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INVESTIGATION OF THE USE OF AN ELECTRONIC MULTIFUNCTION DISPLAY AND AN ELECTROMECHANICAL HORIZONTAL SITUATION INDICATOR FOR GUIDANCE AND CONTROL OF POWERED-LIFT SHORT-HAUL AIRCRAFT

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16. Abstract

This project represents an investigation of the use which pilots make of a moving map display from en route through the terminal area and including the approach and go-around flight phases. The content and function of each of three primary STOLAND* displays are reviewed from an operational point of view. The primary displays are the Electronic Attitude Director Indicator (EADI), the Horizontal Situation Indicator (HSI) and the Multifunction Display (MFD). Manually controlled flight with both flight director guidance and raw situation data is examined in detail in a simulated flight experiment with emphases on tracking reference flight plans and maintaining geographic orientation after missed approaches. Eye-point-of-regard and workload measurements, coupled with task performance measurements, pilot opinion ratings, and pilot comments are presented. The experimental program was designed to offer a systematic objective and subjective comparison of pilots' use of the moving map MFD in conjunction with the other displays. The measurements, ratings and comments provide not only an indication of the utility of the MFD in relation to the HSI, but also some suggestions for improvements to the information content and format of all of the primary STOLAND displays and their associated controls.

*STOLAND is a versatile digital navigation, guidance and control system developed by Ames Research Center for conducting experiments with advanced STOL aircraft.

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FOREWORD

The research reported here was performed for the Aircraft Guidance and Navigation Branch, Flight Systems Research Division, Ames Research Center, under National Aeronautics and Space Administration (NASA) Contract NAS2-8973. The NASA Technical Manager was D. Neil Warner, Jr., and the Systems Technology, Inc. (STI) Project Engineer was Warren F. Clement. The work was accomplished in the period from September 1975 through August 1976.

Special recognition is their due for the major contributions by the pilots in the flight simulation itself and also through their helpful suggestions. The pilots were James I. Haag, Gordon Hardy, William S. Hindson, Roger H. Hoh, and Ivan L. Turner.

The author also wishes to acknowledge the assistance of Delamar M. Watson of the Aircraft Guidance and Navigation Branch at Ames Research Center in designing the flight plans and checklists; Jim John and Pier Del Frate of the Computer Sciences Corp. staff at Ames Research Center in programming and operating the simulation; and his STI colleagues: Roger H. Hoh in planning the scenario, Richard H. Klein and Wayne F. Jewell in making the eye-point-of-regard measurements and reducing the data, Robert L. Stapleford in planning the secondary tasks, Dunstan Graham in editing the report, and the production staff of Systems Technology, Inc., for their painstaking work in the preparation of the report.

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INTRODUCTION AND OVERALL SUMMARY

Instrument flying is basically a task of interpreting a set of needles and numbers to determine answers to the questions "Where am I?" and "Where am I going?" Under normal circumstances a trained pilot can accomplish this task with a fair degree of precision and at a reasonable workload level. However, in a high workload and/or a high stress situation, other factors are competing for the pilot's attention, thereby making it difficult or impossible for the pilot to maintain a clear mental picture of his position and direction of flight. The pilot is then said to be "behind the airplane," i.e., things are happening so fast that by the time he reacts it may be too late.

A moving map display eliminates the necessity for the pilot to convert images of needles and numbers into a two-dimensional image of his geographic position and direction of flight. Thus, the moving map display should provide a significant reduction in that particular cognitive workload. The pilot can now tell at a glance his complete horizontal status in terms of: 1) position; 2) direction of flight; and 3) rate of closure on specific fixes. The desirability of such a map display is therefore not really in question; it is definitely better than a display of relative bearings and course deviation on needles. More appropriate (and subtle) questions are "How much better?" and "Under what conditions is the moving map display worth the potential additional cost?"

The investigation reported here has been designed to provide some answers to the foregoing questions by making a systematic comparison of an electronic moving map display and an electromechanical Horizontal Situation Indicator (HSI) used in conjunction with other instruments (EADI, altimeter, airspeed indicator, etc.) in the NASA-Ames digital avionics system for guidance and control of powered-lift, short-haul aircraft. This research forms one part of the joint DOT/NASA STOL Operating Systems Experiments Program.

The overall objective of the joint DOT/NASA STOL Operating Systems Experiments Program is to provide data to aid the design of terminal area guidance, navigation and control systems, and the definition of operational procedures for powered-lift and light wing-loading, short-haul aircraft under instrument flight rules (IFR). As a first step in this program, experimental digital automatic and flight director guidance and control systems have been developed for the NASA Augmentor Wing powered-lift short-haul aircraft by Sperry Flight Systems (under NASA contract). This system, called STOLAND, is based on the application of current CTOL system techniques and displays to the experimental short-haul aircraft.

Two of the primary displays used in the system are an Electronic Attitude Director Indicator (EADI) and a standard Horizontal Situation Indicator (HSI). In addition, this digital system has a computer driven, cathode ray instrument called the Multifunction Display, or MFD, which displays the aircraft position and predicted motion on a moving map of the area. Thus, in STOLAND the MFD is the moving map display. Also displayed are other status data including heading, altitude, raw navaid data, and reference flight paths.

Operation of the STOLAND system and its primary displays is described in Ref. 1. A review of the display content and function of the MFD, HSI, and EADI from an operational point of view is presented in Section II of this report. At the conclusion of Section II there is a concise summary of the review of the display content and function of the primary STOLAND displays.

Section III of this report then describes an experimental simulation of STOLAND operation designed to gather data for a systematic comparison of the MFD and HSI from an operational point of view under simulated instrument flight rules. The operational flight phases of interest in this simulation are: 1) the terminal routine within a 56 km (30 nm) radius of Crows Landing ALF, Colusa County, California; 2) the landing approach down to the minimum decision altitude for "see-to-land" visibility conditions; and 3) the missed approach procedure.

Besides the usual sequence of straight course segments at constant altitude interspersed among turns and descents and the occasional holding pattern within the terminal area, a STOL transport, on nearly every flight, will typically be required to slow down and convert to operation below the speed for minimum thrust (or power) required ("backside operation" for short); and to negotiate curved courses and decelerating steep precision approaches down to instrument minima followed by a short field landing. Each of these segments of the approach course and path can keep both pilots fully occupied even when decelerations, descents, or turns are made separately under IFR. However, when some STOL segments may involve combined maneuvers, a significant improvement in the pilot/vehicle system will be required to achieve such instrument operations routinely and still maintain a level of safety consistent with present standards.

The purpose of this research is to investigate the use which pilots make of the MFD in conjunction with other displays from en route to the terminal area including the approach and landing flight phases. Various features of each of the primary STOLAND displays, the MFD, HSI, and EADI, are used in the three phases of flight mentioned above when the STOLAND system is operated in each of three ways: a) flown in the fully automatic mode with the pilot(s) in a monitoring role; b) flown manually using flight director guidance to reduce workload and task requirements to an acceptable level; or c) flown manually using raw instrument situation data. Eye-point-of-regard and workload measurements, coupled with task performance measurements, were employed in the experimental program to determine the pilots' use of the MFD in conjunction with the other displays. The results of the experiments are described in detail in Section III. A concise summary of the results of the experimental comparison of the MFD and the HSI together with the conclusions drawn from the data is presented at the end of Section III.

There are then not only indications of the utility of the MFD as a supplement to the HSI but also some suggestions for improvements to the information content and format of all of the primary STOLAND displays. The conclusions from the investigation appear in Section IV, and the suggestions are presented at the end of Appendix D.

Supporting references and appendices follow Section IV at the end of the report.

SECTION II

REVIEW OF CONTENT AND FUNCTION OF THE STOLAND DISPLAYS

A. PURPOSE

Operation of the STOLAND system and its primary displays is described in Ref. 1. Excerpts from this document have been reproduced here in Appendix A to illustrate the displays.

The purpose of this initial review is to verify that the presentation of essential feedbacks for guidance, navigation, control and monitoring, at each level of pilot participation, is in accord with the best display design practice from the viewpoints of pilot confidence and acceptance with due consideration for en route and terminal area flight safety and operational capability. Among the more crucial questions behind this review are those concerning the adequacy of the STOLAND displays (and vehicle flight controls), if the pilot be required to take over and complete the short approach manually in the event of an automatic system failure.

As the starting point for the introduction of practical criteria for comparative display evaluation, we have turned to recent developments in human response theory and pilot/vehicle analysis (Refs. 2-4) as well as to the more traditional pilot opinion rating metrics (Ref. 5). In performing this review we shall apply the known relationships between predictable (and measurable) properties of pilot behavior in STOLAND control tasks and some of the practical cockpit display design parameters listed in Table 1. Our prior experience with STOLAND pilot/vehicle analysis and simulation (Refs. 6-8) will provide the necessary foundation for this review.

B. PREREQUISITES

To begin with, quantitative descriptions of the flight profile, vehicle dynamics, piloting tasks and constraints are required. These descriptions are already available in Refs. 6-8 based on our prior contributions to the

TABLE 1

PREDICTABLE DISPLAY-RELATED PARAMETERS FOR GUIDANCE, NAVIGATION, CONTROL, AND MONITORING BASED ON MANUAL CONTROL DISPLAY THEORY

Display content, i.e., displayed variables required for negotiating the flight profile and various tasks. Display content is based on the essential feedbacks and inputs for each task, subject to the allocation of control functions between the pilot and the automatic aids.

Display reference system, e.g., coordinates, orientation and format

Preferred combinations of displayed variables for reducing scanning workload, e.g., inner and outer loop associations

Control-and-displayed variable associations required for each task

Dynamic behavior required of the crew members, i.e., piloting technique

Dynamics of the display media and compensation thereof

Display locations and arrangement for least scanning workload

Display scale range, resolvable quantum, and angular subtense at the flight eye location

Potential parafoveal appeal of the format

STOLAND program. Using the material in these references (especially Ref. 6), we have prepared a prospectus for control techniques in Appendix A to this report. The prospectus for control techniques helps to establish the essential feedbacks. From these follow not only sensor and control requirements but also the first six predictable display-related parameters in Table 1. The method of developing essential feedbacks is described in Ref. 9 and was first applied to control-display design for the short landing approach problem in Ref. 10.

The prospectus in Appendix A uses the updated transfer functions and dimensional stability and control derivatives from Appendix D in Ref. 6. These reflect the latest available aerodynamic data anticipated for the Augmentor Wing aircraft. The multiloop coupling numerators used here in Appendix A are computed without the SAS so as to provide a more critical appraisal of manual control techniques and STOLAND displays, if the pilot should be required to take over and complete the short approach in the event of an automatic system failure.

The prospectus for control techniques necessarily depends on the flight profile, the dynamics and the controls of the Augmentor Wing Jet STOL Research Aircraft (AWJSRA or C-8M) designated for the present study of STOLAND displays. Therefore, this review of the content and function of the MFD, HSI, and EADI represents a further extension of the earlier cited work based on the same aircraft.

The AWJSRA presently being flown at NASA-Ames Research Center utilizes a combination of blown flaps and thrust vector control for lift augmentation. Reference to the "nozzle" control in this report designates the hot thrust vector control on the AWJSRA. Other flight and propulsion controls are conventional, viz., flap angle for lift augmentation, elevator for pitching moment control, aileron for rolling moment control, rudder for yawing moment control and turn coordination, and throttle for thrust magnitude control.

C. VEHICLE-CENTERED DESIGN REQUIREMENTS (From Ref. 7)

During en route phases of flight the best cruising speed of the AWJSRA is 82 m/s (160 kt) (IAS) at the altitude assigned by Air Traffic Control. This speed is reduced to 72 m/s (140 kt) on entering the terminal area until conversion to the approach speed, and 46 m/s (90 kt) is used for negotiating curved segments or holding patterns. Conversion from 140 kt to 90 kt is usually accomplished during straight and level flight to reduce the pilot workload associated with combined maneuvers and deceleration. While at 90 kt, the glide slope is usually acquired during wings level flight, although a descending turn may precede <u>and</u> follow acquisition of the glide slope. During the last stage of descent on the glide slope the final turning phase of the approach is initiated. About halfway around the turn the deceleration from

46 m/s (90 kt) to 31 m/s (60 kt) is initiated and is completed prior to completing the turn. The final approach is on a straight path. Deceleration and speed control are provided by the pilot. The trim management system and speed stability augmentation system (SAS) described in Ref. 8, but not yet implemented, are designed so as to reduce pilot workload.

There are several vehicle-centered design requirements that should be discussed at the outset. First, glide slope capture and subsequent tracking must be at or below 48 m/s (94 kt). Because of flap placards, drag capability is not sufficient to decelerate the vehicle on a 7.5 deg glide slope in the presence of a tailwind when the speed is higher than 94 kt (Ref. 7).

A second design requirement is that the vehicle control technique be properly altered as a function of frontside/backside flight conditions. When the vehicle is on the frontside of the thrust-required curve, i.e., $V \geq 44$ m/s (85 kt), the conventional technique of flight path control via elevator is preferred. Conventional flight path/attitude response times are proportional to speed; and at the higher speeds, larger path mode bandwidths can be achieved with attitude (through elevator) than with thrust or nozzle. Also, at these speeds the nozzles and/or thrust do not have sufficient control power to provide an adequate direct lift control (DLC) capability because the nozzle trim angle is less than 30 deg. At lower speeds where the vehicle is flying on the backside of the thrust-required curve, the STOL technique of controlling flight path with thrust and airspeed with attitude is preferred for reasons converse to those cited above for conventional control. The STOL technique avoids any flight path instability because of backsidedness. As a matter of fact, with the trimmed nozzles aligned nearly vertical, the only effective method of controlling speed <u>is</u> with attitude. Each of the above points is illustrated by the prospectus for control techniques at 46 m/s (90 kt) and 31 m/s (60 kt) in Appendix A.

A last vehicle-centered design requirement is for glide slope interception and acquisition at any speed from 60 to 90 kt. The normal procedure to expedite the approach and keep noise levels down is to decelerate to 90 kt while straight and level, intercept the glide slope, and slow to 60 kt when on the glide slope. However, the pilot should also be able to slow to 60 kt while straight and level and then intercept the glide slope. This situation might be necessary for approaches in a tailwind or for maintaining approach spacing.

This concludes our summary of vehicle-centered design requirements from Ref. 7. Next we shall summarize some pilot- and system-performance-centered requirements which affect the prospectus before resuming our review of the content and function of the primary STOLAND displays in the light of the prospectus of essential displayed feedbacks.

D. PILOT PERFORMANCE-CENTERED DESIGN REQUIREMENTS

Establishing the essential feedbacks represents the first step in the control-display optimization procedure — optimization of guidance and flight control topology. Foremost among pilot-centered design requirements, the topological prospectus of essential feedbacks must remedy aircraft handling quality deficiencies. Otherwise, the pilot must compensate for any dynamic deficiencies of the aircraft by appropriate adjustments of his dynamic properties. (In this context the "aircraft" includes the displays and controls.) There is a cost for this adjustment — in workload-induced stress, in concentration of pilot faculties, and in reduced potential for coping with the unexpected. This cost can also be traded for the cost of automatic control. Whereas an effective man/machine split can definitely solve stability problems by machine-aided stability augmentation, machine-aided control (in the guidance sense) will be effective only to the extent that the display-and-flight-control system design recognizes: a) the pilot's supervisory "trim and control" authority; b) his desire to participate at not more than a saturated work level throughout the flying task; and c) the necessity that he have the ability and opportunity to make key decisions requiring judgment of progress in the precision en route, terminal area, approach and landing tasks.

E. SYSTEM PERFORMANCE-CENTERED DESIGN REQUIREMENTS

Foremost among system performance-centered design requirements which affect the topological prospectus throughout the flight profile, the flight control system must provide:

- Acceptable margins of stability to establish and maintain specified equilibrium states of vehicle motion, i.e., operating points.
- Desired responses to specified inputs, both deterministic and stochastic.
- Suppression of the effects of undesired inputs, both deterministic and stochastic.
- Suppression of the effects of pilot, vehicle and component variations and uncertainties, i.e., least sensitivity of stability, disturbance regulation and command-following performance to variations in flight conditions, gain, equalization, time delay, unattended operation, noise sources, sensor location or orientation, control surface loads, and authority limitations.

Essential feedbacks derive from all of the foregoing requirements.

F. ESSENTIAL DISPLAYED FEEDBACKS

One of the most concise graphic ways to summarize the essential feedbacks is by means of a block diagram for each of the flight segments involving a particular piloting technique. Fortunately in the case of the AWJSRA, symmetric motions are uncoupled from asymmetric motions, and we can separately consider: a) the longitudinal-vertical control techniques; and b) the lateral-directional techniques. Therefore, we have prepared several block diagrams of essential feedbacks appropriate for a particular control technique. These essential feedbacks constitute the prerequisites for the content and function of the primary guidance and control displays, the EADI, HSI, and MFD. Throughout and following a discussion of the block diagrams next, we shall subsequently proceed to consider each primary STOLAND display described in Ref. 1 and illustrated in Appendix A together with whether or not it provides the essential feedbacks and other attributes from Table 1 in ways which favor the pilot-centered requirements.

1. Longitudinal-Vertical Control Techniques

The longitudinal-vertical control techniques can be divided, for convenience, into two groups based on the phases of flight for which the techniques are appropriate, viz.: a) en route and terminal area flight; and b) final approach on the glide slope. We shall present examples of each in turn.

a. En Route and Terminal Area Flight

At constant altitude. Figure 1 presents a block diagram of essential displayed feedbacks together with compensatory piloting techniques for longitudinal and vertical flight control en route and in the terminal areas under IFR at a reference airspeed, V_r, above that for minimum thrust required (i.e., for frontside operation) and at a reference altitude, h_r. All of the pilot's trim control functions are based on indicated airspeed. Examples of some trim configuration management schedules are given in Refs. 6 and 8. Cruising airspeed regulation with respect to V_r is accomplished with the throttle based on airspeed error. Decelerating airspeed control is accomplished with the nozzle, again based on airspeed error. Although the numerical airspeed display on the EADI (Appendix A, Fig. A-1) represents an essential feedback which is always available to the pilot for the purpose of monitoring and trim management, the numerical form of display has no parafoveal appeal and has been shown in Ref. 11 to be unsuitable for the purpose of tracking. However, the airspeed error tracking display on the EADI is available only when the STOLAND "Flight Director" or "Automatic" modes are operating (Ref. 1). Thus, when the pilot is using raw situation data for flight control, he should derive airspeed tracking error with respect to the reference "bug" on his airspeed indicator to the left of the EADI, which definitely requires an extra scan transition and fixation away from the EADI (Appendix A, Fig. A-4). This will tend to corrupt the pilot's perceived airspeed error signal, u_e, with relatively more internally generated scanning noise than would the airspeed error tracking display on the EADI, which offers at least moderate parafoveal appeal.

Cruising altitude regulation with respect to h_r is accomplished through pitch attitude regulation with the elevator using the EADI (Appendix A,

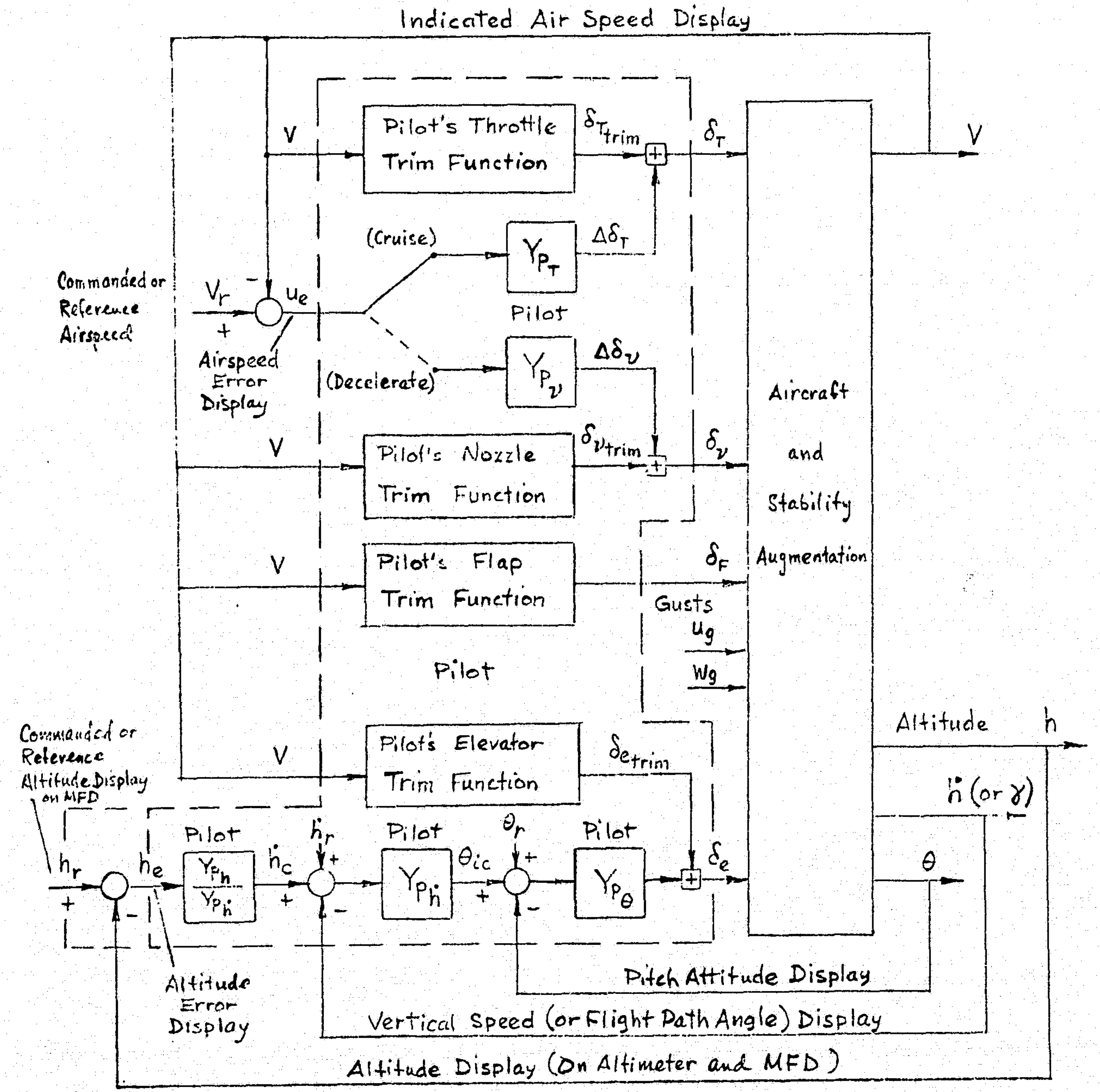

Figure 1. Block Diagram of Essential Displayed Feedbacks with Compensatory Piloting Techniques for Longitudinal and Vertical Flight Control of the AWJSRA En Route and in the Terminal Area Under IFR at a Reference Airspeed, V_r, Above that for Minimum Thrust Required and at a Reference Altitude, h_r

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Fig. A-1). The commanded or reference altitude, h_r, is displayed numerically only in the list of "next waypoint data" in the lower left corner of the MFD. The barometric altitude is displayed in the upper left corner of the MFD (Appendix A, Fig. A-3). The altitude error display on the EADI is provided by the normal displacement of the path deviation "window" with respect to the case-fixed airplane symbol which serves also as the point of reference for pitch attitude. Thus, inner and outer loop tracking displays appear well coordinated from the pilot's viewpoint, and both may even be perceived in the same fixation. In addition, there is an altitude error display provided (for monitoring) on the HSI by the vertical deviation indicator at the right edge (labeled "glide slope scale and pointer" in Appendix A, Fig. A-2). It also, however, provides altitude error with respect to any reference flight path. Besides the "ILS" and "MLS" modes, these altitude error displays on the EADI and HSI are available for en route and terminal area flight only in the "Reference Flight Path" mode when the path has been captured laterally. Verifying that the numerical value of altitude is correct requires an extra scan transition and fixation away from the EADI either to the barometric altimeter at the left of the EADI (Appendix A, Fig. A-4) or to the numerical barometric altitude display on the opposite side at the top of the MFD (Appendix A, Fig. A-3).

Vertical path damping is provided by the vertical speed ($\dot{h}$) or flight path angle (γ) feedback. (Recall that for small angles, $\gamma \doteq \dot{h}/V_o$, where V_o is the trimmed speed, so that $\dot{h}$ and γ are dynamically equivalent, although the sensitivity of γ to changes in $\dot{h}$ will be inversely proportional to the trimmed speed.) The EADI provides γ and its inner loop associate, pitch attitude, θ, in the form of an ideal superimposed multiloop tracking display commensurate with the pitch angle scale and compatible with the motion of the path deviation window in the manner of a "state and rate" combination (Ref. 12). The whole value of either $\dot{h}$ or γ can be selected for display in numerical form near the top of the EADI, but this is not in a suitable form for the purpose of tracking control (Ref. 11). It is, however, acceptable for verifying steady values of vertical speed or angle in climbing and descending flight. This we shall discuss subsequently in connection with Fig. 2.

The signals within the pilot labeled $\dot{h}_r$ and θ_r in Fig. 1 contain both deterministic and random components. The deterministic components represent the trimmed values of vertical speed (or flight path angle) and pitch attitude, respectively, remembered by the pilot. The random components represent internally generated scanning noise. If the pilot chooses to scan the conventional instantaneous vertical speed indicator (IVSI) at the left of the altimeter in closing his vertical speed feedback loop, he will incur a relatively greater penalty in the form of scanning noise than if he uses the EADI to close a flight path angle loop. Given the greater sensitivity of the IVSI and its format which is incompatible with the EADI format anyway, there is little choice but to locate the IVSI on the instrument panel in a peripheral relationship to the altimeter where movements of its relatively sensitive pointer will be detected by the pilot's parafoveal vision.

Climbing and descending en route and in the terminal area. Figure 2 presents a block diagram of essential displayed feedbacks together with compensatory piloting techniques for longitudinal and vertical flight control en route and in the terminal area under IFR at a reference airspeed, V_r, above that for minimum thrust required and climbing or descending along a reference flight path angle, γ_r. On the EADI the reference path angle is defined by the pitch scale (although there is no cursor to identify the reference value) so that the angle itself has to be remembered by the pilot or verified by scanning to the numerical flight path angle reference display at the extreme right of the MFD (Appendix A, Fig. A-4). Since "frontside" operation is presumed, vertical flight path regulation in Fig. 2 is accomplished through pitch attitude regulation with the elevator, and speed regulation is with the throttle as described in Fig. 1. The EADI content and format are ideal. The deceleration and trim functions are identical to those already described in connection with Fig. 1.

Operation of the "FP Acceleration" symbol on the EADI (Appendix A, Fig. A-1) is not described in the text of Ref. 1, so we can only speculate about its intended purpose. One possibility is to present $\gamma_o + \theta$ to the pilot as an inner loop signal to provide the necessary lead equalization for regulating γ. In such a role, the perturbed pitch attitude θ is a surrogate for $T_{\theta_2}\dot{\gamma}$ at frequencies above the inverse flight path time constant, $1/T_{\theta_2}$ (see below). That

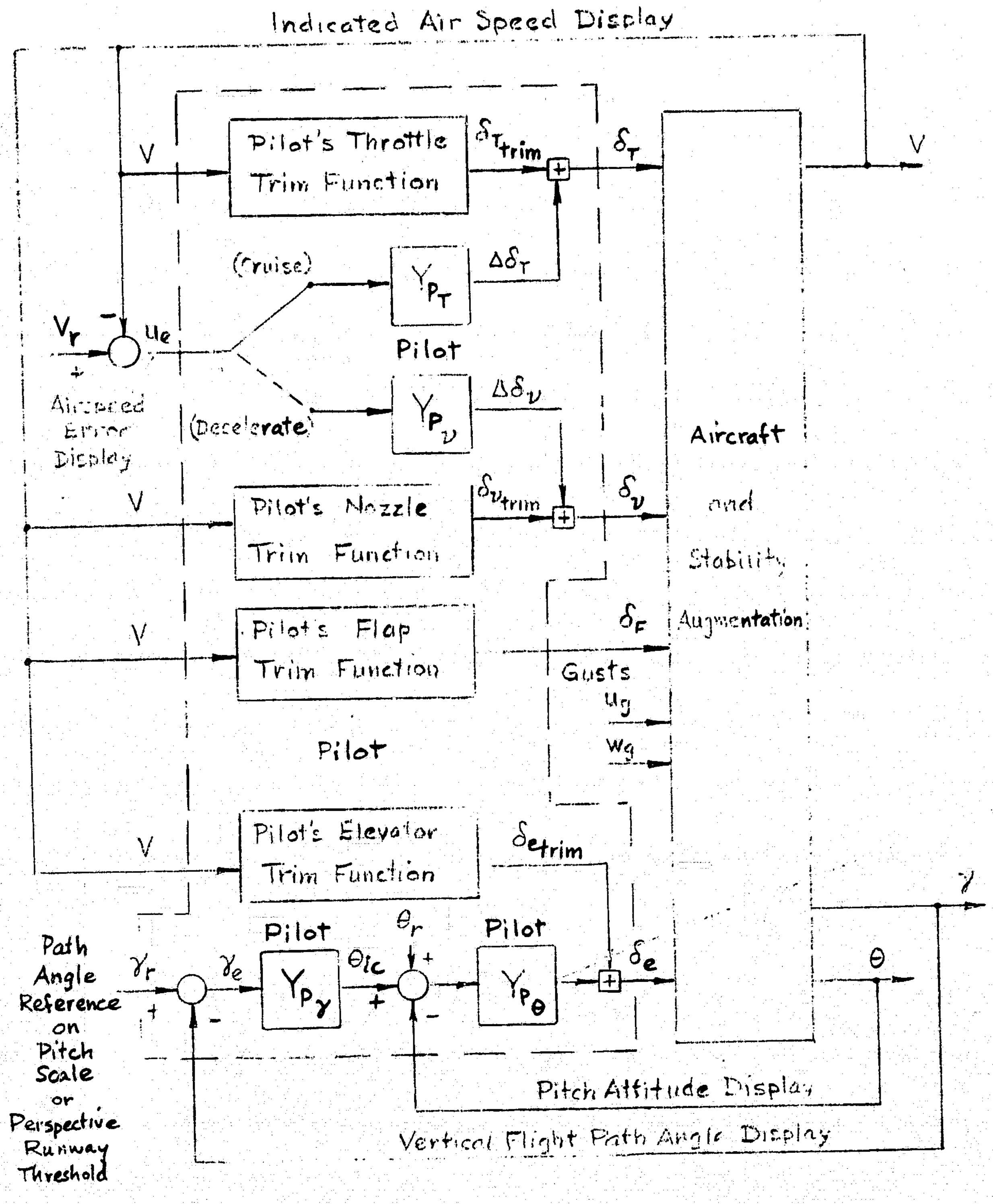

Figure 2. Block Diagram of Essential Displayed Feedbacks with Compensatory Piloting Techniques for Longitudinal and Vertical Flight Control of the AWJSRA En Route and in the Terminal Area Under IFR at a Reference Airspeed, V_r, Above that for Minimum Thrust Required and Climbing or Descending along a Reference Flight Path Angle, γ_r, Defined by the Displayed Pitch Scale.

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this is so can be seen from the simple but accurate approximate differential equation relating γ and θ in the low- to mid-frequency region, viz.,

$$\theta = \gamma + T_{\theta_2}\dot{\gamma}$$

where

$$1/T_{\theta_2} \doteq -Z_w + (Z_{\delta_e}/M_{\delta_e})M_w$$

where the stability derivatives, Z_w and M_w, and the control power derivatives are according to the notation of Ref. 9. Obviously this is a redundant use of the "FP Acceleration" symbol, because θ is already presented on the EADI; however, it would provide a compatible "state and rate" format for flight path angle control.

A second possibility is to present potential flight path angle, γ_p, on the "FP Acceleration" symbol, viz.,

$$\gamma_p = \gamma_o + \frac{a_x}{g}$$

where γ_o is the trimmed flight path angle; a_x, the perturbed longitudinal acceleration; and g, the gravitational acceleration. Since, in level flight,

$$a_x \doteq g\theta + \dot{u}$$

this possibility includes the first with the additional anticipation of changes in flight path afforded by changes in speed, u.

A third possibility for the "FP Acceleration" symbol has nothing to do with flight path acceleration. Instead, the symbol would represent the reference path angle, γ_r, which has otherwise to be remembered by the pilot while looking at the EADI.

b. Final Approach on the Glide Slope

Before we discuss the essential displayed feedbacks required for tracking the glide slope, we shall review several displays on the EADI which are essential to the pilot for monitoring approach progress. These are:

- Radio Altitude
- Minimum Decision Altitude
- Approach Progress

The numerical radio altitude display has no parafoveal appeal and therefore requires a scan transition and separate fixation within the field of the EADI for perception. Thus the pilot would have to interrupt his tracking fixation on the center of the EADI in order to monitor radio altitude visually. This would contribute scanning noise in the pilot's control action. Given the range and resolution (Appendix A, Fig. A-1) of radio altitude presented, the numerical form of display offers the least clutter and least chance for misinterpretation, as long as it is not intended for tracking.

The minimum decision altitude indication is discrete and appears to be presented in an excellent location within the EADI for attracting the pilot's attention during precision tracking — in the center of the airplane symbol. However, when one reflects on the rationale of the minimum decision altitude, presentation only on the EADI would seem insufficient, since the pilot approaching his minimum decision altitude will possibly also be scanning out of the cockpit with his head up.

The approach progress display employs color coding for a sequence of discrete lighted letters arrayed vertically in the right bezel of the EADI. The array offers some parafoveal appeal when the lights change, which may be sufficient to attract the pilot's attention without requiring scanning.

Next we shall review the essential displayed feedbacks required for tracking the glide slope while trimmed for both "frontside" and "backside" operation.

Airspeed above that for minimum thrust required ("frontside" operation). Figure 3 presents a block diagram of essential displayed feedbacks together

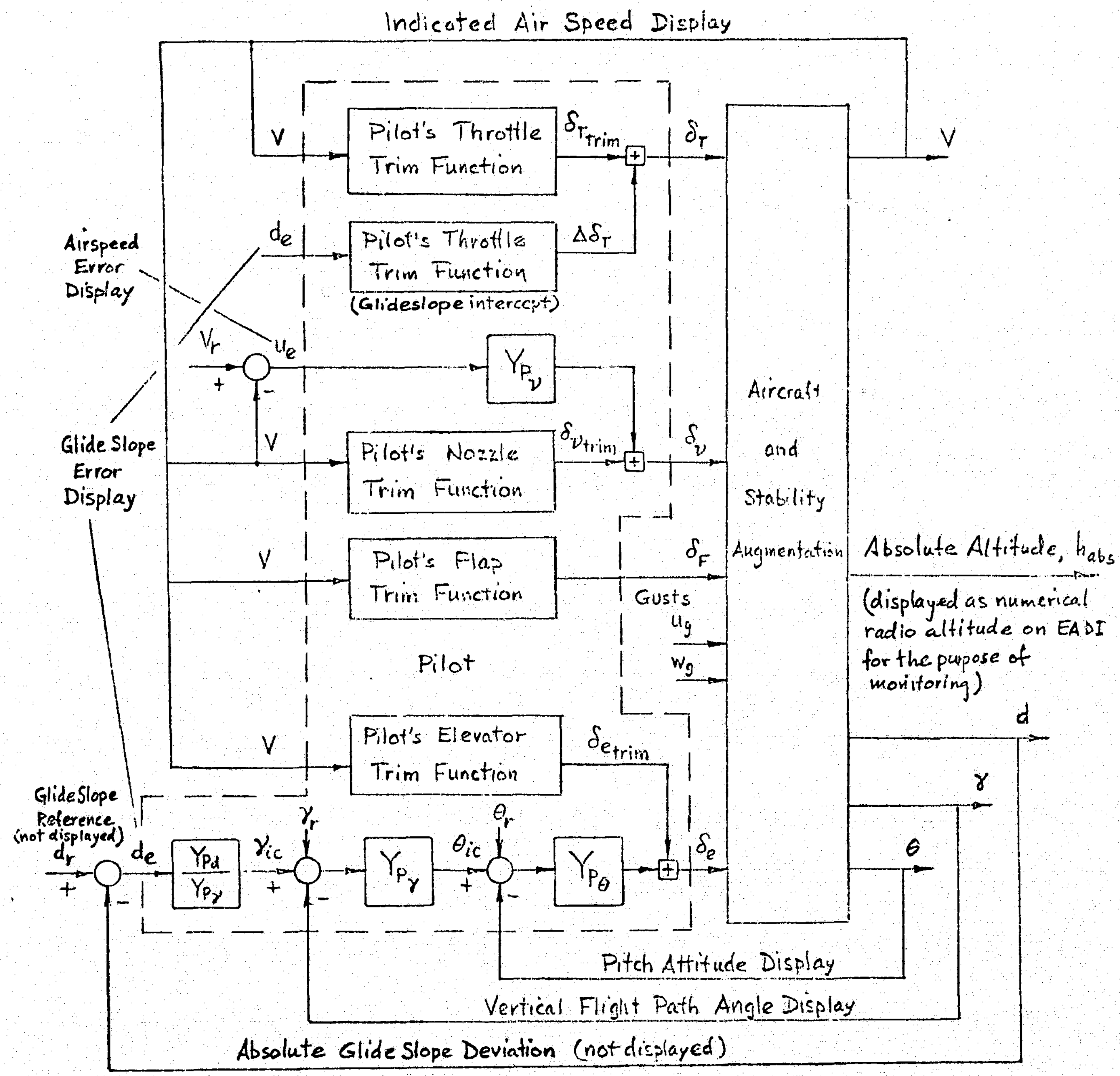

Figure 3. Block Diagram of Essential Displayed Feedbacks with Compensatory Piloting Techniques for Longitudinal and Vertical Flight Control of the AWJSRA on Acquiring the Glide Slope for Final Approach under IFR at a Decreasing Reference Airspeed, V_r, Above that for Minimum Thrust Required.

with compensatory piloting techniques for longitudinal and vertical flight control on acquiring the glide slope for final approach under IFR at a decreasing "frontside" reference airspeed, V_r. The pilot's deceleration and trim functions are identical to those already described in connection with Fig. 1 with the addition of a discrete change in the throttle trim function at glide slope intercept. For acquiring and tracking the glide slope, the glide slope error window display is provided on the EADI by the same path deviation window already described in connection with altitude control in Fig. 1. In addition the pilot can monitor glide slope deviation on the HSI (Appendix A, Fig. A-2). Comparison of the lower portions of Figs. 1 and 3 devoted to the pilot's elevator control technique will reveal their similarity. The vertical flight path angle display on the EADI provides the feedback for path damping, and glide slope displacement regulation is accomplished through pitch attitude regulation. Here again, the EADI provides d_e, γ, and θ in the form of an ideal superimposed multiloop tracking display as described previously in connection with Fig. 1.

Airspeed below that for minimum thrust required. Figure 4 presents a block diagram of essential displayed feedbacks together with compensatory piloting techniques for longitudinal and vertical flight control on acquiring the glide slope for final approach under IFR at a decreasing reference airspeed, V_r, below that for minimum thrust required (i.e., for "backside" operation). Although the deceleration and trim functions remain identical to those already discussed in connection with Fig. 1, airspeed regulation is now accomplished through the regulation of pitch attitude with elevator, and glide slope displacement regulation through flight path angle regulation with throttle, subject to monitoring angle of attack for stall margin. Regardless of the airspeed, the perspective runway symbol provides a reference for the flight path angle display in the "Reference Flight Path" and the "MODILS" approach modes.

2. Lateral-Directional Control Techniques

Figure 5 presents block diagrams of essential displayed feedbacks with compensatory and pursuit piloting techniques for lateral-directional flight control en route, in the terminal area, and on landing approach under IFR.

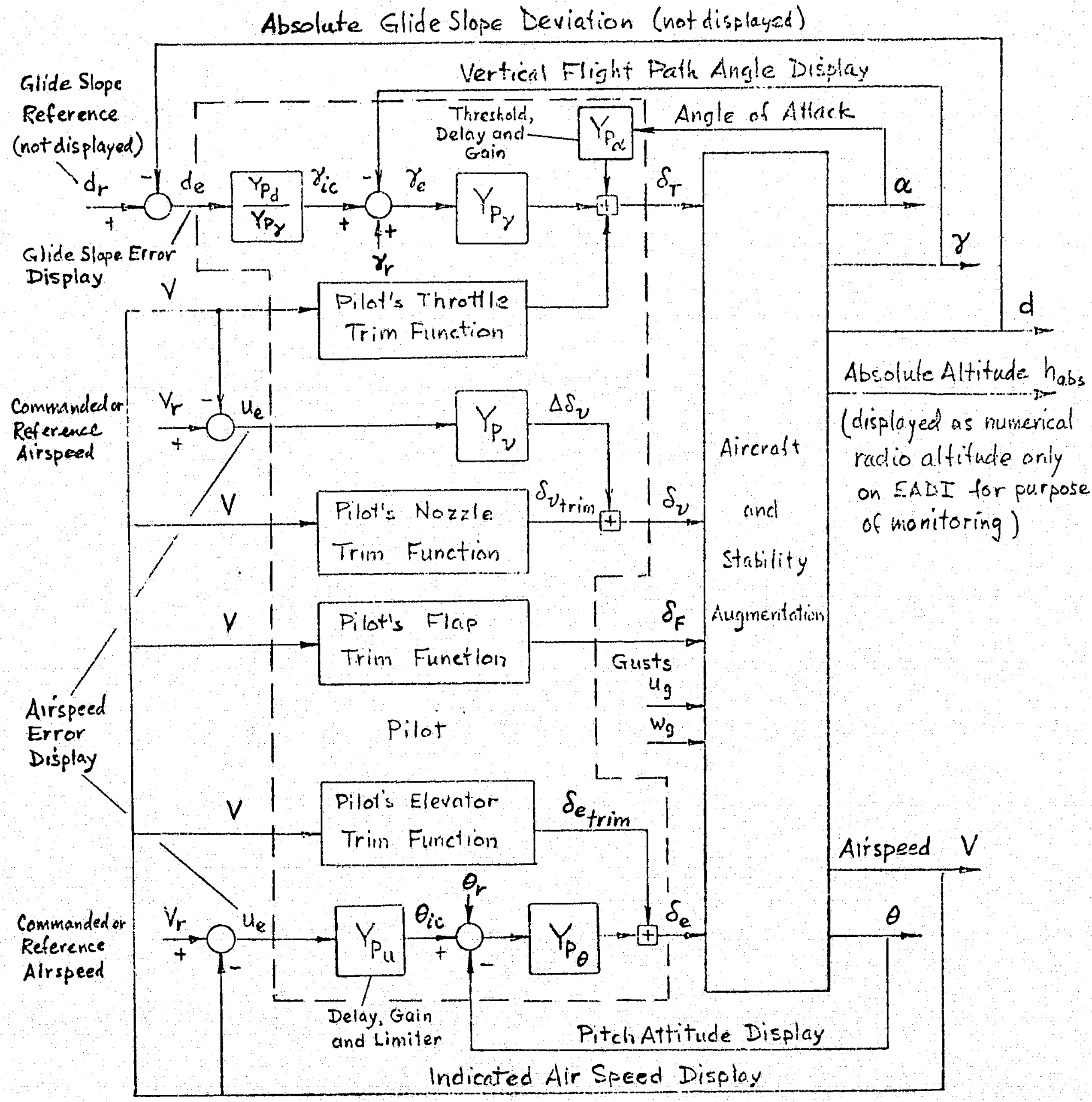

Figure 4. Block Diagram of Essential Displayed Feedbacks with Compensatory Piloting Techniques for Longitudinal and Vertical Flight Control of the AWJSRA on the Glide Slope for Final Approach Under IFR at a Decreasing Reference Airspeed, V_r, Below that for Minimum Thrust Required

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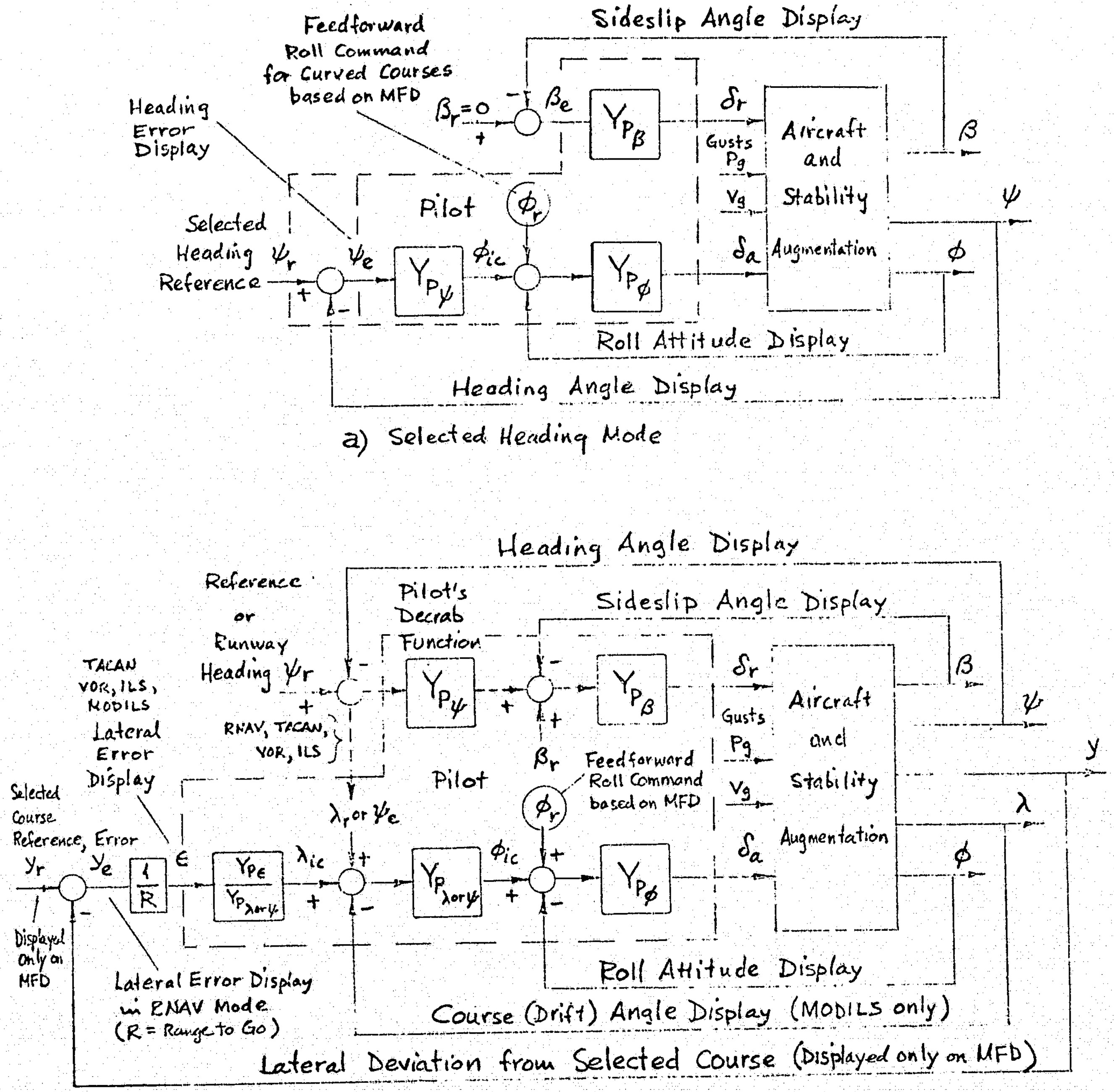

a) Selected Heading Mode

(b) Reference Flight Path (RNAV), TACAN, VOR/DME, ILS, and MLS Modes

Figure 5. Block Diagram of Essential Displayed Feedbacks with Compensatory and Pursuit Piloting Techniques for Lateral-Directional Flight Control En Route, in the Terminal Area, and on Landing Approach Under IFR

Pursuit piloting techniques involve the opportunities for adopting feedforward roll commands for flying curved courses in the presence of winds based on the explicit graphical plan view of the terminal area situation, the required course and the predicted track afforded by the MFD (Appendix A, Fig. A-3). In contrast, the HSI (Appendix A, Fig. A-2) presents only compensatory information with respect to the desired course and presents polar coordinates of position which require mental imaging by the pilot.

