the lights are and know what is supposed to happen next. When the next light turns on, they would not have to stop what they are doing at precisely the moment the light turns on in order to know what the light is indicating.

Display flags. As previously indicated, the ADI, HSI and Radar Altimeter flags were too small. Pilots universally agreed that these flags should be large, international orange in color, shape coded, and should say what element they represent (Fig. M-3, p 10).

Annunciator design. The autopilot axis annunciator was well received. The system annunciator panel that reflected the display system elements and flight director was somewhat of a problem in its present design. The main problem seemed to be that the elements were not coded such that the element that had failed was obvious without reading the lights. In addition, the systems affected by the failure would also be indicated. For example, a vertical gyro failure would disable the flight director in pitch. Both lights would illuminate as is appropriate since both systems were affected. It was suggested, however, that the element failed be brighter than the systems affected for more rapid detection of the failed element (Fig. M-8,p14).

Another suggestion was that annunciator lights of relatively narrow design be placed in a row on both sides of the ADI-HSI group, and right up against the instruments. Lights in the left column would be for the Captain's instruments and those on the right column would be for the First Officer's instruments. The annunciator design might even be incorporated into the ADI-HSI hardware. This idea was interesting because it suggested that the fault warning annunciator function should be located at the ADI-HSI. If, as earlier discussed, good flags can be shown to elicit pilot detection capabilities that are equivalent to lights, all of the display annunciators can be represented by more modern flight director systems.

A fourth suggestion was to make part of the instrument case out of electro-luminescent material that would light red if the function failed. Thus, a radar altimeter failure would be indicated by the radar instrument itself glowing or flashing red or orange. The caution light would be retained to reflect a problem anywhere.

International orange was the color most suggested for annunciators. One-half of the pilots were in favor of flashing annunciators; one-half were opposed.

No subject suggested auditory voice warning such as the system used on the B-58, which uses a voice message to indicate the problem. Several subjects suggested auditory warnings in addition to the caution light as an alerting device.

Fault-warning system design and learning. The single most important design characteristic of fault-warning system displays is that the display MUST be intuitively obvious. No matter what question was asked, almost all pilot responses contained elements of this requirement. The reason is that fault-warning systems do not normally indicate anything. Only when a failure occurs is the system exercized. How often, for example, does a commercial Captain see a warning flag on a modern flight director? How often does he see all flags? Unless the fault-monitor system false-alarms frequently, how often will the Captain see the elements of the fault-warning display? If the avionic sub-systems meet the reliability standards that are being specified, the flight crew may see the entire fault-warning system exercised only during periodic simulator training. Such training must be good enough that the flight crew will retain their skill in interpereting failures and taking corrective action. For Category III operations, there is no time margin for "reviewing ground school," in the words of one subject pilot. This being the case, the fault-warning display system must be so intuitively obvious that having once learned the system operation, the interpretation of the display will be permanently retained. The design of the system and its method of annunciating problems to the flight crew can go a long way toward establishing an intuitively obvious display. Design features like covering failed functions, biasing failed information from view, or illuminating failed instruments are certainly more intuitively obvious than an annunciator panel. Design features like the above along with annunciations that suggest the proper course of action (or alternative courses) indicate the design direction for fault-warning displays.

CONCLUSIONS

The major conclusions drawn from this study are:

1. Softover control failures were not a pilot detection problem.

2. Passive control failures require a full monitor system.

3. Autopilot flare failures without monitor system annunciation were frequently missed.

4. Pilots took longer to detect display flags outside the ADI than flags inside the ADI.

5. Second failures were frequently undetected; the pilot was manual in one axis during second failures.

6. Generally, the incorrect responses, incorrect decisions and performance data suggest that additional monitor system improvement is necessary.

   a. Light regrouping, audio warning and larger flags should be tested.

   b. Coordinated crew procedures should also help.

7. Go-around performance was good in the vertical plane, but lateral problems were evident.

8. Split-axes touchdowns in this study were not successful.

9. Rollout on raw information was unsatisfactory; simulation problems emerged.

10. These conclusions are restricted to the context of the present study. There was no crew member to help the pilots find failures. On the other hand, on each and every approach, the pilots could expect a failure; performance differences occurred in spite of the fact that pilots were looking for failures and their scan patterns were restricted to the inside of the cockpit (they could not look out).

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APPENDIX A

APPENDIX A

TABLE A-1
Analysis of Variance Source Table for Go-Arounds

Source	Degrees of Freedom
Total	202
Control	1
Failure	2
Control X Failure	2
Error	197

TABLE A-2
Analysis of Variance Source Table for Touchdowns

Source	Degrees of Freedom
Total	321
Control	2
Failure	2
Control X Failure	4
Error	313

TABLE A-3
Analysis of Variance Source Table for Control Failures

Source	Degrees of Freedom
Subject	17
Group	1
Error	16
Control	1
Failure	2
IC	1
IF	2
CF	2
IG	1
CG	1
FG	2
ICG	1
IFC	2
CFG	2
ICF	2
ICFG	2
Error	176
IS	16
CS	16
FS	32
ICS	16
IFS	32
CFS	32
ICFS	32
Total	215

TABLE A-4
Analysis of Variance Source Table for Display Failures

Source	Degrees of Freedom
Subject	17
Group	1
Error	16
Display	3
Control	2
Failure	2
DC	6
DF	6
CF	4
DG	3
CG	2
FG	2
DCG	6
DFG	6
CFG	4
DCF	12
DCFG	12
Error	560
DS	48
CS	32
FS	32
DCS	96
DFS	96
CFS	64
DCFS	192
Total	647

TABLE A-5
Analysis of Variance Source Table for Flare Mode Failure

Source	Degrees of Freedom
Subject	17
Group	1
Error	16
Failure	2
FG	2
Error	32
FS	32
Total	53