Part a of Fig. 5 shows the displayed feedbacks and control technique for selecting and flying a particular heading. The desired heading angle is selected and displayed numerically at the extreme right of the MFD (Appendix A, Fig. A-4). Corresponding selected heading cursors appear on the heading dial and tape of the HSI (Appendix A, Fig. A-2) and MFD (Appendix A, Fig. A-3), respectively, but there is no heading scale presented on the EADI with its inner loop associate, roll attitude. Thus scanning between the EADI and either the HSI or MFD is assuredly required in order to turn to and hold a selected heading.

RECOMMENDATION: The scanning transition workload presently required between the EADI and either the HSI or MFD to fly or monitor a selected heading might be reduced in either of two ways:

a) Present a duplicate of the MFD moving heading tape and selectable "bug" just below the roll scale at the top of the EADI in place of the programmable readout. Change the roll scale to be movable, i.e., horizon-oriented, and fix the single roll indicator to the case. Coordinate the display of both roll scale and heading tape in horizon-oriented "inside-to-outside" relationship with respect to the case-fixed index. This provides a compatible "state and rate" format with the essential content for flying the selected heading with the technique in Fig. 5a through aileron control (Ref. 12).

b) Transfer the case-fixed roll scale and moving roll indicator to the bottom of the EADI and present a duplicate of the MFD moving heading tape and "bug" just above or below the roll scale. Coordinate the case-oriented display of both roll scale and heading tape with the horizon-oriented index. This also provides a compatible "state and rate" format with the essential content for flying the selected heading with the technique in Fig. 5a through aileron control. This offers a distinct advantage over Item a (above) in that the moving heading tape can retain the case orientation familiar to the pilot and similar to the one on the MFD.

Since the AWJSRA is provided with automatic turn coordination by the stability augmentation subsystem (SAS), the pilot need only monitor its effectiveness with the sideslip angle display feedback to the rudder shown in Fig. 5. The sideslip angle display is not part of the EADI but is provided at its left side on the instrument panel. If the sideslip angle display (or an inclinometer) were located at the bottom of the EADI and coupled with the second recommendation above, the monitoring workload could be further reduced.

The signal within the pilot in Fig. 5 labeled φ_r may contain both deterministic and random components. The deterministic component may be a feed-forward roll command based on the MFD for flying a curved course in the presence of wind. The random component may be the pilot's scanning noise. The heading error display, ψ_e, is the difference between the selected heading (ψ_r) "bug" and the present heading (ψ) index; the perceived signals ψ_e, ψ_r, and ψ, all of which are explicitly displayed, may also be contaminated with scanning noise.

Part b of Fig. 5 shows the displayed feedbacks and control technique(s) for selecting and flying a particular course exemplified by lateral guidance from Reference Flight Paths (RNAV), TACAN, VOR/DME, ILS or MLS.* The lateral error display on the EADI is provided by the lateral displacement of the center of the path deviation window with respect to the center of the airplane symbol. Lateral displacement error from the desired course can also be monitored directly on the MFD or on the HSI course deviation indicator. A course (drift) angle display on the EADI for path damping is provided only in the MODILS mode of guidance. (MODILS is a particular microwave landing system.) Alternatively, when flying with raw situation data, the pilot must scan to the HSI or MFD for heading angle feedback to provide lateral path damping in the RNAV, TACAN, VOR or ILS modes. This is less than desirable and reinforces the previous recommendation that the EADI be provided with a heading scale.

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*The navigational aids represented by the initials are: Area Reference Navigation (RNAV), Tactical Air Navigation (TACAN), Very High Frequency Omnidirectional Radio (VOR) with Distance Measuring Equipment (DME), Instrument Landing System (ILS) and Microwave Landing System (MLS). All employ cylindrical coordinates or a portion thereof.

When the pilot is using guidance from RNAV, TACAN, VOR/DME, ILS or MLS, the desired course angle may be selected and will be displayed numerically at the extreme right of the MFD (Appendix A, Fig. A-4). The corresponding selected course will be displayed by the (course) pointer on the HSI (Appendix A, Fig. A-2) and by the (course) vector on the MFD (Appendix A, Fig. A-3). Whereas the HSI is always oriented "heading up," the pilot may choose to orient the MFD either "heading up" or "course up" for the purpose of monitoring lateral-directional control or even "north up" for the purpose of flight planning.

When the pilot is using guidance from RNAV, the pilot must also select one among four reference flight paths which he has set up and stored in advance by designating a sequence of waypoint coordinates for each reference flight path. After the pilot has selected the number of the waypoint at which he wishes to enter the reference flight path, this waypoint designation number (WPT) and its altitude (CALT) will appear in the lower left corner of the MFD, if enabled by the pilot. All guidance prior to passing the entry waypoint is three-dimensional spatial guidance. When the entry waypoint is passed, four-dimensional spatial and temporal guidance is initiated. The airspeed error from the commanded speed is presented on the EADI for the purpose of control, and the time to the next waypoint (TWPT) in the lower left corner of the MFD for the purpose of planning and monitoring. In addition, STOLAND navigation computations release a "ghost" aircraft, also displayed on the MFD, which travels along the reference flight path at whatever speed is required for the aircraft to arrive at the final waypoing on schedule. The time difference (ΔT) between the position of the "ghost" and the actual aircraft, and the predicted time error (PTE) shown in Appendix A, Fig. A-3, and described in Ref. 1 are replaced in the lower left corner of the MFD in other versions of STOLAND. For example, in one version the predicted time of arrival (TOA) and the time delay available (TDA) at the final waypoint are displayed (vide Ref. 13). Present clock time is presented in the (opposite) upper right corner of the MFD.

The content and scale of the stored maps for the MFD are selectable by the pilot on the MFD control (Appendix A, Fig. A-4). Presently available options are described in Ref. 1. The route of the selected flight path is displayed on the MFD whether or not a map has been selected.

The most dramatic differences between the HSI and MFD are in their respective formats which present the essential displayed feedbacks for confirming present position in relation to the flight plan. Although the HSI does not pretend to offer past and future position explicitly, even the interpretation of its format for present position requires mental gymnastics by the pilot when flying a curved course. The HSI was designed for flying a straight course and, coupled with the STOLAND navigation computations, does a reasonable job of displaying the essential information for keeping track of present position when flying a sequence of different straight courses between waypoints. In contrast, as noted at the beginning of this lateral-directional topic, the MFD presents an explicit map of the terminal area situation with either a portion of the route or the entire intended course, its waypoints and navigational aids in graphic relationship with the past track, present position, and predicted future track of the aircraft. The MFD thus offers the essential ingredients both for relieving the pilot of considerable mental workload in confirming his position, and for enabling him to adopt higher-than-compensatory levels of skill while negotiating curved courses and changes in flight plan in the presence of winds.

G. FLIGHT DIRECTOR COMMAND DISPLAYS

The purpose of a flight director system is to reduce the pilot' perceptual equalization and scanning workload by combining the various displayed and processed variables used by the pilot in performing a given task into one command display which presents a single-loop compensatory tracking task for each axis of control. The flight director command displays must be properly integrated with, but must not clutter, the confidence-inspiring situation or status information display to which the pilot is accustomed. Whereas closed-loop analysis using existing pilot models will yield directly the vehicle motion variables which must be displayed in order to accomplish a given task (e.g., Ref. 7), successful integration of the command and status displays depends on symbolic contrast, density, stereotypes and motion harmony in the display format, which must, at our present level of understanding, be validated by real-time simulation and flight test with pilots.

With regard for its impact on closed-loop system performance and pilot workload, a good flight director system is competitive with an automatic flight control system for command-following and disturbance suppression. For certain other inputs, such as radio guidance or wind anomalies, the piloted flight director system performance may be superior to that of a fully automatic system. The flight director should permit safer operation by the pilot and copilot in their normal roles as active controllers and monitors of the situation. In this way, they are kept in the loop in case of aircraft or system failures. However, an additional purpose of the flight director command display is to provide an overall monitor on the automatic system performance both to instill confidence in the pilot and to permit him to take over gracefully in case of a malfunction.

The flight director command displays on the EADI are shown in Fig. A-1 in Appendix A. There are three command symbols and a speed error symbol, each uniquely associated with a control, sometimes in a particular flight regime. The pitch command bar is always associated with the elevator control, and the roll command bar, always with the aileron control. During "frontside" operation the speed error symbol on the vertical scale at the left edge of the EADI provides a basis for throttle trimming activity. During "backside" operation the throttle command symbol on the left wingtip of the airplane symbol on the EADI provides for the necessary direct powered-lift modulation.

In an EADI for conventional aircraft there are only the two central command bars in cruciform arrangement, one for column and one for wheel. Therefore, these are familiar stereotypes and their form and directions of motion are geometrically compatible with both the outer loop path deviation "window" and the motions of the top of the column and wheel controls. Although the direction of motion of the pitch command bar is also in harmony with the pitch axis of the EADI when the wings are level, the direction of motion of the roll command is not compatible with the roll axis of the EADI, because of its cruciform arrangement. Whether the "roll" command symbol should roll or translate laterally remains an issue subject to individual pilot preference, although results of direct comparative experiments with objective heading error measures sensitive to the roll command format have been published in Ref. 14. These favor the conformable rolling director command.

The throttle command symbol and its location on the left wingtip are based on the stereotype in Refs. 15 and 16 used for direct lift command in a helicopter flight director. However, the throttle, which is used for height regulation on final approach in the STOL mode in the AWJSRA, is operated by the pilot with his right hand, and the numerical radio altitude display for monitoring final approach altitude is on the right side of the EADI. Therefore, we offer the following recommendation.

> RECOMMENDATION: Relocate the throttle command symbol on the right wingtip of the airplane symbol to reduce the scanning distance for monitoring numerical radio altitude and to correlate the command symbol location with the throttle control location on the right of the command pilot.

The control laws for the command displays should be such that when the pilot nulls the command bars, the aircraft will be directed to the desired course and path in accord with the system performance-centered design requirements cited previously. In addition to these guidance performance requirements, the feedback quantities for the flight director must be weighted, filtered and equalized in accord with a set of pilot-centered requirements, so that the pilot can close each flight director system loop with ease and efficiency. These requirements for STOL flight director systems are beyond the scope of this report and have already been presented and discussed in Ref. 3 and applied to the AWJSRA in Refs. 6 and 7.

H. SUMMARY AND CONCLUSIONS WITH RESPECT TO CONTENT AND FUNCTION OF THE STOLAND DISPLAYS

1. Summary

We have summarized the preceding review of the content and function required of each primary STOLAND display in tabular form with qualifying comments about some of the other perceptually related attributes listed in Table 1. Table 2 presents a summary review of the EADI; Table 3, of the HSI; and Table 4, of the MFD.

TABLE 2. SUMMARY REVIEW OF CONTENT AND FUNCTION OF EADI

CONTENT	ESSENTIAL FOR	DISPLAYED IN COMBINATION WITH	SCANNING TRANSITION WORKLOAD	COORDINATES, ORIENTATION AND FORMAT	POTENTIAL PARAFOVEAL APPEAL	SCALE QUANTUM AND RANGE
Pitch Attitude and Horizon	Elevator control of flight path (front-side) and speed (backside)	Airplane Symbol, Path Deviation, Speed Error, Pitch Command Bar	Low; centrally located	Angular, earth, inside-out, analog	Excellent	2 deg over ±10 deg
Roll Attitude and Horizon	Aileron control of course and heading	Airplane Symbol, Path Deviation, Crossed Command Bars	Low; centrally located horizon; roll scale upper center	Angular, earth, inside-out, analog	Excellent for horizon; moderate for scale	10 deg over ±30 deg
Radio Altitude	Monitoring progress of final approach; glide slope gain adaptation and terrain clearance	Nothing else (Monitoring value only)	Moderate; upper right location	Linear, case, numeric	Nil	1 ft over 2500 ft
Indicated Airspeed	Trimming and sustaining flight; longitudinal control	Nothing else; useless for any function except monitoring trim value	Moderate; upper left location	Linear, case, numeric	Nil	1 kt from 30 to 909 kt
Vertical Speed (Optional) (See also flight path angle)	Damping height regulation and controlling ascent and descent	Programmable display, useless for any function except monitoring value	Moderate; upper central location	Linear, case, numeric	Nil	100 ft/min over ±9900
Heading (Optional)	Damping course deviations and controlling direction	Programmable display, useless for any function except monitoring value	Moderate; upper central location	Angular, case, numeric	Nil	1 deg over 360 deg
Angle of Attack (Optional)	Monitoring stall margin of safety	Programmable display (monitoring value only) but lacks identity	Moderate; upper central location	Angular, case, numeric	Nil	1 deg over ±90 deg
Distance to Touch-down (Optional)	Monitoring approach progress; localizer gain adaptation	Programmable display (monitoring value only) but lacks identity	Moderate, upper central location	Linear, case, numeric	Nil	1 ft over 9999 ft
Flight Path Angle (Inertial, except when source is unavailable, then aerodynamic)	Damping glide slope displacement regulation and controlling ascent and descent near the ground	Programmable display (Optional) Monitoring value only, but lacks identity	Moderate; upper central location	Angular, case, numeric	Nil	1 deg over ±90 deg
		Airplane Symbol, Pitch Attitude, Perspective Runway	Low; centrally located	Angular, earth, inside-out, analog	Excellent	2 deg over ±10 deg

TABLE 2 (Concluded)

CONTENT	ESSENTIAL FOR	DISPLAYED IN COMBINATION WITH	SCANNING TRANSITION WORKLOAD	COORDINATES, ORIENTATION AND FORMAT	POTENTIAL PARAFOVEAL APPEAL	SCALE QUANTUM AND RANGE
Minimum Decision Altitude Indication	Initiating missed approach procedure	Airplane Symbol	Low; centrally located	Discrete, case, alternating black and white contrast of small square	Excellent	Go/No-Go Indication
Pitch Flight Director Command Bar	Elevator control of flight path (frontside) and speed (backside) and for monitoring automatic control	Airplane Symbol, Pitch Attitude, Path Deviation, Speed Error	Low; centrally located	Angular, case, analog	Excellent	None, but consonant with pitch attitude, path deviation
Roll Flight Director Command Bar	Aileron control of course and heading and for monitoring automatic control	Airplane Symbol, Path Deviation	Low; centrally located	Angular, case, analog	Excellent	None, but consonant with path deviation
Airspeed Error	Throttle control of speed (frontside) and elevator control of speed (backside)	Nothing else	Moderate; left edge location	Apparently angular, actually linear; case; analog	Moderate	Five-point scale; no numerals
Throttle Director Command	Throttle control of flight path (backside)	Airplane Symbol, Path Deviation	Low, centrally located	Angular, case; analog bar	Poor, when nulled; good when fluctuating	None, but consonant with path deviation
ILS Window (Path Deviation)	Control of Displacement from path and course	Airplane Symbol, Pitch Attitude, Speed Error, Crossed Command Bars	Low; centrally located	Angular and linear, case, analog	Excellent	Ref. 1, e.g., window is 762 m (2500 ft) laterally by 61 m (200 ft) vertically
Drift Angle	Aileron control of approach course and decrab with rudder	Airplane Symbol, Flight Path Angle, Perspective Runway	Low; centrally located	Angular, earth, analog	Excellent	None, but consonant with course, hdg
Perspective Runway	Control of flight path and approach course	Flight Path Angle, Drift Angle	Low; centrally located	Angular, earth, perspective	Excellent	See Ref. 1
Airplane Symbol	Display reference	Items listed above	Low; centrally located	Case ref.	Excellent	None
Approach Progress	Monitoring	Nothing else	Moderate; right edge location	Discrete, case, colored lights	Poor, except when changing	Go/No-Go indication

TABLE 3. SUMMARY REVIEW OF CONTENT AND FUNCTION OF HSI

CONTENT	ESSENTIAL FOR	DISPLAYED IN COMBINATION WITH	SCANNING TRANSITION WORKLOAD	COORDINATES, ORIENTATION AND FORMAT	POTENTIAL PARAFOVEAL APPEAL	SCALE QUANTUM AND RANGE
Heading	Damping course deviations and controlling direction	Selected Heading, Compass Bearings, course and deviation	High; lower central location with respect to EADI	Angular, earth, inside-out, numeric	Nil	5 deg over 360 deg
Selected Heading	Heading reference	Heading, etc.	Low with respect to heading	Same as heading	Good with respect to heading	Same as heading
Selected Course	Course reference	Compass Bearings, Course Deviation, To/From	Low with respect to heading to waypoint, high from nav. aid	Same as heading	Good with respect to heading to waypoint, poor from nav. aid	Same as heading
Bearing 1	Present position	Compass, etc. DME 1	High	Same as heading	Fair to poor	Same as heading
DME 1	Present position	Bearing 1	High	Linear, case, numeric	Nil	1 nm over 299 nm
Bearing 2	Present position	Compass, etc. DME 2	High	Same as heading	Fair to poor	Same as heading
DME 2	Present position	Bearing 2	High	Linear, case, numeric	Nil	1 nm over 299 nm
To/From	Course reference	Selected course	Low with respect to selected course	Discrete, earth, inside-out, analog	Fair	None
Course Deviation (CDI)	Control of displacement from selected course	Selected course, Airplane Symbol, To/From	Low with respect to selected course, heading	Linear or angular, earth, inside-out, analog	Good with respect to selected course	See Ref. 1, e.g., ±2 dots = ±762 m (±2500 ft)
Vertical Deviation (VDI)	Control of displacement from vertical path, selected altitude or glide slope	Nothing else	High; right edge location with respect to CDI	Linear or angular, case, analog	Poor	See Ref. 1, e.g., ±2 dots = ±61 m (±200 ft)
Warning Flags for Course Deviation and Vertical Deviation	Monitoring validity of deviations	Course deviation and vertical deviation	Low	Discrete, case, colored label	Good	None

TABLE 4. SUMMARY REVIEW OF CONTENT AND FUNCTION OF MFD

CONTENT	ESSENTIAL FOR	DISPLAYED IN COMBINATION WITH	SCANNING TRANSITION WORKLOAD	COORINDATES, ORIENTATION AND FORMAT	POTENTIAL PARAFOVEAL APPEAL	SCALE QUANTUM AND RANGE
Barometric Altitude	Monitoring altitude assigned by ATC	Heading Scale but not with altitude assigned by ATC	High; upper left location	Linear, case, numeric	Nil	10 ft over 99999 ft
Time	Monitoring schedule	Heading Scale	High; upper right location	Hr:Min:Sec case, numeric	Nil	1 sec over 24 hr
Map 1	Terminal area feature identification	Flight Path, Waypoints, Aircraft Symbol, Course or Heading Vector	Moderate	Selectable	Fair (Uncluttered)	Selectable
Map 2	Low altitude en-route feature identification	Same as above	High	Selectable	Poor (Cluttered)	Selectable
Map 3	Experimental display undefined	Same as above	—	—	—	—
Flight Path Route with Waypoints	Flight Path Reference STAR assigned by ATC; development of pursuit level of control for curved course	Map, Aircraft Symbol, Course or Heading Vector	Depends on map, but low, if centrally located	Depends on map; selectable coordinates and orientation, analog format	Depends on map, but probably better with CRS UP or HDG UP	Depends on map
Aircraft Symbol with Trend Vector and History Dots	Past track, present position, future track, course deviation, distance-to-go	Map, Flight Path, Waypoints, Course or Heading Vector	Low, if centrally located in CRS UP or HDG UP Orientation	Selectable coordinates and orientation, analog format	Depends on map, but probably better with CRS UP or HDG UP	Depends on map
Course or Heading Vector	Damping course deviations and controlling direction	Map, Aircraft Symbol, Flight Path, Waypoints	Low, if centrally located in CRS UP or HDG UP, orientation	Angular; NORTH UP, CRS UP, or HDG UP; analog format	Depends on map, but probably better with CRS UP or HDG UP	No scale; 360 deg range
Heading Scale and Numeric	Monitoring	Barometric Altitude and Time	High; upper central location	Angular, earth, inside-out, numeric	Nil	1 deg over 360 deg
Waypoint and Time Data	Next waypoint identification, altitude and time schedule control	Nothing else but appears cluttered like a check list	High; lower left location	Altitude and time; case; numeric	Nil	See App. A, Fig. A-3
Reference IAS, FPA, ALT, HDG, CRS	Monitoring	Mode Select Panel (App. A, Fig. A-4)	High; extreme right location	Linear or angular; case; numeric	Nil	See App. A, Fig. A-4

2. **Conclusions**

a. The EADI provides inner loop attitude, flight path angle, outer loop path and course deviation, and speed information in the form of an ideal superimposed multiloop compensatory tracking display for all phases of flight involving rectilinear paths and courses and which demand precision flying under IFR.

b. The MFD supplements the EADI with an explicit course or heading oriented moving map format including track predictor, present position, track history, reference flight path, waypoints, course deviation, distance and time to next waypoint. The MFD presents an ideal pursuit-and-compensatory format for all phases of horizontal navigation involving curved courses and time schedule control as well as straight segments.

c. The pilot's scanning transition workload between EADI and MFD is likely to be highest in the terminal area and especially in following a curved approach course. A recommendation for reducing the pilot's scanning transitions between the EADI and MFD is offered by coordinating the presentation of a heading scale (from the MFD) on the EADI with the roll scale.

d. During straight final approach under IFR, the pilot's scanning transition workload should be largely confined to the EADI, which provides all the essential control information with runway perspective, discrete data for monitoring approach progress, explicit numerical airspeed for trim management, and explicit numerical radio altitude for monitoring terrain clearance and height above runway threshold area.

e. The multiaxis flight director format presented on the EADI is a familiar stereotype both for controlling flight manually and for monitoring automatic flight control. Although originally based on a format for operating only on the "frontside" of the thrust required curve, the director now incorporates a suitable stereotype for direct lift control in "backside" operation. However, a recommendation is offered for reducing the scanning transition workload among director axes within the EADI during "backside" operation. This involves relocation of the throttle command symbol.

f. All the essential information for monitoring a standard or modified terminal arrival route, holding pattern, missed approach or departure route is provided on the MFD together with numerical commanded and actual barometric altitude. However, the commanded altitude appears in a clutter of "next waypoint data" and is widely separated from barometric altitude.

g. The MFD offers a geographic format requiring less mental workload and time delay by the pilot to interpret essential information for horizontal navigation when it is compared with the HSI presentation of relative bearings and distances to navaids. However, the HSI remains entirely acceptable for three dimensional straight course-following in area navigation (RNAV), because it is coupled to STOLAND computations.

SECTION III

EXPERIMENTAL COMPARISON OF THE MFD AND HSI WITHIN THE CONTEXT OF THE WHOLE COCKPIT

This section describes the experimental simulation of STOLAND operation designed to gather objective and subjective data for making a systematic comparison of the MFD and HSI from an operational point of view under simulated instrument flight rules.

A. SYNOPSIS OF THE EXPERIMENT

If the display content has been suited to the task, differences in the display format and symbology may be apparent only if the pilot is at a saturated level of workload in a realistic flight simulation or in actual flight. Consequently, we attempted to emphasize a realistic air navigation environment for short-haul aircraft in the experimental design summarized in Table 5. Three classes of independent variables are shown in the table. The level of pilot involvement is divided between two independent classes, one of which we have called "technique," i.e., either manual or automatic, and the other of which we have called "the level of display," i.e., either situation (raw data only) or flight director and situation on the EADI with the HSI and MFD the obvious independent display variables for comparison.

The flight phases of interest in this experiment were threefold: 1) the terminal routine within 56 km (30 nm) of Crows Landing; 2) the landing approach under instrument flight rules (IFR); and 3) the missed approach under IFR conditions. We included the three flight phases within a class of independent variables representing the level of the pilot's guidance and control involvement, i.e., whether the pilot is purely tracking a standard terminal arrival route (STAR) assigned initially by a traffic controller and stored in the STOLAND system as a reference flight path, or whether the pilot is selecting different radio navaids en route, following an area navigation (RNAV) route, and maintaining geographic orientation throughout a missed approach and holding pattern assignment.

TABLE 5. SUMMARY OF EXPERIMENTAL DESIGN

<table>
<tr><th rowspan="3">PILOT-ING TECH-NIQUE</th><th rowspan="3">GUIDANCE AND CONTROL WORKLOAD</th><th colspan="5">LEVEL OF DISPLAY</th></tr>
<tr><th colspan="2">SITUATION (RAW DATA)</th><th colspan="3">FLIGHT DIRECTOR AND SITUATION ON EADI</th></tr>
<tr><th>HSI</th><th>MFD</th><th>HSI</th><th>MFD</th><th>BOTH HSI AND MFD</th></tr>
<tr><td rowspan="2">Manual</td><td>Tracking a STAR sequence</td><td>✓ XSCC* Highest Workload</td><td>✓ XSCC*</td><td>✓</td><td>✓</td><td>✓ EPR†</td></tr>
<tr><td>Selecting different radio navaids en route for STOLAND and maintaining geographic orientation</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓ EPR†</td></tr>
<tr><td>Automatic</td><td>Tracking a STAR sequence</td><td></td><td></td><td></td><td>Lowest Workload</td><td></td></tr>
</table>

10 cells × 2 replications × 5 pilots = 100 runs

*XSCC ≡ Measurement of excess control capacity with cross-coupled secondary control task

†EPR ≡ Measurement of eye-point-of-regard

Dependent Variables (i.e., Measurements)

a. Flight plan performance errors

- Airspeed error with respect to commanded flight profile
- Lateral distance error with respect to commanded course
- Altitude or glide slope displacement error
- Elapsed time between waypoints in flight plan

b. Other aircraft motion and control variables [e.g., pitch and roll attitudes, pitch and roll rates, heading, turn rate, airspeed inertial velocity, angles of attack and sideslip, course and path angles (or ground and vertical velocities), translational accelerations]

c. Eye-point-of-regard in azimuth and elevation

d. Subjective display ratings (e.g., controllability-and-precision, status utility, clutter, attentional demand)

e. Excess control capacity

f. Caution advisory response latency

Radar vectoring without STOLAND guidance was originally proposed as an alternative for reducing the cockpit workload normally required to follow a STAR assigned by air traffic control. However, the reference flight path mode of STOLAND already makes it almost as easy for the pilot to follow a STAR as if he were given radar vectors. Furthermore, the reference flight path mode of STOLAND is essential to the measurement of navigational errors in the experiment, and it is not possible for the purpose of this experiment to display the equivalent of a low altitude en route IFR chart on the MFD. Therefore, we decided to replace the cells originally proposed for radar vectoring in Table 5 with cells representing higher levels of cockpit workload which involve reselecting radio navigation aids en route.

Another factor which affected the experimental design was a preliminary finding (during early training) while using the automatic mode of STOLAND. The automatic mode is so devoid of pilot workload that a critical comparison of the HSI and MFD cannot be made, because the pilot is not nearly saturated with monitoring tasks. Since some failures of the automatic mode may require that the pilot revert to flying with raw situation data anyway, because even the STOLAND flight director guidance is provided by the automatic software, we decided to drop all of the cells in Table 5 involving the automatic technique from the experimental design.

We have indicated in Table 5 the cells in the experimental design which we believe to be most relevant by checkmarks. We have also indicated the cells which involve the highest and lowest workloads and the two cells which are most amenable to eye-point-of-regard comparison.

Pilot workload is high to begin with when flying the simulated C-8M Augmentor Wing manually with combinations of powered and aerodynamic lift. Since the several STAR's involve holding patterns and curved paths as well as straight segments, reliance on the HSI (and EADI) without the MFD places the highest workload demand on the pilot, because he must keep track of his position mentally with the aid of his en route and terminal area charts as he progresses along the assigned STAR.

Since the pilot will scan to and fixate on instruments which display redundant information, there is a danger in presenting both the HSI and MFD when the pilot is required to fly with only raw situation data. Having both horizontal displays may actually increase his scanning workload unnaturally when he is already saturated or oversaturated. Therefore, we covered the horizontal display which was not being evaluated in eight cells of Table 5, because the pilot will scan even to instruments which display no information or which are temporarily inactive. However, both the HSI and MFD were uncovered and presented to the pilot simultaneously in the two cells of Table 5 in the extreme right column when the pilot was using the flight director and situation on the EADI. We expected that any outstanding bias in the partitioning of the eye-point-of-regard distribution between the HSI and MFD might afford a measure of pilot preference for (or confidence in) monitoring the horizontal situation.

Also listed on Table 5 is the estimated minimum number of 100 runs required for two replications of 10 cells counterbalanced for order effects with 5 pilots. Below the table of independent variables and cells, there appears a list summarizing the dependent variables, that is, the measurements which we made. These measurements will be discussed in more detail in subsequent subsections. All are self-evident except perhaps "excess control capacity." This is proportional to the value of the aircraft's spiral divergence required to load the pilot to the point of saturation with control tasks while satisfying primary task performance with respect to a unique norm or error criterion established for each pilot. Excess control capacity is measured by increasing the spiral divergence until a stationary value is reached by the cross-coupled adaptive regulator of the divergence in balance with the performance error criterion. The stationary value of the spiral divergence may be normalized by its critical limit of controllability for each pilot to form a fraction which represents his particular excess control capacity with respect to the primary task. To the pilot flying the aircraft, the increased spiral divergence seems like a malfunction in lateral stability augmentation, so the measurement can be made while the flight simulation retains high face validity. The measurement is so naturally embedded within one dynamic characteristic mode of the airplane, the spiral divergence, that the pilot does not view the workload inducing task as quite so artificial a secondary task as the caution advisory response task, although we shall sometimes refer to the excess control capacity task as the "cross-coupled secondary control task" for convenience in the language of the report.

B. FLIGHT ENVIRONMENT, GUIDANCE AND CONTROL TASK SIMULATION

The investigation was conducted on the NASA-Ames fixed-base STOLAND simulation facility. This facility includes: 1) a fully instrumented cockpit; 2) a six-degree-of-freedom C-8M Augmentor Wing aircraft/environment/navigation simulation program implemented on an Electronic Associates, Inc. (EAI) 8400 digital computer; and 3) a complete STOLAND digital avionics system. Ames personnel were responsible for programming operation, checkout, and maintenance of these parts of the simulation throughout this experiment.

A simplified block diagram of the STOLAND simulation facility is shown in Fig. 6, which is adapted from the block diagram in Fig. 8 of Ref. 17. The

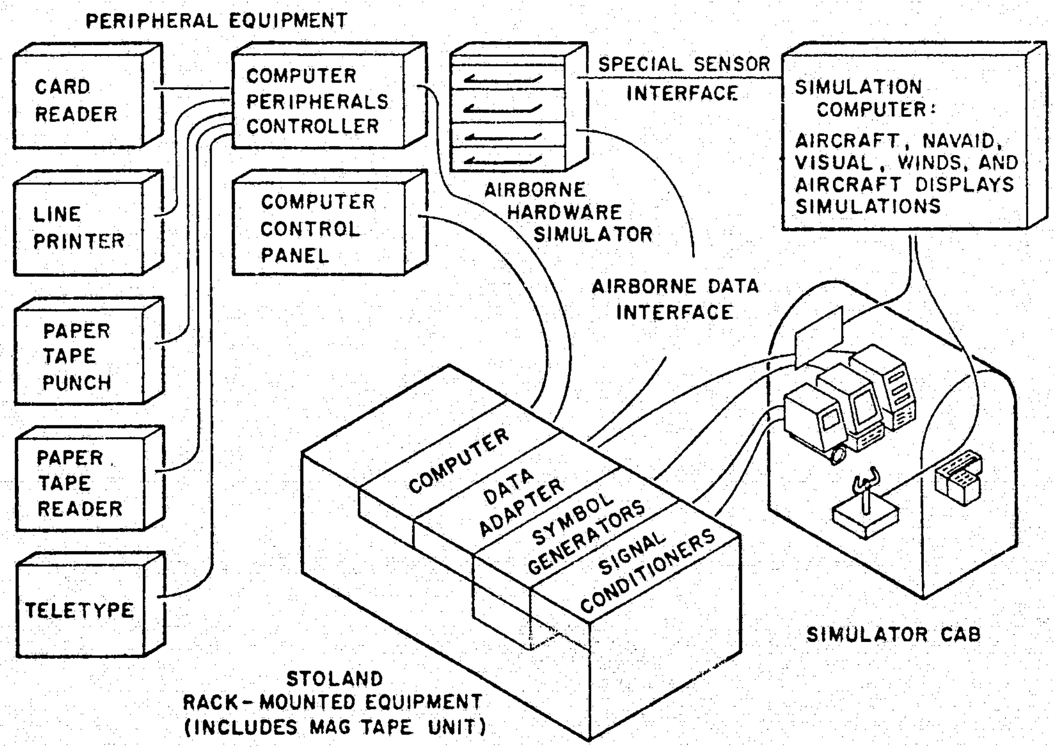

Figure 6. Block Diagram of STOLAND Simulation Facility (Ref. 17)

present investigation was conducted on this facility. Peripheral equipment is connected to the STOLAND digital computer to allow rapid program assembly, modification, and validation. The EAI 8400 digital computer simulates the C-8M Augmentor Wing aircraft, its navigational aids, the wind and gust environment, and drives the remaining displays which are not part of the STOLAND system.

The visual field simulator was not required for this investigation because the approaches were either terminated at the minimum decision altitude or were converted to missed approach procedures, and no landings were made.

The cross-coupled secondary control task, which is designed to measure the pilot's excess control capacity by adaptive adjustment of spiral divergence in the aircraft, and the caution advisory response task, which is designed to measure the pilot's excess capacity for monitoring, were implemented on the 8400 simulation computer.

Guidance and control task error performance analysis with respect to each assigned route was provided by a subroutine within the 8400 computer. Up to four reference flight paths (i.e., routes) for measuring error performance, however, can be stored in the STOLAND computer. Waypoints for the four stored routes can be changed from the STOLAND keyboard for data entry by either the pilot or investigator. Regardless of whether the pilot is following a STAR assigned initially by the controller or following a radar vector route communicated sequentially by the controller, the appropriate reference route must be stored and selected in the STOLAND computer in order to obtain the proper error performance measures as the flight progresses. Error performance measures were confined to three-dimensional spatial coordinates and did not include time errors, because the HSI does not provide any temporal guidance error display anyway. In this connection, we should emphasize that the content of the MFD and HSI are not strictly equivalent, because no waypoint numbers appear on the HSI and no heading scale appears on the MFD, if the pilot elects the north-up orientation. Furthermore, the format of the altitude presentation on the MFD is purely numerical, and is more unsuitable for tracking than even the counter-pointer altimeter, let alone the vertical deviation indicator (VDI) on the HSI. However, it is as unconventional for the pilots to use the VDI anywhere except on glide slope as it is to use the displacement "window" on the EADI. Therefore, we may, insofar as the tracking control aspects of this experiment are concerned, be comparing the EADI (supported by the MFD) with the HSI (supported by the EADI). Notwithstanding, insofar as the geographic orientation aspects of the experiment are concerned, we are comparing the HSI (supported by an RNAV chart and approach chart) with the MFD, which presents a moving map of the same RNAV and approach chart. Whether any differences between the two methods of presenting geographic orientation will be reflected in the measure of excess control capacity provided by the secondary roll tracking task remains to be seen in the subsequent presentation of the results. The displacement "window" on the EADI was deleted when runs were made to test the HSI alone, since the HSI presents lateral and vertical deviation anyway. The displacement scaling of one "half-window" on the EADI was consistent with the displacement scaling of one dot on the HSI, viz., 381 m (1250 ft) laterally and 30.5 m (100 ft) vertically.

Our previous recommendation (see Section II) that heading be provided on the EADI's programmable display during the experiment was accepted. Our recommendation that the former throttle director and speed error displays be interchanged had already been incorporated in the EADI by Ames Research Center personnel prior to the experiment. We suggested to each pilot that the MFD be used in the course- or heading-up orientation for consistency with the HSI and because the heading tape on the MFD appears only when the course- or heading-up orientation is selected. However, the radio magnetic indicator (RMI) was always available to present a compass rose when the HSI was covered in the event that a pilot elected to keep the MFD north-up. The choice of map scale on the MFD was left to the pilot; however, he was instructed that the STAR waypoint numbers would appear only if the 1.5 or 0.5 nm/in. scales were selected.

The reference flight path mode was used throughout the approach tracking portions of the experiment to insure that navigational errors were measured consistently for data acquisition. Attempts to convert measurements to an

MLS reference on approach were successful, but it was discovered during checkout that navigational measurements were subsequently lost on go-arounds, and that a major programming change beyond the scope of this experiment would have been required to recover the navigation errors from the MLS.

A steady wind speed of 10 m/s (20 kt) from the east or west as required by the flight plan to produce a prevailing tailwind en route was used throughout the experiment to increase workload when turns were required. One combined wind speed and turbulence level was used, because this is not one of the independent experimental variables in this investigation, rather it is designed to contribute to a high level of pilot workload. The magnitude and direction of the wind corresponded to seasonally prevalent mean values, and the root-mean-square level of the turbulence was measured between 0.9 and 1.2 m/s (3 and 4 ft/sec) depending on the variability in the small-sample statistic.

C. SECONDARY TASKS FOR WORKLOAD MEASUREMENT

As if the workload of the simulated C-8M Augmentor Wing aircraft alone were not enough in itself, we added two other secondary tasks, as planned, to provide measurements of workload margins. These additional tasks are the cross-coupled adaptive spiral divergence and the caution advisory response tasks. That the addition of these tasks oversaturated two pilots during curved-course following with Flight Plan 2 using raw data is verified by their acknowledged inattention to the caution advisory task in turns (see below).

The cross-coupled secondary control task, which is designed to measure the pilot's excess control capacity by adaptive adjustment of the spiral divergence in the aircraft, was embedded in the C-8M Augmentor Wing aircraft simulation. The necessary changes and additions are described in Appendix B. STI personnel were responsible for operation and checkout of the secondary tasks for workload measurement.

Appendix B also describes the functional details of the caution advisory response task, which is designed to measure the pilot's simple reaction time to a master caution light stimulus. This task is designed to provide a measure of the pilot's excess capacity for monitoring by comparing loaded and unloaded reaction times. It was simulated on the 8400 computer.

D. SIMULATION SCENARIO

The simulation scenario was formulated to make possible the most direct correspondence between simulation results and satisfaction of the basic program objectives. This was accomplished by addressing each of the questions posed in Section I and formulating more specific questions which we hoped to be able to answer from the results of the simulator experiment. In order to conduct the most meaningful comparison of the MFD and HSI, we considered the following four questions in preparing the terminal arrival routes for the scenario.

1. What is the degree of improvement offered by the moving map display (MFD) over the HSI as a function of pilot workload?

2. When is a moving map display <u>essential</u> for safety?

3. Can the MFD replace the HSI or is it strictly an addition to the existing panel?

4. What is the minimum display content required to make the MFD a useful display?

The simulation scenario has been formulated to obtain answers to these questions under varying levels of pilot workload in a reasonably realistic air navigation environment in order to promote the practical usefulness of the results.

1. Requirements

The first of the above questions leads to a requirement for routes which provide varying levels of workload directly involving the use of the HSI and MFD by the pilot. The primary purpose of the MFD is to minimize the time required by the pilot to become and remain confidently geographically oriented with respect to a set of navaids and courses. Therefore, the proper way to vary workload among routes is by introducing navigation problems of varying complexity which tend to cause the pilots to become disoriented (with respect to position rather than attitude). Examples of tasks which frequently cause geographic orientation problems are holding patterns with a nondirect entry and curved path tracking. The high workload routes involved both of these maneuvers.

The second of the above questions results in a requirement for tasks where safety is a predominant factor, even in the simulator. The missed approach task is appropriate here because it is, by definition, an unplanned abort. It is felt that the necessity (or lack thereof) of an MFD for providing geographic orientation will be most obvious to the pilots during the missed approach procedures in the simulation.

The third question requires trajectories which emphasize both tracking (strong point of HSI) and orientation (strong point of MFD). Tracking is almost always a primary task in simulation experiments. However, orientation problems require a system of navaids, airways, intersections, and the like which are rarely available on research simulators. Nevertheless, the STOLAND simulator does provide simultaneous data from a VOR (selectable), a TACAN (selectable), and an MLS (MODILS at Crows Landing).

The fourth question is really beyond the scope of the present investigation. However, a meaningful evaluation of the MFD requires that some minimum level of information be available on the display. Based on the review of the MFD content in Section II, we expect that the minimum level of information will include barometric altitude, present time, the uncluttered terminal area map, the selected flight route, the aircraft symbol, the trend vector, the heading tape, the next waypoint and its commanded altitude. As a result of the simulation, the pilot commentary will also contribute to the interpretation of what constitutes the minimum display content required to make the MFD useful.

We planned the experiment so as to provide answers to the third question (above) in two ways. First, the HSI was covered during some of the tests described; therefore, pilot performance measures and subjective ratings will reflect the relative success of simulated operations using only the MFD with the EADI. Second, we expect that any outstanding bias in the distribution of eye-point-of-regard (EPR) measurement when both HSI and MFD are available to the pilot may suggest a preference for one display — perhaps even to the exclusion of the other.

2. Standard Terminal Arrival Routes (STAR's)

We shall describe in this topic four routes to Crows Landing designed to induce various levels of workload in the scenario and to avoid over-repetition of the same route throughout the experiment. Each route is described with an accompanying approach plate, including the speed and altitude profiles, in Appendix C.

Waypoint coordinates for the four flight plans were calculated to accommodate the STOLAND requirements for reference flight paths. Tables of the waypoint coordinates are included in Appendix C. Missed approach procedures are also included for Flight Plans 3 and 4. The four flight plans had the following features.

1) Straight Approach with Procedure Turn. This route is based on the course for the standard military TACAN approach to Crows Landing with a missed approach consisting of a TACAN radial and a DME holding pattern with a direct entry. This route, however, was shortened to provide a 7.5 deg glide slope and procedure turn for practicing the configuration changes peculiar to the simulated Augmentor Wing aircraft.

2) Figure-8 Approach. This route provides a curved path in the form of a figure-8 requiring high attentional workload in the presence of wind and turbulence. It is based on a route designed by Ames Research Center personnel for the STOLAND acceptance test. It was expected that this route would provide as crucial a test as possible for comparison of the HSI and MFD in tracking.

3) Curved Approach and Go-Around to Holding Fix. This trajectory involves a considerable amount of configuration changing, turning, and generally planning ahead to keep oriented and on course. The pilots were given a few approaches without the missed approach as a medium workload task and to maximize the effect of the missed approach as an unexpected event. The missed approach trajectory is designed to disorient the pilot and to get him behind the airplane.

4) <u>En Route Navigation, Curved Approach and Go-Around to Holding Fix.</u> The intent of this trajectory is to generate an alternate high workload situation. It is expected that the high workload tasks will reveal the requirement (or lack thereof) for an MFD.

The basic features which are expected to induce very high pilot workload in the Flight Plan 3 and 4 are:

- Altitude and speed transitions with the Augmentor Wing.
- Identification and tracking of VOR and TACAN radials.
- The curved approach.
- Missed approach with an intermediate climbing turn and required configuration changes.
- Complex holding pattern entry within 3 minutes of missed approach initiation.

E. DATA MEASUREMENTS AND RECORDS

Each of the types of measurements referred to in Table 5 has a specific role to fulfill in the subsequent analysis and presentation of the results of this investigation. We shall outline each type of measurement more specifically and discuss its role in this subsection.

1. Performance

This group of measurements comprises three dimensions of flight plan error performance: airspeed and lateral and vertical position with respect to the reference flight path stored in STOLAND. The time- and ensemble-averaged values and variability of flight plan performance errors in each flight phase (en route, terminal area, initial, and final approach) are intended to be judged in the sense of an acceptance test by comparison with standards of safety and schedule reliability (e.g., Refs. 18-20). Appendix B herein presents a sample specification of the measurements, processing, and hard copy records provided.

An x-y plotter provided a plan position display of flight progress. The x-y plotter was driven by the present position outputs from the navigation simulation. The altitude output was provided separately on an x-z plotter beside the x-y plotter. The plotters were provided with six waypoint group timing marks synchronized with the simulation.

Flight performance errors are generally insensitive to display format, except possibly in circumstances where the pilot is oversaturated. Therefore, we do not expect the performance errors to help much in discriminating between the HSI and MFD, but we must at least be assured that the pilots can maintain acceptable standards of safety and schedule reliability with each horizontal display candidate.

2. Pilot Acceptance

The "other aircraft motion and control variables" listed in Table 5 represent motions whose variability from trimmed values or steady-state norms can be judged by comparison with standards of pilot acceptance (e.g., Refs. 20 and 21). The measurements, processing, and hard copy records for these variables are also described in Appendix B.

The EAI 8400 computer was core-memory-limited for this experiment by the data acquisition requirements for the en route and terminal area phases of flight. It was therefore necessary to reduce the number of variables for which we originally planned to collect samples and to reduce to six the number of groups of flight segments over which we averaged the collected samples of data.

3. Eye-Point-of-Regard

Azimuth and elevation angular coordinates of the pilot's eye-point-of-regard were recorded on-line on two channels of a strip chart oscillograph with synchronized time identification. (The other four channels were for calibration.) An edited list of fixation dwell time intervals was then prepared for each of up to eight unique fixation points identifiable from a visual inspection of the strip chart records. This visual inspection and editing step was necessary in order to screen out artifacts such as blinks and secondary scans within a display and to compensate for occasional long-term direct voltage drift in the measurements.

Reference 22 describes the eye-point-of-regard statistics programs which provides the following quantities for up to eight unique fixation points or instrument locations:

- Total dwell time, T_i
- Number of fixations, N_i
- Mean dwell time, $\overline{T}_{d_i}$
- Dwell time standard deviation, σ_{T_i}
- Dwell fraction, η_i
- Look fraction, ν_i
- Look rate, $\overline{f}_{s_i}$
- Dwell time histogram at 0.25 sec intervals

The data for all instruments include:

- Total dwell time, $\sum T_i$
- Total number of fixations, N_M
- Scan rate, $\overline{f}_s$
- One-way transition links

The program was operated by STI (off-line) from a timesharing computation facility at its Mountain View branch office. We expected that the partitioning of the eye-point-of-regard distribution between the HSI and MFD, if biased, might afford a measure of pilot preference or confidence in monitoring the situation when he is controlling with the flight director.

4. Subjective Rating

Four simple pilot rating scales for use in research on and evaluation of manual control displays were derived and used in the pilot experiments reported in Ref. 23 and are well suited to the present investigation. The scales shown in Table 6 are of interval-scale quality and will permit averaging and other standard parametric statistical analyses. The use of four trait categories (task controllability and precision; status utility; clutter; and attentional demand) should help to separate subjective identification of these often confounded effects. Hard copy rating forms for the EADI, HSI, and MFD were filled out by each pilot in the cockpit at the conclusion of each simulated flight.

TABLE 6. PILOT OPINION RATING SCALES

RATING SCALE FOR UTILITY OF STATUS INFORMATION

CRITERIA	DESCRIPTIVE PHRASE	RATING
Usefulness[a] of the information supplied, on the specified display unit, on the vehicle status — especially the relevant flight path vector states, such as: altitude, speed, heading attitude, path error, etc. [a]Useful with respect to the mission phase, task criteria, and operator's sense of vehicle safety.	All desired states presented with adequate resolution and readability	S1
	Many of desired states presented, with a few deficiencies in scaling, resolution, or readability	S2
	Some desired states presented, and/or some problems with scaling, resolution, or readability	S3
	Inadequate number of states, or serious deficiencies in scaling, resolution, or readability	S4
	No direct status information or unusable	S5

RATING SCALE FOR CLUTTER

CRITERIA	DESCRIPTIVE PHRASE	RATING
Degree of subjective symbol-background clutter on specified display unit	Completely uncluttered — e.g., only one pair of elements	K1
	Mostly uncluttered — no confusing or distracting elements	K2
	Some clutter — multiple elements competing for attention	K3
	Quite cluttered — difficult to keep track of desired quantities among competitors	K4
	Completely cluttered — nearly impossible to tell desired elements or quantities due to competing elements	K5

RATING SCALE FOR TASK CONTROLLABILITY AND PRECISION

CATEGORY		DESCRIPTIVE PHRASE	RATING
CONTROLLABLE	PRECISE		
Yes	Yes	Very easy to control, with good precision	C1
Yes	Yes	Easy to control, with fair precision	C2
Yes	No	Controllable, with inadequate precision	C3
Yes	No	Marginally controllable	C4
No	No	Uncontrollable	C5

RATING SCALE FOR DISPLAY ATTENTIONAL WORKLOAD

CRITERIA	DESCRIPTIVE PHRASE	RATING
Demands on the operator attention, skill, or effort	Completely undemanding and relaxed	D1
	Mostly undemanding	D2
	Mildly demanding	D3
	Quite demanding	D4
	Completely demanding	D5

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5. Excess Control Capacity

An "integrated" display such as the MFD does not necessarily eliminate eye scanning between symbols and improve tracking coherence, but it may very well increase the pilot's excess control capacity for coping with the unexpected. This hypothesis deserves further test and quantification in the present investigation, because the results obtained in Ref. 23 with a cross-coupled adaptive measure of excess control capacity appear to offer a more <u>unique on-line</u> measure of display quality than scanning workload fraction and a more <u>sensitive</u> measure than subjective rating.

The secondary cross-coupled adaptive workload task regulated the spiral divergence of the aircraft inversely as a function of changes in primary task performance with respect to a norm or error criterion. The block diagram in Fig. 7 shows the principle of this unique secondary task. The error criterion

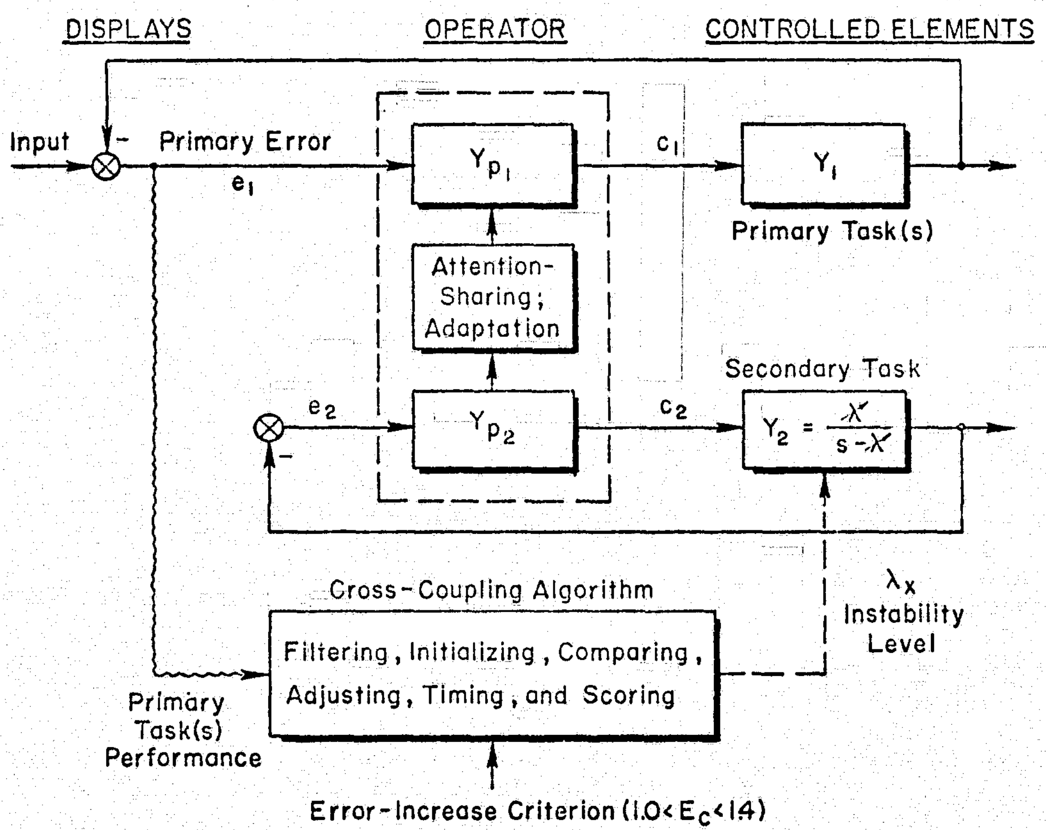

Figure 7. Principle of Cross-Coupled Adaptive Workload Task

E_c was either 1.1 or 1.2 times the unloaded performance error for best results in the tests here. The spiral instability was increased until a stationary value was reached by the cross-coupled adaptive regulator in balance with the performance error criterion. Either the stationary or the average value of the spiral divergence was then normalized by its critical limit of controllability for each pilot to form a fraction which represented his excess control capacity with respect to the primary task. Mechanization of the cross-coupled workload task is described in Appendix B together with the measurements and records provided. This on-line task was incorporated within the aircraft simulation program on the Ames Research Center's EAI 8400 computer. The present investigation for comparative evaluation of the HSI and MFD employed the cross-coupled workload task only when a pilot flew with raw situation data. This was done in order to avoid conflicts with the existing STOLAND flight director in the roll axis. The primary task performance measure was a weighted scalar combination of three-dimensional errors as described in Appendix B.

The six groups of flight segments over which we were capable of averaging collected samples of data also restricted the discriminability of the excess control capacity measurement with the cross-coupled secondary control task. This restriction occurred because each pilot's personal unloaded tracking error scores, which are identified with each group of flight segments and are used in regulating the secondary task, must reflect an average error between more than one pair of waypoints. Each flight segment so defined sometimes involved different levels of workload. Thus his unloaded tracking error scores, which must be stored and used in the appropriate group of flight segments to regulate the secondary task, will not necessarily uniquely match each part of the flight plan having a common level of workload. Consequently there is considerable variability in the excess control capacity measurements between waypoints, and we were compelled to rely on the ergodic hypothesis in order to establish statistical significance of the average measurements of excess control capacity over the six groups of waypoints to which the data acquisition was limited.

Another factor which limited the discriminability of the excess control capacity measurement was the lateral control authority limitation. The

±25 deg of wheel authority limited the full attention baseline critical roll divergence to a value between 1.2 and 1.4 rad/sec and required that we limit the partial-attention divergence in practice to 0.3 rad/sec to avoid aborting runs because of loss of control in steady turns. We also introduced an automatic feedback to reduce the instability abruptly prior to arriving at a waypoint where a turn was required to acquire another straight segment of the flight plan. This worked successfully to prevent loss of control when the cross-coupled spiral divergence reached and was limited at 0.3 rad/sec prior to the transient turn entry. In some instances, then, we used the secondary task as a constant loading task at the fixed level of 0.3 rad/sec during straight course segments where the workload was lower than the average for a particular group of segments including a curved course. (For purposes of comparison, the actual spiral divergence of the C-8M Augmentor Wing at 120 kt is 0.067 rad/sec. This requires only 10.3 sec to double in amplitude.)

6. Caution Advisory Response Latency

Appendix B also describes another secondary task — this one discrete — having high face validity in terms of recognizing and acknowledging caution advisories. This task is applicable to all cells in the experimental design, Table 5. The pilot was required to acknowledge the advisory by pressing a switch whenever he noticed the master caution light. The master caution light was re-illuminated at random intervals of time (from an exponential distribution) after it had been extinguished by acknowledgment. Here the measure of excess capacity for monitoring is T_O/T_L, where T_L is the pilot's loaded response latency in extinguishing the master caution light and T_O is his unloaded response latency obtained with the pilot fixating on the center of the EADI but not performing any other tasks. Results in Ref. 24, with a similar task, report good sensitivity and low variability in response to changes in horizontal display format.

The caution advisory light, as originally implemented on the forward console below the STOLAND Mode Select Panel, could not always be seen by the pilots. Therefore the alerting light was also connected to a marker beacon lamp at the right of the EADI on the instrument panel, although the response switch remained on the console. The mean time between advisories was 48 sec for all runs.

F. PILOTS

Five pilots, with diverse experience, participated in this simulation exercise. Two were research pilots with experience in the aircraft being simulated. Two were commercial airline pilots based at San Francisco, and the fifth was a general aviation instrument instructor with experience as an engineering pilot. A brief summary of each pilot's background follows. Each pilot is identified by a code numeral used as a designator in presenting the results. Pilot 2 was on reserve for this simulation and did not have to be called to participate; therefore, we shall omit his background.

- Pilot No. 1. Research pilot with experience in several STOL aircraft (DHC-5, DHC-6, AWJSRA, BR 941S) as well as conventional aircraft (CV-340, CV-990, Lear Jet). Military experience in conventional single engine fighter and attack aircraft and extensive light aircraft experience. Research simulator experience in a variety of handling qualities experiments, e.g., space shuttle, DHC-6, and AWJSRA.

- Pilot No. 2. On reserve; did not participate.

- Pilot No. 3. Commercial airline first officer with an Air Transport Pilot (ATP) rating and over 7800 hours, of which over 1000 hours have been under IFR. Commercial experience includes Boeing 707 and 727 series and Lockheed 188A (Electra) aircraft. Military experience includes F-105D, F-100D, F-84F and T-33 aircraft; has additional light aircraft experience and NASA-Ames research flight simulation experience.

- Pilot No. 4. Commercial airline captain with an ATP rating and over 18,500 hours, of which over 800 hours have been under IFR. Has additional 300 hours simulator time under IFR. Commercial experience includes Boeing 707 and 720 series, Lockheed 049, 749, 1049, 1649 (Constellation) series, Douglas DC-4 and Martin 202A, 404 aircraft. U.S. Air Force experience includes B-25J, C-46, C-47 and C-54 aircraft; has additional light aircraft experience and NASA-Ames research flight simulation experience.

- Pilot No. 5. General aviation pilot; has over 2500 hours with Commercial Flight Instructor, Aircraft, and Instrument as well as multi-engine ratings. Attended Flight Safety, Inc. DC-9 Jet Familiarization course and American Airlines DC-10 School; has served as an engineering pilot on several display evaluation programs including flight director concepts for conventional and STOL aircraft. Experience includes use of ground-based and in-flight variable stability simulators (NASA Ames S-16, Flight Simulator for Advanced Aircraft, and Princeton Variable Stability Navion) for handling qualities research.

- Pilot No. 6. Research pilot with over 3500 hours among V/STOL (various rotary wing and CL-84); STOL (DHC-2, -3, -5, -6, and AWJSRA), conventional twin and single engine jet (T-33, CL-41, F-101, F5, LR23), and light aircraft. Has 200 hours of variable stability helicopter evaluation experience; instrument time includes 325 hours of fixed-wing experience in flight and 200 hours in simulator with an additional 75 hours of V/STOL simulator experience under IFR.

G. TRAINING AND TEST AGENDA

Because of the unusual aircraft, novel EADI and MFD and the unfamiliar STAR's, a considerable period of pilot training was required to establish stationary levels of proficiency comparable to that achieved for the HSI on straight courses. Flight Plan 1 was employed primarily for training in order to avoid overrepetition of the other flight plans with which formal data measurements were taken. Measurement of skill development was made throughout training and testing using the various techniques planned, so that reasonable stationarity in the formal results could be identified.

The test runs for each pilot are displayed in Tables 7 through 11.

Although care was given to counterbalance the order of presentation of the various cases (in Tables 7 through 11) for each pilot, we were frequently constrained to juxtapose runs with the HSI or MFD having other attributes in common, because the pilots were required to render subjective comparative ratings of the HSI and MFD thereafter. We were also constrained by setup and calibration time for the eye-point-of-regard measurements to juxtapose runs with raw situation data or the flight director.

TABLE 7

RUN LOG FOR PILOT 1

(First digit of case number identifies flight plan number)

CASE NUMBER	RUN NUMBER	MANUAL TECHNIQUE EXCEPT AS NOTED	LEVEL OF DISPLAY (FD = FLIGHT DIRECTOR)	HORIZONTAL DISPLAY	EXCESS CONTROL CAPACITY	CAUTION ADVISORY RESPONSE	EYE POINT OF REGARD	SUBJECTIVE DISPLAY RATING	COMMENTS
061	239-241		EADI Horizon	None	Yes Baseline	No	No	No	
062	96	Automatic	FD and Situation	Both	No	Yes Baseline	No	No	
201	93		Situation	Both	No	Yes	No	No	Training
201	140		Situation	Both	Yes	Yes	Yes	No	
201	156		Situation	Both	No	No	Yes	No	
202	94		FD and Situation	Both	No	Yes	No	No	Training
202	141		FD and Situation	Both	No	Yes	Yes	No	
202	157		FD and Situation	Both	No	No	Yes	No	
203	95	Automatic	FD and Situation	Both	No	No	No	No	
203	96	Automatic	FD and Situation	Both	No	Yes	No	No	
204	98		Situation	HSI	No	Yes	No	No	
204	142		Situation	HSI	Yes	Yes	No	No	
205	99, 138		Situation	MFD	No	Yes	No	No	
205	139		Situation	MFD	Yes	Yes	No	No	
208	135		FD and Situation	HSI	No	No	No	No	
209	137		FD and Situation	MFD	No	Yes	No	No	
301	154		Situation	Both	No	No	Yes	No	
302	155		FD and Situation	Both	No	No	Yes	No	
304	153		Situation	HSI	No	Yes	No	Yes	
305	152		Situation	MFD	No	Yes	No	Yes	
308	151		FD and Situation	HSI	No	Yes	No	No	
309	150		FD and Situation	MFD	No	Yes	No	No	
411	220		Situation	Both	No	No	Yes	No	
412	221		FD and Situation	Both	No	Yes	Yes	No	
414	212		Situation	HSI	No	Yes	No	Yes	
415	211		Situation	MFD	No	Yes	No	Yes	
418	213		FD and Situation	HSI	No	Yes	No	No	
418	223		FD and Situation	HSI	No	Yes	No	Yes	
419	222		FD and Situation	MFD	No	Yes	No	Yes	

TABLE 8. RUN LOG FOR PILOT 3

(First digit of case number identifies flight plan number)

CASE NUMBER	RUN NUMBER	MANUAL TECHNIQUE EXCEPT AS NOTED	LEVEL OF DISPLAY (FD = FLIGHT DIRECTOR)	HORIZONTAL DISPLAY	EXCESS CONTROL CAPACITY	CAUTION ADVISORY RESPONSE	EYE POINT OF REGARD	SUBJECTIVE DISPLAY RATING	COMMENTS
061	68-70		EADI Horizon	None	Yes Baseline	No	No	No	
062	65	Automatic	FD and Situation	Both	No	Yes Baseline	No	No	
101	46, 49		Situation	Both	No	No	No	No	Training
102	44, 45		FD and Situation	Both	No	No	No	No	Training
104	51, 52		Situation	HSI	No	No	No	No	Training
108	50		FD and Situation	HSI	No	No	No	No	Training
201	117		Situation	Both	No	Yes	Yes	No	
202	55a		FD and Situation	Both	No	No	No	No	Training
202	118		FD and Situation	Both	No	Yes	Yes	Yes	
204	53, 114		Situation	HSI	No	No (R53) Yes (R114)	No	No	Lost data (R53)
204	58, 59 115		Situation	HSI	Yes	No	No	No (R58, 115) Yes (R59)	
205	55b, 113		Situation	MFD	No	No (R55b) Yes (R113)	No	No	Training (R55b)
205	56, 60, 116		Situation	MFD	Yes	No (R56, 60) Yes (R116)	No	No (R56) Yes (R60) No	
208	111		FD and Situation	HSI	No	Yes	No	No	
209	112		FD and Situation	MFD	No	Yes	No	No	
301	148		Situation	Both	No	Yes	Yes	No	
302	149		FD and Situation	Both	No	Yes	Yes	No	
303	65	Automatic	FD and Situation	Both	No	Yes	No	No	
304	147		Situation	HSI	Yes	Yes	No	No	
305	146		Situation	MFD	Yes	Yes	No	No	
308	62, 64 145		FD and Situation	HSI	No	No	No	No	
309	61, 128, 131, 144		FD and Situation	MFD	No	No	No	No	
311	178		Situation	Both	No	Yes	Yes	Yes	*
314	174, 177, 245		Situation	HSI	No	Yes	No	No	
315	175, 246		Situation	MFD	No	Yes	No	No	
318	173, 247		FD and Situation	HSI	No	Yes	No	No	
319	172, 248		FD and Situation	MFD	No	Yes	No	No	
401	134		Situation	Both	No	Yes	Yes	No	
408	133		FD and Situation	HSI	No	Yes	No	No	
409	132		FD and Situation	MFD	No	Yes	No	No	
411	243		Situation	Both	No	Yes	Yes	No	
412	209		FD and Situation	Both	No	Yes	Yes	No	
414	208		Situation	HSI	No	Yes	No	Yes	
415	210		Situation	MFD	No	Yes	No	Yes	
418	242		FD and Situation	HSI	No	Yes	No	Yes	
419	244		FD and Situation	MFD	No	Yes	No	Yes	

*Inadvertently omitted from Quarterly Progress Report 1072-3.

TABLE 9. RUN LOG FOR PILOT 4

(First digit of case number identifies flight plan number)

CASE NUMBER	RUN NUMBER	MANUAL TECHNIQUE EXCEPT AS NOTED	LEVEL OF DISPLAY (FD = FLIGHT DIRECTOR)	HORIZONTAL DISPLAY	EXCESS CONTROL CAPACITY	CAUTION ADVISORY RESPONSE	EYE POINT OF REGARD	SUBJECTIVE DISPLAY RATING	COMMENTS
061	161-2		EADI Horizon	None	Yes Baseline	No	No	No	
062	83	Automatic	FD and Situation	Both	No	Yes Baseline	No	No	
101	31, 32		Situation	Both	No	No	No	No	Training
102	33, 37 38		FD and Situation	Both	No	No	No	No	Training
102	92		FD and Situation	Both	No	No	Yes	No	Training
103	83	Automatic	FD and Situation	Both	No	Yes	No	No	Training
104	80		Situation	HSI	No	Yes	No	Yes	Training
104	84, 86		Situation	HSI	Yes	Yes	No	No	Training
104	85		Situation	HSI	Yes	No	No	No	Training
104	90		Situation	HSI	Yes	Yes	No	No	Training
105	81		Situation	MFD	No	No	No	No	Training
105	82		Situation	MFD	No	Yes	No	Yes	Training
105	89, 91		Situation	MFD	Yes	Yes	No	No	Training
108	71		FD and Situation	HSI	No	No	No	No	Training
109	72, 74		FD and Situation	MFD	No	Yes	No	No	Training
109	73		FD and Situation	MFD	No	No	No	No	Training
201	107, 261		Situation	Both	No	Yes	Yes	No	
202	158		FD and Situation	Both	No	No	No	No	
202	165, 257		FD and Situation	Both	No	Yes	Yes	No	
204	159		Situation	HSI	No	No	No	Yes	
204	164, 256		Situation	HSI	Yes	Yes	No	No	
205	160		Situation	MFD	No	No	No	Yes	
205	163, 260		Situation	MFD	Yes	Yes	No	No	
208	106		FD and Situation	HSI	No	Yes	No	Yes	
209	105		FD and Situation	MFD	No	Yes	No	Yes	
311	186		Situation	Both	No	Yes	Yes	No	
312	183, 187		FD and Situation	Both	No	Yes	No (R183) Yes (R187)	No	
314	185		Situation	HSI	No	Yes	No	Yes	
315	184		Situation	MFD	No	Yes	No	Yes	
318	253		FD and Situation	HSI	No	Yes	No	Yes	
319	254		FD and Situation	MFD	No	Yes	No	Yes	
411	258		Situation	Both	No	Yes	Yes	No	
412	259		FD and Situation	Both	No	Yes	Yes	No	
414	197		Situation	HSI	No	Yes	No	Yes	
415	198		Situation	MFD	No	Yes	No	Yes	
418	195		FD and Situation	HSI	No	Yes	No	No	
419	196		FD and Situation	MFD	No	Yes	No	No	

TABLE 10. RUN LOG FOR PILOT 5

(First digit of case number identifies flight plan number)

CASE NUMBER	RUN NUMBER	MANUAL TECHNIQUE EXCEPT AS NOTED	LEVEL OF DISPLAY (FD = FLIGHT DIRECTOR)	HORIZONTAL DISPLAY	EXCESS CONTROL CAPACITY	CAUTION ADVISORY RESPONSE	EYE POINT OF REGARD	SUBJECTIVE DISPLAY RATING	COMMENTS
061	91-93		EADI Horizon	None	Yes Baseline	No	No	No	
062	79	Automatic	FD and Situation	Both	No	Yes Baseline	No	No	
101	41		Situation	Both	No	No	No	No	Training
102	40		FD and Situation	Both	No	No	No	No	Training
103	79	Automatic	FD and Situation	Both	No	Yes	No	No	
104	78		Situation	HSI	No	Yes	No	Yes	
104	87		Situation	HSI	Yes	No	No	No	Lost data
105	77		Situation	MFD	No	Yes	No	Yes	
105	88		Situation	MFD	Yes	No	No	No	
108	75		FD and Situation	HSI	No	Yes	No	No	
109	76		FD and Situation	MFD	No	Yes	No	No	
201	104		Situation	Both	No	Yes	Yes	No	
201	119		Situation	Both	No	Yes	Yes	No	
202	120		FD and Situation	Both	No	Yes	Yes	No	
204	121		Situation	HSI	No	Yes	No	Yes	
204	125		Situation	HSI	Yes	Yes	No	No	
205	123		Situation	MFD	No	Yes	No	Yes	
205	124		Situation	MFD	Yes	Yes	No	No	
208	103		FD and Situation	HSI	No	Yes	No	Yes	
208	126		FD and Situation	HSI	No	Yes	No	No	
209	100		FD and Situation	MFD	No	Yes	No	No	
209	101		FD and Situation	MFD	No	Yes	No	Yes	
209	127		FD and Situation	MFD	No	Yes	No	No	

TABLE 11

RUN LOG FOR PILOT 6

(First digit of case number identifies flight plan number)

CASE NUMBER	RUN NUMBER	MANUAL TECHNIQUE EXCEPT AS NOTED	LEVEL OF DISPLAY (FD = FLIGHT DIRECTOR)	HORIZONTAL DISPLAY	EXCESS CONTROL CAPACITY	CAUTION ADVISORY RESPONSE	EYE POINT OF REGARD	SUBJECTIVE DISPLAY RATING	COMMENTS
311	182		Situation	Both	No	Yes	Yes	No	Training
312	179		FD and Situation	Both	No	Yes	No	No	Training
312	205		FD and Situation	Both	No	Yes	Yes	Yes	
314	181		Situation	HSI	No	Yes	No	Yes	Training
314	224		Situation	HSI	No	Yes	No	Yes	
315	180		Situation	MFD	No	Yes	No	Yes	Training
315	225		Situation	MFD	No	Yes	No	Yes	
318	204		FD and Situation	HSI	No	Yes	No	No	Training
318	226		FD and Situation	HSI	No	Yes	No	Yes	
319	203		FD and Situation	MFD	No	Yes	No	No	Training
319	227		FD and Situation	MFD	No	Yes	No	Yes	
411	194		Situation	Both	No	No	Yes	No	EPR data not usable
411	217		Situation	Both	No	Yes	Yes	Yes	
412	216		FD and Situation	Both	No	Yes	Yes	No	
414	207		Situation	HSI	No	Yes	No	No	
415	214		Situation	MFD	No	Yes	No	No	
415	218		Situation	MFD	No	Yes	No	No	
418	192		FD and Situation	HSI	No	Yes	No	No	
419	191		FD and Situation	MFD	No	Yes	No	No	

The first digit of the "case number" in Tables 7 through 11 identifies the flight plan number. If the second digit of the case number be "0," the pilot was restricted to tracking the reference flight plan using the "reference flight path" mode of STOLAND; if the second digit of the case number be "1," the emphasis was on geographic orientation using different radio navaids en route, missed approach, go-around and holding pattern as well as on tracking the approach course and glide slope. If the first and second digits of the case number be "06," the run was for the purpose of acquiring baseline performance on a secondary task and did not involve a flight plan.

H. RESULTS OF THE EXPERIMENT

Before introducing the several forms of comparative results, we will reiterate an important point which we made previously, viz., that the display content of the MFD and the HSI are not strictly equivalent. Therefore, we may, insofar as the tracking control aspects of this experiment are concerned, be comparing the EADI (supported by the MFD) with the HSI (supported by the EADI without displacement information). Notwithstanding this, insofar as the geographic orientation aspects of the experiment are concerned, we are comparing the HSI [supported by an area navigation (RNAV) chart and an approach chart] with the MFD, which presents a moving map of the same RNAV and approach chart. Although we will continue to label the displays being compared as "HSI" and "MFD" for conciseness in presenting the results where one or the other horizontal display was uncovered, the reader should clearly understand that "HSI" means "HSI, EADI (without the displacement window) and other instruments" and that "MFD" means "EADI, MFD and other instruments." The reader may wish to review Ref. 1 for a more complete pictorial description of the instrument panel arrangement, content, and symbology. By design, the HSI and MFD are being compared within the context of the whole STOLAND display and control arrangement in the simulation cockpit.

We shall now turn to the presentation of the several forms of comparative results of the experiment under the following subordinate topical headings:

- Blunders
- Tracking errors
- Excess control capacity
- Pilot opinion ratings
- Pilot comments
- Eye-point-of-regard measurements

1. Blunders

About 160 simulated flights, each lasting from 10 to 25 minutes in time, and distributed as shown in Tables 12 and 13, were conducted among the four standard terminal arrival routes in Appendix C. For each entry in Tables 12 and 13 the numbers of runs are sequentially listed for Flight Plans 1, 2, 3, and 4. Notice also from the "pilot subtotals" columns at the right that, because of other commitments, the exposure of Pilots 1 and 5 was necessarily less than that for Pilots 3, 4, and 6.

The most dramatic results are the 20 "blunders" partitioned in Tables 14 and 15. The types of "blunders" identified include loss of geographic orientation, loss of altitude awareness, and loss of roll attitude control as well as some others. Table 14 partitions the 9 blunders which occurred in the first phase of the experiment while the pilots were tracking primarily reference Flights Paths 1, 2, and 3. The format of the table includes the number of blunders followed by the run number/pilot number. Table 15 partitions the remaining 11 blunders which occurred during terminal area and en route flight with emphasis on geographic orientation (as well as tracking) in the second phase of the experiment involving only Flight Plans 3 and 4 with three different radio navaids.

While tracking reference flight paths exclusively (Table 14), five blunders involved the HSI and four, the MFD. However, during terminal area and en route flight with emphasis on geographic orientation (Table 15), eight blunders involved the HSI, two the MFD, and 1 both displays. The flight director was (or should have been) in use during 11 of the 20 runs wherein blunders occurred. Since 7 of these 11 blunders were also associated with

TABLE 12

DISTRIBUTION OF RUNS AMONG PILOTS WHILE TRACKING REFERENCE FLIGHT PATHS; NUMBERS OF RUNS ARE SEQUENTIALLY LISTED FOR FLIGHT PLANS 1, 2, 3, 4

PILOT	RAW DATA			FLIGHT DIRECTOR			PILOT SUB-TOTALS
	HSI	MFD	BOTH	HSI	MFD	BOTH	
1	0, 2, 1, 0	0, 3, 1, 0	0, 3, 1, 0	0, 1, 1, 0	0, 1, 1, 0	0, 3, 1, 0	19
3	2, 5, 1, 0	0, 5, 1, 0	2, 1, 1, 1	1, 1, 3, 1	0, 1, 4, 1	2, 2, 1, 0	36
4	5, 3, 0, 0	4, 3, 0, 0	2, 2, 0, 0	1, 1, 0, 0	3, 1, 0, 0	4, 3, 0, 0	32
5	2, 2, 0, 0	2, 2, 0, 0	1, 2, 0, 0	1, 2, 0, 0	1, 3, 0, 0	1, 1, 0, 0	20
Display Subtotals	9, 12, 2, 0	6, 13, 2, 0	5, 8, 2, 1	3, 5, 4, 1	4, 6, 5, 1	7, 9, 2, 0	
Data Subtotals	20, 33, 6, 1			14, 20, 11, 2			
Flight Plan Totals	34, 53, 17, 3						
TOTAL	107						

TABLE 13

DISTRIBUTION OF RUNS AMONG PILOTS DURING TERMINAL AREA AND EN ROUTE FLIGHT WITH EMPHASIS ON GEOGRAPHIC ORIENTATION. NUMBERS OF RUNS ARE FOR FLIGHT PLANS 3, 4 ONLY. (FLIGHT PLANS 1, 2 NOT USED)

PILOT	RAW DATA			FLIGHT DIRECTOR			PILOT SUBTOTALS
	HSI	MFD	BOTH	HSI	MFD	BOTH	
1	0, 1	0, 1	0, 1	0, 2	0, 1	0, 1	7
3	3, 1	2, 1	1, 1	2, 1	2, 1	0, 1	15
4	1, 1	1, 1	1, 1	1, 1	1, 1	2, 1	13
6	2, 1	2, 2	1, 2	2, 1	2, 1	2, 1	19
Display Subtotals	6, 4	5, 5	3, 5	5, 5	5, 4	4, 4	
Data Subtotals	14, 14			14, 13			
Flight Plan Totals	28, 27						
TOTAL	55						

TABLE 14

DISTRIBUTION OF BLUNDERS WHILE TRACKING REFERENCE FLIGHT PATHS*

BLUNDERS	RAW DATA		FLIGHT DIRECTOR	
	HSI	MFD	HSI	MFD
Loss of geographic orientation	2 {51/3† 58/3}	None	None	None
Loss of altitude awareness	1 147/3	None	None	1 76/5
Loss of roll attitude control	1 85/4	1 81/4	None	2 {122/3 73/4}
Impacted ground at GPIP‡ (below MDA§)	1 121/5	None	None	None

*Refer to Table 12 for the different numbers of runs to which each pilot was exposed.

†Format for presentation of data is: number of blunders followed by designation of run no./pilot.

‡Glide path intercept point.

§Minimum descent altitude.

TABLE 15

DISTRIBUTION OF BLUNDERS DURING TERMINAL AREA AND EN ROUTE FLIGHT WITH EMPHASIS ON GEOGRAPHIC ORIENTATION*

BLUNDERS	RAW DATA		FLIGHT DIRECTOR‡	BOTH HSI AND MFD WITH FD
	HSI	MFD	HSI	
Loss of geographic orientation	None	None	3 { 192/6†, 195/4, 247/3 }	None
Loss of altitude awareness	None	2 { 214/6 ("crash"), 218/6 (missed capture) }	1 242/3	None
Loss or roll attitude control	None	None	2 { 203/6, 253/4 }	1 209/3
"Co-pilot error" §	None	None	1 195/4	None
Experimenter's error#	1 207/6	None	None	None

*Refer to Table 13 for the different numbers of runs to which each pilot was exposed.

†Format for presentation of data is: number of blunders followed by designation of run no./pilot.

‡There were none with MFD and Flight Director (FD).

§Although there was no copilot in this experiment, this error was committed by a test assistant after the pilot requested that he help with the tuning of radios during an interval of workload saturation. Although counted in the 11 blunders cited, it is not a "pilot error" and may be omitted, if desired.

#This error resulted from a failure to explain to the pilot the purpose of the "TACAN/WAY PT" switch on the HSI. Thus it is not originally attributable to "pilot error" and may also be omitted from the 11 blunders cited, if desired.

the HSI (Table 15), the combination of using the HSI for orientation with the flight director for tracking while selecting different radio navaids for guidance seemed to conspire to produce the most blunders. There were no blunders involving the MFD and flight director in Table 15 and only three in Table 14. Therefore, we would conclude from the simulation, on the basis of the blunder distribution alone, that the MFD seems to offer a worthwhile improvement in safety, since 13 of 20 blunders involved runs wherein the MFD was not available to the pilot. [The benefits of safety in airline operations are difficult to quantify in terms commeasurable with cost. The difficulties are both theoretical and practical. By means of an argument too involved to repeat here, however, Ref. 25 concludes that the risk-value preference for voluntary activities (such as flying) is:

$$v = -8050\, r^{1/3} \left(\frac{\Delta r}{r}\right) = \left[\frac{\$/\text{person}}{\text{year}}\right]$$

where r is the existing risk of a fatality per person-hour and Δr is the change in risk provided by new technology or operating procedures. (The latter is negative for an improvement in safety.) Thus, for example, if the risk of a fatality per person-hour is 10^{-6} (typical of commercial aviation), a 1 percent improvement in safety ($\Delta r/r = -0.01$) is worth $0.805 per person per year. This figure, multiplied by the number of persons per year exposed to the risk yields the utility to those people of the improvement in safety.]

The blunder distribution provides a quantitative basis for answering the first two questions which were posed in the formulation of the scenario, viz.,

- What is the degree of improvement offered by the moving map display (MFD) over the HSI as a function of pilot workload?
- When is a moving map display essential for safety?

Recall that the pilot workload was increased further in the second phase of the experiment by introducing navigation problems associated with the missed approach which tended to cause the pilot to become disoriented with respect to geographic position. This resulted in blunder distribution ratios of 8:2:1 among the HSI, the MFD and both displays in the second phase of the experiment involving 55 runs distributed in the ratios 20:19:16 among the displays in the same order. The blunder-to-run proportions in the second phase were thus 0.4:0.11:0.06 among HSI, MFD and both displays. In the first phase of the experiment which involved tracking reference flight paths exclusively, the blunder-to-run proportions were 0.14:0.11:0 among HSI, MFD and both displays. In terms of this particular proportion, the MFD is independent of the increase in workload, whereas the HSI suffers an adverse increase with the increase in radio navaid/orientation workload — especially when the flight director is in use. The numerical values of this particular proportion thus afford measures of the relative improvement offered by the moving map display (MFD) over the HSI as a function of the increase in pilot workload. The proportions also suggest (by their greater disparity) that the moving map was more essential for safety in the second phase of the experiment than in the first phase.

2. Tracking Errors

Probably the least dramatic results are to be found among the flight plan tracking errors in three dimensions (lateral and vertical displacement and airspeed) and the related variations in aircraft motions. Examples of these results are given in the plan views, Figs. 8-14, and the sampled statistics in Figs. 15-18. As one would expect, there are very consistent differences between tracking errors with and without the flight director among the plan views and between the altitude errors in Figs. 17 and 18. It is therefore no surprise that the flight director provides much more precise tracking of the reference flight plans than otherwise. However, there is no consistent evidence of differences between tracking errors with the HSI versus the MFD. Figures 8, 9, and 15 offer some examples of larger tracking errors with the HSI using raw situation data and no flight director, but even these differences became less distinct with more practice in the prevailing wind. Flying a curved course precisely in the presence of wind with no flight director was very difficult on the first encounter — even with foreknowledge of the prevailing wind. One pilot called it unrealistic. All, however, were able to do it acceptably on the simulator with practice and intense concentration. In fact, those pilots who were using STOLAND for the first time considered the HSI a good display because of the way in which it was coupled to the

(Text continues on p. 77)

PILOT 1 24 February 1976

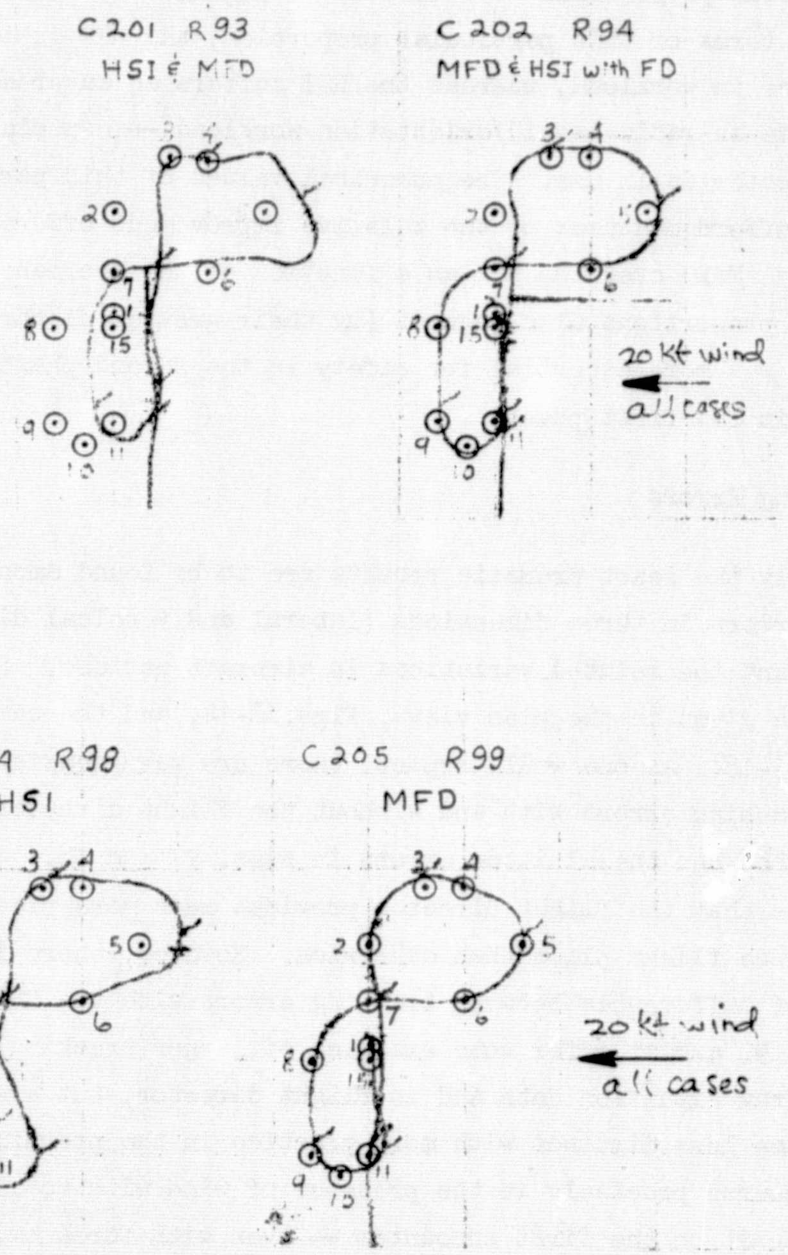

Figure 8. Some Plan Views of Flight Path 2 as Executed by Pilot 1 Using Various Displays. Circled Waypoints Define Reference Flight Plan 2.

PILOT 1 1 March 1976

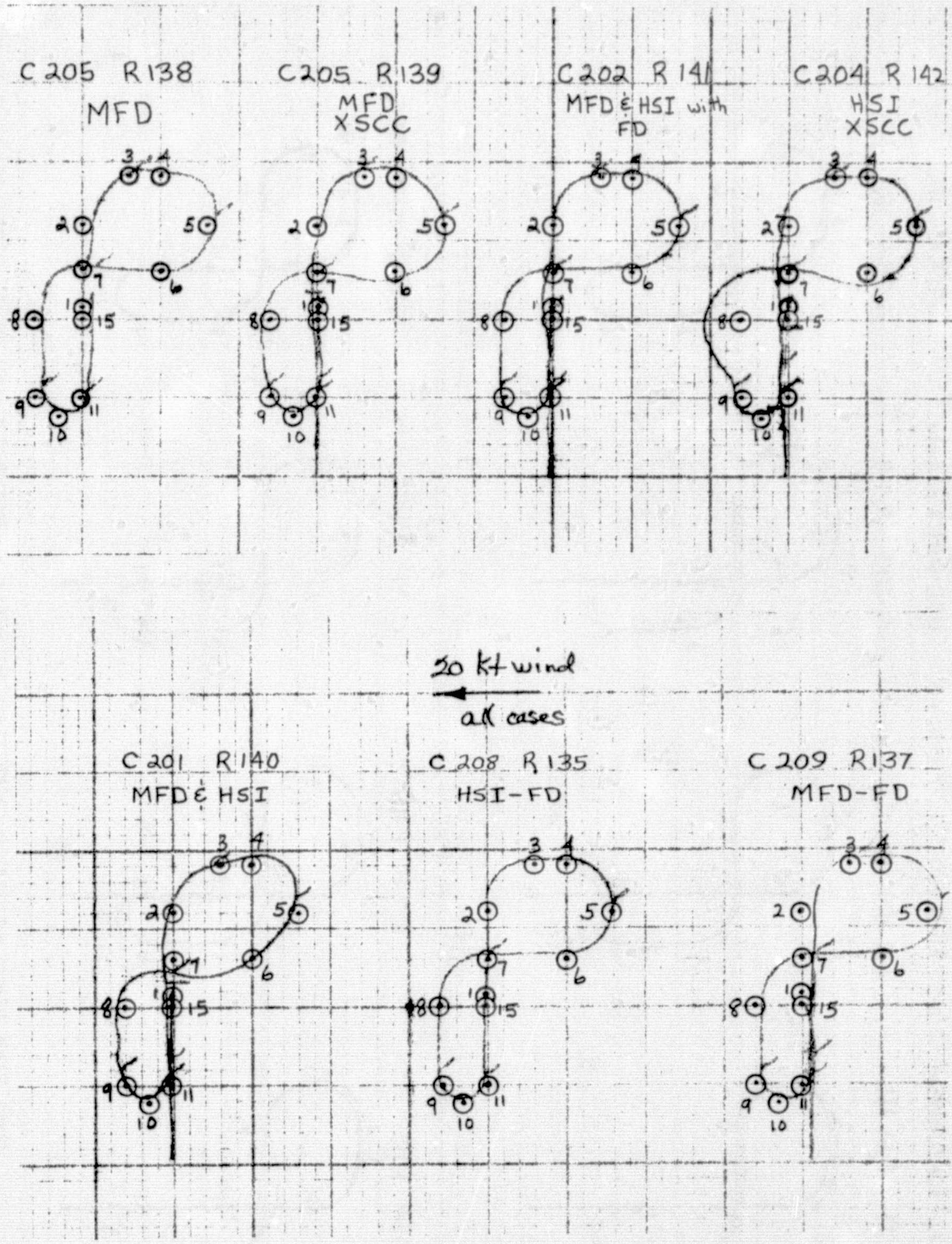

Figure 9. Some Plan Views of Flight Path 2 as Executed by Pilot 1 Using Various Displays. Circled Waypoints Define Reference Flight Plan 2.

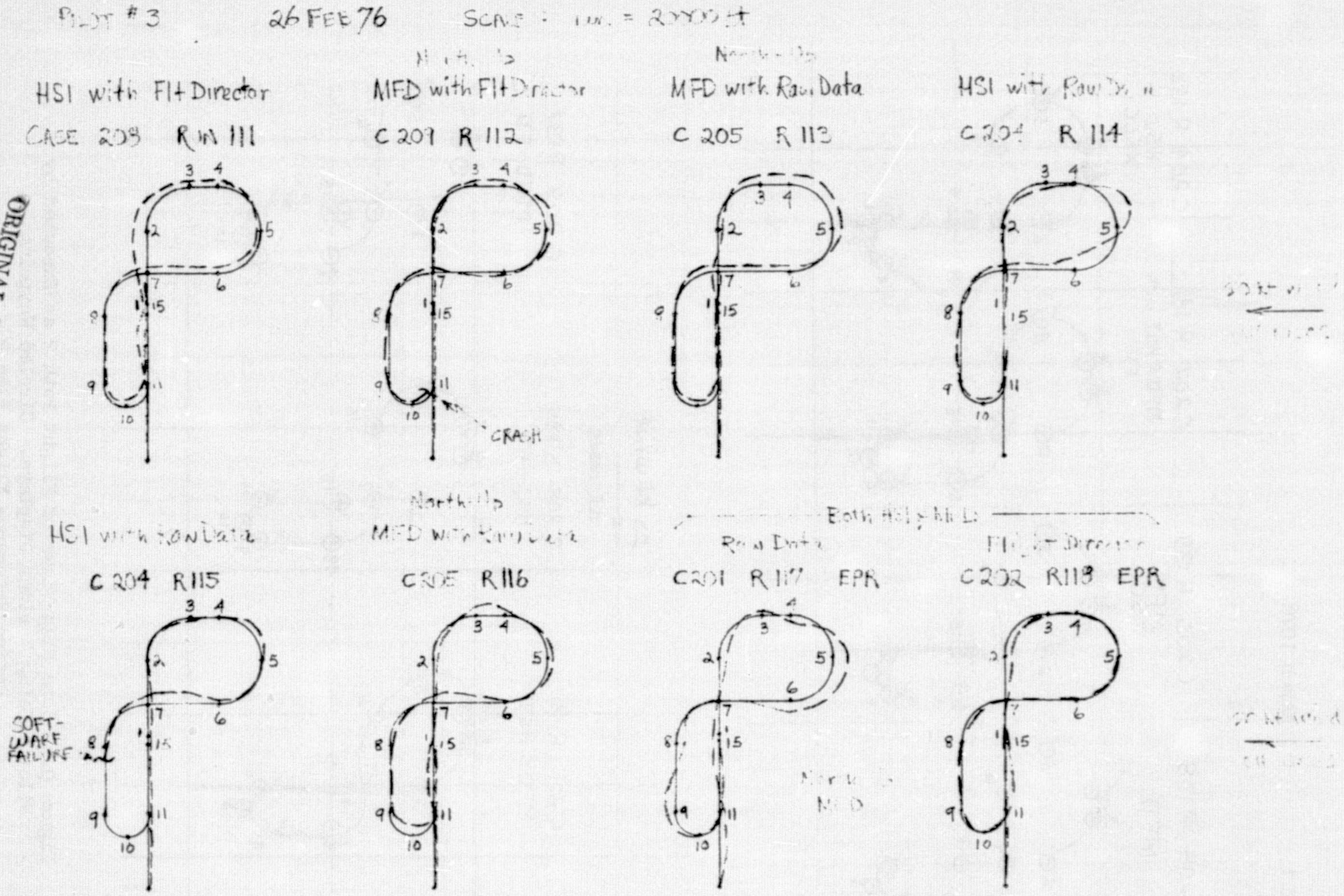

Figure 10. Some Plan Views of Flight Path 2 as Executed by Pilot 3 Using Various Displays; Solid Lines Represent the Reference Flight Plan; Broken Lines, the Trajectory of the Aircraft

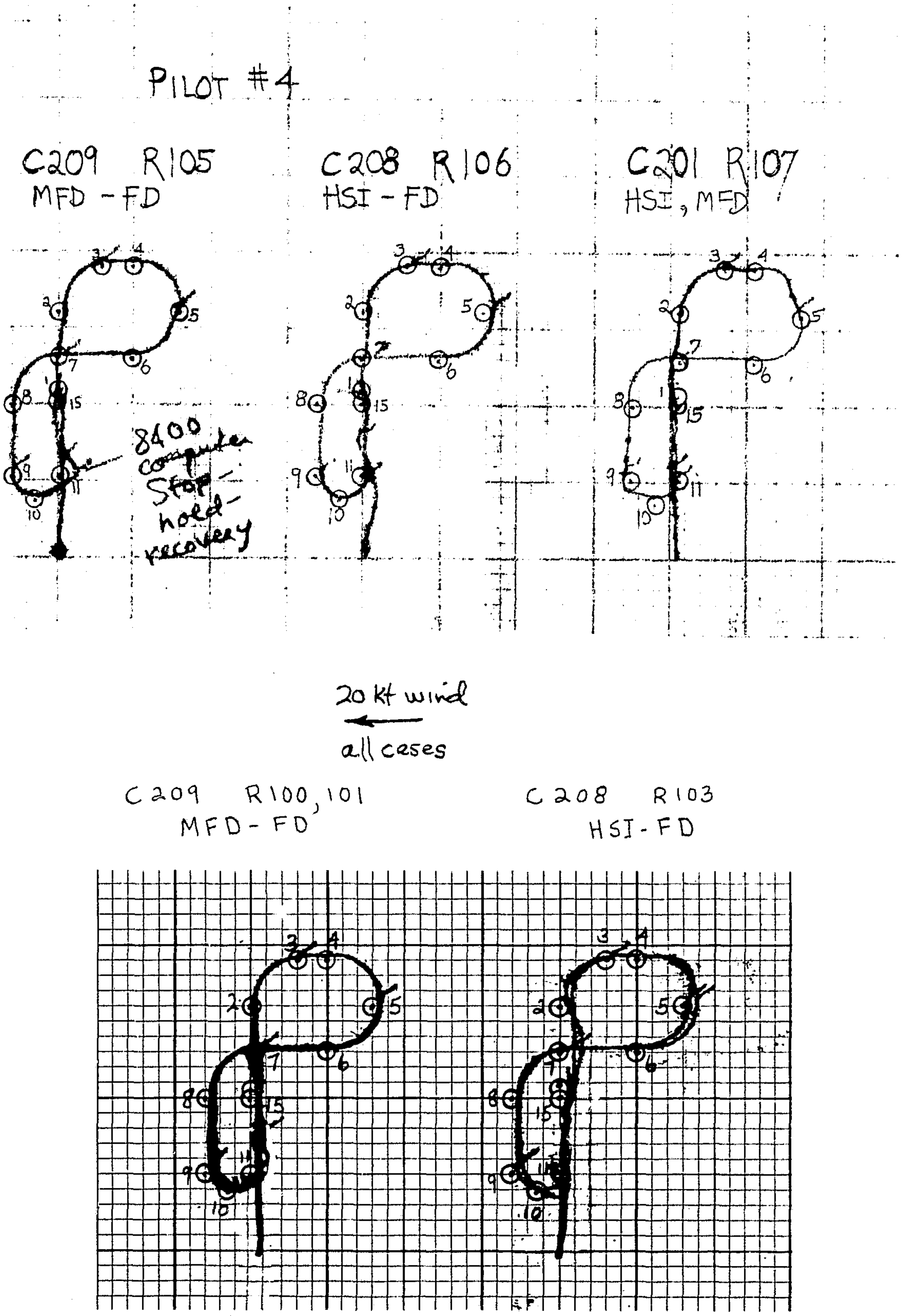

Figure 11. Some Plan Views of Flight Path 2 as Executed by Pilot 4 Using Various Displays. Circled Waypoints Define Reference Flight Plan 2.

PILOT 5 25 February 1976

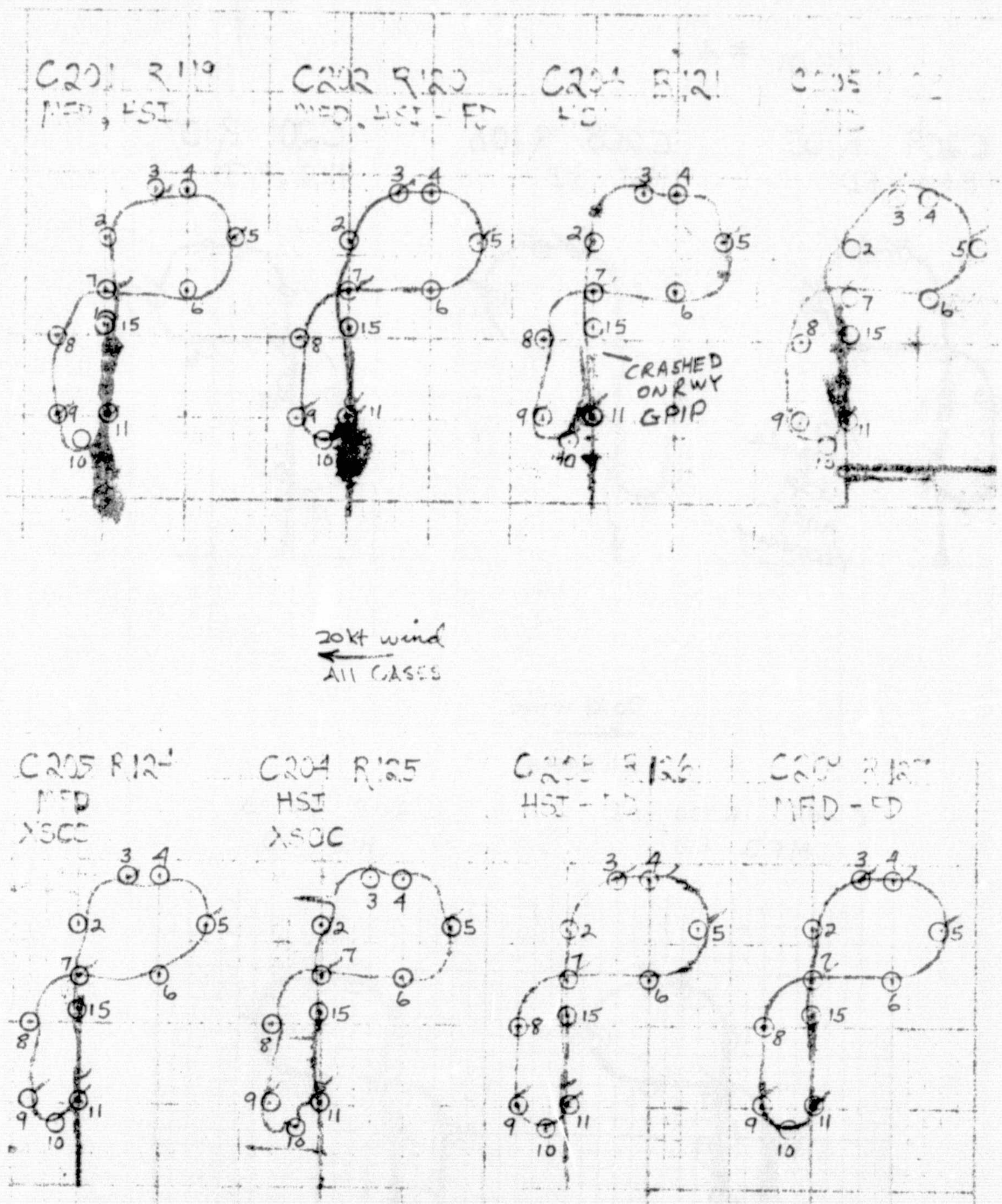

Figure 12. Some Plan Views of Flight Path 2 as Executed by Pilot 5 Using Various Displays. Circled Waypoints Define Reference Flight Plan 2.

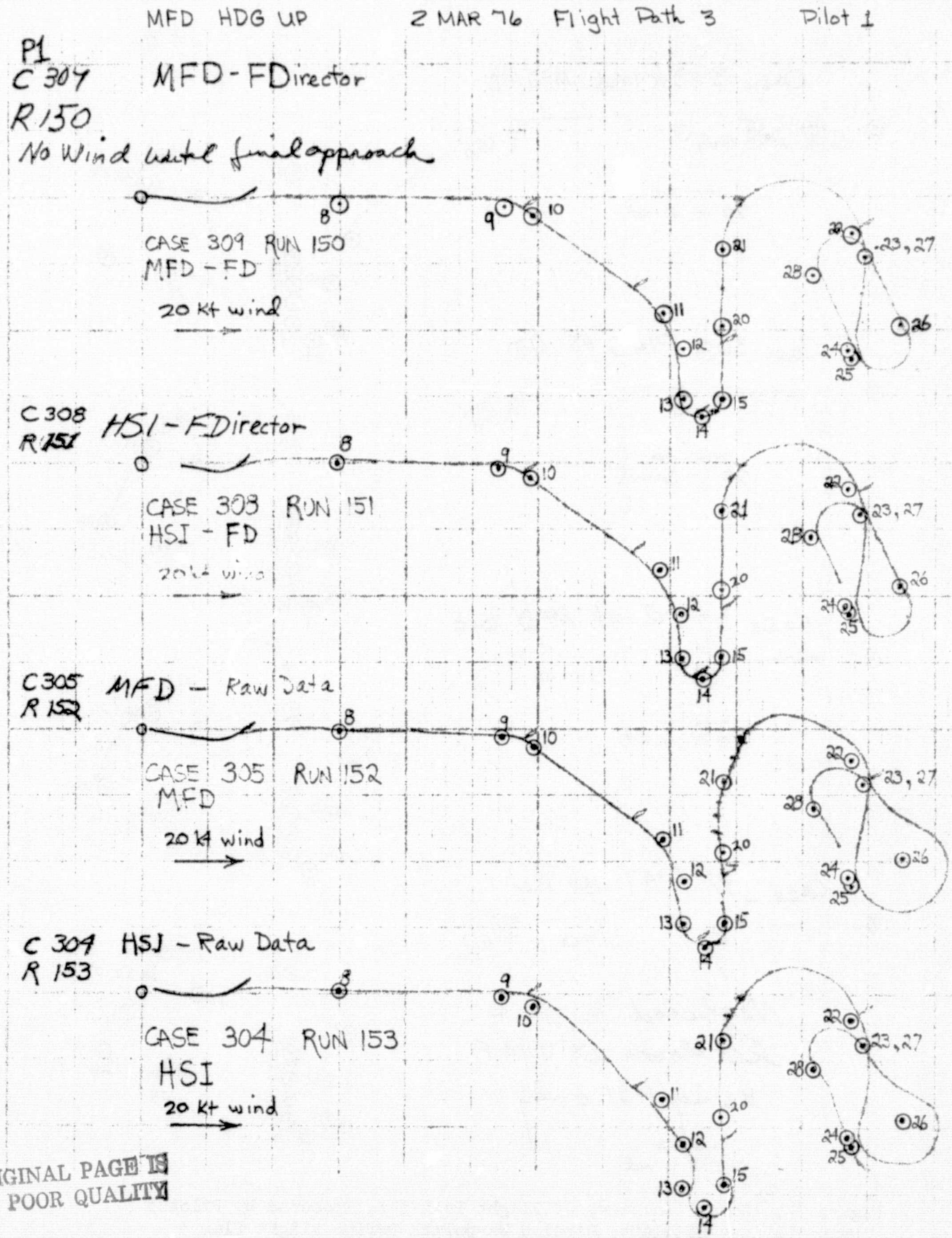

Figure 13. Some Plan Views of Flight Path 3 as Executed by Pilot 1 Using Various Displays; Circled Waypoints Define Flight Plan 3

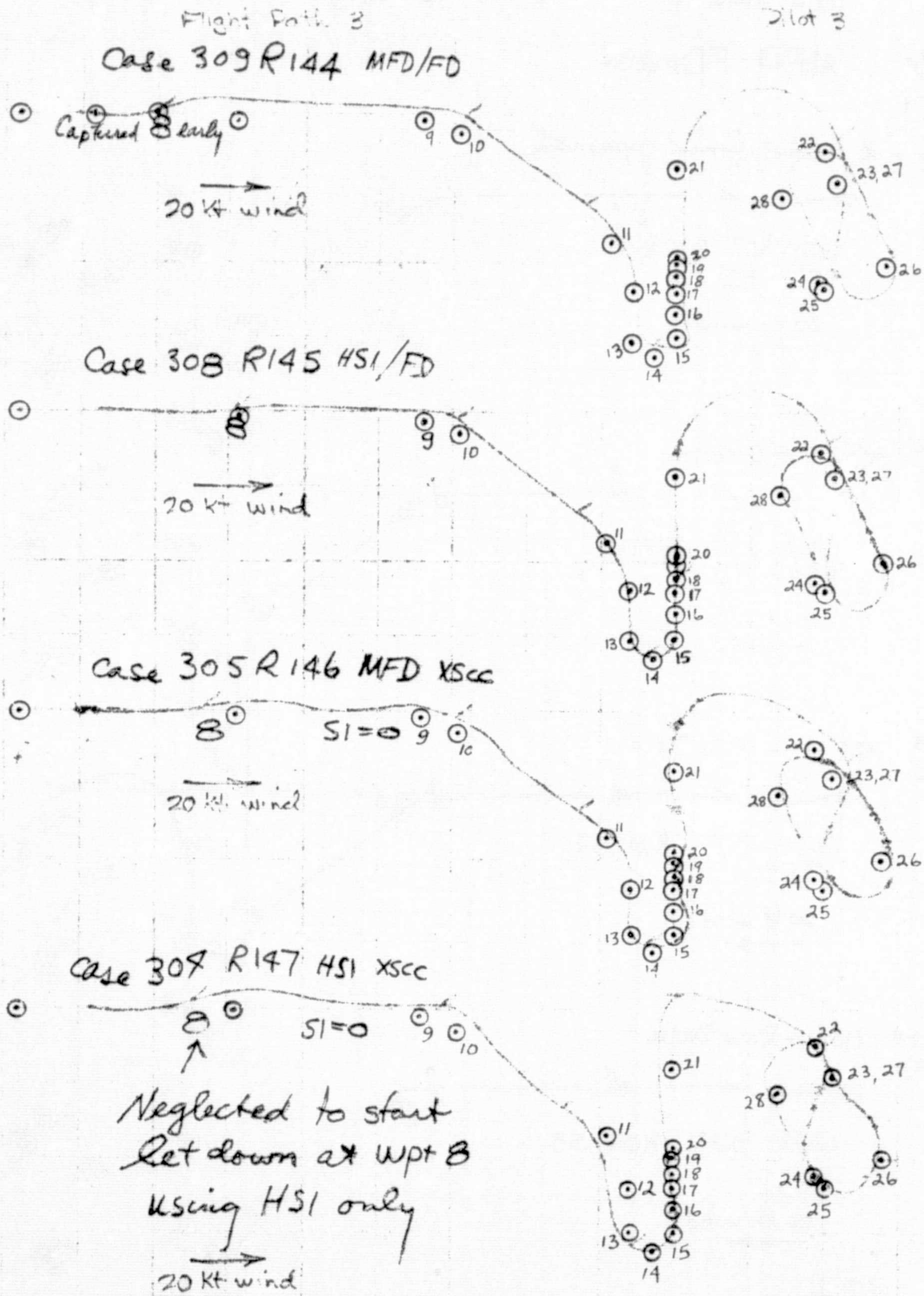

Figure 14. Some Plan Views of Flight Path 3 as Executed by Pilot 3 Using Various Displays; Circled Waypoints Define Flight Plan 3

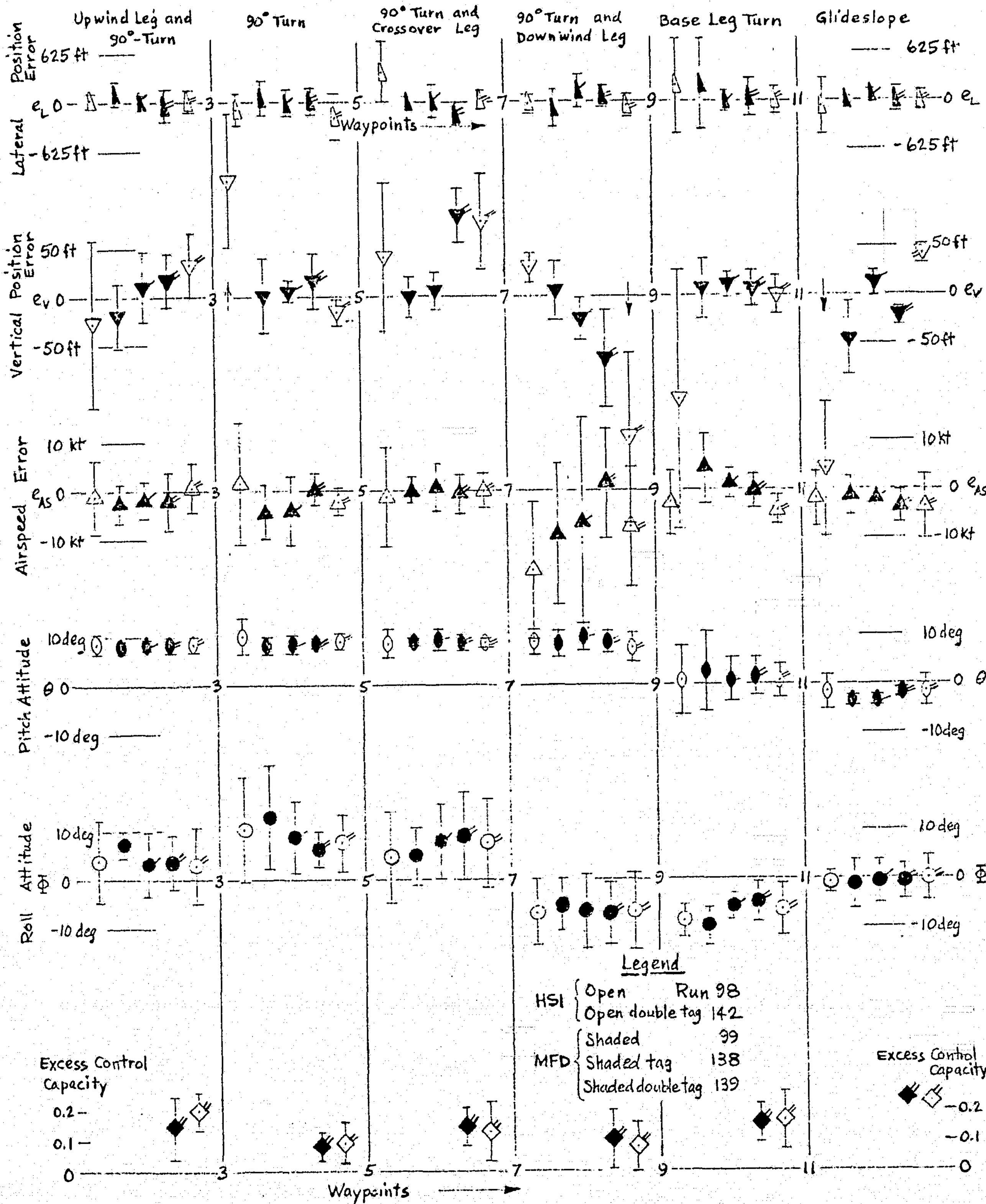

Figure 15. Sampled Statistics for Flight Plan 2; All Runs with Raw Data by Pilot 1; Mean Values ± One Standard Deviation

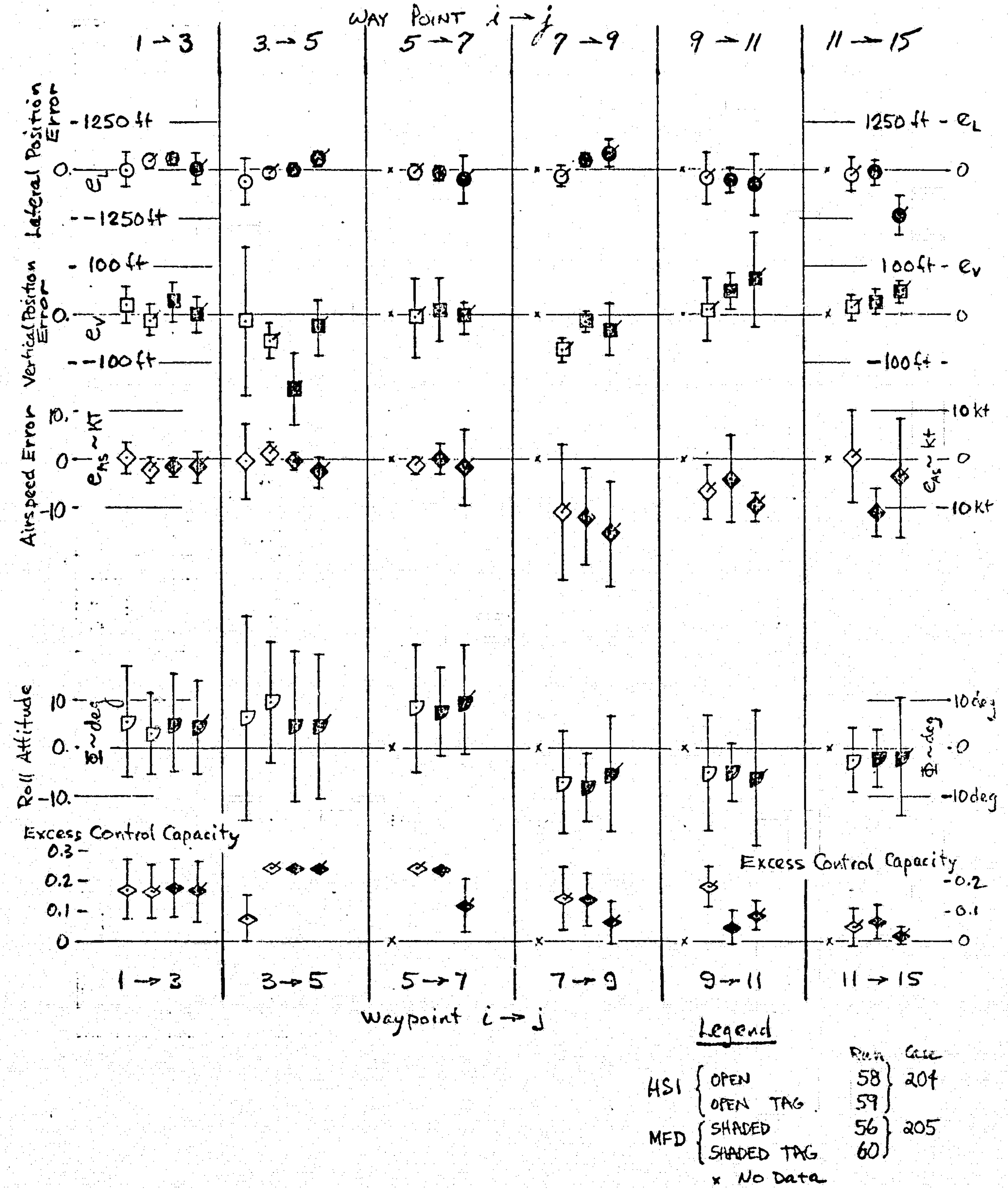

Figure 16. Sampled Statistics for Flight Plan 2 with Pilot 3; All Runs with Raw Situation Data and No Flight Director; Mean Values ± One Standard Deviation

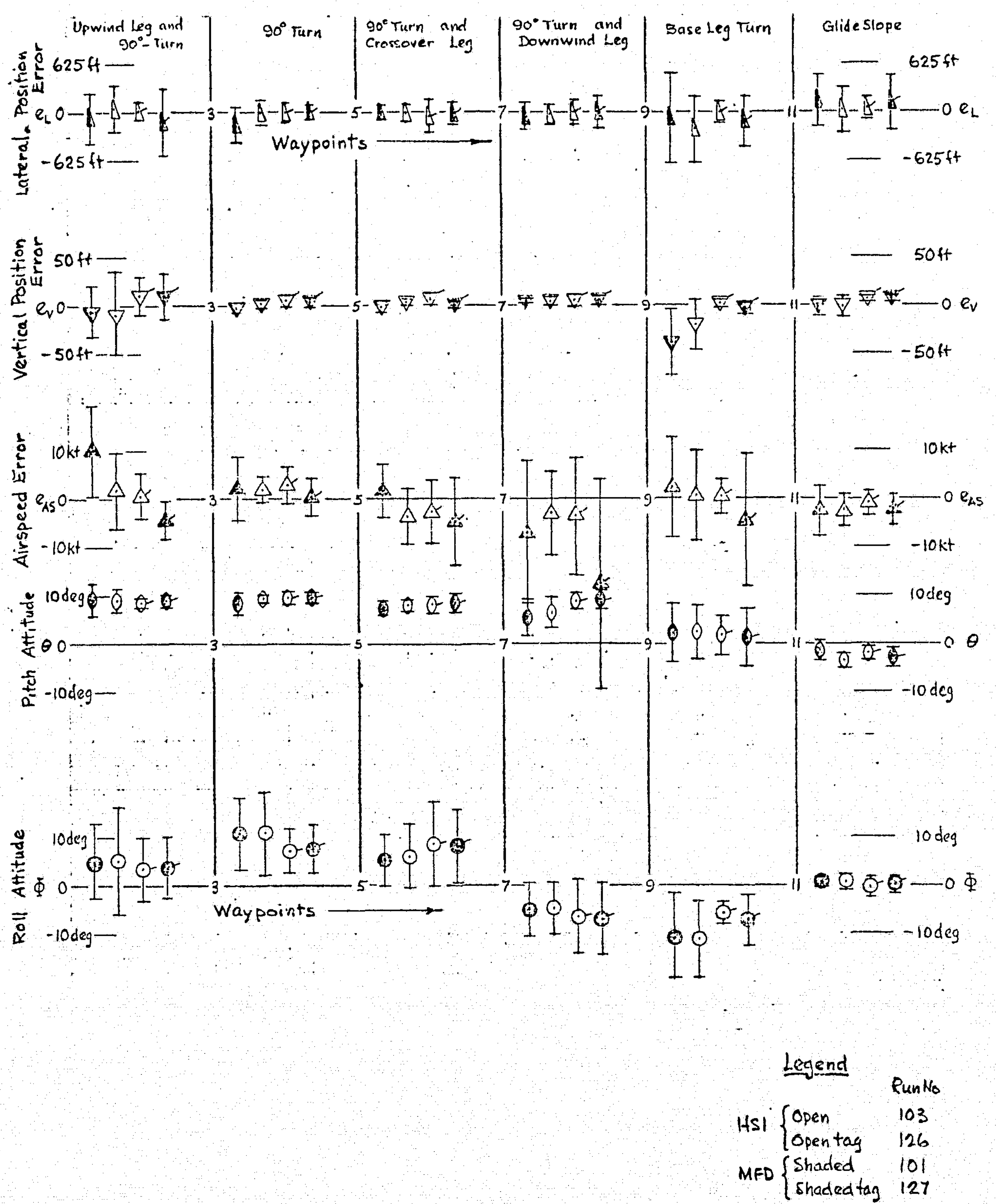

Figure 17. Sampled Statistics for Flight Plan 2 with Pilot 5; All Runs with Flight Director; Mean Values ± One Standard Deviation

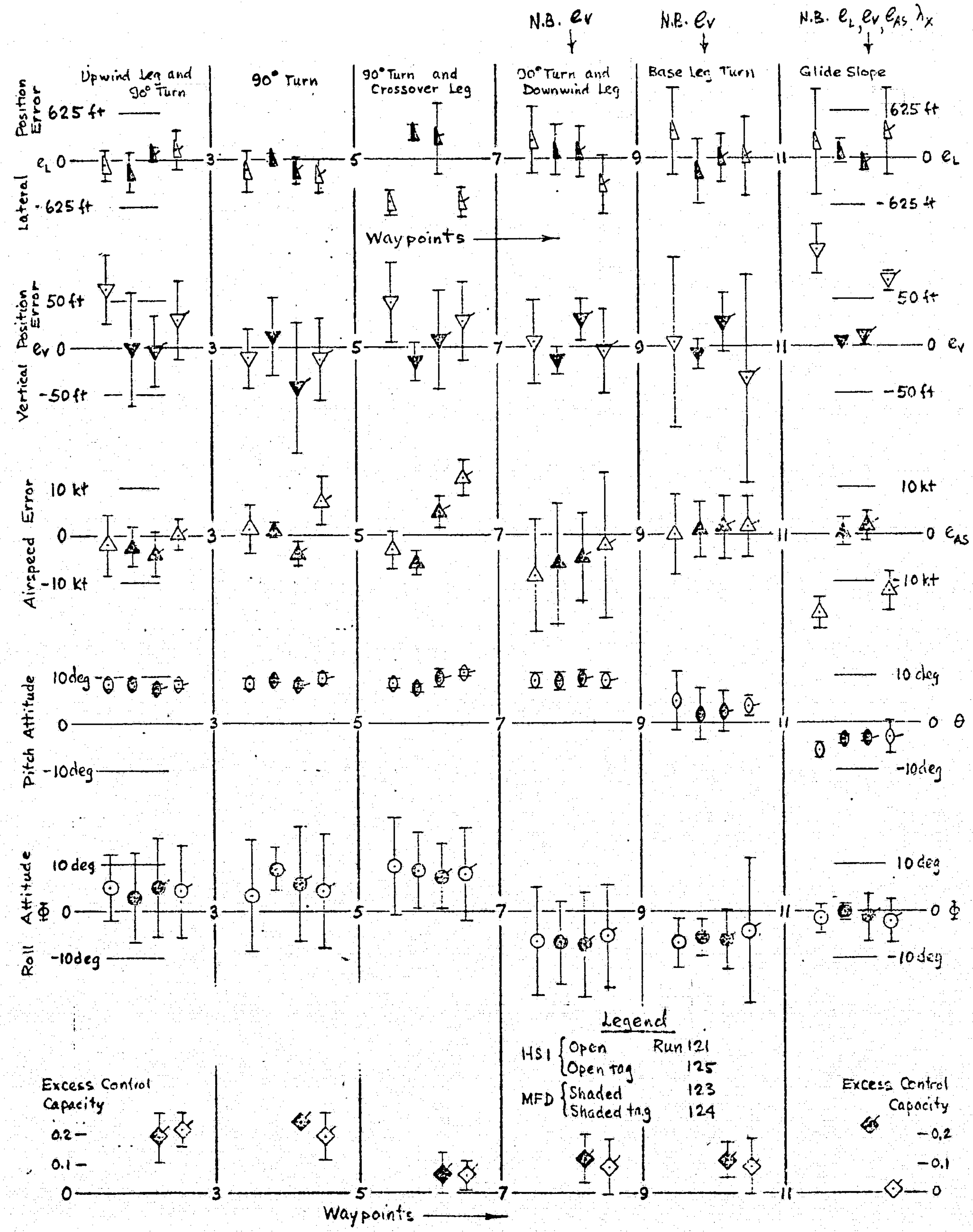

Figure 18. Sampled Statistics for Flight Plan 2; All Runs with Raw Data by Pilot 5; Mean Values ± One Standard Deviation

reference flight path automatically without pilot intervention to select each new course segment. However, no waypoint numbers appeared on the HSI, and their addition would eliminate one (unnecessary) reason for part of the intense concentration required when using the HSI without the MFD.

Appendix G herein presents the balance of the graphical summaries of sampled tracking error statistics for the experiment. The flight director continues to provide for more precise tracking of the assigned altitude and the glide slope than otherwise (see Figs. G-1 to G-5 for examples). Again there is no consistent evidence of differences between tracking errors with the HSI versus the MFD even with only raw data. Yet, as we mentioned in beginning the discussion of results, the "MFD" implies the use of the integrated EADI as the tracking display, and occasionally better altitude-keeping performance appears with the "MFD" than with the "HSI" (see Figs. G-2b, G-3, G-6 to G-8 for examples).

Figure 19 provides some evidence of differences in altitude tracking error performance between the "HSI" and "MFD," which may be attributable to differences in skill development or scanning policies or both. Figure 19 presents the sampled root mean square (rms) vertical position error versus the sampled rms normal component of the gust velocity for each of the six waypoint groups in Flight Plan 2. (Recall that, although one turbulence level was set in the simulation, the measured root-mean-square level fluctuated, depending on the variability in the small-sample statistic.) The interpretation of the unit gain crossover frequency, ω_c, for the vertical position tracking loop associated with each data point is based on the disturbance crossover model $\sigma_{e_V} \doteq \sigma_{w_g}/\omega_c$ without pilot remnant, where σ_{e_V} is the rms vertical position error and σ_{w_g} is the rms normal gust velocity. In most of the waypoint groups for Flight Plan 2 in Fig. 19 except 7-9 (90 deg turn and downwind leg), there is evidence in the escalating crossover frequencies for some skill development between replicates, but there is also evidence for a larger differential in crossover gain between the HSI and MFD in the earlier encounters. The inferred crossover gain for the HSI is the lowest in 5 of 6 waypoint groups during the earliest run (98) among those for which data is shown in Fig. 19. The inferred crossover gain for the MFD is highest during

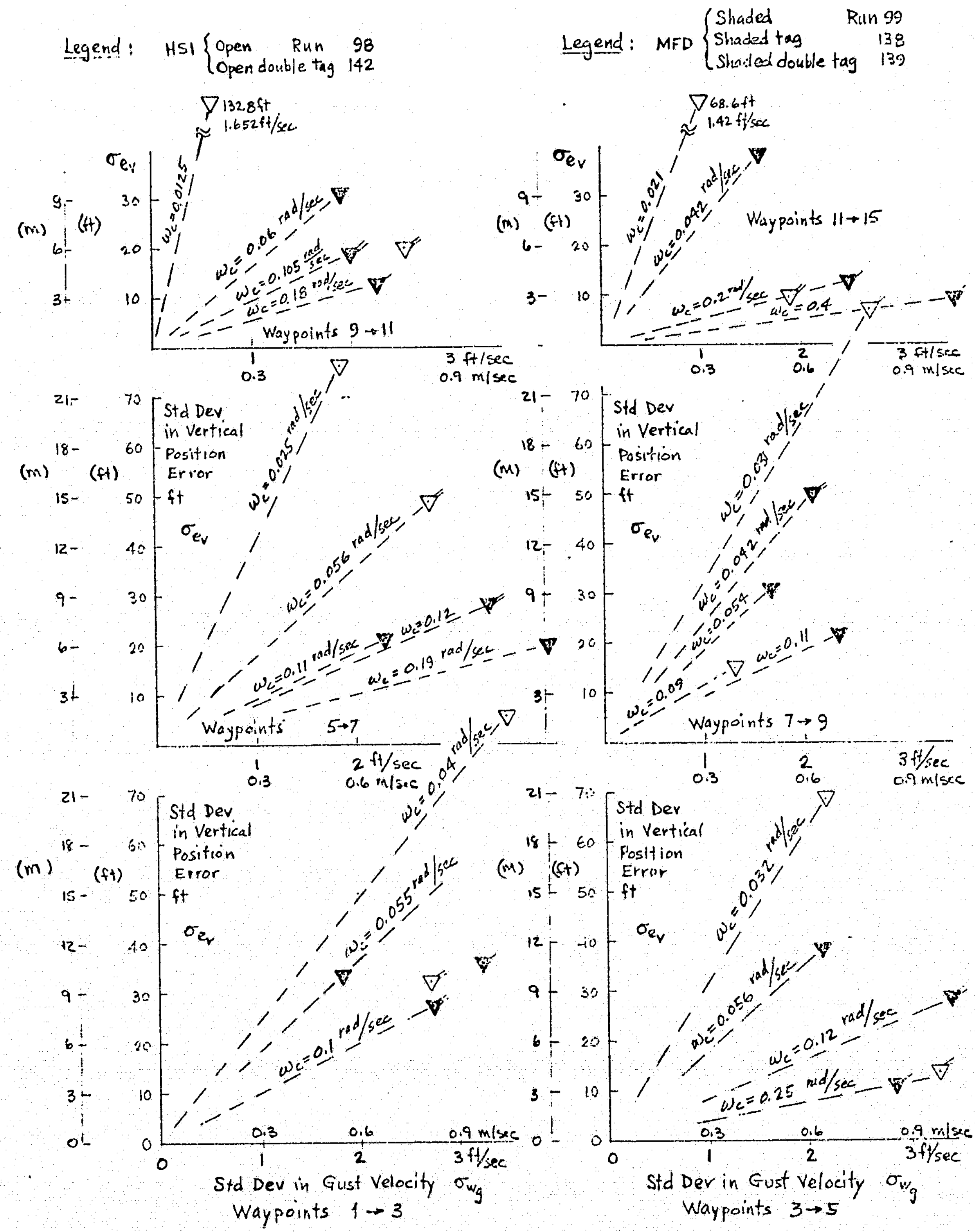

Figure 19. Sampled Standard Deviation in Vertical Position Error vs. Sampled Standard Deviation in Normal Gust Velocity for Flight Plan 2. All Runs with Raw Data by Pilot 1. Interpretation of Unit Gain Crossover Frequency ω_c Is Based on the Disturbance Crossover Model $\sigma_{e_v} = \sigma_{w_g}/\omega_c$ Without Remnant

the final approach (Waypoints 11-15) in the latest run (139) among those shown. One plausible interpretation for the trends in Fig. 19 is based on the pilot's evolution of a scanning policy involving the EADI which simply improves his vertical position loop tracking gain with practice, regardless of whether the HSI or MFD is used.

3. Excess Control Capacity

The measurement of excess control capacity was provided by the average cross-coupled adaptive spiral divergence in selected runs with either the HSI or the MFD. The null hypothesis of equality between mean values of excess control capacity within comparable pairs of waypoint groups with either display arrangement was tested for significant differences. The results of these tests are listed in Table 16 by pilot and flight plan. The column heading "neither" identifies the number of comparable pairs of waypoint groups for which the null hypothesis was accepted. The probability of

TABLE 16

NUMBER OF COMPARABLE PAIRS OF WAYPOINT GROUPS FOR WHICH ONE OR THE OTHER DISPLAY ARRANGEMENT EXHIBITED SIGNIFICANTLY GREATER AVERAGE EXCESS CONTROL CAPACITY AT THE 0.05 LEVEL*

PILOT	FLIGHT PLAN	HSI/EADI	NEITHER	EADI/MFD
1	2	1	4	1
3	2	3	4	1
3	3	1	1	4
4	2	5	1	6
5	2	1	1	4
Totals		11	11	16

*The null hypothesis is "neither." The probability of rejecting the null hypothesis when it is true is 0.05. Behrens', Scheffe's, and Tukey's tests (Refs. 26-28) produced consistent results.

rejecting the null hypothesis when it is true is 0.05. Behrens', Scheffe's, and Tukey's tests (Refs. 26-28) produced consistent results under the ergodic hypothesis, because the number of samples available within each waypoint group was on the order of several hundred or more.

The column headings "HSI" or "MFD" identify the numbers of comparable pairs of waypoint groups for which the null hypothesis was rejected, i.e., for which one or the other display arrangement exhibited significantly greater average excess control capacity at the 0.05 level. The totals show that the null hypothesis was rejected for 27 of 38 pairs at the 0.05 level. Of these 27 pairs, the "MFD" exhibited greater average excess control capacity for 16, and the "HSI" greater for 11 pairs. In the individual case of Pilot 3 tracking Flight Plan 2 involving only a curved approach, the partition is in favor of the "HSI," a result which was consistent with that pilot's own appraisal of that flight plan. However, the partition for Pilot 3 with Flight Plan 3, involving a missed approach and holding pattern and is in favor of the MFD.

4. Excess Monitoring Capacity

The measurement of excess monitoring capacity was inversely proportional to the average caution advisory response time. The null hypothesis of equality between mean response times within comparable pairs of runs with either display arrangement was tested for significant differences after a correction for the skewness of the response time distribution was made. The results of these tests are listed in Table 17 by pilot. The column heading "neither" identifies the number of comparable pairs of runs for which the null hypothesis was accepted. The probability of rejecting the null hypothesis when it is true is 0.05. Again Behrens', Scheffe's, and Tukey's tests produced consistent results, because there were usually at least eleven samples in the ensemble for each run. The column headings "HSI" or "MFD" identify the numbers of comparable pairs of runs for which the null hypothesis was rejected, i.e., for which one or the other display arrangement exhibited significantly greater average excess monitoring capacity at the 0.05 level. The totals show that the null hypothesis was rejected for 13 of 38 pairs at the 0.05 level. Of these 13 pairs, the "MFD" exhibited greater average excess control capacity for 10, and the "HSI" greater for 3 pairs.

Table 17a presents a partition of the number of comparable pairs of runs for which one or the other display arrangement exhibited significantly greater average excess monitoring capacity at the 0.05 level when the flight director was available to the pilot. The null hypothesis was rejected among only 5 of 16 pairs, and the 5 rejections are split 3:2 in favor of the MFD.

Table 17b presents partition of the number of comparable pairs of runs for which one or the other display arrangement exhibited significantly greater average excess monitoring capacity at the 0.05 level when only the raw situation data was available to the pilot. The null hypothesis was rejected among 8 of 22 pairs, and the 8 rejections are split 7:1 in favor of the MFD.

Table 18 presents a different type of partition of the number of comparable pairs of runs for which either the raw situation data or the flight director exhibited greater average excess monitoring capacity at the 0.05 level

TABLE 17

NUMBER OF COMPARABLE PAIRS OF RUNS FOR WHICH ONE OR THE OTHER DISPLAY ARRANGEMENT EXHIBITED SIGNIFICANTLY GREATER AVERAGE EXCESS MONITORING CAPACITY AT THE 0.05 LEVEL*

PILOT	HSI/EADI	NEITHER	EADI/MFD
1	1	4	1
3	0	7	2
4	0	9	2
5	1	4	1
6	1	1	4
Totals	3	25	10

*The null hypothesis is "neither." The probability of rejecting the null hypothesis when it is true is 0.05. Behrens', Scheffe's, and Tukey's tests (Refs. 26-28) produced consistent results.

TABLE 17 (Concluded)

a) PARTITION F: FLIGHT DIRECTOR AVAILABLE TO THE PILOT

PILOT	HSI/EADI	NEITHER	EADI/MFD
1	1	1	0
3	0	5	0
4	0	3	0
5	1	1	1
6	0	1	2
Totals	2	11	3

b) PARTITION R: ONLY RAW SITUATION DATA AVAILABLE TO PILOT

PILOT	HSI/EADI	NEITHER	EADI/MFD
1	0	3	1
3	0	2	2
4	0	6	2
5	0	3	0
6	1	0	2
Totals	1	14	7

TABLE 18

NUMBER OF COMPARABLE PAIRS OF RUNS FOR WHICH EITHER THE RAW SITUATION DATA OR THE FLIGHT DIRECTOR EXHIBITED SIGNIFICANTLY GREATER AVERAGE EXCESS MONITORING CAPACITY AT THE 0.05 LEVEL*
WHEN BOTH HSI AND MFD WERE AVAILABLE TO THE PILOT

PILOT	RAW DATA	NEITHER	FLIGHT DIRECTOR
1	0	1	1
3	2	2	0
4	0	3	2
5	0	0	2
6	0	1	1
Totals	2	7	6

*The null hypothesis is "neither." The probability of rejecting the null hypothesis when it is true is 0.05. Behrens', Scheffe's, and Tukey's tests (Refs. 26-28) produced consistent results. The runs represented in this table are mutually exclusive of the runs represented in Tables 17, 17a, and 17b.

when both HSI and MFD were available to the pilot. Thus the runs represented in Table 18 are mutually exclusive of the runs represented in Tables 17, 17a, and 17b. In Table 18, the null hypothesis was rejected for 8 of 15 pairs, and the 8 rejections were split 6:2 in favor of the flight director.

5. Pilot Opinion Ratings

Summaries of the subjective opinion ratings of the HSI and MFD by each of Pilots 3, 4, and 5 during the tracking of reference flight paths are presented in Table 19. A comparison of the two pages of Table 19 shows that the task controllability and precision was rated substantially the same by these pilots regardless of whether they were using the HSI or MFD. There is, however, a slight tendency to favor the MFD with fair precision, whereas there are more ratings of the HSI with inadequate precision. Comparison of the ratings for utility of status information between the HSI and MFD shows more

TABLE 19a

MFD — SUMMARY OF 3 RATINGS OF MFD BY EACH OF PILOTS 3, 4, 5 WHILE TRACKING REFERENCE FLIGHT PATHS
(Each Check or Symbol Indicates One Rating by One Pilot)

PILOT OPINION RATING SCALES

RATING SCALE FOR UTILITY OF STATUS INFORMATION

CRITERIA	DESCRIPTIVE PHRASE	RATING	
Usefulness[a] of the information supplied, on the specified display unit, on the vehicle status — especially the relevant flight path vector states, such as: altitude, speed, heading attitude, path error, etc.	All desired states presented with adequate resolution and readability	S1	
	Many of desired states presented, with a few deficiencies in scaling, resolution, or readability	S2	✓✓✓✓✓✓✓
	Some desired states presented, and/or some problems with scaling, resolution, or readability	S3	✓✓
[a]Useful with respect to the mission phase, task criteria, and operator's sense of vehicle safety.	Inadequate number of states, or serious deficiencies in scaling, resolution, or readability	S4	
	No direct status information or unusable	S5	

RATING SCALE FOR CLUTTER

CRITERIA	DESCRIPTIVE PHRASE	RATING	
Degree of subjective symbol-background clutter on specified display unit	Completely uncluttered — e.g., only one pair of elements	K1	
	Mostly uncluttered — no confusing or distracting elements	K2	
	Some clutter — multiple elements competing for attention	K3	✓✓✓✓✓✓
	Quite cluttered — difficult to keep track of desired quantities among competitors	K4	✓✓✓
	Completely cluttered — nearly impossible to tell desired elements or quantities due to competing elements	K5	

RATING SCALE FOR TASK CONTROLLABILITY AND PRECISION

CATEGORY: CONTROLLABLE	CATEGORY: PRECISE	DESCRIPTIVE PHRASE	RATING	
Yes	Yes	Very easy to control, with good precision	C1	
Yes	Yes	Easy to control, with fair precision	C2	ⓇⒻⓇ
				*
Yes	No	Controllable, with inadequate precision	C3	
Yes	No	Marginally controllable	C4	Ⓡ
No	No	Uncontrollable	C5	

* Controllable with difficulty or high workload, but fair precision   * C2.5 ⓇⒻⒻⓇⓇ

RATING SCALE FOR DISPLAY ATTENTIONAL WORKLOAD

CRITERIA	DESCRIPTIVE PHRASE	RATING	
Demands on the operator attention, skill, or effort	Completely undemanding and relaxed	D1	
	Mostly undemanding	D2	
	Mildly demanding	D3	✓✓
	Quite demanding	D4	✓✓✓✓✓✓
	Completely demanding	D5	✓

Ⓡ = Raw data.   Ⓕ = Flight director and situation.

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TABLE 19b

HSI — SUMMARY OF 3 RATINGS OF HSI BY EACH OF PILOTS 3, 4, 5 WHILE TRACKING REFERENCE FLIGHT PATHS
(Each Check or Symbol Indicates One Rating by One Pilot)

PILOT OPINION RATING SCALES

RATING SCALE FOR UTILITY OF STATUS INFORMATION

CRITERIA	DESCRIPTIVE PHRASE	RATING	
Usefulness[a] of the information supplied, on the specified display unit, on the vehicle status — especially the relevant flight path vector states, such as: altitude, speed, heading attitude, path error; etc.	All desired states presented with adequate resolution and readability	S1	
	Many of desired states presented, with a few deficiencies in scaling, resolution, or readability	S2	✓✓✓✓✓
	Some desired states presented, and/or some problems with scaling, resolution, or readability	S3	✓
[a]Useful with respect to the mission phase, task criteria, and operator's sense of vehicle safety.	Inadequate number of states, or serious deficiencies in scaling, resolution, or readability	S4	✓✓✓
	No direct status information or unusable	S5	

RATING SCALE FOR CLUTTER

CRITERIA	DESCRIPTIVE PHRASE	RATING	
Degree of subjective symbol-background clutter on specified display unit	Completely uncluttered — e.g., only one pair of elements	K1	
	Mostly uncluttered — no confusing or distracting elements	K2	✓
	Some clutter — multiple elements competing for attention	K3	✓✓✓✓✓✓✓
	Quite cluttered — difficult to keep track of desired quantities among competitors	K4	✓
	Completely cluttered — nearly impossible to tell desired elements or quantities due to competing elements	K5	

RATING SCALE FOR TASK CONTROLLABILITY AND PRECISION

CATEGORY		DESCRIPTIVE PHRASE	RATING	
CONTROLLABLE	PRECISE			
Yes	Yes	Very easy to control, with good precision	C1	
		Easy to control, with fair precision	C2	ⓇⒻ
				*
	No	Controllable, with inadequate precision	C3	ⓇⓇⓇ
		Marginally controllable	C4	Ⓡ
No		Uncontrollable	C5	

*Controllable with difficulty or high workload, but fair precision *C2.5 ⒻⒻⓇ

RATING SCALE FOR DISPLAY ATTENTIONAL WORKLOAD

CRITERIA	DESCRIPTIVE PHRASE	RATING	
Demands on the operator attention, skill, or effort	Completely undemanding and relaxed	D1	
	Mostly undemanding	D2	
	Mildly demanding	D3	✓✓
	Quite demanding	D4	✓✓✓✓
	Completely demanding	D5	✓✓✓

Ⓡ = Raw data. Ⓕ = Flight director aid situation.

favorable ratings for the MFD and a bimodal distribution of ratings for the HSI. The serious deficiencies in the HSI were noted in tracking curved paths. Comparison of the ratings for clutter shows a central tendency to recognize some clutter with multiple elements competing for attention in the HSI, whereas the ratings for the MFD are skewed more in the direction of an unfavorable appraisal of the clutter. Comparison of the ratings for display attentional workload shows more of a central tendency toward "quite demanding" attention for the MFD, whereas the ratings for the HSI tend to be slightly more unfavorable toward the "completely demanding" appraisal.

In Table 20 we present summaries of the ratings by each of Pilots 1, 3, 4, and 6 during the second phase of the experiment emphasizing geographic orientation as well as tracking. A comparison of the two pages of Table 20 shows a slightly less favorable central tendency in the ratings of the task controllability and precision when using the HSI, whereas the ratings are more uniformly distributed over four descriptive phrases when using the MFD. Ratings of task controllability and precision with the flight director in use are uniformly distributed over four descriptive phrases when using either the HSI or MFD. Comparison of the ratings for utility of status information between the HSI and MFD shows more favorable ratings for the MFD and a markedly unfavorably skewed distribution of ratings for the HSI which exhibits a mode beside the descriptive phrases: (S4) "inadequate number of states...." Comparison of the ratings for clutter shows few differences in the tendency of both groups of ratings to centralize beside the descriptive phrase: (K3) "some clutter." Only one rating of the MFD was more unfavorable than K3. Comparison of the ratings for display attentional workload shows a more favorable central tendency beside the descriptive phrase: (D3) "mildly demanding" for the MFD, whereas the distribution of ratings for the HSI is unfavorably skewed with a mode beside the descriptive phrase" (D4) "quite demanding."

6. Pilot Comments

All of the pilots have provided a great number of verbal comments in the course of the experiment. Therefore, we have provided in Appendix D an edited list of the comments offered by each pilot approximately in chronological

TABLE 20a

MFD — SUMMARY OF 3 RATINGS OF MFD BY EACH OF PILOTS 1, 3, 4, 6 DURING SECOND PHASE OF EXPERIMENT EMPHASIZING GEOGRAPHIC ORIENTATION
(Each Check or Symbol Indicates One Rating by One Pilot)

PILOT OPINION RATING SCALES

RATING SCALE FOR UTILITY OF STATUS INFORMATION

CRITERIA	DESCRIPTIVE PHRASE	RATING	
Usefulness[a] of the information supplied, on the specified display unit, on the vehicle status — especially the relevant flight path vector states, such as: altitude, speed, heading attitude, path error, etc.	All desired states presented with adequate resolution and readability	S1	
	Many of desired states presented, with a few deficiencies in scaling, resolution, or readability	S2	✓✓✓✓✓
	Some desired states presented, and/or some problems with scaling, resolution, or readability	S3	✓✓✓✓✓✓✓
[a]Useful with respect to the mission phase, task criteria, and operator's sense of vehicle safety.	Inadequate number of states, or serious deficiencies in scaling, resolution, or readability	S4	
	No direct status information or unusable	S5	

RATING SCALE FOR CLUTTER

CRITERIA	DESCRIPTIVE PHRASE	RATING	
Degree of subjective symbol-background clutter on specified display unit	Completely uncluttered — e.g., only one pair of elements	K1	
	Mostly uncluttered — no confusing or distracting elements	K2	✓✓
	Some clutter — multiple elements competing for attention	K3	✓✓✓✓✓✓✓✓✓
	Quite cluttered — difficult to keep track of desired quantities among competitors	K4	✓
	Completely cluttered — nearly impossible to tell desired elements or quantities due to competing elements	K5	

RATING SCALE FOR TASK CONTROLLABILITY AND PRECISION

CATEGORY		DESCRIPTIVE PHRASE	RATING	
CONTROLLABLE	PRECISE			
Yes	Yes	Very easy to control, with good precision	C1	
Yes	Yes	Easy to control, with fair precision	C2	®Ⓕ®
			*	
Yes	No	Controllable, with inadequate precision	C3	®Ⓕ®
Yes	No	Marginally controllable	C4	®Ⓕ®
No	No	Uncontrollable	C5	

* Controllable with difficulty or high workload, but fair precision — *C2.5 ®Ⓕ®

RATING SCALE FOR DISPLAY ATTENTIONAL WORKLOAD

CRITERIA	DESCRIPTIVE PHRASE	RATING	
Demands on the operator attention, skill, or effort	Completely undemanding and relaxed	D1	
	Mostly undemanding	D2	✓
	Mildly demanding	D3	✓✓✓✓✓✓✓
	Quite demanding	D4	✓✓
	Completely demanding	D5	✓✓

® = Raw data. Ⓕ = Flight director and situation.

TABLE 20b

HSI — SUMMARY OF 3 RATINGS OF HSI BY EACH OF PILOTS 1, 3, 4, 6 DURING SECOND PHASE OF EXPERIMENT EMPHASIZING GEOGRAPHIC ORIENTATION

(Each Check or Symbol Indicates One Rating by One Pilot)

PILOT OPINION RATING SCALES

RATING SCALE FOR UTILITY OF STATUS INFORMATION

CRITERIA	DESCRIPTIVE PHRASE	RATING	
Usefulness[a] of the information supplied, on the specified display unit, or the vehicle status — especially the relevant flight path vector states, such as: altitude, speed, heading attitude, path error; etc.	All desired states presented with adequate resolution and readability	S1	
	Many of desired states presented, with a few deficiencies in scaling, resolution, or readability	S2	✓✓✓
	Some desired states presented, and/or some problems with scaling, resolution, or readability	S3	✓✓✓
[a]Useful with respect to the mission phase, task criteria, and operator's sense of vehicle safety.	Inadequate number of states, or serious deficiencies in scaling, resolution, or readability	S4	✓✓✓✓✓✓
	No direct status information or unusable	S5	

RATING SCALE FOR CLUTTER

CRITERIA	DESCRIPTIVE PHRASE	RATING	
Degree of subjective symbol-background clutter on specified display unit	Completely uncluttered — e.g., only one pair of elements	K1	
	Mostly uncluttered — no confusing or distracting elements	K2	✓✓✓
	Some clutter — multiple elements competing for attention	K3	✓✓✓✓✓✓✓✓✓
	Quite cluttered — difficult to keep track of desired quantities among competitors	K4	
	Completely cluttered — nearly impossible to tell desired elements or quantities due to competing elements	K5	

RATING SCALE FOR TASK CONTROLLABILITY AND PRECISION

CATEGORY		DESCRIPTIVE PHRASE	RATING	
CONTROLLABLE	PRECISE			
Yes	Yes	Very easy to control, with good precision	C1	
		Easy to control, with fair precision	C2	(F)
				*
	No	Controllable, with inadequate precision	C3	(R)(R)(F)(R)(R)(R)
		Marginally controllable	C4	(R)(F)(R)
No		Uncontrollable	C5	

* Controllable with difficulty or high workload, but fair precision   * C2.5   (R)(F)

RATING SCALE FOR DISPLAY ATTENTIONAL WORKLOAD

CRITERIA	DESCRIPTIVE PHRASE	RATING	
Demands on the operator attention, skill, or effort	Completely undemanding and relaxed	D1	
	Mostly undemanding	D2	✓
	Mildly demanding	D3	✓✓
	Quite demanding	D4	✓✓✓✓✓
	Completely demanding	D5	✓✓✓✓

(R) = Raw data.   (F) = Flight director and situation.

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order. These comments are helpful in interpreting difficulties, pilot ratings and EPR data. They also suggest potential improvements to the displays and controls.

7. **Eye-Point-of-Regard** (EPR)

This experiment has resulted in the acquisition of a large archive of high quality data with the STI Eye-Point-of-Regard System Model EPR-2. It remains necessary, however, to review the EPR data to gain insight into a pilot's scanning process before encoding the fixation data for processing by a computer program to produce summaries of EPR statistics. For this reason, the raw data must presently be screened and digitized manually, which consumes a relatively great amount of time (and money). Under the present contract it will be possible to present EPR data for only 8 of 31 runs. Much more data are available for possible future reduction.

The EPR data acquisition was confined to runs wherein both HSI and MFD (as well as all other active displays and controls in the cockpit) were available to the pilot. The reduced data to be presented are from the runs identified in Table 21.

Tables of statistics for the reduced EPR data are presented in Appendix E together with definitions of the properties of the raw and reduced data.

For the reader who may be unacquainted with the motivations, nomenclature, and uses for EPR studies in flight control and monitoring tasks, we have also included in Appendix F excerpts from Ref. 2 which provide essential background for interpreting EPR data and which help the interested reader to dig deeper into other references.

We shall now proceed to review and compare plots of some of the EPR data, presuming that the reader is familiar with the material of Appendix F and at least the definitions of symbols and terminology in Appendix E.

Plots of dwell fraction (DF) versus waypoint (WP) intervals over which the data were averaged are compared in Parts "a" of Figs. 20-23. Each part of each figure presents data for the EADI, HSI, and MFD so that direct comparisons can be made between pairs of comparable runs with and without the flight director.

TABLE 21. RUN IDENTIFICATION FOR THE REDUCED EYE-POINT-OF-REGARD DATA

RUN NUMBER	PILOT	FLIGHT PLAN	LEVEL OF DISPLAY	CASE NUMBER	FIGURE NUMBER
148	3	3	Situation (raw data)	301	23, 25
149	3	3	Flight Director and Situation	302	23, 24
154	1	3	Situation	301	22
155	1	3	Flight Director and Situation	302	
156	1	2	Situation	201	21
157	1	2	Flight Director and Situation	202	
261	4	2	Situation	201	20
257	4	2	Flight Director and Situation	202	

Plots of look fraction (LF) versus waypoint intervals are compared in Parts "b" of Figs. 20-23.

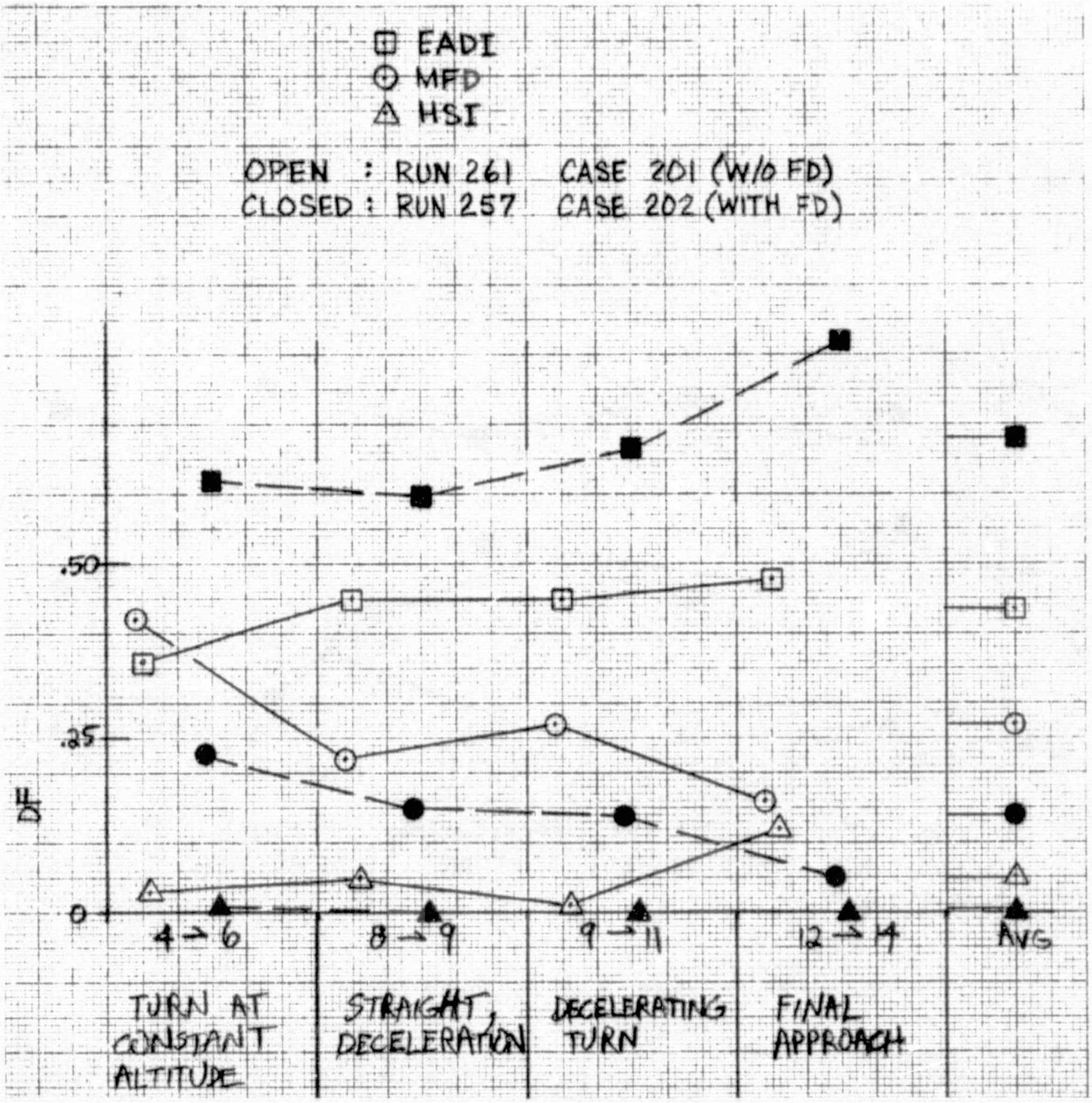
Plots of look rate (LR) versus waypoint intervals are compared in Parts "c" of Figs. 20-23.

Plots of overall average scan rate (SR) versus waypoint intervals are compared in Parts "d" of Figs. 20-23.

Plots of scan transition link fractions (TF) between primary displays are compared in Parts "e" of Figs. 20-23.

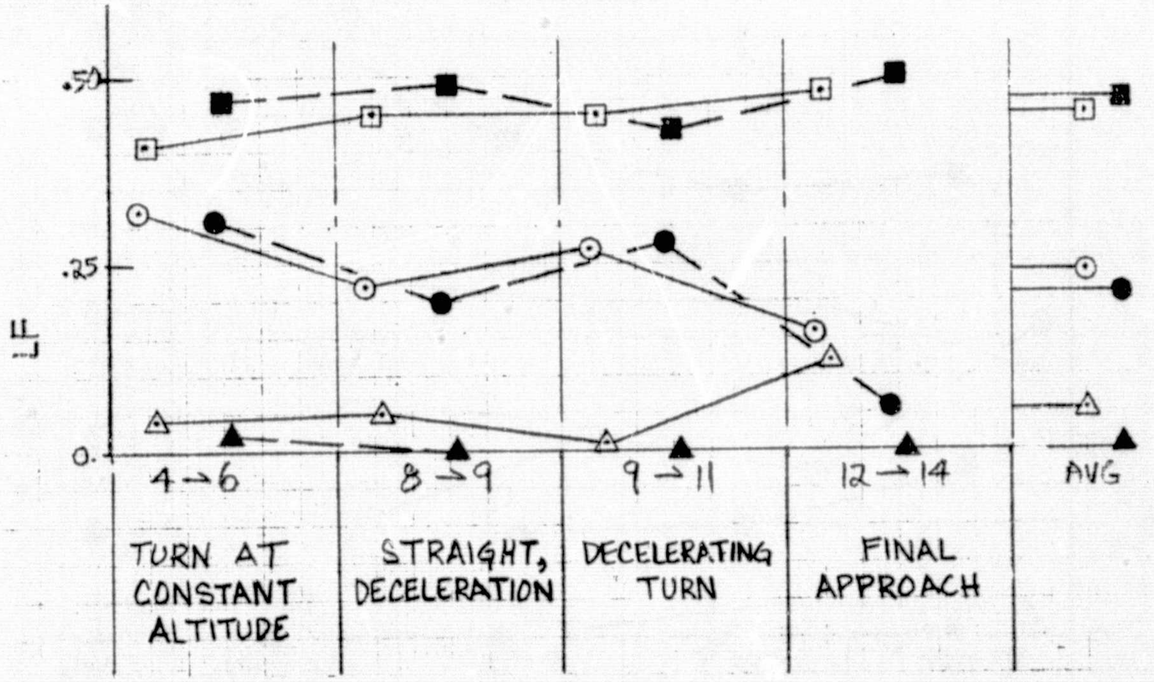
Illustrative (typical) histograms of dwell interval on the three primary displays are confined to Run 148 in Fig. 24 and Run 149 in Fig. 25, because of the otherwise unwieldy volume of histograms. The histograms for the HSI and MFD are helpful in providing clues for possibly discriminating between roles for purely monitoring or for both controlling and monitoring, depending on the relative proportions of dwell intervals in the neighborhood of 0.25 to 0.5 sec (monitoring) and greater than 0.5 sec (controlling and monitoring).

[text continues on page 125]



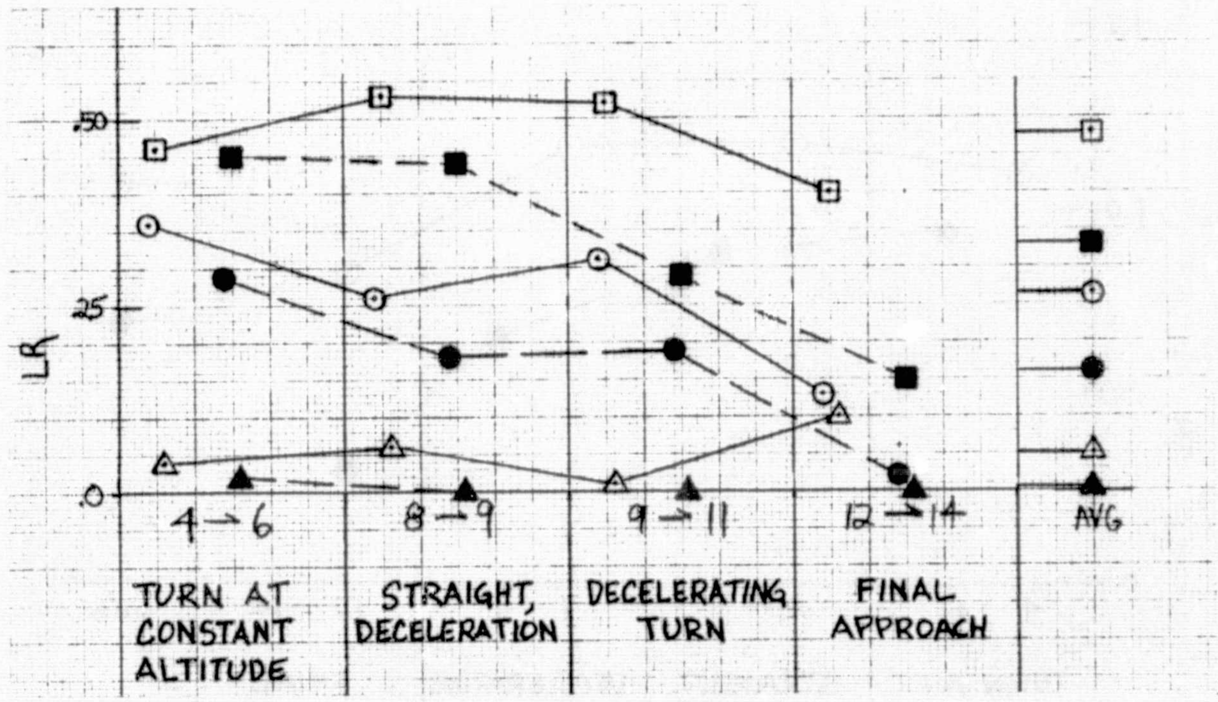
a. Dwell Fraction Data for Runs 261 and 257
Pilot 4, Flight Plan 2

Figure 20. Averaged Eye-Point-of-Regard Data for the Primary Displays by Waypoint Groups for Flight Plan 2 with Pilot 4, Runs 261 and 257



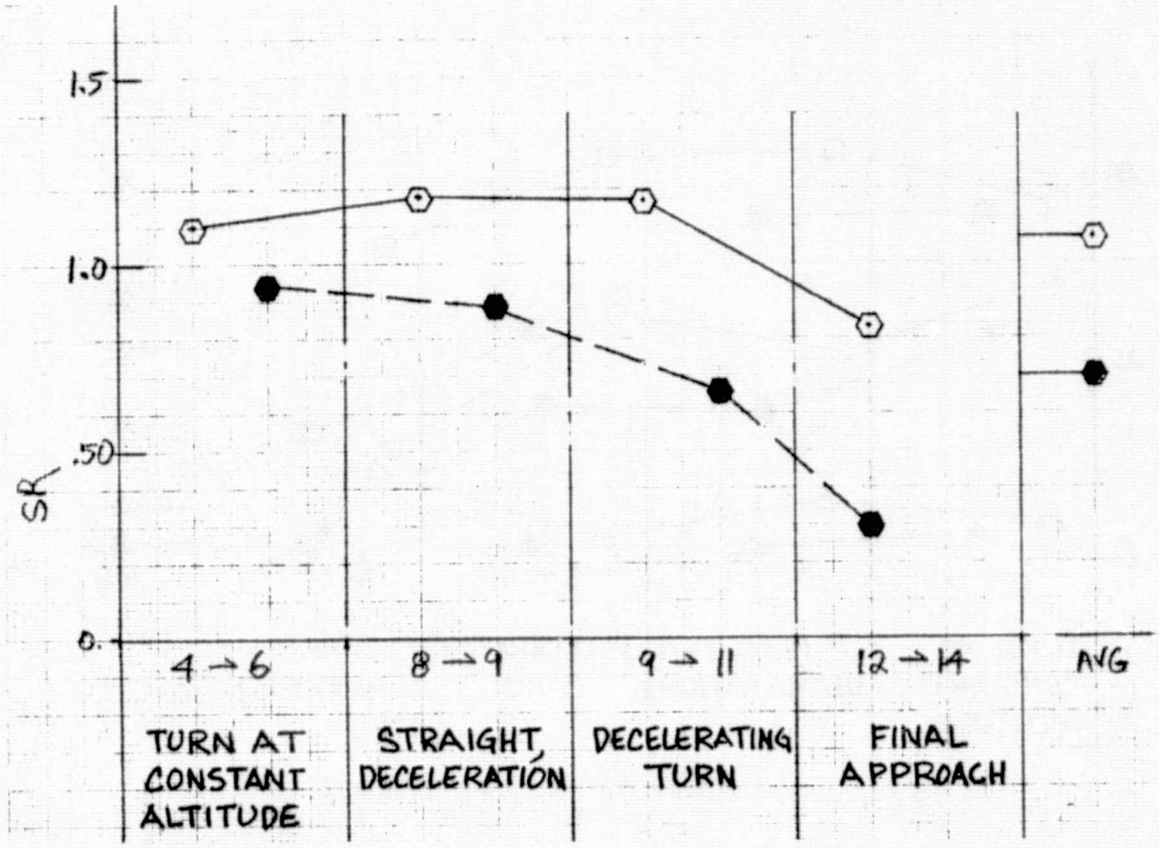
b. Look Fraction Data for Runs 261 and 257

Figure 20 (Continued)



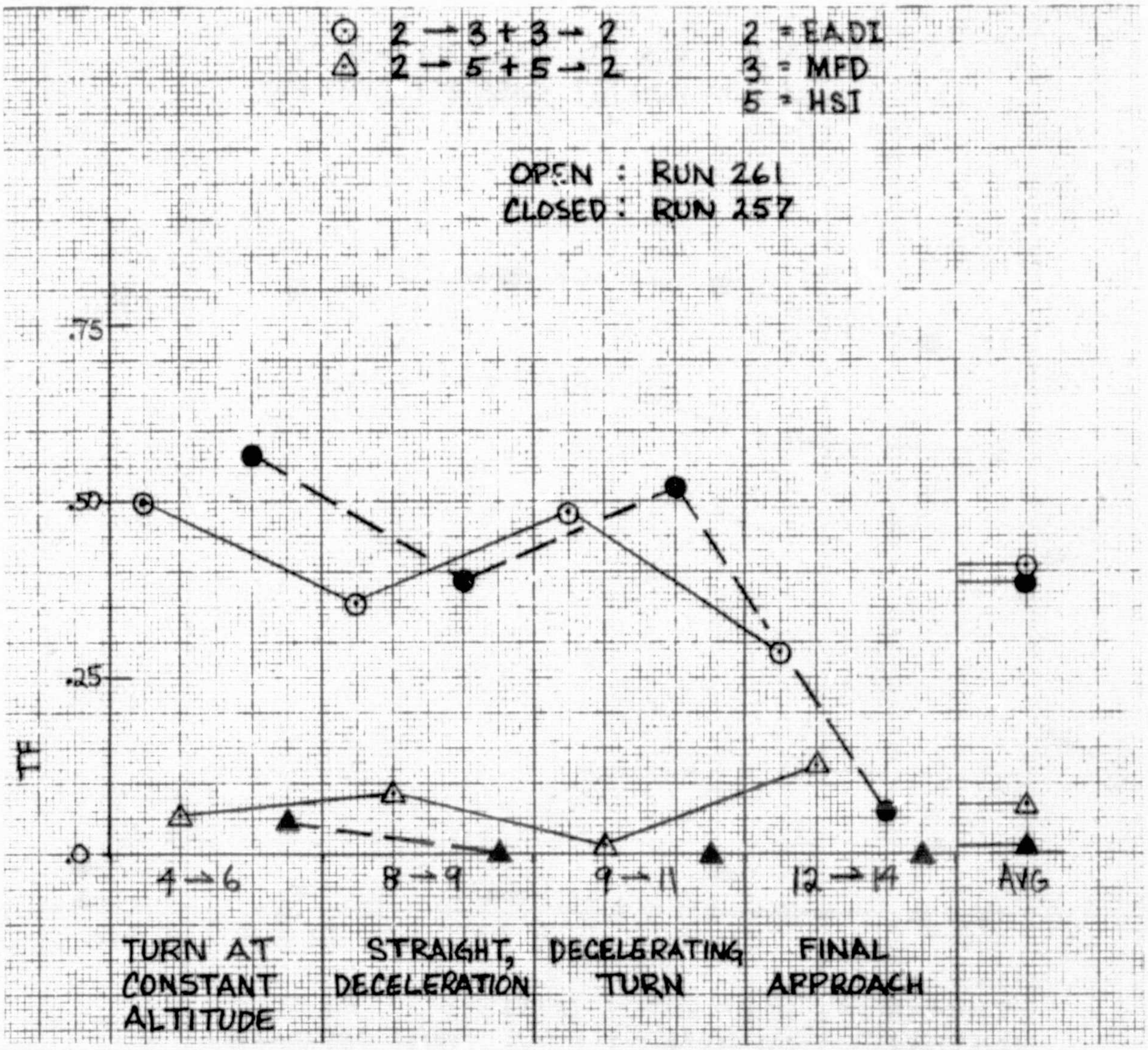
c. Look Rate Data for Runs 261 and 257

Figure 20 (Continued)



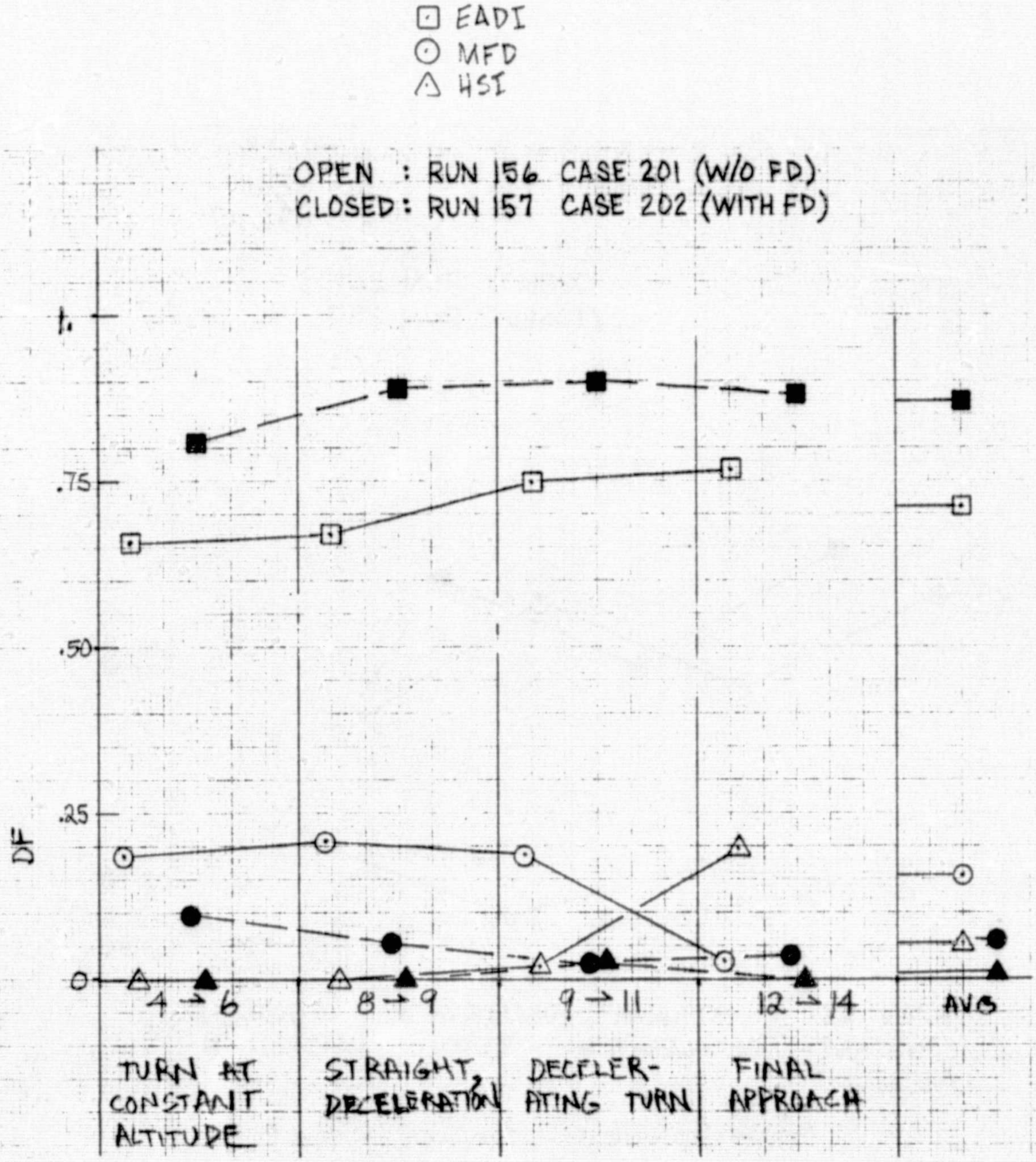
d. Scan Rate Data for Runs 261 and 257

Figure 20 (Continued)



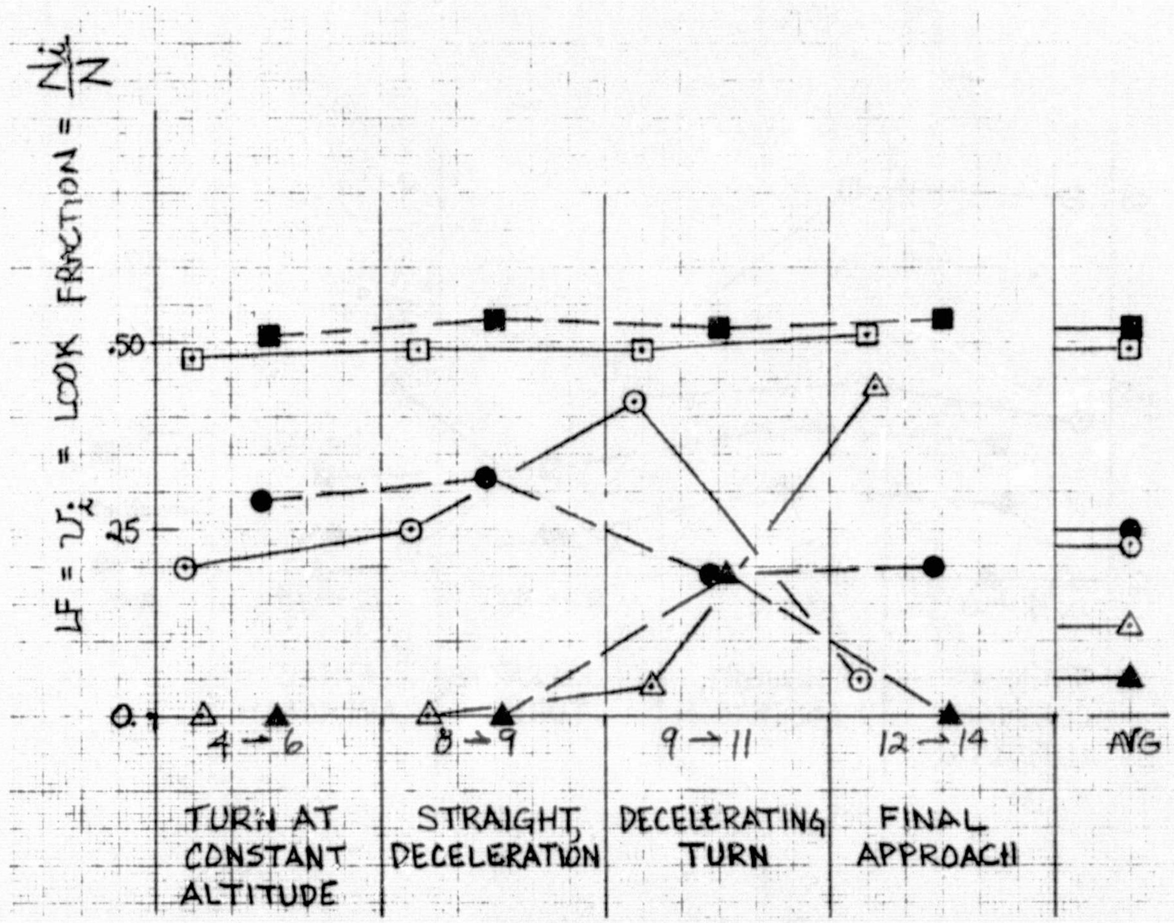
e. Transition Link Data for Runs 261 and 257

Figure 20 (Concluded)



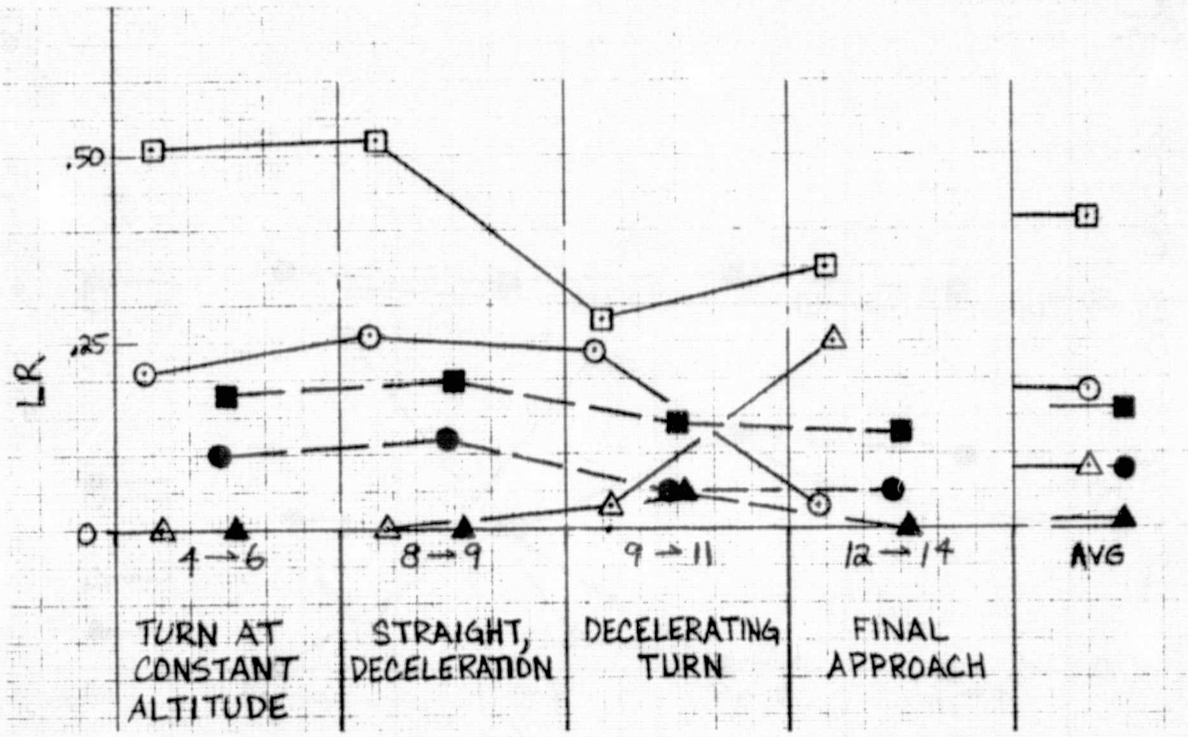
a. Dwell Fraction Data for Runs 156 and 157

Figure 21. Averaged Eye-Point-of-Regard Data for the Primary Displays by Waypoint Groups for Flight Plan 2 with Pilot 1, Runs 156 and 157



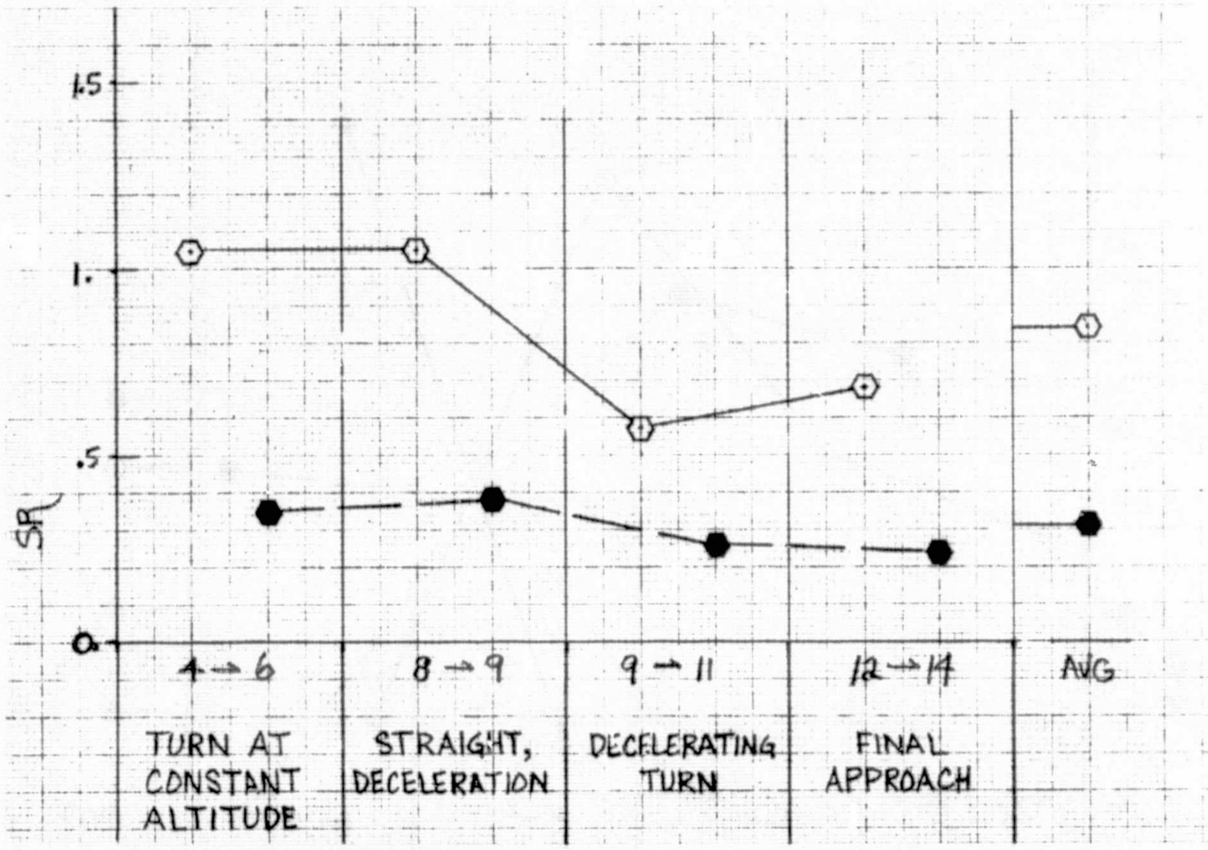
b. Look Fraction Data for Runs 156 and 157

Figure 21 (Continued)



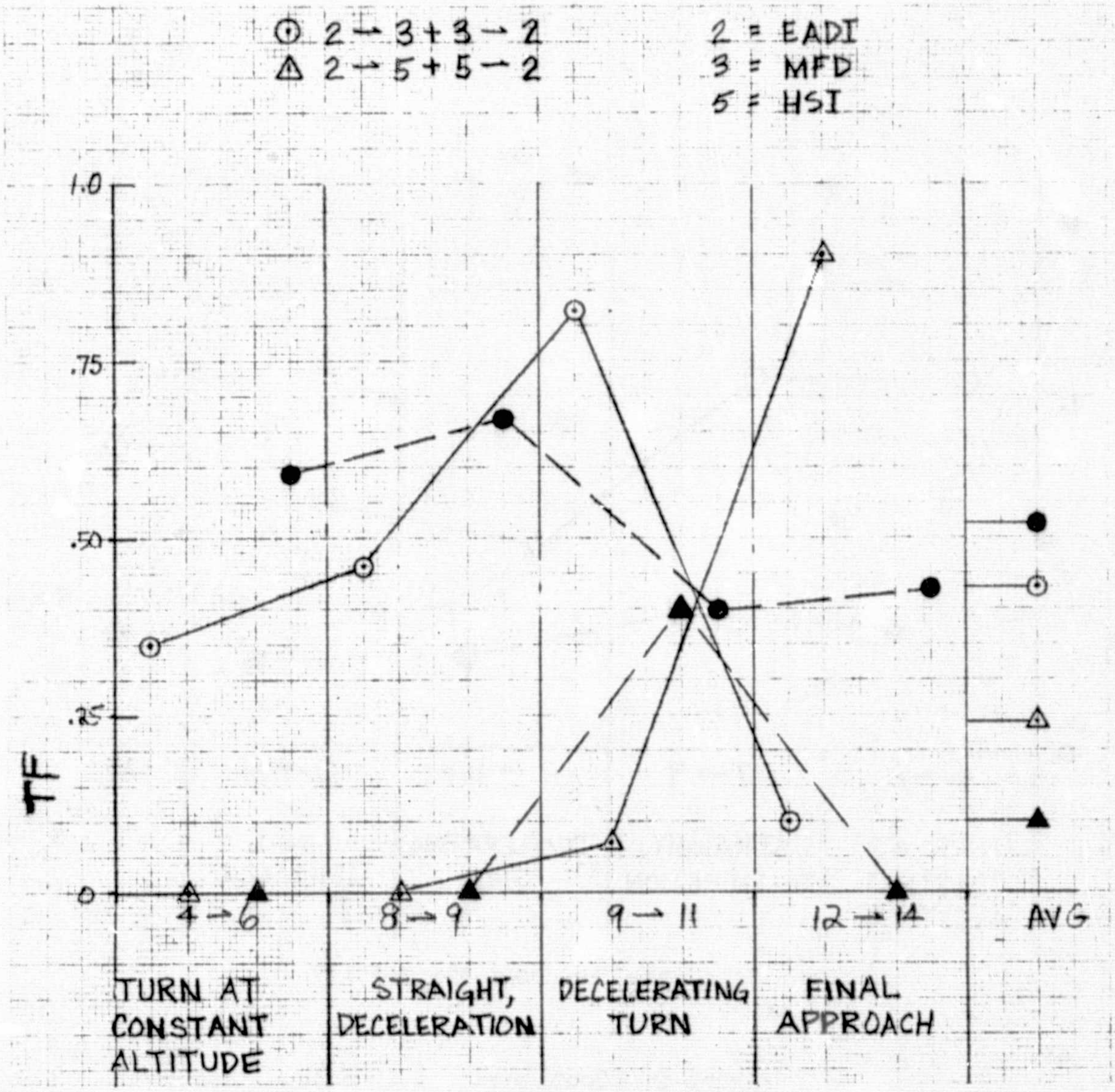
c. Look Rate Data for Runs 156 and 157

Figure 21 (Continued)



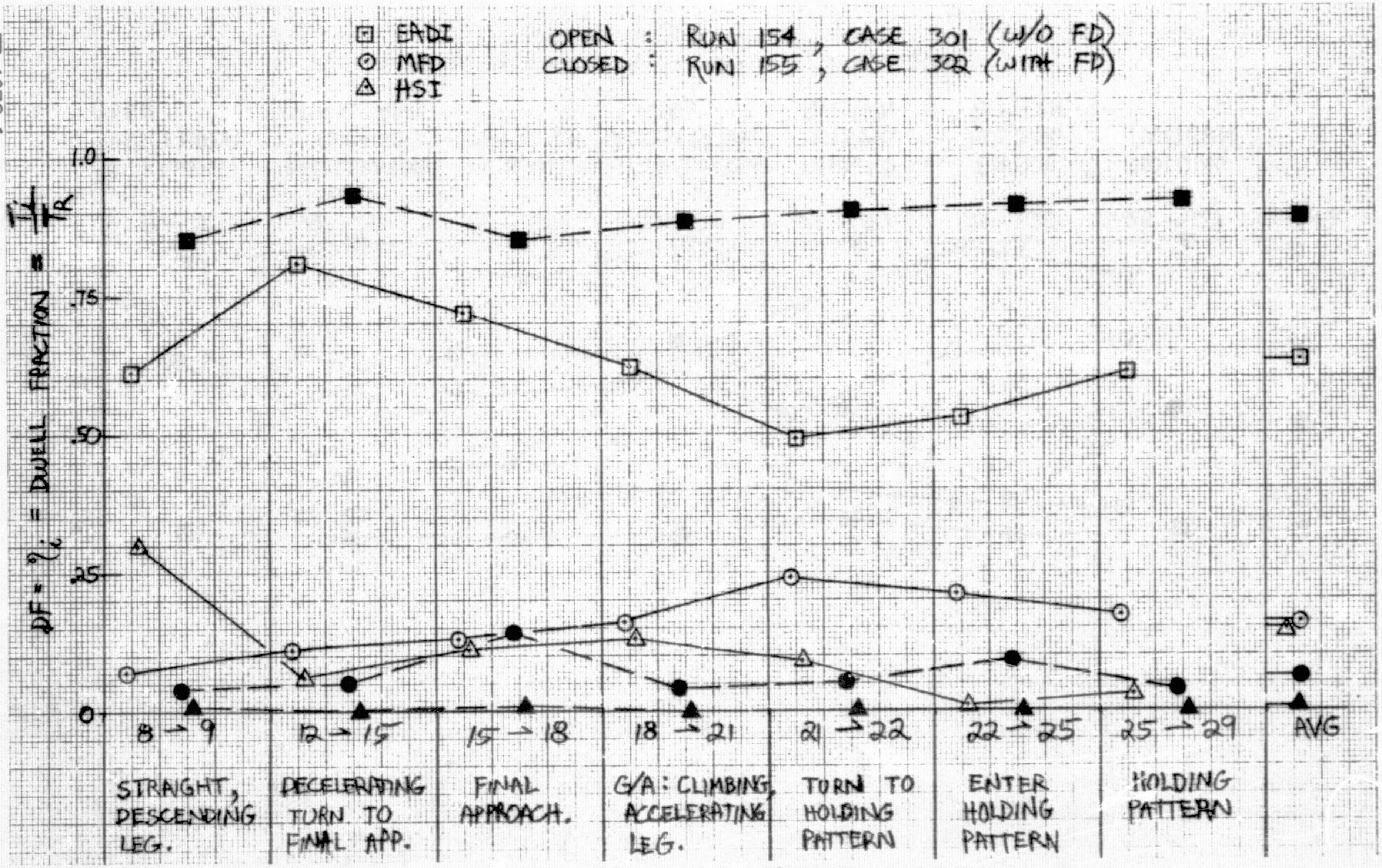
d. Scan Rate Data for Runs 156 and 157

Figure 21 (Continued)



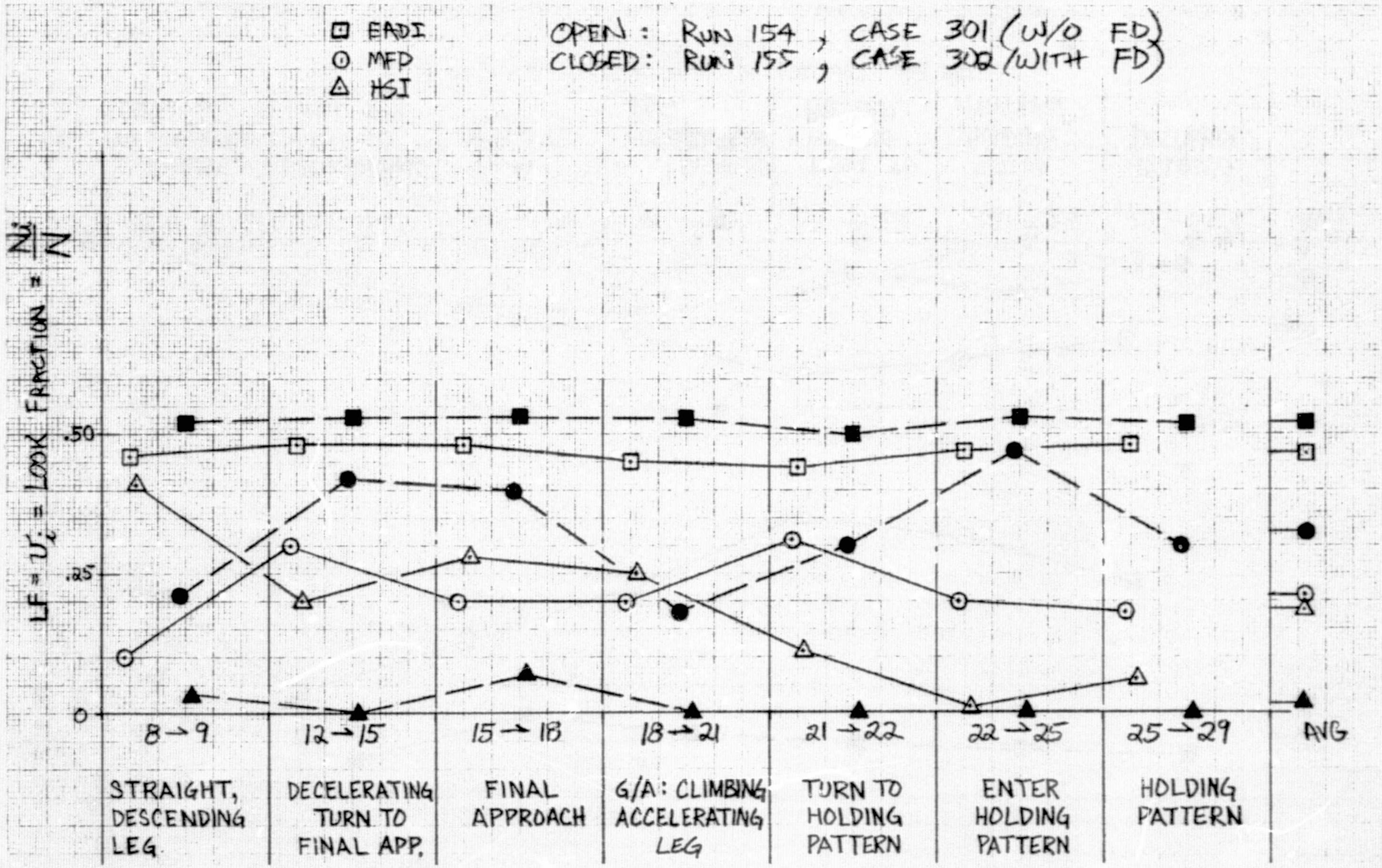
e. Transition Link Data for Runs 156 and 157

Figure 21 (Concluded)



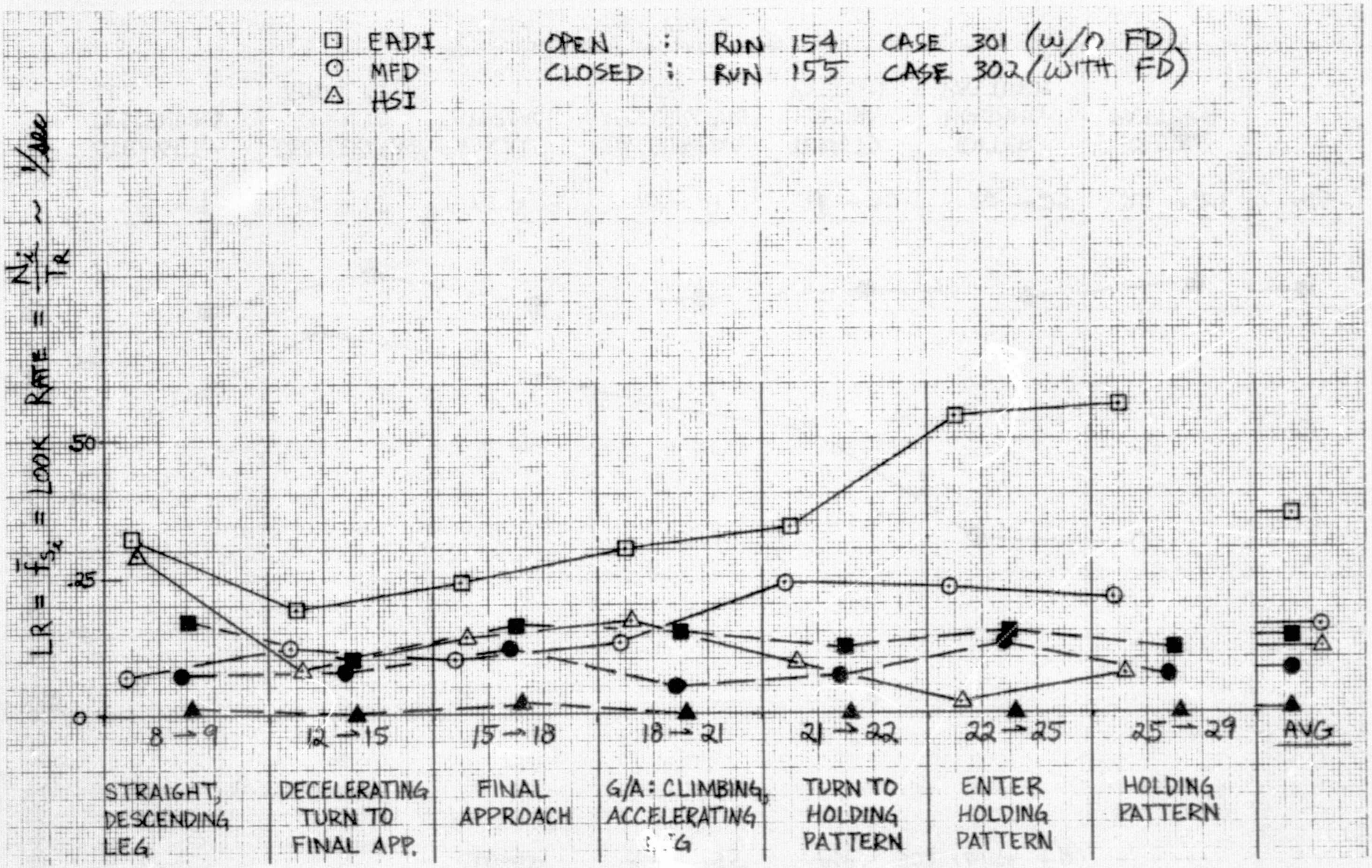
a. Summary of Dwell Fraction Data for EADI, MFD, and HSI
Pilot 1, Flight Plan 3

Figure 22. Averaged Eye-Point-of-Regard Data for the Primary Displays by Waypoint Groups for Flight Plan 3 with Pilot 1, Runs 154 and 155



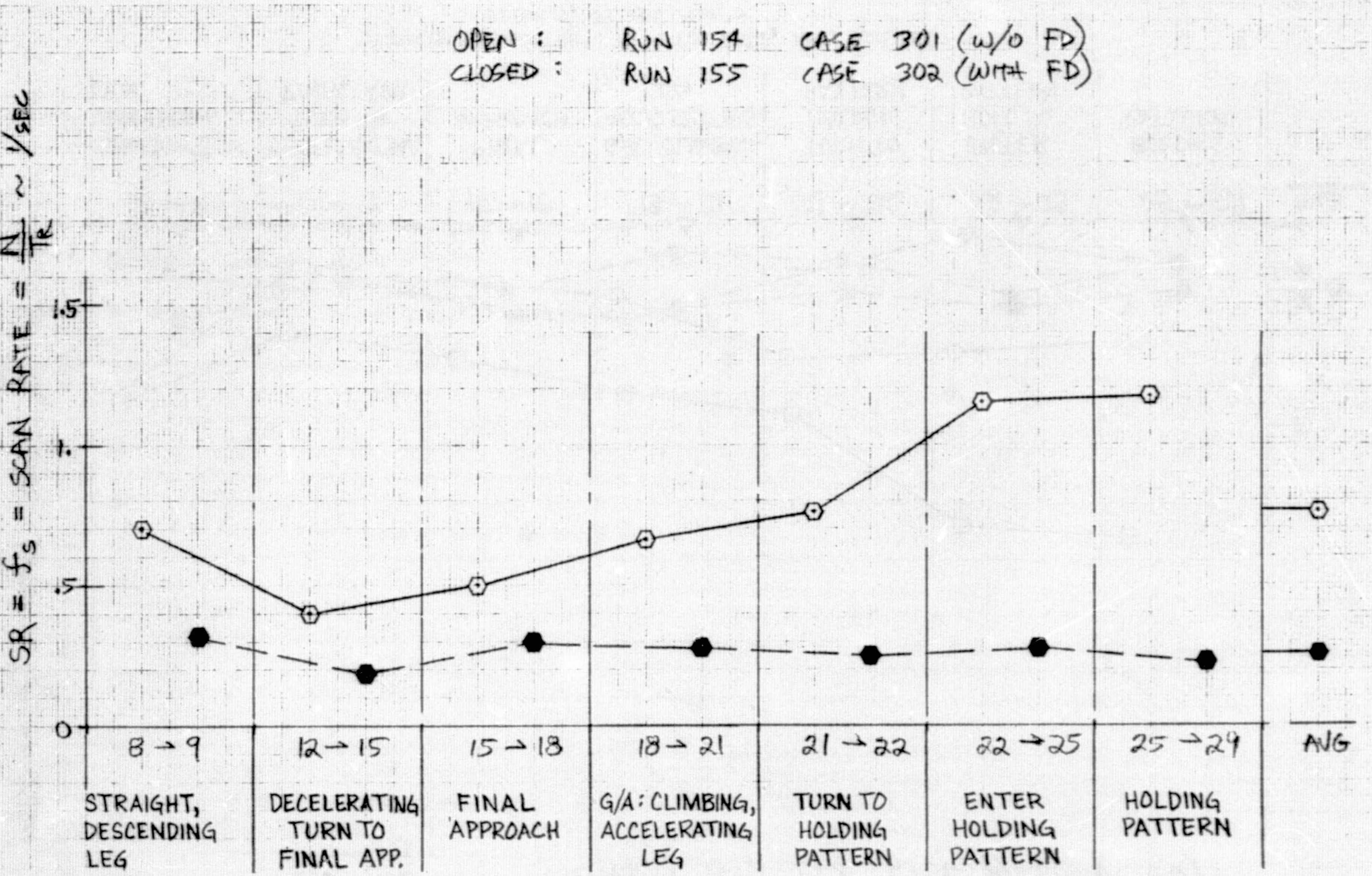
b. Summary of Look Fraction Data for EADI, MFD, and HSI
Pilot 1, Flight Plan 3

Figure 22 (Continued)



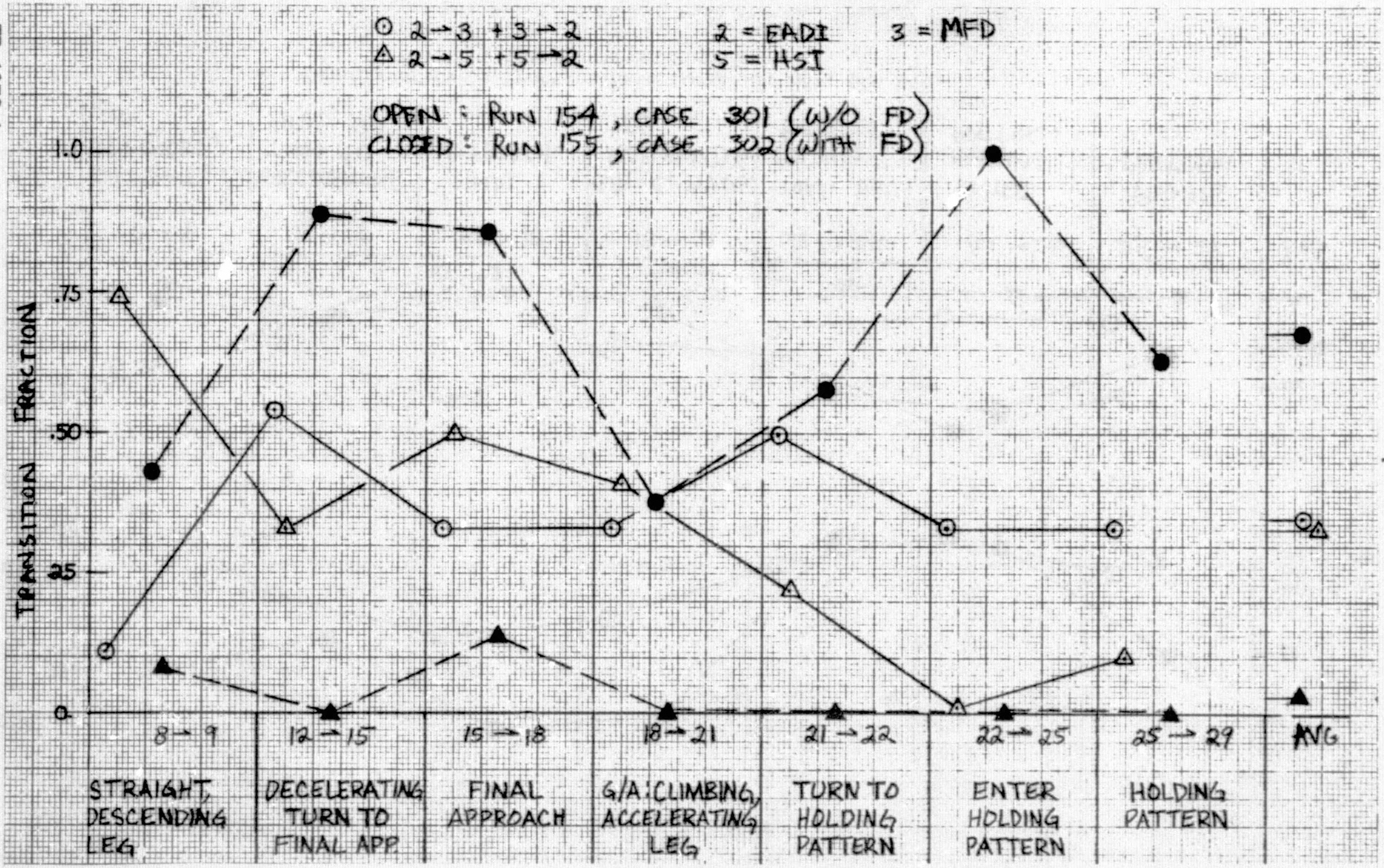
c. Summary of Look Rate Data for EADI, MFD, and HSI
Pilot 1, Flight Plan 3

Figure 22 (Continued)



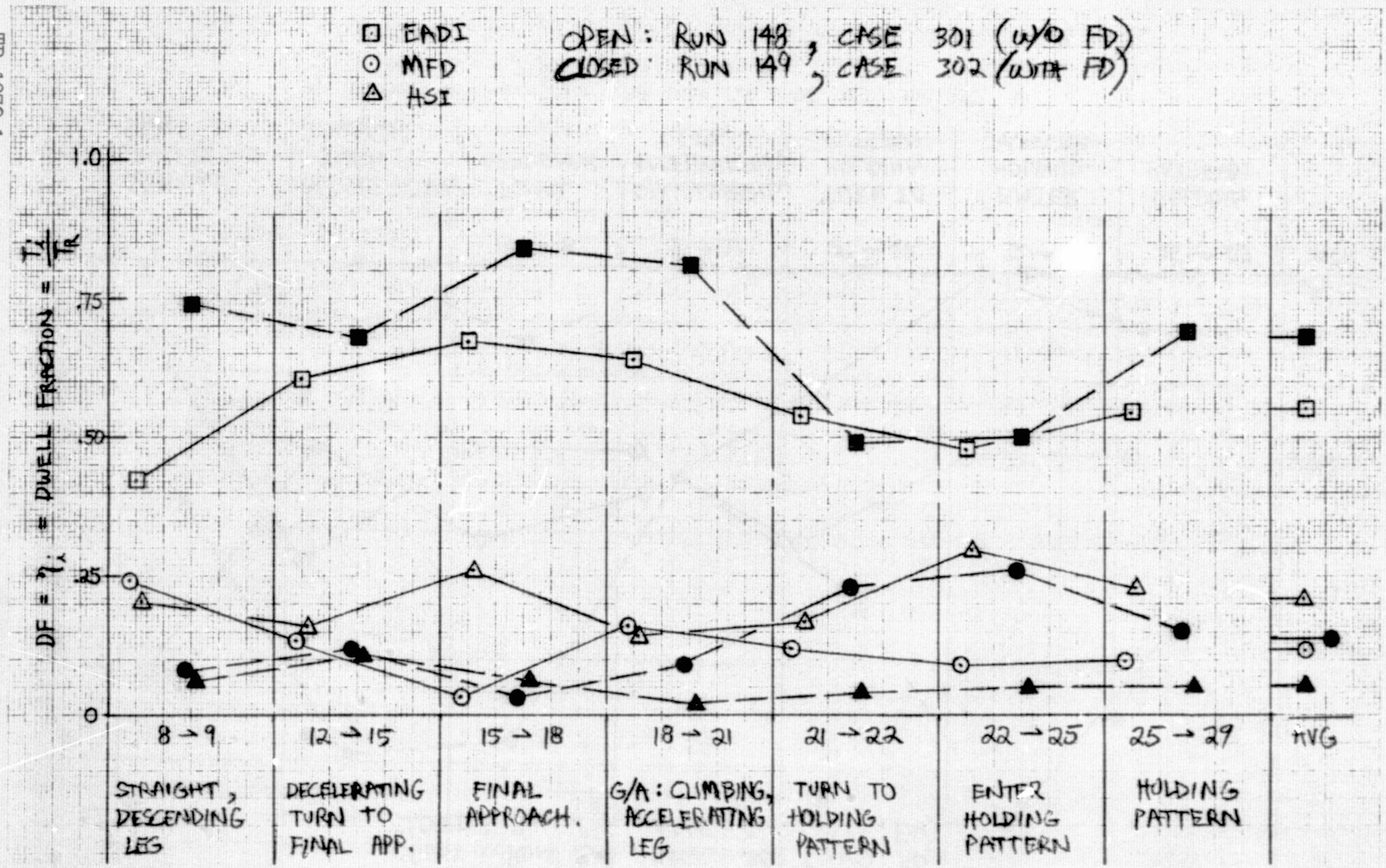
d. Summary of Scan Rate Data
Pilot 1, Flight Plan 3

Figure 22 (Continued)



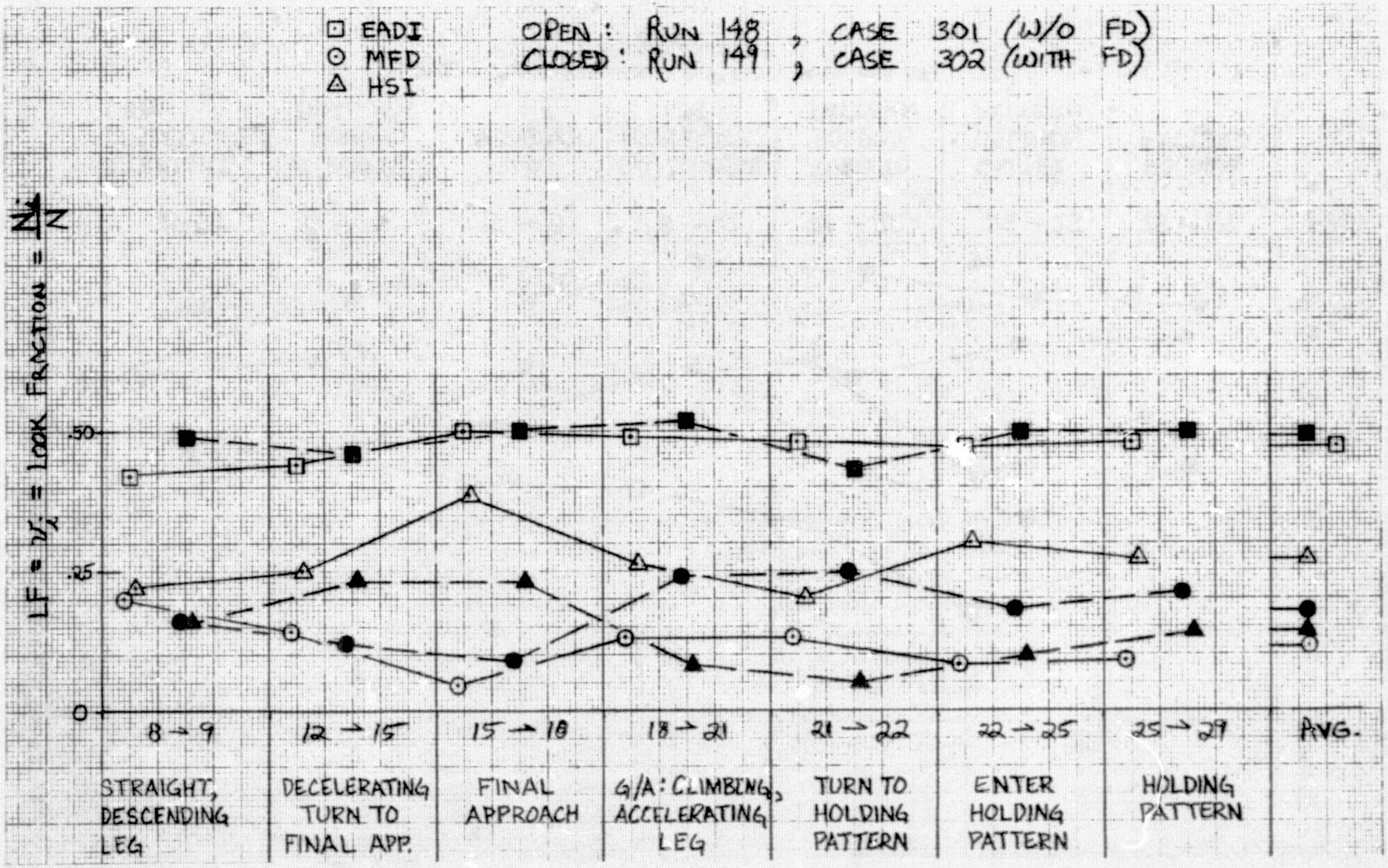
e. Summary of Transition Link Data for EADI, MFD, and HSI
Pilot 1, Flight Plan 3

Figure 22 (Concluded)



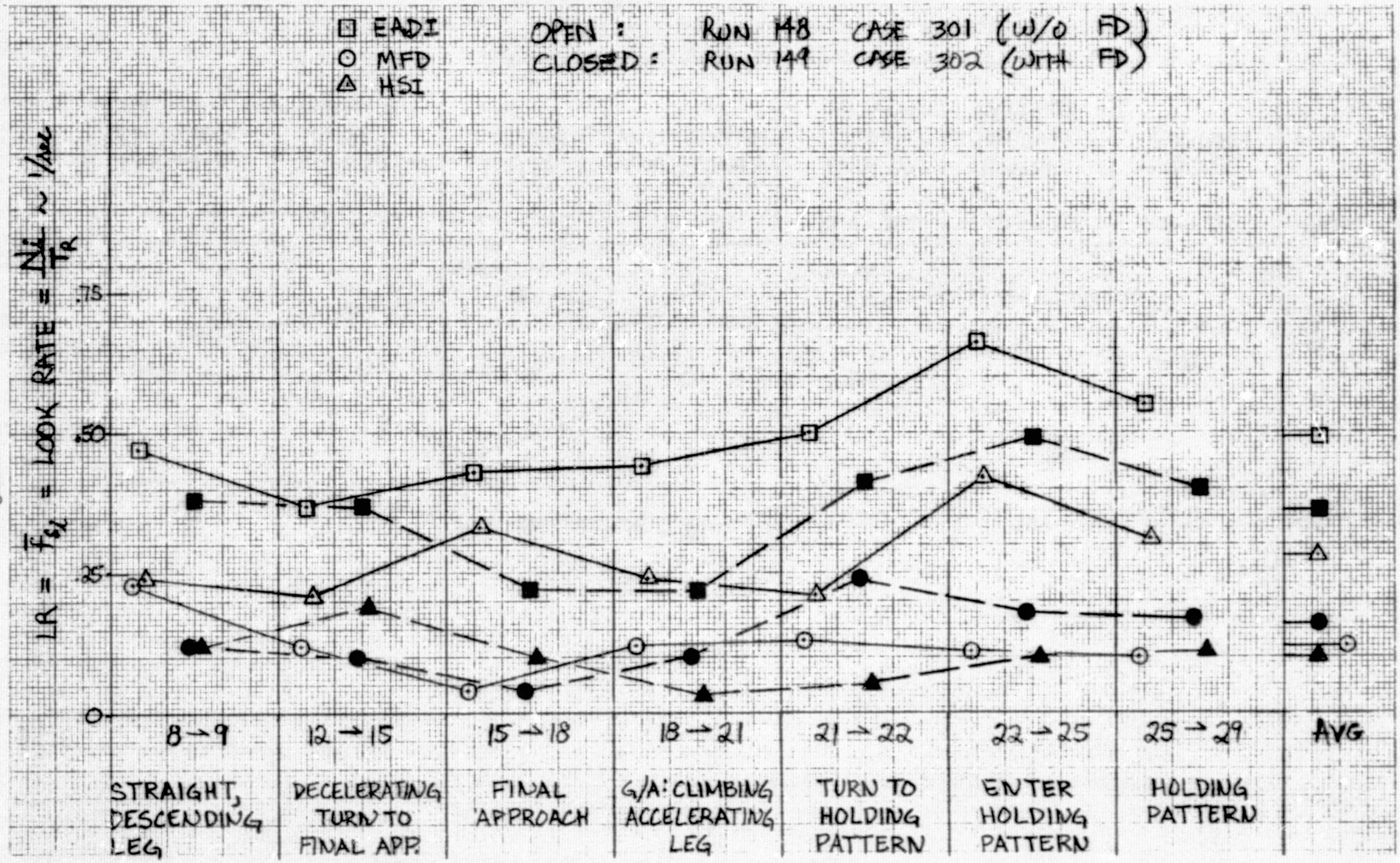
a. Summary of Dwell Fraction Data for EADI, MFD, and HSI
Pilot 3, Flight Plan 3

Figure 23. Averaged Eye-Point-of-Regard Data for the Primary Displays by Waypoint Groups for Flight Plan 3 with Pilot 3, Runs 148 and 149



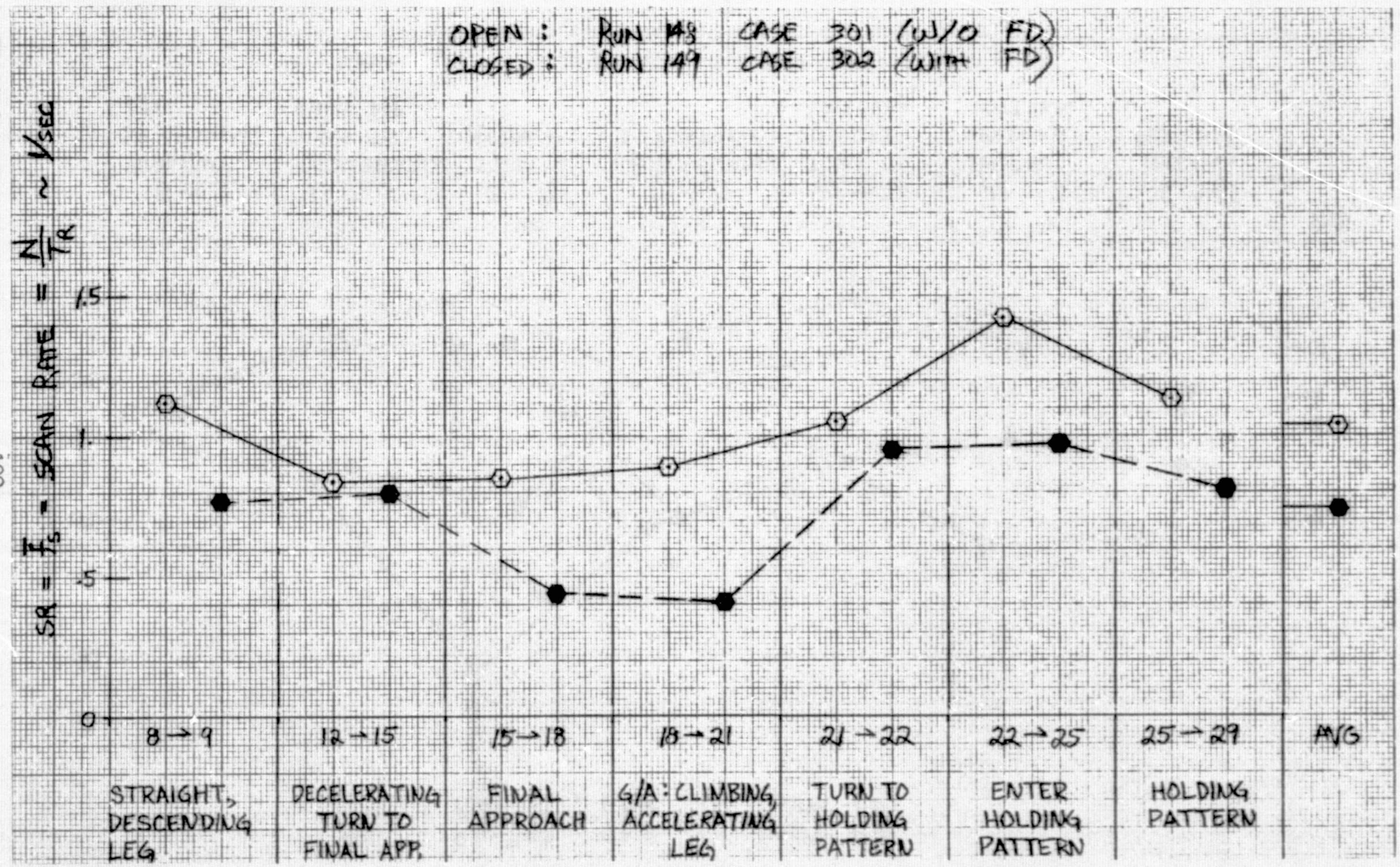
b. Summary of Look Fraction Data for EADI, MDF, and HSI
Pilot 3, Flight Plan 3

Figure 23 (Continued)



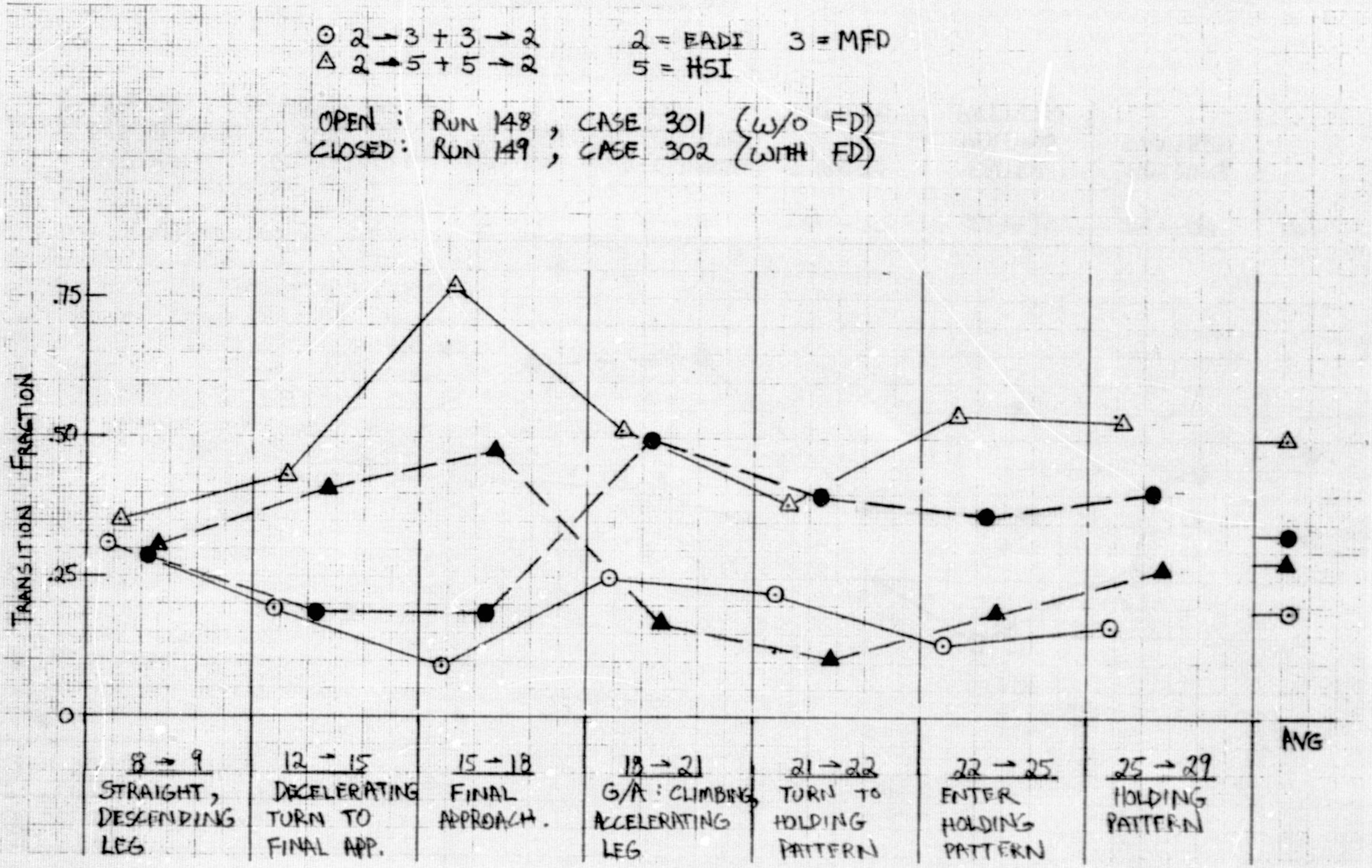
c. Summary of Look Rate Data for EADI, MFD, and HSI
Pilot 3, Flight Plan 3

Figure 23 (Continued)



d. Summary of Scan Rate Data
Pilot 3, Flight Plan 3

Figure 23 (Continued)



e. Summary of Transition Link Data for EADI, MFD, and HSI
Pilot 3, Flight Plan 3

Figure 23 (Concluded)

```
                    FREQUENCY HISTOGRAM OF DWELL TIMES ~ n/N

                    .         .1        .2        .3        .4        .5
              n     ..........↑.........↑.........↑.........↑.........↑
       0.000  0
       0.250  1     XX
       0.500  7     XXXXXXXXXXXXXXXXXXXX
       0.750  5     XXXXXXXXXXXXXX
       1.000  1     XX                                    EADI
       1.250  3     XXXXXXXX
       1.500  5     XXXXXXXXXXXXXX                       N=34
       1.750  1     XX
       2.000  1     XX
       2.250  0
       2.500  1     XX
       2.750  1     XX
       3.000  1     XX
       3.250  0
t ~ sec 3.500  2     XXXXX
       3.750  0
       4.000  1     XX
       4.250  2     XXXXX
       4.500  1     XX
       4.750  0
       5.000  0
       5.250  0
       5.500  0
    ** 7.000  1     XX

                    .         .1        .2        .3        .4        .5
                    ..........↑.........↑.........↑.........↑.........↑
       0.000  0
       0.250  1     XXXXXXXXX
       0.500  5     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
       0.750  4     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX            MFD
       1.000  1     XXXXXXXXX                                         "

                    .         .2        .4        .6        .8        1.0
                    ..........↑.........↑.........↑.........↑.........↑
       0.000  0
       0.250  4     XXXXXXXXXXXXXXXXXX
       0.500  6     XXXXXXXXXXXXXXXXXXXXXXXXXXX                     HSI
       0.750  1     XXXX                                             "
```

a. Waypoints 8 to 9

Figure 24. Frequency Histograms of Dwell Times for Run 149 (EADI, MFD, and HSI Only)

FREQUENCY HISTOGRAM OF DWELL TIMES

```
                 .         .1        .2        .3        .4        .5
                  .........↑.........↑.........↑.........↑.........↑
  0.000    0
  0.250    5   XXXXXXXXXXXXX
  0.500   10   XXXXXXXXXXXXXXXXXXXXXXXXXX
  0.750    2   XXXXX
  1.000    1   XX
  1.250    4   XXXXXXXXXX
  1.500    2   XXXXX
  1.750    3   XXXXXXXX
  2.000    0
  2.250    2   XXXXX
  2.500    0
  2.750    1   XX                                      EADI
  3.000    0                                            37
  3.250    1   XX
  3.500    2   XXXXX
  3.750    2   XXXXX
  4.000    1   XX
  4.250    0
  4.500    0
  4.750    0
  5.000    0
**5.250    0
 13.250    1   XX

                 .         .1        .2        .3        .4        .5
                  .........↑.........↑.........↑.........↑.........↑
  0.000    0
  0.250    0
  0.500    2   XXXXXXXXXXXXXXXXXXX
  0.750    1   XXXXXXXXXX
  1.000    3   XXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  1.250    3   XXXXXXXXXXXXXXXXXXXXXXXXXXXXX                  MFD
  1.500    0
  1.750    0
  2.000    0
  2.250    1   XXXXXXXXXX

                 .         .2        .4        .6        .8        1.0
                  .........↑.........↑.........↑.........↑.........↑
  0.000    0
  0.250    3   XXXXXXX
  0.500   14   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  0.750    1   XX                                                 HSI
  1.000    1   XX                                                  19
```

b. Waypoints 12 to 15

Figure 24 (Continued)

FREQUENCY HISTOGRAM OF DWELL TIMES

```
                   .         .1        .2        .3        .4        .5
                    .........↑.........↑.........↑.........↑.........↑
0.000    0
0.250    0
0.500    1   XXXXXXXXX
0.750    1   XXXXXXXXX
1.000    1   XXXXXXXXX
1.250    0
1.500    1   XXXXXXXXX
1.750    0
2.000    0
2.250    0
2.500    0
2.750    1   XXXXXXXXX
3.000    1   XXXXXXXXX
3.250    0
3.500    0
3.750    0
4.000    0
4.250    0
4.500    1   XXXXXXXXX
4.750    0
5.000    1   XXXXXXXXX
5.250    0
5.500    0
5.750    0
6.000    0
6.250    0
6.500    1   XXXXXXXXX
6.750    0
7.000    0
7.250    1   XXXXXXXXX
7.500    0
7.750    0
8.000    0
8.250    1   XXXXXXXXX
```

EAPI
11

```
                   .         .1        .2        .3        .4        .5
                    .........↑.........↑.........↑.........↑.........↑
0.000    0
0.250    1   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.500    0
0.750    0
1.000    1   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

MFD 2

```
                   .         .2        .4        .6        .8       1.0
                    .........↑.........↑.........↑.........↑.........↑
0.000    0
0.250    1   XXXXXXXXXX
0.500    3   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.750    1   XXXXXXXXXX
```

HSI
5

c. Waypoints 15 to 18

Figure 24 (Continued)

FREQUENCY HISTOGRAM OF DWELL TIMES

```
              .         .1        .2        .3        .4        .5
               .........↑.........↑.........↑.........↑.........↑
   0.000    0
   0.250    0
   0.500    0
   0.750    4  XXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   1.000    2  XXXXXXXXXXXXXX
   1.250    0
   1.500    0
   1.750    0
   2.000    0
   2.250    1  XXXXXXX
   2.500    1  XXXXXXX
   2.750    0
   3.000    0
   3.250    1  XXXXXXX
   3.500    0
   3.750    0
   4.000    0
   4.250    0
** 5.250    1  XXXXXXX
   5.500    0
   5.750    0
   6.000    0
   6.250    0
*  8.250    1  XXXXXXX
   8.500    0
   8.750    0
   9.000    0
   9.250    0
   9.500    1  XXXXXXX
   9.750    0
  10.000    0
  10.250    0
  10.500    0
**12.500    1  XXXXXXX
```

EADI
15

```
              .         .1        .2        .3        .4        .5
               .........↑.........↑.........↑.........↑.........↑
   0.000    0
   0.250    0
   0.500    3  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   0.750    1  XXXXXXXXXXXXXXXX
   1.000    1  XXXXXXXXXXXXXXXX
   1.250    0
   1.500    1  XXXXXXXXXXXXXXXX
```

MFD
6

```
              .         .2        .4        .6        .8        1.0
               .........↑.........↑.........↑.........↑.........↑
   0.000    0
   0.250    2  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

HSI
2

d. Waypoint 18 to 21

Figure 24 (Continued)

FREQUENCY HISTOGRAM OF DWELL TIMES

```
                      .1        .2        .3        .4        .5
         .........†.........†.........†.........†.........†

0.000   0
0.250   5  XXXXXXXXXXXXXXX
0.500   6  XXXXXXXXXXXXXXXXXX
0.750   3  XXXXXXXXX
1.000   3  XXXXXXXXX
1.250   5  XXXXXXXXXXXXXXX
1.500   3  XXXXXXXXX
1.750   2  XXXXXX
2.000   4  XXXXXXXXXXXX
2.250   1  XXX
2.500   0
2.750   1  XXX
```

EADI

33

```
                      .2        .4        .6        .8       1.0
         .........†.........†.........†.........†.........†

0.000   0
0.250   0
0.500   3  XXXXXXX
0.750  10  XXXXXXXXXXXXXXXXXXXXXXXXXX
1.000   4  XXXXXXXXXX
1.250   1  XX
1.500   0
1.750   0
2.000   1  XX
```

MFD

19

```
                      .2        .4        .6        .8       1.0
         .........†.........†.........†.........†.........†

0.000   0
0.250   0
0.500   3  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.750   0
1.000   0
1.250   0
1.500   1  XXXXXXXXXXXX
```

HSI

4

e. Waypoints 21 to 22

Figure 24 (Continued)

FREQUENCY HISTOGRAM OF DWELL TIMES

```
                 .        .1        .2        .3        .4        .5
                  .........↑.........↑.........↑.........↑.........↑
 0.000    0
 0.250    5   XXXXXXXXXXXXXXXX
 0.500    6   XXXXXXXXXXXXXXXXXXXX
 0.750    6   XXXXXXXXXXXXXXXXXXXX
 1.000    3   XXXXXXXXXX
 1.250    4   XXXXXXXXXXXXX
 1.500    3   XXXXXXXXXX
 1.750    2   XXXXXX
 2.000    0
 2.250    0
 2.500    0
 2.750    0
 3.000    0
 3.250    1   XXX
```

EADI
30

```
                 .        .1        .2        .3        .4        .5
                  .........↑.........↑.........↑.........↑.........↑
 0.000    0
 0.250    0
 0.500    3   XXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.750    4   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 1.000    1   XXXXXXXXX
 1.250    0
 1.500    0
 1.750    0
 2.000    1   XXXXXXXXX
 2.250    0
 2.500    0
 2.750    0
 3.000    1   XXXXXXXXX
 3.250    0
 3.500    0
 3.750    0
 4.000    0
 4.250    0
 4.500    0
 4.750    1   XXXXXXXXX
```

MFD
11

```
                 .        .2        .4        .6        .8       1.0
                  .........↑.........↑.........↑.........↑.........↑
 0.000    0
 0.250    2   XXXXXXXXXXXXXXXX
 0.500    4   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

HSI
6

f. Waypoints 22 to 25

Figure 24 (Continued)

FREQUENCY HISTOGRAM OF DWELL TIMES

```
            .         .1        .2        .3        .4        .5
            ..........↑.........↑.........↑.........↑.........↑
0.000    0
0.250    3  XXXXX
0.500    6  XXXXXXXXXX
0.750   12  XXXXXXXXXXXXXXXXXXXX
1.000    4  XXXXXXX
1.250    4  XXXXXXX
1.500    6  XXXXXXXXXX
1.750    4  XXXXXXX
2.000    6  XXXXXXXXXX
2.250    2  XXX
2.500    1  X
2.750    2  XXX
3.000    1  X
3.250    1  X
3.500    1  X
3.750    0
4.000    0
4.250    2  XXX
4.500    1  X
4.750    0
5.000    0
5.250    0
5.500    0
**7.250  1  X
```

EADI
57

```
            .         .1        .2        .3        .4        .5
            ..........↑.........↑.........↑.........↑.........↑
0.000    0
0.250    1  XXXX
0.500   10  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.750   10  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
1.000    1  XXXX
1.250    0
1.500    1  XXXX
1.750    0
2.000    0
2.250    0
2.500    0
2.750    0
3.000    0
3.250    0
3.500    1  XXXX
```

MFD
24

```
            .         .2        .4        .6        .8        1.0
            ..........↑.........↑.........↑.........↑.........↑
0.000    0
0.250   10  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.500    5  XXXXXXXXXXXXXXX
0.750    1  XXX
```

HSI
16

ORIGINAL PAGE IS OF POOR QUALITY

g. Waypoints 25 to 29

Figure 24 (Concluded)

FREQUENCY HISTOGRAM OF DWELL TIMES ~ n/N

```
                 .        .1        .2        .3        .4        .5
              n  .........↑.........↑.........↑.........↑.........↑
 0.000        0
 0.250        4  XXXXXXX
 0.500       22  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.750        7  XXXXXXXXXXXXX
 1.000        9  XXXXXXXXXXXXXXXXX                              EADI
 1.250        4  XXXXXXX
 1.500        4  XXXXXXX                                        N= 5[illegible]
 1.750        0
 2.000        2  XXX
```

```
                 .        .1        .2        .3        .4        .5
                 .........↑.........↑.........↑.........↑.........↑
 0.000        0
 0.250        1  XXXX
 0.500        5  XXXXXXXXXXXXXXXXXXXX
 0.750        8  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX               MFD
 1.000        4  XXXXXXXXXXXXXXXX                               25
 1.250        3  XXXXXXXXXXXX
 1.500        2  XXXXXXXX
 1.750        0
 2.000        1  XXXX
 2.250        1  XXXX
```

```
                 .        .1        .2        .3        .4        .5
                 .........↑.........↑.........↑.........↑.........↑
 0.000        0
 0.250        1  XXX
 0.500       10  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX              HSI
 0.750        8  XXXXXXXXXXXXXXXXXXXXXXXXXXXXX                      27
 1.000        6  XXXXXXXXXXXXXXXXXXXXXX
 1.250        2  XXXXXXX
```

a. Waypoints 8 to 9

Figure 25. Frequency Histograms of Dwell Times for Run 148 (EADI, MFD, HSI Only)

FREQUENCY HISTOGRAM OF DWELL TIMES

```
                 .         .1         .2         .3         .4         .5
                  .........↑.........↑.........↑.........↑.........↑
0.000    1  XX
0.250    1  XX
0.500    7  XXXXXXXXXXXXXXXXXX
0.750    4  XXXXXXXXXX
1.000    7  XXXXXXXXXXXXXXXXXX
1.250    2  XXXXX
1.500    2  XXXXX
1.750    3  XXXXXXXX
2.000    2  XXXXX
2.250    1  XX
2.500    1  XX
2.750    0
3.000    0
3.250    1  XX
3.500    0
3.750    1  XX
4.000    1  XX
4.250    3  XXXXXXXX
```

EADI
37

```
                 .         .1         .2         .3         .4         .5
                  .........↑.........↑.........↑.........↑.........↑
0.000    0
0.250    1  XXXXXXXX
0.500    0
0.750    4  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
1.000    3  XXXXXXXXXXXXXXXXXXXXXXXXX
1.250    3  XXXXXXXXXXXXXXXXXXXXXXXXX
1.500    0
1.750    1  XXXXXXXX
```

MFD
12

```
                 .         .2         .4         .6         .8        1.0
                  .........↑.........↑.........↑.........↑.........↑
0.000    1  XX
0.250    0
0.500   13  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.750    4  XXXXXXXXX
1.000    0
1.250    3  XXXXXXX
```

HSI
21

b. Waypoints 12 to 15

Figure 25 (Continued)

FREQUENCY HISTOGRAM OF DWELL TIMES

```
                      .1        .2        .3        .4        .5
          . . . . . . . ↑ . . . . . . . . . ↑ . . . . . . . . . ↑ . . . . . . . . . ↑ . . . . . . . . . ↑

0.000   0
0.250   2   XXXXXXXXX
0.500   3   XXXXXXXXXXXXX
0.750   2   XXXXXXXXX
1.000   4   XXXXXXXXXXXXXXXXXX
1.250   1   XXXX
1.500   0
1.750   3   XXXXXXXXXXXXX
2.000   1   XXXX
2.250   1   XXXX
2.500   2   XXXXXXXXX
2.750   1   XXXX
3.000   1   XXXX
3.250   0
3.500   1   XXXX
```

EADI

22

```
                      .1        .2        .3        .4        .5
          . . . . . . . ↑ . . . . . . . . . ↑ . . . . . . . . . ↑ . . . . . . . . . ↑ . . . . . . . . . ↑

0.000   0
0.250   0   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.500   1   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.750   1
```

IAFD

2

```
                      .1        .2        .3        .4        .5
          . . . . . . . ↑ . . . . . . . . . ↑ . . . . . . . . . ↑ . . . . . . . . . ↑ . . . . . . . . . ↑

0.000   0
0.250   0   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.500   7   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.750   8   XXXXXXXXXXXX
1.000   2
```

HSI

17

c. Waypoints 15 to 18

Figure 25 (Continued)

FREQUENCY HISTOGRAM OF DWELL TIMES

```
                  .         .1        .2        .3        .4        .5
                   .........↑.........↑.........↑.........↑.........↑
0.000    0
0.250    5   XXXXXXXXXXXXXXXXXXX
0.500    4   XXXXXXXXXXXXXXX
0.750    3   XXXXXXXXXXX
1.000    2   XXXXXXX
1.250    4   XXXXXXXXXXXXXXX
1.500    0
1.750    1   XXX
2.000    0
2.250    2   XXXXXXX
2.500    1   XXX
2.750    1   XXX
3.000    0
3.250    0
3.500    1   XXX
3.750    0
4.000    0
4.250    1   XXX
4.500    1   XXX
```

EADI
26

```
                  .         .1        .2        .3        .4        .5
                   .........↑.........↑.........↑.........↑.........↑
0.000    0
0.250    0
0.500    1   XXXXXXXXXXXXXX
0.750    3   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
1.000    2   XXXXXXXXXXXXXXXXXXXXXXXXXXXX
1.250    0
1.500    0
1.750    0
2.000    0
**4.250  1   XXXXXXXXXXXXXX
```

MFD
7

```
                  .         .2        .4        .6        .8        1.0
                   .........↑.........↑.........↑.........↑.........↑
0.000    0
0.250    2   XXXXXXX
0.500   11   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.750    1   XXX
```

HSI
14

d. Waypoints 18 to 21

Figure 25 (Continued)

FREQUENCY HISTOGRAM OF DWELL TIMES

```
                .         .1         .2         .3         .4         .5
                 .........↑.........↑.........↑.........↑.........↑
0.000    0
0.250    3   XXXXXXX
0.500   12   XXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.750    8   XXXXXXXXXXXXXXXXXXX
1.000    7   XXXXXXXXXXXXXXXXX
1.250    3   XXXXXXX
1.500    1   XX
1.750    4   XXXXXXXXX
2.000    1   XX
2.250    1   XX
2.500    0
2.750    0
3.000    0
3.250    1   XX
```

EADI
41

```
                .         .1         .2         .3         .4         .5
                 .........↑.........↑.........↑.........↑.........↑
0.000    0
0.250    0
0.500    3   XXXXXXXXXXXXXXXXXXXXXXXXXXX
0.750    5   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
1.000    2   XXXXXXXXXXXXXXXXXX
1.250    1   XXXXXXXXX
```

MED
11

```
                .         .1         .2         .3         .4         .5
                 .........↑.........↑.........↑.........↑.........↑
0.000    0
0.250    2   XXXXXXXXXXX
0.500    8   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.750    4   XXXXXXXXXXXXXXXXXXXXXXX
1.000    0
1.250    2   XXXXXXXXXXX
1.500    0
1.750    1   XXXXX
```

-HSI
17

e. Waypoints 21 to 22

Figure 25 (Continued)

FREQUENCY HISTOGRAM OF DWELL TIMES

```
                .         .2        .4        .6        .8        1.0
                 .........↑.........↑.........↑.........↑.........↑
0.000     0
0.250     4     XXXX
0.500    21     XXXXXXXXXXXXXXXXXXXXXXXXX
0.750    11     XXXXXXXXXXXXX
1.000     4     XXXX
1.250     0
1.500     0
1.750     1     X
```

EADI
41

```
                .         .2        .4        .6        .8        1.0
                 .........↑.........↑.........↑.........↑.........↑
0.000     0
0.250     0
0.500     2     XXXXXXXXXXXXXX
0.750     4     XXXXXXXXXXXXXXXXXXXXXXXXXXXX
1.000     1     XXXXXXX
```

MFD
7

```
                .         .2        .4        .6        .8        1.0
                 .........↑.........↑.........↑.........↑.........↑
0.000     0
0.250     2     XXX
0.500    16     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.750     6     XXXXXXXXXXX
1.000     0
1.250     2     XXX
```

HSI
26

f. Waypoints 22 to 25

Figure 25 (Continued)

FREQUENCY HISTOGRAM OF DWELL TIMES ~ n/N

```
                 .         .1        .2        .3        .4        .5
          n      .........†.........†.........†.........†.........†
0.000     0
0.250     5      XXXXXX
0.500    29      XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.750    16      XXXXXXXXXXXXXXXXXXXXXX
1.000     8      XXXXXXXXXXX
1.250     6      XXXXXXXX                                    FADI
1.500     3      XXX
1.750     4      XXXXX                                       N = 73
2.000     2      XX
2.250     2      XX
2.500     1      X
2.750     2      XX
```

```
                 .         .2        .4        .6        .8        1.0
                 .........†.........†.........†.........†.........†
0.000     0
0.250     0
0.500     1      XXX
0.750     4      XXXXXXXXXXXXXX                                  MFD
1.000     8      XXXXXXXXXXXXXXXXXXXXXXXXXXXX
1.250     0
1.500     1      XXX
```

```
                 .         .2        .4        .6        .8        1.0
                 .........†.........†.........†.........†.........†
0.000     0
0.250     1      X
0.500    26      XXXXXXXXXXXXXXXXXXXXXXXXXXXXX                   HSI
0.750    10      XXXXXXXXXXX
1.000     4      XXXX
1.250     3      XXX
```

g. Waypoints 25 to 29

Figure 25 (Concluded)

Data for the five fixation points other than the three primary displays which were analyzed were not plotted but are tabulated in Appendix E. These other five fixation points were the instantaneous vertical speed indicator, the barometric altimeter, the airspeed indicator, the set of all fixations to the right of the primary displays (i.e., the STOLAND mode select panel, function switches, and engine instruments), and the set of all fixations above the primary instrument panel (i.e., the flight plan).

We shall call attention to the following observations and possible interpretations thereof among the plotted data.

a. With few exceptions there are relatively more looks at and longer dwells on the MFD than the HSI. There are probably at least two underlying reasons for this:

   1) When using only raw situation data, it may be easier to close the heading loop with the relatively shorter and less frequent looks at the more familiar HSI, because the outer loop lateral as well as vertical position error signals are available on the HSI.

   2) When using the flight director, it may be easier to monitor the aircraft's heading and geographic position using the moving map display on the MFD, because the outer loop lateral and vertical position error signals can be monitored on the EADI with the flight director.

   A comparison of Pilot 3's histograms (Figs. 24 and 25) of dwell interval for Runs 149 (flight director) and 148 (raw data) from Waypoints 18 to 29 (the missed approach, go-around, and holding pattern) will illustrate the basis for both reasons above. In Figs. 25d to 25g (raw data) the HSI receives more looks than the MFD. Although the distribution of dwells on the HSI is weighted in favor of slightly shorter intervals, most of the dwells on the HSI exceed 0.5 sec for the purpose of control as would be expected. The characteristically slightly longer dwells on the MFD in no way equalize the dwell fraction on the MFD with that on the HSI (Fig. 23b). In Figs. 24d to 24g (flight director) the MFD receives more looks than the HSI. The distribution of dwells on the HSI is shifted to shorter values and truncated relatively more than on the MFD so that the dwell fraction on the MFD exceeds that on the HSI (Fig. 23b).

   Most of the pilots said that they rarely used the heading tape on the MFD, because it was so hard to interpret; and that they rarely monitored the numerical heading on the EADI, because they were unaccustomed to the form and location. However, an analog display of heading relative to course was provided in conjunction with the moving map display on the MFD so that relative heading could be checked within the same fixation during which geographic position was monitored on the MFD.

One of the exceptions to Observation "a" above may be found among the approaching Waypoints 8 to 18 for Pilot 3 in Run 149 with the flight director (Figs. 23a-23c and 23e). Here his dwell fractions on the HSI and MFD are comparable, but his transitions from the EADI to the HSI (and therefore his looks at the HSI) were more frequent from Waypoints 12 to 18 than were his transitions from the EADI to the MFD. This observation is consistent with some of the preferential comments by Pilot 3 regarding the HSI when tracking curved or straight reference flight paths as in the approach. The dwell interval histograms in Fig. 24b from Waypoints 12 to 15 confirm that his number of looks at the MFD was about half the number of looks at the HSI and that the dwell intervals on the MFD were longer — in fact, Table E-4b (Appendix E) shows that his mean dwell interval was 1.2 sec on the MFD and 0.6 sec on the HSI between Waypoints 12 and 15, which accounts for the rough equality in dwell fraction on the MFD with half the look rate on the HSI.

Another exception to Observation "a" above may be found between Waypoints 9 and 11 for Pilot 1 in Run 157 with the flight director (Figs. 21a-21c and 21e). Waypoints 9 and 11 define a 180 deg decelerating base leg turn to final approach course with glide slope intercept at the midpoint of the turn. During this turn Pilot 1, who seldom ever looked at the HSI in either Runs 155 or 157 with flight director, cast 4 looks at the HSI and 4 looks at the MFD with identical average dwell intervals (Table E-2b, Appendix E), and, therefore, identical average dwell fractions (Fig. 21a), look fractions (Fig. 21b), look rates (Fig. 21c), and transition link fractions (Fig. 21e). Since Pilot 1 did not look at the HSI between comparable Waypoints 12 and 15 in Run 155, it is difficult to draw a conclusion from these two counter-examples. Pilot 1 always used the MFD in the heading-up orientation and never commented on feelings of disorientation during the base leg turn (as did Pilot 3) so it is unlikely that disorientation with the MFD would account for crosschecking the HSI during this turn in Run 157 with flight director. A more likely hypothesis is that for crosschecking glide slope deviation between the EADI and HSI in the vicinity of glide slope capture through transfer of training, even though glide slope deviation is available from the "window" amidst the clutter on the EADI when using the flight director. Although Pilot 1 never commented specifically on any perceptual uncertainty associated with the window on the EADI, both Pilots 4 and 6 experienced difficulties of interpretation in using the window (see comments in Appendix D).

b. Except for the glide slope tracking portion of Run 156 using Flight Plan 2 with only raw data (no flight director), Pilot 1 never looked at the HSI, even for altitude-keeping. (The VDI on the HSI always displayed altitude error prior to capturing the glide slope.)

Instead, Table E-2a (Appendix E) shows that Pilot 1 preferred to use the customary barometric altimeter prior to glide slope capture. His comments indicate that he preferred the MFD for its curved course predictor until he acquired the glide slope.

c. In contrast, except for the holding pattern portions of Run 154 using Flight Plan 3 with only raw data, Pilot 1 never looked at the barometric altimeter. Instead, Fig. 22a shows that Pilot 1 spent relatively more dwell fraction on the HSI than on the MFD in the en route descent (Waypoints 8 to 9 in Fig. 22a) followed by comparable but slightly more average dwell fraction on the MFD than on the HSI until well into the go-around. After that he increased his dwell fraction on the MFD even more throughout the holding pattern. Although numerical barometric altitude remained available on the MFD, in this instance, he began to look at the barometric altimeter only after he reached the holding fix.

d. Except for the en route descent and go-around portions of Run 148 using Flight Plan 3 with only raw data, Pilot 3 spent relatively more dwell fraction on the HSI than on the MFD even throughout the holding pattern. Table E-4a (Appendix E) also shows that Pilot 3 referred consistently to the barometric altimeter throughout Run 148 with a dwell fraction between 0.02 and 0.04.

e. Pilot 4 provided no exceptions to Observation "a" above throughout both of his runs (261 and 257) using Flight Plan 2. When using the flight director, Pilot 4 never looked at the HSI from Waypoints 8 to 14 (from downwind leg throughout final approach). When using only raw data, Pilot 4 still spent relatively more looks at and longer dwells on the MFD than the HSI (Fig. 20a to 20c, 20e).

f. The overall scan rate as well as the individual look rates for Pilot 1 using Flight Plan 3 (Figs. 22c and 22d) are roughly one-half those for Pilot 3 (Figs. 23c and 23d). This is because Pilot 1 spent a large amount of time looking at the EADI even when using only raw data, whereas Pilots 3 and 4 maintained more active scan patterns among all instruments.

g. The overall scan rate decreases during the final approach among all 8 runs, viz., Waypoints 12 to 14 of Flight Plan 2 and 12 to 18 of Flight Plan 3.

In conclusion, the reduced EPR data reveal that, with few exceptions (particularly in the case of Pilot 3), there are relatively more looks at and longer dwells on the MFD than the HSI when using raw data and especially when using the flight director. This finding is consistent with the respective pilot comments and tends to confirm an expressed preference by Pilot 1 for the

MFD in curved path tracking and in negotiating holding patterns. While not definitive in the case of Pilot 4 because of the single flight plan for which his data were reduced, the EPR data from two runs also suggest a preference by Pilot 4 for the MFD in curved path tracking. In the case of Pilot 3 the EPR data suggest an equitable distribution of looks and dwells between the HSI and MFD throughout the approach with the flight director, but a preference for the MFD during the missed approach, go-around, and throughout the holding pattern in Flight Plan 3. In the case of Pilot 3 using raw data the EPR measurements offer little basis for inferring a preference between the HSI and MFD, because both horizontal displays are scanned, in turn, from the EADI fairly consistently throughout Flight Plan 3, except during the straight final approach where the HSI receives relatively more looks.

I. SUMMARY OF RESULTS

1. On the basis of the blunder distribution alone from the simulation, the MFD seems to offer a worthwhile improvement in safety, since 13 of 20 blunders among 160 runs involved runs wherein the MFD was <u>not</u> available to the pilot. Six involved runs with the MFD, but not the HSI, and only one involved a run with both. The blunder distribution provides a quantitative basis for answering the first two questions which were posed in formulating the scenario, viz.,

   - What is the degree of improvement offered by the moving map display (MFD) over the HSI as a function of pilot workload?
   - When is a moving map display essential for safety?

   The numerical value of the blunder-to-run exposure ratio was 0.11 for the MFD in both the first (tracking) and second (geographically orienting) phases of the experiment, whereas the similar ratio for the HSI increased from 0.14 in the first to 0.4 in the second phase, which involved an increase in radio navaid/orientation workload. The numerical values of this particular ratio thus afford measures of the relative improvement offered by the moving map display (MFD) over the HSI as a function of the increase in pilot workload in the second phase of the experiment. The ratios also suggest (by their greater disparity) that the moving map was more essential for safety in the second phase of the experiment (involving missed approaches and holding patterns) than in the first phase (involving purely approach tracking).

2. The flight director provides for more precise tracking of the assigned altitude and the glide slope than otherwise. However, there is no consistent evidence of marked differences between tracking errors with the HSI versus the MFD among the five practiced pilots who participated in the simulation. There are instances where altitude-keeping was more precise with the MFD when using only situation data. (This may be because ready interpretation of the MFD leaves more time for attention to altitude tracking.)

3. The null hypothesis of equality between average excess control capacity within comparable pairs of flight plan waypoint groups using either the HSI or the MFD arrangement was tested for significant differences. The results show that the null hypothesis was rejected for 27 of 38 pairs of comparable waypoint groups at the 0.05 level, where 0.05 is the probability of rejecting the null hypothesis when it is true. Of these 27 rejected pairs, the MFD exhibited greater average excess control capacity for 16, and the HSI greater for 11 pairs.

4. The null hypothesis of equality between average excess monitoring capacity within comparable pairs of runs using either the HSI or the MFD arrangement was tested for significant differences. The results show that the null hypothesis was rejected for 13 of 38 pairs of comparable runs at the 0.05 level. Of these 13 rejected pairs, the MFD exhibited greater average excess monitoring capacity for 10, and the HSI greater for 3 pairs.

5. The pilots provided subjective ratings of (a) task controllability and precision, (b) utility of status information, (c) symbol-background clutter on the display, and (d) display attentional workload each on five-point descriptive scales. Summarized comparisons of all ratings for the MFD and the HSI in each category follow.

a. Task Controllability and Precision. There is a slightly less favorable central tendency to rate the HSI "controllable, with inadequate precision," in tracking curved paths in the presence of wind, whereas the ratings favor the MFD as "controllable, with fair precision." Ratings with the flight director in use are uniformly distributed over four descriptive phrases from "easily" to "marginally" controllable and exhibit no central tendency with either HSI or MFD.

b. Utility of Status Information. The MFD received more favorable ratings than the HSI. Ratings of the usefulness of information supplied covered the three adjectives "adequate":"some":"inadequate" in the ratios 4:3:0 for the MFD and 4:2:5 for the HSI. The bimodality of ratings for the HSI is believed to be associated with the favorable view of the HSI for tracking rectilinear flight paths and the unfavorable view of the HSI for maintaining geographic orientation while tracking curved paths in the presence of wind.

c. Clutter. Ratings of both the HSI and MFD as having "some clutter" predominate, but there is a slight tendency to rate the MFD less favorably.

d. Display Attentional Workload. Ratings of the MFD show a central tendency between "mildly" and "quite demanding," whereas ratings of the HSI exhibit a less favorably skewed mode between "quite" and "completely demanding."

6. The reduced eye-point-of-regard (EPR) data for 8 runs among Pilots 1, 3, and 4 reveal that, with few exceptions, there are relatively more looks at and longer fixation dwells on the MFD than the HSI when using raw situation data and especially when using the flight director. This finding is consistent with the comments by Pilots 1 and 4 and tends to confirm an expressed preference by Pilot 1 for the MFD in curved path tracking and in negotiating holding patterns. While not definitive in the case of Pilot 4 because of only a single flight plan for which his data were reduced, the EPR data from two runs also suggest a preference by Pilot 4 for the MFD in curved path tracking. In the case of Pilot 3 the EPR data suggest an equitable distribution of looks and dwells between the HSI and MFD throughout the approach with the flight director, but a preference for the MFD during the missed approach, go-around, and throughout the holding pattern in Flight Plan 3. In the case of Pilot 3 using raw data, the EPR measurements offer little basis

for inferring a preference between the HSI and MFD, because both horizontal displays are scanned, in turn, from the EADI fairly consistently throughout Flight Plan 3, except during the straight final approach where the HSI receives relatively more looks. Direct cross-checking between HSI and MFD is rare, but such scan transitions are predominantly unidirectional from HSI to MFD by Pilots 1, 3, and 4 when using raw situation data.

7. All of the pilots provided a great number of helpful supporting comments in the course of the experiment. Several recommendations for specific STOLAND display modifications are based on the pilot comments. There was a consensus among the pilot comments which acknowledged the excellence of the HSI for tracking rectilinear inclined courses, yet recognized the superiority of the existing MFD for maintaining confidence in geographical orientation while tracking curved approach courses and establishing holding patterns in the presence of wind. This consensus provides an answer to the third question posed in the formulation of the scenario, viz.,

   - Can the MFD replace the HSI or is it strictly an addition to the existing panel?

   The evidence is against its equivalence as a replacement in its present form.

8. Based on the review of the STOLAND display content in Section II, we gave a preliminary answer to the fourth question posed in formulating the scenario, viz.,

   - What is the minimum display content required to make the MFD a useful display?

   As a result of the simulation and the pilot commentary therefrom, we revise the list of information given to exclude the heading tape and substitute the course/heading vector, so that the complete list will include barometric altitude, present time, the uncluttered terminal area map, the selected flight route, the aircraft symbol, the trend vector, the course/heading vector, the next waypoint and its commanded altitude.

A summary of specific, significant recommendations for STOLAND display improvements, based on pilot comments, is presented at the conclusion of Appendix D.

SECTION IV

CONCLUSIONS

A sophisticated set of measurements has been made to compare a moving map display (MFD) with a conventional horizontal situation indicator (HSI). The measurements included:

- Tracking performance
- Excess control capacity
- Monitoring capability
- Pilot ratings
- Eye-point-of-regard statistics

In addition, the incidence of "blunders" and specific pilot comments were recorded.

The displays were compared in simulated operation of the Augmentor Wing Jet STOL Research Aircraft (AWJSRA) involving the tracking of courses and the execution of complex procedures.

All the measurements were consistent with each other and with the pilots' verbal comments. With a single very minor exception, in every case in which the two displays could be compared, either there was no difference between them, or the evaluation favored the MFD. (The minor exception to this statement involved a very slightly worse pilot rating of the quality of "clutter," on the MFD.)

Otherwise, conclusions drawn from the measured results and experience in the conduct of the tests are as follows.

1. Combined use of both displays represents a significant contribution to safety.
2. The present form of either display can be improved.
3. There is little evidence for the use of the MFD as a tracking display, whereas the HSI is definitely considered by the pilots as a tracking

display. The first phase of the experiment, confined to the tracking of reference flight plans, provided a comparison of the EADI (supported by MFD) with the HSI (supported by the EADI). The emphasis of the second phase of the experiment was changed to compare the HSI and MFD as they provide confidence and precision in geographic orientation problems rather than tracking problems. Among the missed approaches in this phase of the experiment there is evidence in the eye-point-of-regard data and the subjective ratings that the MFD was preferred by all of the pilots.

4. The combinations of two and three primary displays tested offer comparable performance, safety, and workload on straight courses among waypoints, but in flying curved courses in the presence of wind, pilot confidence is better and subjective impressions are that workload is less demanding when using the MFD and the EADI rather than when using the HSI and EADI. Among the significant differences in measured excess control capacity during tracking, the MFD exhibited greater average excess control capacity in a slight majority of comparisons.

5. The caution advisory response task for measuring excess monitoring capacity was learned reasonably well by the pilots. There is, however, little consistent evidence of differences in response times attributable to the HSI versus the MFD in monitoring reference flight plans. Among the minority of significant differences in measured excess monitoring capacity throughout the experiment, the MFD exhibited greater average excess monitoring capacity in a majority of comparisons.

6. The flight director improved error performance much more dramatically than did the MFD when compared with the HSI using the raw data. Even with the flight director, however, intense concentration is required when using the HSI alone to keep track of closely spaced waypoints [i.e., less than 2.8 km (1.5 nm) apart], but good performance results as long as the flight director is available.

7. HSI Bearing Pointer No. 2 alerts the pilot to turns, and curved courses can be flown with the HSI in prevailing winds using the reference flight path mode of STOLAND. However, pilot acceptance is inferior, and the

HSI requires intense concentration when flying curved paths without the flight director, because it provides no counter (like that on the MFD) to keep track of waypoint numbers, and there is no coordinated bank angle/course predictor to help in anticipating the effects of wind on curved courses.

8. The MFD course predictor offers a useful bank angle director for curved paths and for turns between straight segments in the presence of wind. All of the pilots learned to use this successfully. However, the MFD is not the only possible display for the presentation of a course director for setting bank angle. For example, a curved course bank angle director could be incorporated within coordinated heading and roll scales on the EADI as recommended in Section II. It is possible that this would be a more cost-effective backup for the flight director for tracking curved courses and reference flight plans because such a presentation on the EADI would be better integrated with the flight control tracking information than is the course predictor on the MFD.

9. The reference flight path mode of the STOLAND system makes it as easy as radar vectoring or area navigation (RNAV) to follow a standard terminal arrival route, but the MFD contributes more confidence at a glance, whereas the HSI requires intensive scanning of DME and the bearing to the waypoint, and mental coordination with the chart, in order to keep track of position. When coupled with the reference flight path mode, the HSI is recognized as a good rectilinear course tracking display by most of the pilots who are familiar with its format. Therefore, in the reference flight path tracking mode, the HSI appears as a more cost-effective raw data backup for the flight director, provided a waypoint counter is incorporated within or near the HSI.

10. The clarity of heading presentation on the HSI is considered superior to that on the MFD by all of the pilots who commented on that feature. The lubber line on the MFD is relatively invisible, and the rectilinear format for heading on the MFD is apparently contrary to the compass rose stereotype to which the pilots are accustomed (or prejudiced).

11. Although the MFD does not appear to be essential for tracking reference flight plans, if the pilot ever deviates far enough in course and altitude to saturate the presentation on the HSI, he is then left to depend on relative bearings and DME to maintain his geographic orientation. Of course, he should have been monitoring his bearings and DME all along; however, the HSI requires much more intense concentration than the MFD in order for the pilot to orient himself geographically. Therefore, the MFD with its moving map is much more forgiving of pilot distractions in providing him with geographic orientation at a glance. It is this use of the MFD in providing geographic orientation when a pilot is not tracking a reference flight plan which all of the pilots seemed to value most during the second phase of the experiment. (This involved negotiating missed approaches, go-arounds, and holding patterns while changing radio navigational aids).

12. A measure affecting safety, the relative proportion of blunders per "flight" in the simulation, remained approximately constant between the two phases of the experiment, i.e., tracking and geographic orientation, when the MFD was used. However, when the pilot workload was increased in the second phase of the experiment by introducing navigation problems associated with the missed approach (which may tend to disorient the pilot geographically), the relative proportion of blunders per "flight" increased adversely when the HSI was used with the flight director. Under these circumstances, the MFD alone appeared to offer a measurable contribution to flight safety.

13. During training it was discovered that the MFD was <u>necessary</u> for ensuring capture of the reference flight path, even though the initial conditions were favorably prealigned. If we had not used the MFD for initial capture, we would have experienced an excessive number of aborts and restarts. This may have been caused in part by excessively stringent capture criteria in the STOLAND software. It happened to be a lot easier to use the MFD for capture (and then to cover it if we were testing the HSI alone) than to alter the capture criteria in the STOLAND software.

14. Setting up STOLAND to capture a reference flight path even with a favorable initial condition provided the pilot with a secondary button-pushing task of considerable difficulty at first, although the pilots eventually learned to do it in about a minute's time by repetition. The administrative keyboard and mode selection activities required by STOLAND represent work with which a copilot should be helping in the aircraft. The addition of a copilot's station to the STOLAND simulator should be considered.

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APPENDIX A

PROSPECTUS OF MANUAL CONTROL TECHNIQUES

Table A-1 presents a prospectus of longitudinal and vertical multiloop manual control techniques for the Augmentor Wing Jet STOL Research Aircraft in terms of limiting forms of multiloop transfer functions with Bode and complex root loci based on Figs. 1 through 4 in the text, Section II. Two flight conditions are illustrated, one on the "backside" and one on the "frontside" of the thrust-required curve. The necessary coupling numerators listed in Table A-2 are based on the longitudinal dimensional stability derivatives in Appendix D of Ref. 6. Other necessary numerators are provided in Appendix D of Ref. 6. The numerators used here are computed without the pitch SAS so as to provide a more critical appraisal of manual control techniques and STOLAND displays, if the pilot be required to take over and complete the short approach in the event of an automatic system failure.

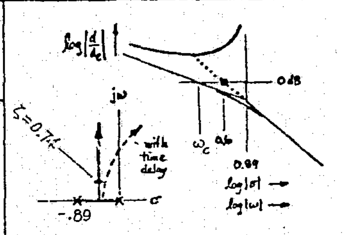
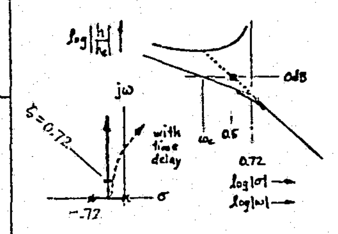
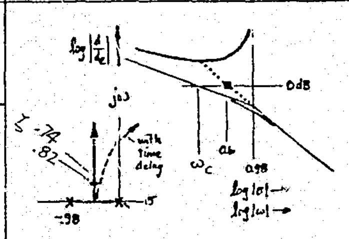
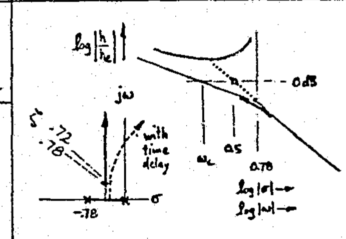
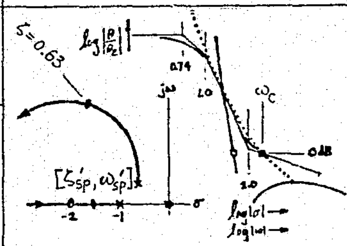
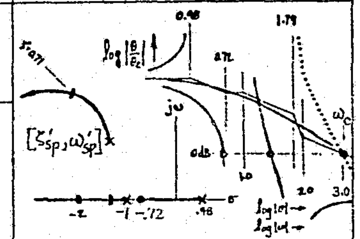
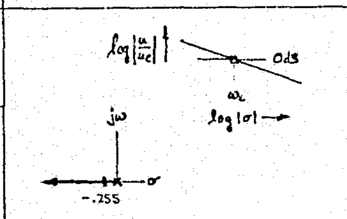
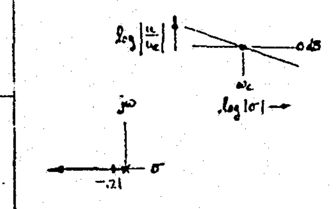
Annotated views of each of the primary STOLAND displays are presented in Figs. A-1 through A-3, and an illustration of the STOLAND simulator instrument panel appears in Fig. A-4.

In the lateral-directional axis, Appendix E of Ref. 6 presents only dimensional stability derivatives and transfer functions which include the effect of the (lateral-directional) SAS below 51 m/s (100 kt). (The lateral SAS is not operative above 51 m/s.) Consequently, the effect of the SAS cannot be removed for our purpose here.

In all four flight conditions from 72 m/s (140 kt) to 31 m/s (60 kt) in Appendix E of Ref. 6, the dutch roll oscillatory mode and the complex roll attitude numerator zeros for a lateral wheel input are nearly identical. This indicates negligible excitation of the dutch roll by wheel inputs. Consequently, for our purposes the augmented roll attitude response transfer function for a wheel input is well represented as:

$$\frac{\varphi}{\delta_W} \doteq \frac{L'_{\delta_W}}{(s + \frac{1}{T_S})(s + \frac{1}{T_R})} \doteq \frac{0.6}{s(s + 1.6)} \qquad \text{(A-1)}$$

TABLE A-1. PROSPECTUS OF MANUAL CONTROL TECHNIQUES

LIMITING FORM OF MULTILOOP TRANSFER FUNCTION FOR		ON FINAL APPROACH AT 60 kt ON 7.5 deg GLIDE SLOPE		IN TERMINAL AREA AT 90 kt IN LEVEL FLIGHT	
		LIMITING FORMS OF TRANSFER FUNCTIONS	BODE AND COMPLEX ROOT LOCI	LIMITING FORMS OF TRANSFER FUNCTIONS	BODE AND COMPLEX ROOT LOCI
ALTITUDE OR GLIDE SLOPE DISPLACEMENT REGULATION	Open Loop	$\left[\frac{d}{d_e}\right]_{\theta,u\to\delta_e} \doteq \frac{Y_{p_d} N^{\dot d\,u}_{\delta_T\delta_e}}{s N^{u}_{\delta_e}} = \frac{25.27\,Y_{p_d}}{(0)(0.89)}$		$\left[\frac{h}{h_e}\right]_{\theta\to\delta_e,\ u\to\delta_T} \doteq \frac{Y_{p_h} N^{\dot h\,u}_{\delta_e\delta_T}}{s N^{\theta\,u}_{\delta_e\delta_T}} = \frac{143.5\,Y_{p_h}}{(0)(0.72)}$	
	Closed Loop	If $Y_{p_d} = 0.0142$ rad δ_T/ft of d_e, $\omega_c \doteq 0.4$ rad/sec $\left[\frac{d}{d_r}\right]_{\theta,u\to\delta_e} \doteq \frac{0.36}{[0.74;\ 0.6]}$		If $Y_{p_h} = 0.00174$ rad θ_c/ft of h_e, $\omega_c = 0.35$ rad/sec $\left[\frac{h}{h_r}\right]_{\theta\to\delta_e,\ u\to\delta_T} \doteq \frac{0.25}{[0.72;\ 0.5]}$	
ALTITUDE OR GLIDE SLOPE DISPLACEMENT REGULATION WITH VERTICAL PATH ANGLE OR VERTICAL VELOCITY FEEDBACK	Open Loop	$\left[\frac{d}{d_e}\right]_{\theta,u\to\delta_e,\ \gamma\to\delta_T} \doteq \frac{Y_{p_d} N^{\dot d\,u}_{\delta_T\delta_e}}{s\left(N^{u}_{\delta_e} + \frac{Y_{p_\gamma}}{U_0} N^{\dot h\,u}_{\delta_T\delta_e}\right)} = \frac{25.27\,Y_{p_d}}{(0)(0.98)}$ if $Y_{p_\gamma} = 0.36$		$\left[\frac{h}{h_e}\right]_{\dot h,\theta\to\delta_e,\ u\to\delta_T} \doteq \frac{Y_{p_h} N^{\dot h\,u}_{\delta_e\delta_T}}{s\left(N^{\theta\,u}_{\delta_e\delta_T} + Y_{p_{\dot h}} N^{\dot h\,u}_{\delta_e\delta_T}\right)} = \frac{143.5\,Y_{p_h}}{(0)(0.78)}$ if $Y_{p_{\dot h}} = 0.000435$ rad/ft/sec	
	Closed Loop	If $Y_{p_d} = \frac{4Y_{p_\gamma}}{U_0} = 0.0142$ rad δ_T/ft of d_e, $\omega_c \doteq 0.37$ rad/sec $\left[\frac{d}{d_r}\right]_{\theta,u\to\delta_e,\ \gamma\to\delta_T} \doteq \frac{0.36}{[0.82;\ 0.6]}$ Provides damping for glide slope displacement, especially in the presence of time delay.		If $Y_{p_h} = 4Y_{p_{\dot h}} = 0.00174$ rad/ft, $\omega_c = 0.32$ rad/sec $\left[\frac{h}{h_r}\right]_{\dot h,\theta\to\delta_e,\ u\to\delta_T} \doteq \frac{0.25}{[0.78;\ 0.5]}$ Provides damping for altitude displacement, especially in the presence of time delay	
PITCH ATTITUDE REGULATION	Open Loop	$\left[\frac{\theta}{\theta_e}\right]_{d\to\delta_T} \doteq \frac{Y_{p_\theta} N^{\theta\,d}_{\delta_e\delta_T}}{N^{d}_{\delta_T}} = \frac{-2.618\,Y_{p_\theta}(0.00144)}{(0.058)[0.84;\ 0.74]}$		$\left[\frac{\theta}{\theta_e}\right]_{u\to\delta_T} \doteq \frac{Y_{p_\theta} N^{\theta\,u}_{\delta_e\delta_T}}{N^{u}_{\delta_T}} = \frac{-2.952\,Y_{p_\theta}(0.72)}{(-0.48)[0.76;\ 1.79]}$	
	Closed Loop	If $Y_{p_\theta} = -\frac{(2)^2}{(1)}$, $\omega_c \doteq 2.9$ rad/sec $\left[\frac{\theta}{\theta_r}\right]_{d\to\delta_T} \doteq \frac{2.618(0.00144)(2.0)^2}{(0.00424)(1.55)[0.629;\ 2.67]}$		If $Y_{p_\theta} = -\frac{(2)^2}{(1)}$, $\omega_c = 3.1$ rad/sec $\left[\frac{\theta}{\theta_r}\right]_{u\to\delta_T} \doteq \frac{2.952(0.72)(2.0)^2}{(0.57)(1.33)[0.71;\ 3.0]}$	
AIRSPEED REGULATION	Open Loop	$\left[\frac{u}{u_e}\right]_{\theta\to\delta_e,\ d\to\delta_T} \doteq \frac{Y_{p_u}\left(N^{u}_{\delta_e} + Y_{p_d}\frac{N^{u\,d}_{\delta_e\delta_T}}{s}\right)}{\left(N^{\theta}_{\delta_e} + Y_{p_d}\frac{N^{\theta\,d}_{\delta_e\delta_T}}{s}\right)} \doteq \frac{-8.5\,Y_{p_u}}{(0)}$		$\left[\frac{u}{u_e}\right]_{h,\theta\to\delta_e} \doteq \frac{Y_{p_T}\left(N^{u\,\theta}_{\delta_T\delta_e} + Y_{p_h}\frac{N^{u\,h}_{\delta_T\delta_e}}{s}\right)}{\left(N^{\theta}_{\delta_e} + Y_{p_h}\frac{N^{h}_{\delta_e}}{s}\right)} \doteq \frac{0.208\,Y_{p_T}}{(0.02)}$	
	Closed Loop	If $Y_{p_u} = -0.03$ rad θ_c/ft/sec, $\omega_c = 0.255$ rad/sec $\left[\frac{u}{u_r}\right]_{\theta\to\delta_e,\ d\to\delta_T} = \frac{0.255}{(0.255)}$		If $Y_{p_T} = 0.9$ deg δ_T/ft/sec, $\omega_c = 0.2$ rad/sec $\left[\frac{u}{u_r}\right]_{h,\theta\to\delta_e} \doteq \frac{0.19}{(0.21)}$	

Note: Transfer functions are defined in simplified form as follows. $(s + a) \Rightarrow (a)$; $[s^2 + 2\zeta\omega s + \omega^2] \Rightarrow [\zeta;\ \omega]$.

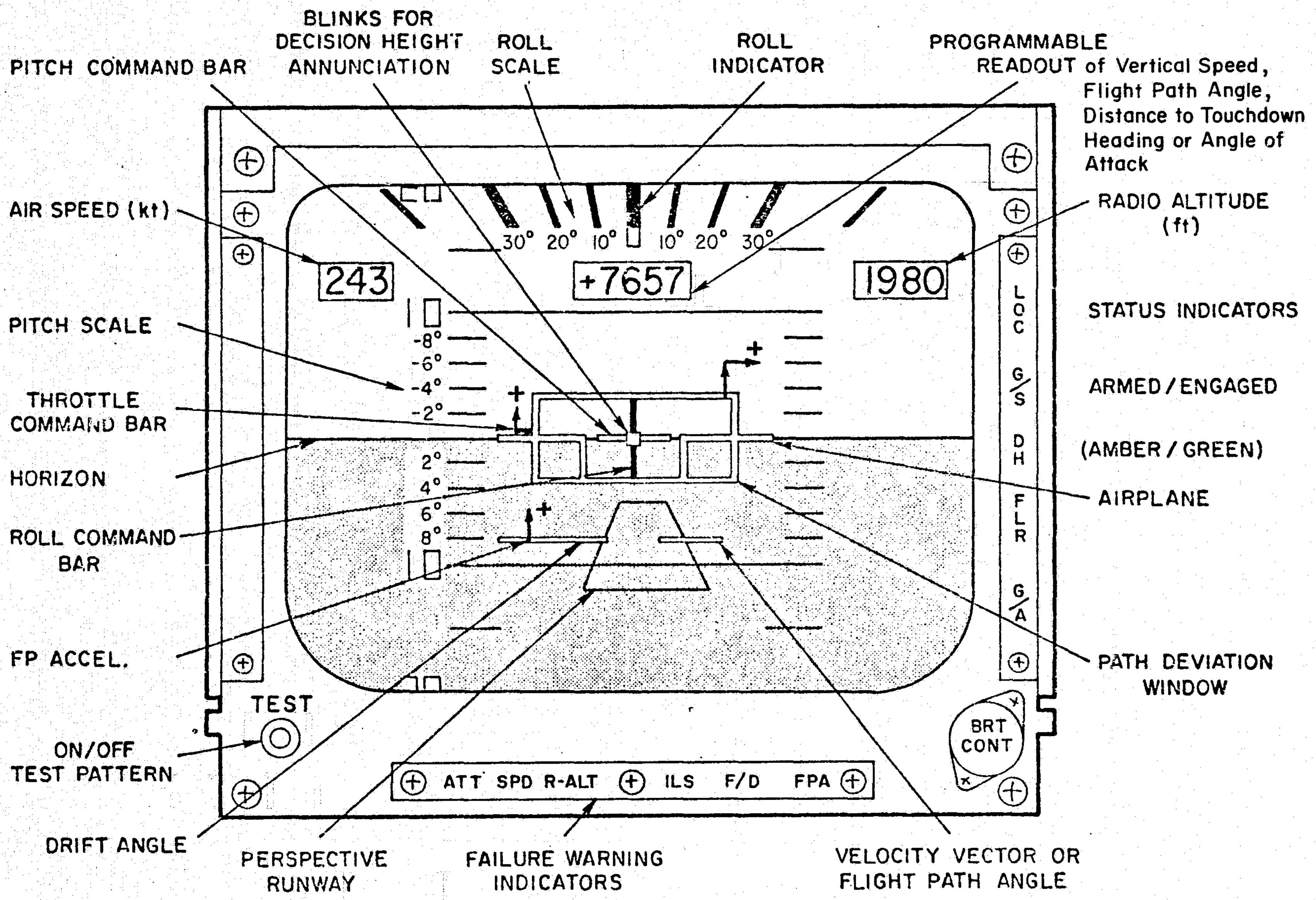


Figure A-1. Annotated View of EADI for STOLAND

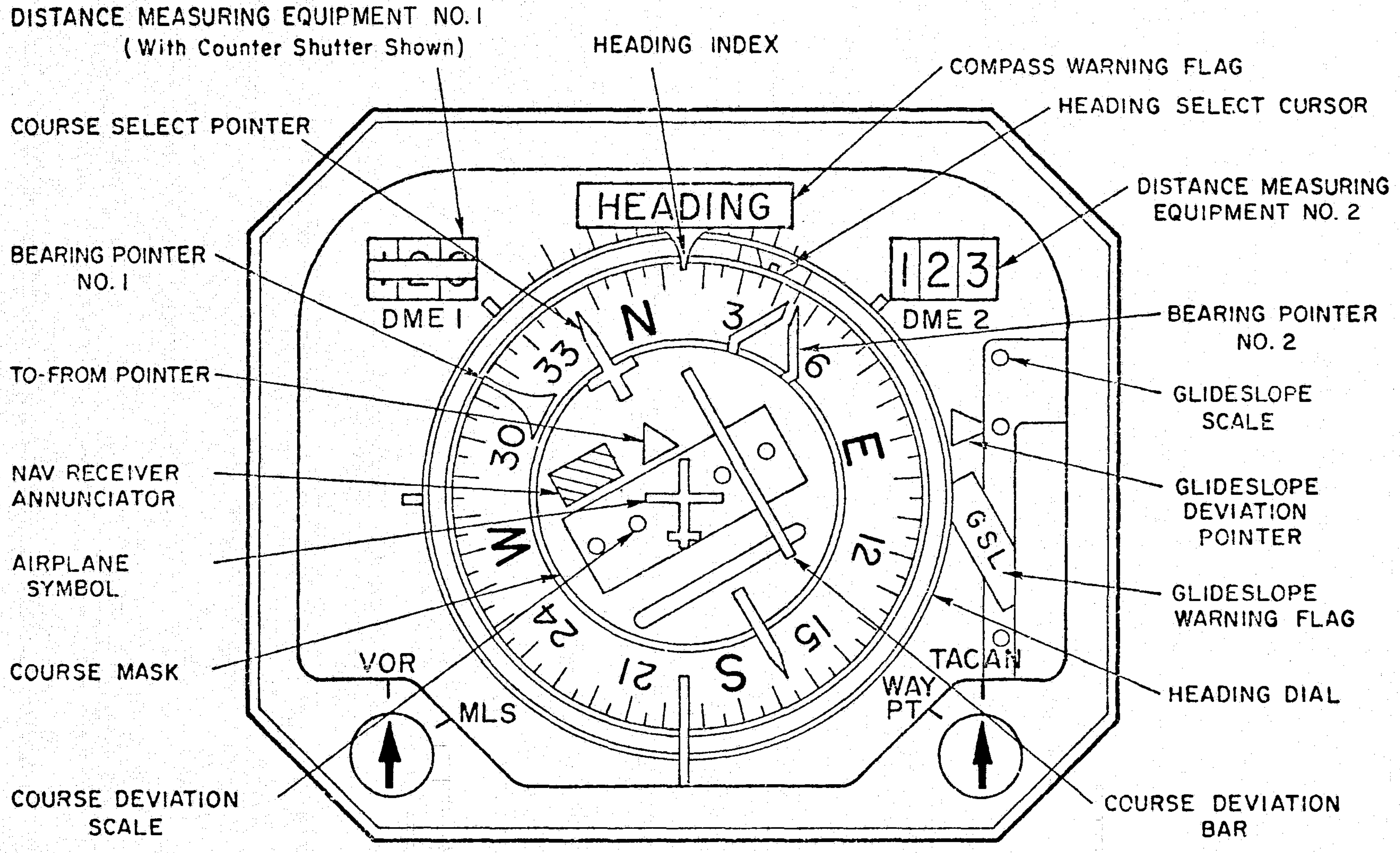


Figure A-2. Annotated View of HSI for STOLAND

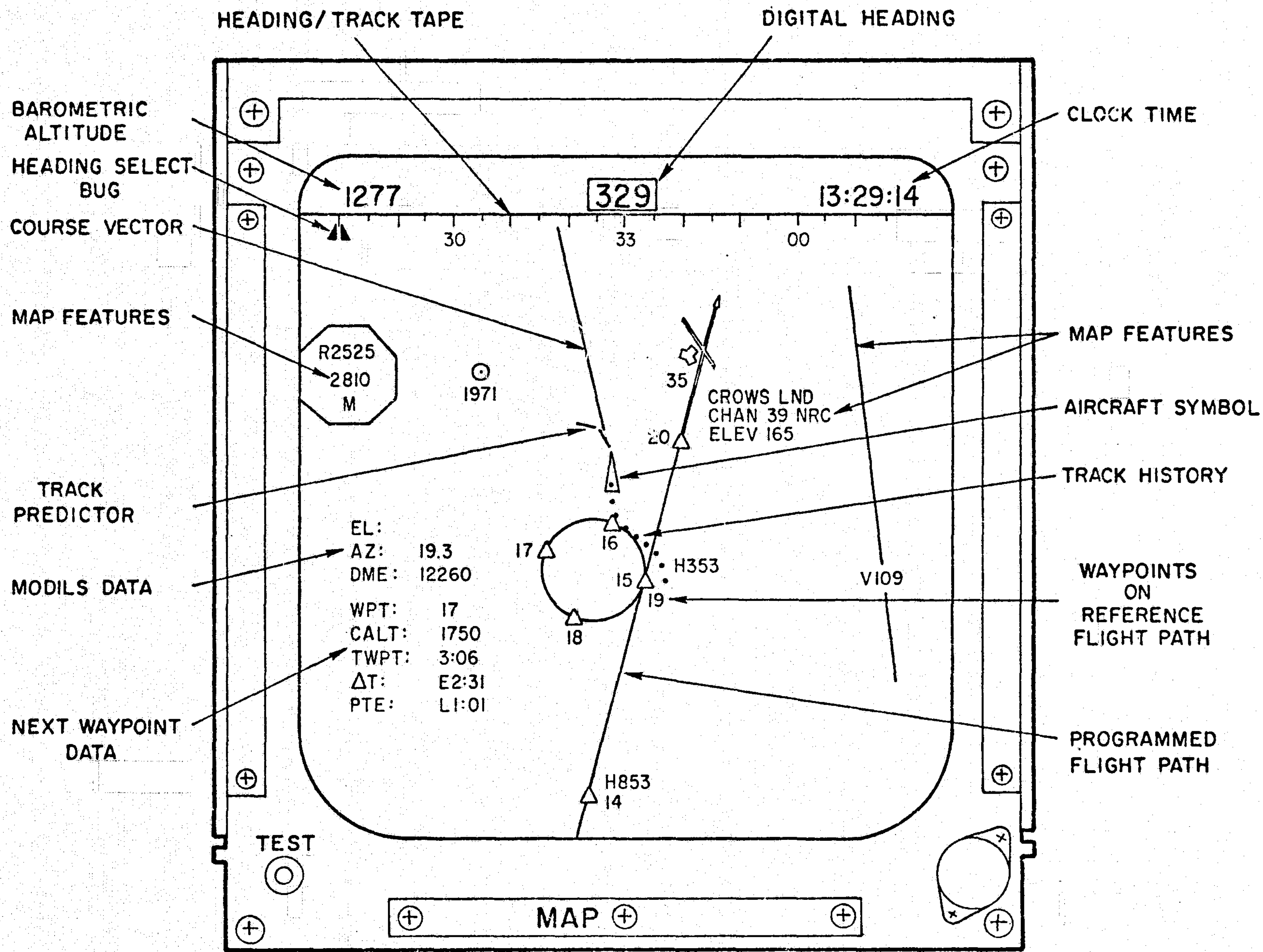


Figure A-3. Annotated View of MFD for STOLAND

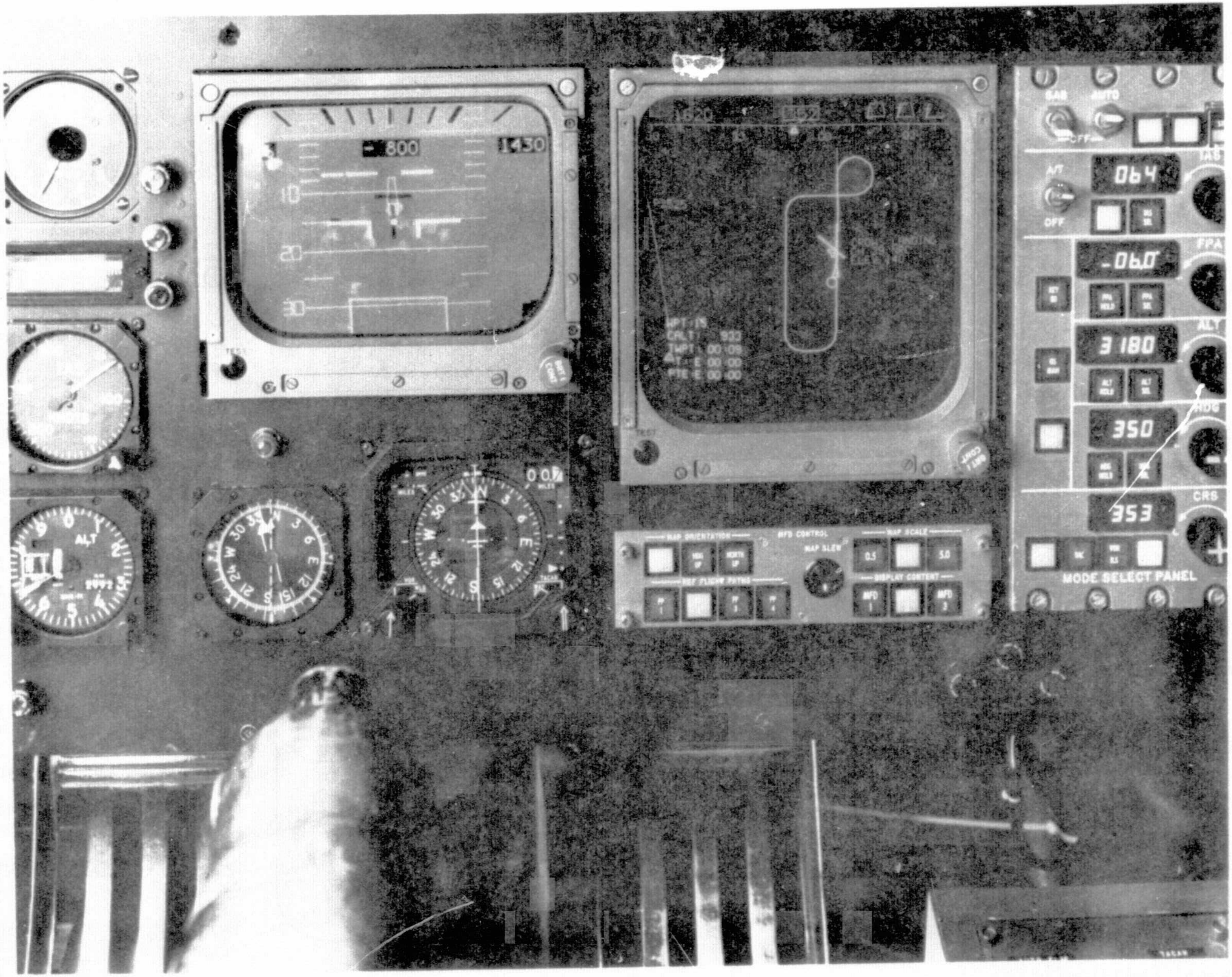


Figure A-4. STOLAND Simulator Instrument Panel

TABLE A-2. SAS-OFF LONGITUDINAL COUPLING NUMERATORS
(Based on Appendix D, Ref. 6, assuming $M_{\delta_T} = X_{\delta_T} = 0$)
$A(s) \Rightarrow A(s+a);\ A[s^2+2\zeta\omega s+\omega^2] \Rightarrow A[\zeta, \omega]$

SYMBOL	31 m/s (60 kt) TAS, γ_I = 7.5 deg	46 m/s (90 kt) TAS, γ_I = 0
$N^{\theta\ u}_{\delta_e\delta_T}$		−0.188(0.72) m/s-rad −0.617(0.72) ft/sec-rad
$N^{\dot{h}\ u}_{\delta_e\delta_T}$		0.682(7.321)(−5.408) m^2/s^2-rad^2 2.236(7.321)(−5.408) ft^2/sec^2-rad^2
$N^{\dot{d}\ \theta}_{\delta_T\delta_e}$ or $N^{\dot{h}\ \theta}_{\delta_T\delta_e}$	−0.231(0.00144) m/s-rad −0.759(0.00144) ft/sec-rad	
$N^{\dot{d}\ u}_{\delta_T\delta_e}$ or $N^{\dot{h}\ u}_{\delta_T\delta_e}$	0.0719[0.0931, 6.854] m/s-rad 0.236[0.0931, 6.854] ft^2/sec^2-rad^2	

over the airspeed range for terminal area operations. The value of L'_{δ_W} increases to about 1.0/sec^2 at 46 m/s (90 kt). This variability in L'_{δ_W} will affect only the estimated pilot gain in the roll attitude loop describing function Y_{p_φ} in Fig. 5 in the text, Section II. Likewise, the variability in $1/T_R$ is small: $1/T_R$ increases only to 1.85 rad/sec at 90 kt. Since the effect of the SAS is implied in Eq. A-1, we shall adopt the SAS as a surrogate for the pilot's rudder closure implied in Fig. 5.

The closed loop roll attitude transfer function based on Eq. A-1 is therefore well-represented by

$$\frac{\varphi}{\varphi_{ic}} \doteq \frac{Y_{p_\varphi} L'_{\delta_W}}{s^2 + \frac{1}{T_R}s + Y_{p_\varphi} L'_{\delta_W}} \qquad \text{(A-2)}$$

The pilot can easily provide modest lead-lag equalization in Y_{p_φ} in the frequency range beginning at and extending above $1/T_R$ to offset his time delay and to increase the effective bandwidth of the roll attitude closure which is bounded from above by $1/2T_R$ at values of pilot gain which provide critical damping of the roll response. The combination of the effect of the pilot's lead-lag equalization and time delay τ_e can be approximated as

$$Y_{p\varphi} \doteq \frac{K_\varphi(1 + T_R s)}{(1 + T_R' s)} \qquad \text{(A-3)}$$

where

$$\frac{1}{T_R} \leq \frac{1}{T_R'} < \frac{1}{\tau_e}$$

Therefore, with the substitution of Eq. A-3, Eq. A-2 becomes approximately

$$\frac{\varphi}{\varphi_{ic}} \doteq \frac{K_\varphi' L_{\delta_w}'(s + \frac{1}{T_R})}{(s + \frac{1}{T_R})[s^2 + \frac{1}{T_R'}s + K_\varphi' L_{\delta_w}']} \qquad \text{(A-4)}$$

where $K_\varphi' = K_\varphi T_R / T_R'$

Thus, the effect of the original rolling subsidence, $1/T_R$, is suppressed.

Now it is reasonable for the pilot's gain to be adjusted so that $\sqrt{K_\varphi' L_{\delta_w}'} > 1/2T_R' > 1$ rad/sec. Then the closed loop roll attitude response ratio φ/φ_{ic} will approach a limiting value of unity at lateral path control frequencies which are much less than 1 rad/sec — on the order of 0.2 rad/sec, and we can replace Eq. A-4 by the value $\varphi/\varphi_{ic} \doteq 1$ for the purpose of representing the course angle and lateral deviation closures in Fig. 5.

The course angle can be expressed with good approximation as

$$\lambda \doteq \frac{g\varphi}{U_o s} - \frac{v_g}{U_o} \qquad \text{(A-5)}$$

and the lateral deviation error in all modes except the reference flight path (RNAV) mode as

$$\epsilon = \frac{1}{R}(y_r - \frac{U_o\lambda}{s}) \qquad \text{(A-6)}$$

In the RNAV mode, the displayed lateral deviation error is

$$y_e = y_r - \frac{U_o\lambda}{s} \qquad \text{(A-7)}$$

Consequently, in all except the MODILS mode, the pilot's internal roll command, φ_{ic} in Fig. 5, will be

$$\varphi_{ic} = Y_{p_y} y_e - Y_{p_\psi} \psi \tag{A-8}$$

where the heading deviation is given by

$$\psi = \frac{g\varphi}{U_o s} \tag{A-9}$$

and the describing function $Y_{p_y} = Y_{p_\epsilon}/R$ in all except the RNAV mode. In the MODILS mode, the pilot's internal roll command, φ_{ic} in Fig. 5, will be

$$\varphi_{ic} = \frac{Y_{p_\epsilon}}{R} y_e - Y_{p_\lambda} \lambda \tag{A-10}$$

If the gain variation with range-to-go, R, is removed (or ignored as when fixed-gain conditions are assumed), $Y_{p_y} \equiv Y_{p_\epsilon}/R$ regardless of the mode, and Eq. A-5 through A-10 can be combined on the basis of Laplace transformation to form the closed loop lateral deviation error:

$$y_e(s) = \frac{s\left(s + \frac{(Y_{p_\psi} + Y_{p_\lambda})g}{U_o}\right) y_r(s) + \left(s + \frac{Y_{p_\psi} g}{U_o}\right) v_g(s)}{s^2 + \frac{(Y_{p_\psi} + Y_{p_\lambda})g}{U_o} s + Y_{p_y} g} \tag{A-11}$$

Equation A-11 can be specialized for each mode with the aid of Table A-3.

TABLE A-3. LATERAL-DIRECTIONAL PILOT DESCRIBING FUNCTIONS FOR EQ. A-11 BY NAVIGATION DISPLAY MODE

MODE	Y_{p_ψ}	Y_{p_λ}	Y_{p_y}
RNAV	> 0	= 0	Independent of R
TACAN	> 0	= 0	Y_{p_ϵ}/R
VOR/ILS	> 0	= 0	Y_{p_ϵ}/R
MODILS	= 0	> 0	Y_{p_ϵ}/R

The implications of various forms for Y_{p_ψ}, Y_{p_λ}, and Y_{p_y} on steady-state errors are discussed in Ref. 3. The closed loop undamped natural frequency of course-following in Eq. A-11 will be $\sqrt{Y_{p_y} g}$, and the damping ratio will be $(Y_{p_\psi} + Y_{p_\lambda})\sqrt{g}/2U_o\sqrt{Y_{p_y}}$. A closed form solution of Eq. A-5 through A-10 in terms of Bessel functions is given in Ref. 13 for the cases where the range R is allowed to vary explicitly as a function of time with a constant ground speed.

APPENDIX B

STOLAND SIMULATOR MODIFICATIONS FOR SECONDARY TASKS

INTRODUCTION

As part of Contract NAS2-8973, it was desired to implement the following additions to the STOLAND/Augmentor Wing simulation. These changes were used in an experiment involving the Digital Integrated Simulation Computer (EAI 8400). The additions consisted of:

- A cross-coupled secondary control task
- A reaction time side task

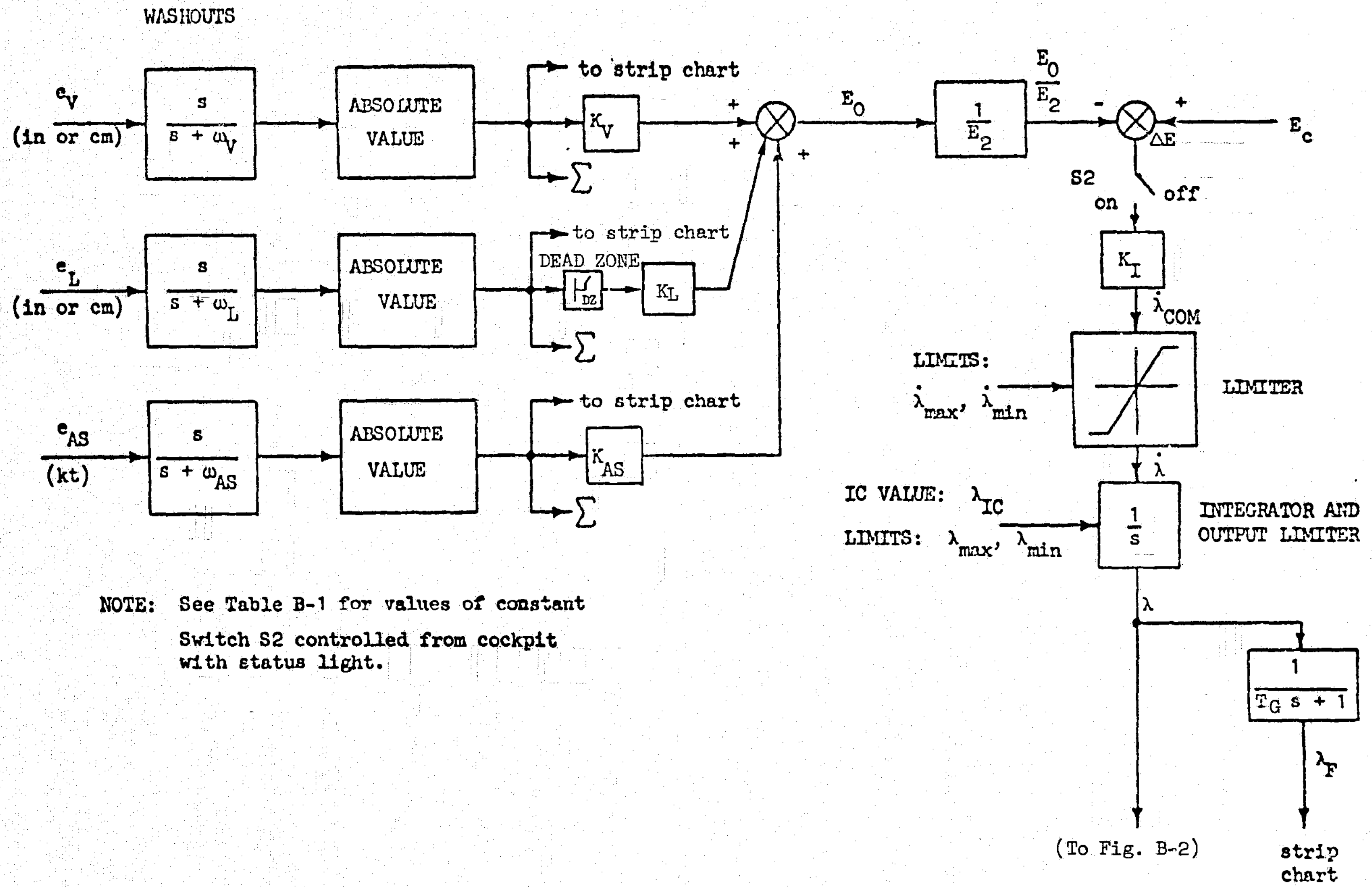
These tasks are described more fully below.

CROSS-COUPLED SECONDARY CONTROL TASK (CCSCT)

The basic concept was to introduce an unstable spiral mode into the pilot's lateral control task. The degree of instability was controlled by the pilot's performance in regulating aircraft position and airspeed. The parameter λ (spiral mode pole) was varied according to the scheme shown in Fig. B-1.

In Fig. B-1 the inputs are labeled as e_V (vertical position error), e_L (lateral position error), and e_{AS} (airspeed error). We defined e_V and e_L as the vertical and lateral deviations of the path deviation window from the center of the EADI screen. The term e_{AS} was defined as the difference between the airspeed commanded by STOLAND and the actual aircraft speed. Note that we computed e_V, e_L, and e_{AS} regardless of whether or not the path deviation window was actually being displayed on the EADI.

After the errors were processed by the washout and the absolute value blocks, we displayed them on a strip chart recorder and computed the average values in the 8400. The symbol Σ is meant to imply the average calculation. At the end of each run the average errors were printed on the lineprinter.



NOTE: See Table B-1 for values of constant
Switch S2 controlled from cockpit with status light.

Figure B-1. Block Diagram of Cross-Coupling Computation for Secondary Control Task

The switch, S2, was located on the computer operator's console with a light to indicate its status (light on for S2 on).

The block labeled "integrator and output limiter" in Fig. B-1 needs explanation in order to distinguish it from an integrator followed by a limiter. The desired logic was achieved with the following FORTRAN statements.

```
XLAM=XLAM+XLAMD*TF
IF(XLAM.GT.XLAMAX)XLAM=XLAMAX
IF(XLAM.LT.XLAMIN)XLAM=XLAMIN
```

where

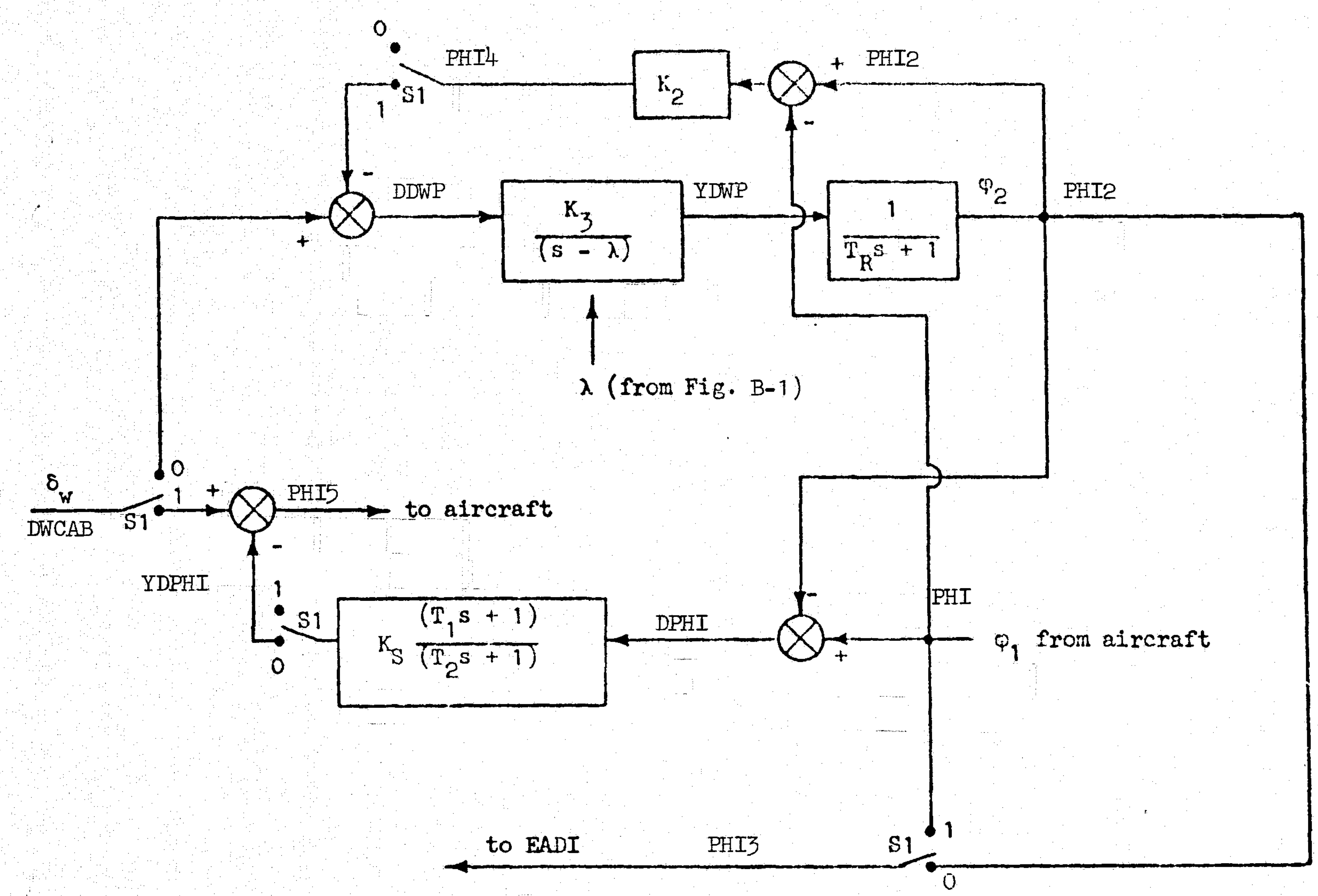
XLAM	=	λ (Fig. B-1)
XLAMD	=	$\dot{\lambda}$ (Fig. B-1)
TF	=	frame time
XLAMAX	=	maximum λ
XLAMIN	=	minimum λ

All of the logic in Fig. B-1 can be placed in the slowest computer loop of the airframe simulation.

Figure B-2 indicates how the λ resulting from Fig. B-1 is used in the cross-coupled secondary control task (CCSCT). This figure is best understood by realizing that it depicts a model-following scheme with switch S1 controlling whether the aircraft model or the CCSCT is controlled by the pilot.

If S1 = 1, the wheel input (δ_w) commands some bank angle (φ_1) from the aircraft model, the K_2 feedback loop around the CCSCT is engaged (thus stabilizing that element), and the output of that loop (φ_2) tracks φ_1.

When S_1 is switched to zero, the wheel input drives the CCSCT (with the K_2 loop disengaged), and its output (φ_2) is fed through lead-lag compensation to drive the aircraft response to match it. Again, $\varphi_1 = \varphi_2$. Note that at the moment of switching, no bank angle transients occur since $\varphi_1 \doteq \varphi_2$ regardless of the position of S_1.



NOTE: Switch S1 controlled from cockpit with status light

See Table B-1 for values of constants

Figure B-2. Model-Following Block Diagram for Embedding Secondary Control Task Within the Roll Axis and Spiral Divergence of an Aircraft

Switch S1 was placed on the computer operator's console together with its status light (light on when S1 = 0). An event marker on the strip charts indicated the status of S1.

The logic shown in Fig. B-2 was included in the computer loop which normally handles pilot wheel inputs.

A list of values of the constants used to mechanize the CCSCT is given in Table B-1.

REACTION TIME SIDE TASK

This task was designed to measure the pilot's simple reaction time under various conditions. To do this, we randomly lighted a caution light in the cockpit and measured the time required for the pilot to respond by pushing a designated button to extinguish the light. The response button was identified as such among the group of ten buttons on the center console.

The algorithm for randomly turning on the caution light was as follows:

Caution light initially off.

Given the input constant θ = Mean Time Between Caution Advisories in seconds, compute

$$h = \frac{T_F}{\theta} \quad \text{where } T_F = \text{frame time (sec)}$$

Each frame time generates (from a uniform distribution) a random number (x) between 0 and 1 such that

if $0 \le x \le h$ caution light on

if $h < x \le 1$ no change in caution light

When the caution light comes on, disable the above test and measure the time until the response button is pushed.

When the response button is pushed, extinguish the caution light and enable the test again.

We stored the response times for each run and printed them at the end of each run along with the average value.

TABLE B-1

NUMERICAL CONSTANTS FOR SECONDARY TASKS

SYMBOL	VALUE
ω_V	0.03 rad/sec
ω_L	0.03 rad/sec
ω_{AS}	0.1 rad/sec
K_V	1.0
K_L	1.0
K_{AS}	0.1
E_2	Unloaded value of E_o for each pilot and waypoint group
E_c	1.1
K_I	0.02
$\dot{\lambda}_{max}$	0.05 rad/sec^2
$\dot{\lambda}_{min}$	−0.05 rad/sec^2
λ_{IC}	0
λ_{max}	0.3 rad/sec
λ_{min}	0
DZ	Corresponded to two halves of lateral displacement window width on EADI or two dots on HSI course deviation scale
T_F	0.062 sec
T_G	0
K_2	5.25
K_3	0.19
T_R	0.625 sec
K_s	17.
T_1	0.625 sec
T_2	0.1 sec
θ	48 sec

Since θ was 48 sec, h was on the order of 10^{-3}. This might cause some problems if the random number generator did not produce a sufficiently uniform distribution.

A switch was provided on the computer operator's console to turn the reaction time side task on or off and a light indicated when it was on. The task was put in the slowest computer loop.

Table B-2 provides a sample of the performance data format provided by hard copy from the EAI 8400 line printer for one of six waypoint groups throughout each run of the simulation.

TABLE B-2. SAMPLE COPY OF FLIGHT PERFORMANCE AND ACCEPTANCE FORMAT

```
***********************************************************************************
*     C/8 AUG WING     SIM-FLT DATA SUMMARY     PROGRAM NAME...HSI/MFD            *
* RUN NUMBER= 93    CASE NUMBER=201    PILOT NUMBER=  1    DATE 02/24/86          *
***********************************************************************************

*******************************************************************************************
*          FROM WPT  9     TO WPT 11               TIME FROM 22:22:33  TO 22:23:32        *
*          INT. TIME   59.7 SEC                    UNLOADED ERROR   0.60          Ec=1.1  *
*******************************************************************************************

                    NUMBER OF DATA POINTS SAMLED , 321.0
```

VARIABLE	MAX	TIME	MIN	TIME	MEAN	STD DEV	UNITS
LAT POS ERROR..	0.440	22:22:45	-0.240	22:22:59	0.117	0.194	IN
VERT POS ERROR.	0.360	22:23:21	-0.110	22:23:32	0.173	0.108	IN
IAS ERROR.......	8.100	22:23: 7	-10.500	22:22:39	0.433	5.785	KNOTS
PITCH ATT.......	10.432	22:22:34	-1.021	22:23:10	5.242	3.570	DEG
ALFA............	16.707	22:23:11	3.947	22:22:45	9.705	2.611	DEG
VERT F.P. ANGLE	2.189	22:22:34	-13.016	22:23:11	-4.449	4.299	DEG
BETA............	11.097	22:23:13	-12.609	22:23:29	-1.311	4.611	DEG
PSI.............	196.323	22:22:33	15.615	22:23:14	99.315	60.789	DEG
PHI.............	16.949	22:23:25	-35.092	22:23: 0	-11.107	12.502	DEG

```
LAT POS ERROR   *MEAN ABSOLUTE WASH OUT *      0.1658
VERT POS ERROR  *MEAN ABSOLUTE WASH OUT *      0.1269
IAS ERROR       *MEAN ABSOLUTE WASH OUT *      3.2446

LAM      * MEAN *        0.150     * STD DEV *      0.110

NUMBER OF DATA POINTS SAMLED , 321.0

MEAN AND STANDARD DEVIATION OF TURBULENCE COMPONENTS
VARIABLE           MEAN    UNITS                STD DEV   UNITS
*****************************************************************
RMS UTURB        4.2666   FT/SEC                1.3693   FT/SEC
RMS VTURB       -0.6577   FT/SEC                1.6840   FT/SEC
RMS WTURB        1.2541   FT/SEC                2.4201   FT/SEC
```

TABLE B-2 (Concluded)

```
***************************************************************************************
*      C/8 AUG WING     SIM-FLT DATA SUMMARY     PROGRAM NAME...HSI/MFD               *
* RUN NUMBER= 93    CASE NUMBER=201    PILOT NUMBER=  1    DATE 02/24/86              *
***************************************************************************************

**************************************************************************************************
*            FROM WPT  9    TO WPT 11                  TIME FROM 22:22:33   TO 22:23:32          *
*            INT. TIME    59.7 SEC                     UNLOADED ERROR   0.60                     *
**************************************************************************************************
```

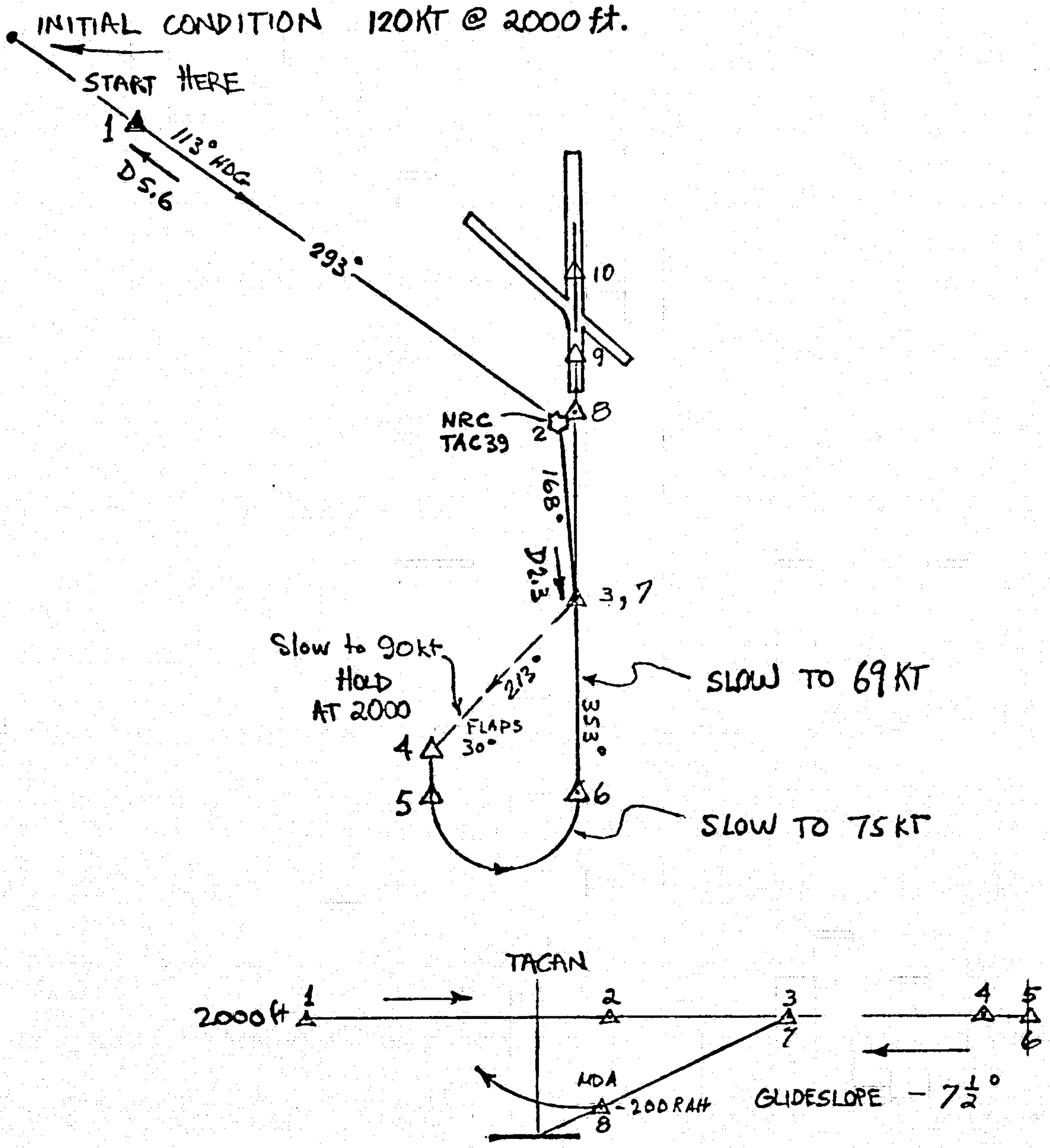
NUMBER OF DATA POINTS SAMLED , 321.0

VARIABLE	MAX	TIME	MIN	TIME	MEAN	STD DEV	UNITS
VERT VELOCITY..	6.055	22:22:34	-31.369	22:23:11	-10.740	10.121	FT/SEC
NORMAL ACCEL...	5.380	22:22:45	-6.731	22:23:12	-0.775	2.133	FT/SEC2
LONG ACCEL.....	6.264	22:22:34	-0.660	22:23: 5	2.538	2.025	FT/SEC2
LAT ACCEL......	3.528	22:23:29	-4.005	22:23:13	0.179	1.355	FT/SEC2
LAT F.P. ANGLE.	179.702	22:22:37	-179.965	22:22:36	79.344	81.563	DEG
LAT VELOCITY...	160.168	22:23: 3	15.826	22:22:33	99.262	41.605	FT/SEC
ROLL RATE......	11.200	22:23:11	-12.289	22:23:27	-0.147	4.073	DEG/SEC
PITCH RATE.....	7.569	22:23:10	-2.794	22:22:55	1.192	1.766	DEG/SEC
YAW RATE.......	6.639	22:23:25	-11.550	22:23:11	-2.500	4.172	DEG/SEC
ALFA RATE......	4.879	22:23:10	-3.586	22:22:55	-0.003	1.543	DEG/SEC
BETA RATE......	7.953	22:23:11	-6.476	22:23:27	-0.130	2.474	DEG/SEC

APPENDIX C

PILOT APPROACH PLATES AND WAYPOINT COORDINATE TABLES

CROWS LANDING NRC TAC 39



ELEV 140 STOLRWY 35

REFERENCE FLIGHT PATH 1

AUGMENTOR WING STI REFERENCE FLIGHT PATH 1, REVISED 16 FEBRUARY 1976

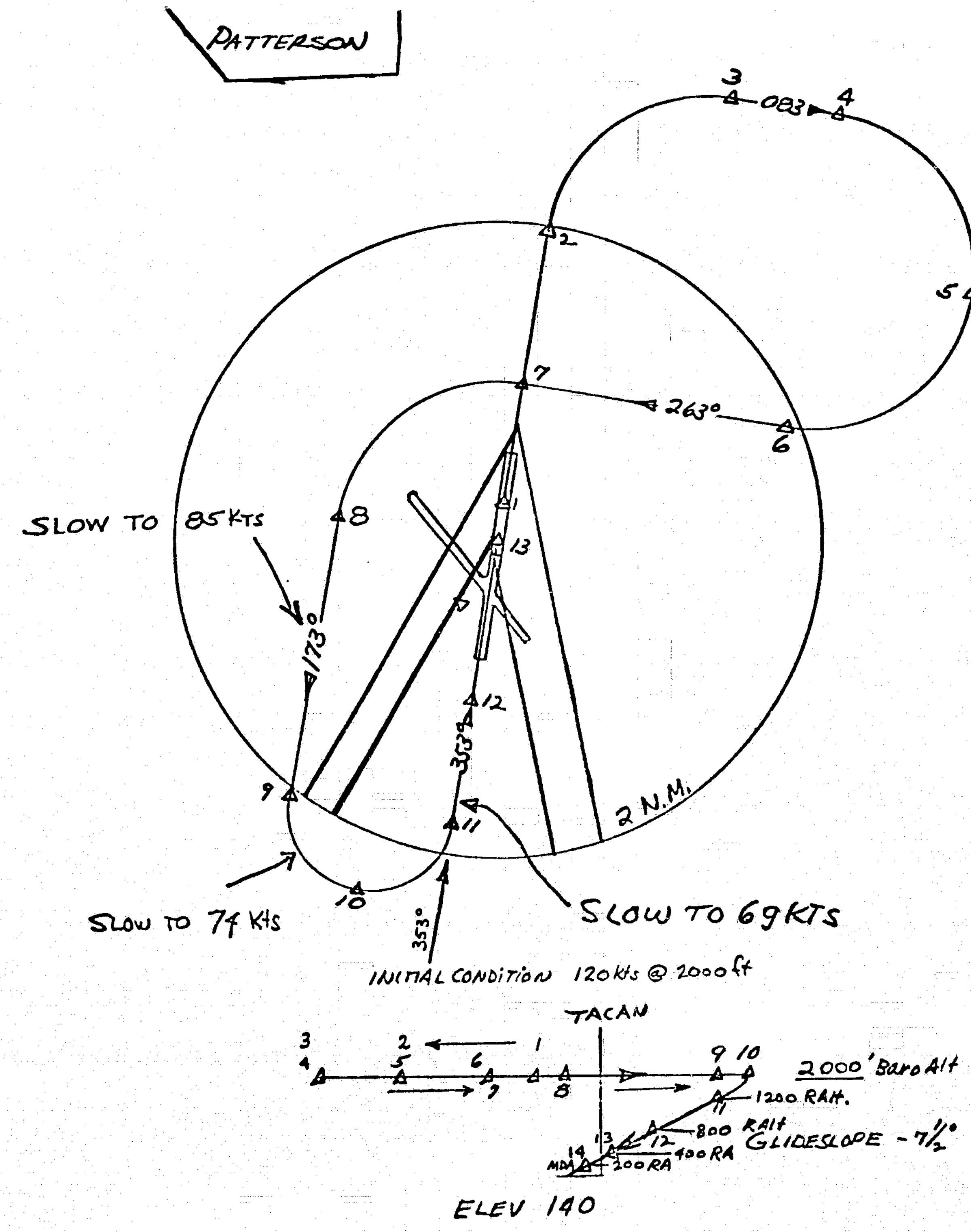
WAYPOINT	DME n.m.*	LOCATION X (ft)	LOCATION Y (ft)	HEIGHT ABOVE AIRPORT Z (ft)	EAS (kt)	TURN RADIUS (ft)	COMMENT
1	5.6	17931	-28919	1860	120	0	START
2	0.5	-2025	-1000	1860	120	0	Fly outbound
3	2.3	-14128	0	1860	120	0	Enter holding pattern
4	4.7	-26744	-8260	1860	90	0	Enter turn, slow to 90 kt
5	4.7	-26748	-8260	1860	90	-4130	Exit holding
6	4.4	-26748	0	1860	75	0	Slow to approach speed
7	2.3	-14128	0	1860	69	0	Glide slope capture
8	0.25	-1520	0	200	69	0	Start go around

* 1 n.m. = 6076 ft = 1852 meters

LOW WORKLOAD

STOLRWY 35
ELEV 140

CROWS LANDING ALF



REFERENCE FLIGHT PATH 2 - ACCEPTANCE TEST
AUGMENTOR WING

AUGMENTOR WING STI REFERENCE FLIGHT PATH 2 (HIGH WORKLOAD)

WAY-POINT	LOCATION X (ft)	LOCATION Y (ft)	HEIGHT ABOVE AIRPORT Z (ft)	EAS (kt)	FLIGHT PATH ANGLE (deg)	TURN RADIUS (ft)	TURN CENTER X (ft)	TURN CENTER Y (ft)	STEADY STATE NOZZLE ANGLE MAX (deg)	STEADY STATE NOZZLE ANGLE MIN (deg)
1	1450	0	1860	120	0				6	6
2	12000	0	1860	120	0	6000	12000	6000	6	6
3	18000	6000	1860	120	0				6	6
4	18000	10000	1860	120	0	6000	12000	10000	6	6
5	12000	16000	1860	120	0	6000	12000	10000	6	6
6	6000	10000	1860	120	0				6	6
7	6000	0	1860	120	0	-6000	0	0	6	6
8	0	-6000	1860	120	0				6	6
9	-9416	-6000	1860	90	0	-3000	-9416	-3000	6	6
10	-12416	-3000	1860	69	-7.5	-3000	-9416	-3000	104	6
11	-9416	0	1240	69	-7.5				104	6
12	-6077	0	800	69	-7.5				104	6
13	-3039	0	400	69	-7.5				90	6
14	-1520	0	200	69	-7.5					
15	940	0	200	120	+7.5					

Based on NASA Flight Path 3 by D. Watson for acceptance test of STOLAND

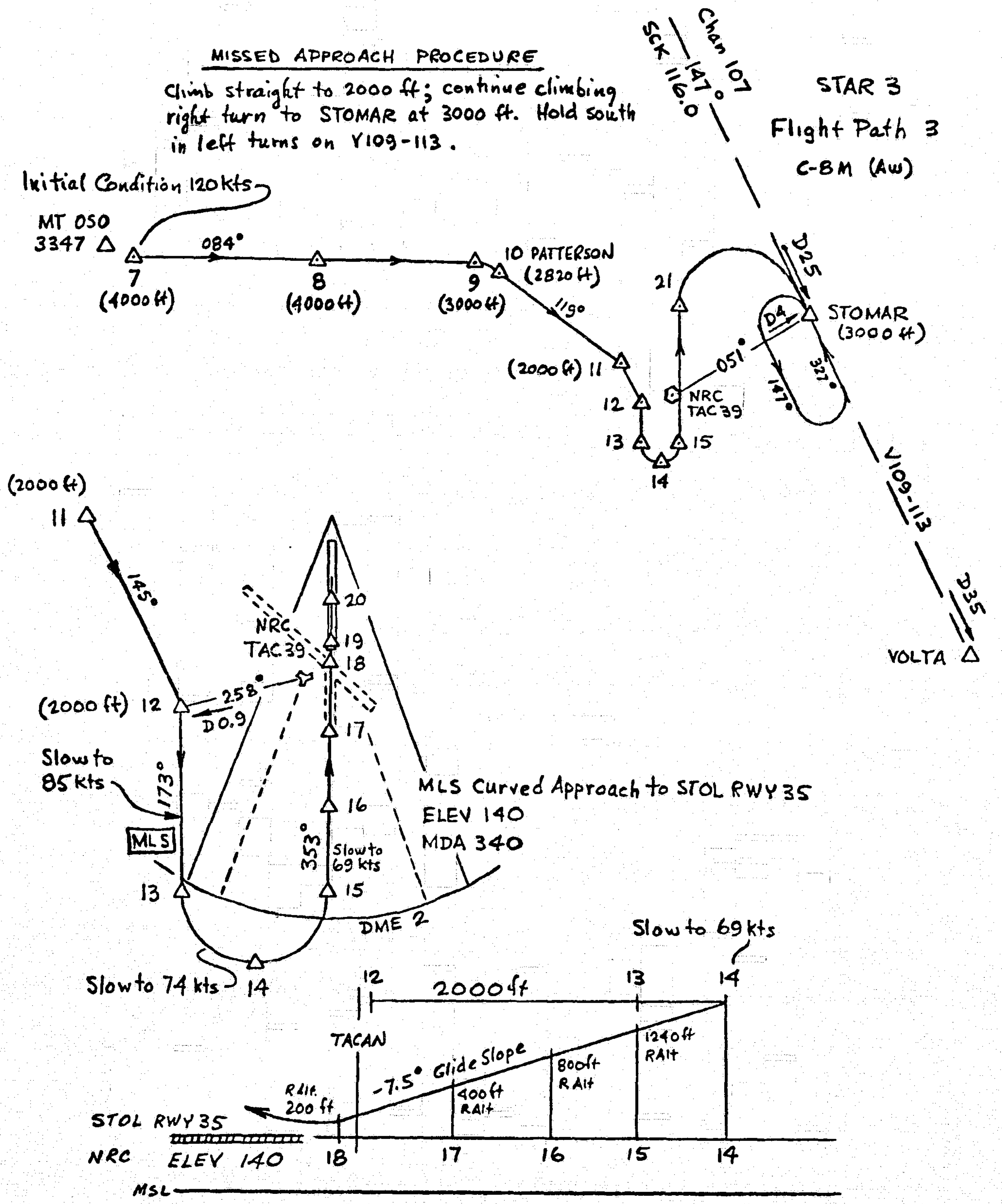
MISSED APPROACH PROCEDURE

Climb straight to 2000 ft; continue climbing right turn to STOMAR at 3000 ft. Hold south in left turns on V109-113.

STAR 3

Flight Path 3

C-8M (Aw)



AUGMENTOR WING STI REFERENCE FLIGHT PATH 3 (HIGH WORKLOAD)

Revised 27 February 1976

WAYPOINT	LOCATION X (ft)	LOCATION Y (ft)	HEIGHT ABOVE AIRPORT Z (ft)	EAS (kt)	FLIGHT PATH ANGLE (deg)	TURN RADIUS (ft)
1 SUNOL	34715	-209616	*	*	*	
2	50906	-186146	*	*	*	
3	67096	-162676	*	*	*	
4	66950	-153386	*	*	*	
5	44720	-123182	*	*	*	
6 MT. OSO	22489	-92977	*	*	*	
7	20930	-88426	3860	120	0	
8	20148	-58425	3860	120	-1.9	
9	19490	-33466	2860	120	-1.9	8000
10 PATTERSON	17931	-28919	2680	120	-1.9	
11	3509	-9353	1860	120	0	8000
12	-2930	-6000	1860	90	0	
13	-9419	-6000	1860	90	0	-3000
14	-12419	-3000	1860	69	-7.5	-3000
15	-9419	0	1240	69	-7.5	
16	-6077	0	800	69	-7.5	
17	-3039	0	400	69	-7.5	
18 G/A WPT	-1520	0	200	69	-7.5	
19	950	0	200	90	0	
20	1450	0	200	120	0	
21	12614	0	1570	120		9948
22	15624	19500	2860	120		0
23 STOMAR	11983	21131	2860	120		0
24	-2535	18868	2860	120		0
25	-3535	19368	2860	120		-4193

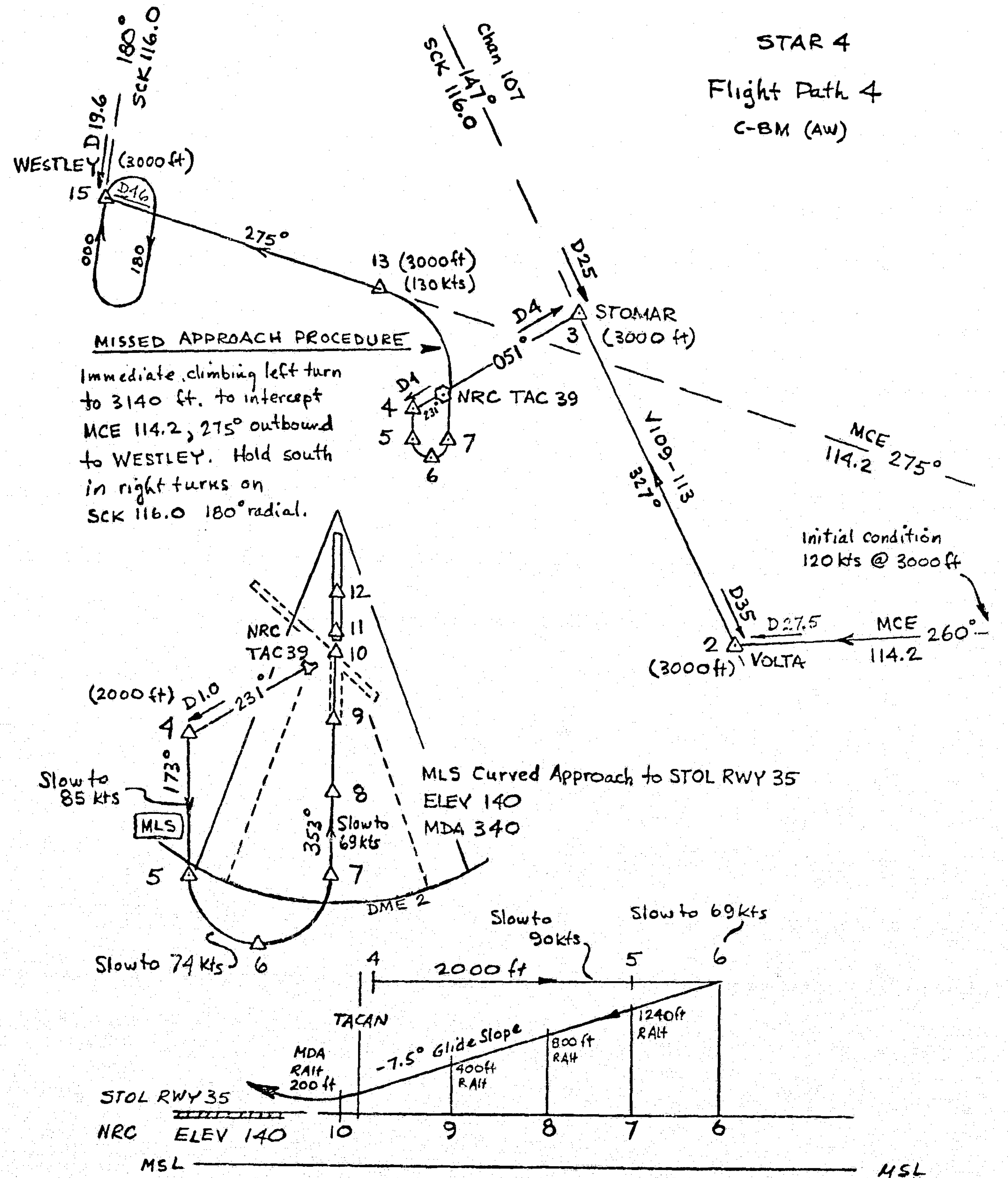
* Initial conditions at Waypoint 7

AUGMENTOR WING STI REFERENCE FLIGHT PATH 3 (HIGH WORKLOAD)

(CONCLUDED)

WAYPOINT	LOCATION		HEIGHT ABOVE AIRPORT	EAS	FLIGHT PATH ANGLE	TURN RADIUS
	X (ft)	Y (ft)	Z (ft)	(kt)	(deg)	(ft)
26	142	26906	2860	120		0
27 STOMAR	11983	21131	2860	120		-4193
28	8306	13593	2860	120		0
29	-1535	18368	2860	120		0

Modification of NASA Flight Path 3 for STI by D. Watson



STAR 4
Flight Path 4
C-BM (AW)
180°
SCK 116.0
D19.6
WESTLEY
(3000 ft)
15
D4.6
000
180
275°
Chan 107
147°
SCK 116.0
13 (3000 ft)
(130 kts)
D25
D4
STOMAR
3
(3000 ft)
051°
NRC TAC 39
D1
4
5
6
7
231°
MISSED APPROACH PROCEDURE
Immediate climbing left turn to 3140 ft. to intercept MCE 114.2, 275° outbound to WESTLEY. Hold south in right turns on SCK 116.0 180° radial.
V109-113
327°
MCE 114.2 275°
Initial condition 120 kts @ 3000 ft
D35
D27.5
MCE 114.2
260°
2
(3000 ft)
VOLTA
12
11
10
NRC TAC 39
(2000 ft)
D1.0
231°
4
9
173°
Slow to 85 kts
MLS
8
353°
Slow to 69 kts
MLS Curved Approach to STOL RWY 35
ELEV 140
MDA 340
5
7
DME 2
Slow to 74 kts
6
Slow to 90 kts
Slow to 69 kts
4
2000 ft
5
6
TACAN
1240 ft RAlt
800 ft RAlt
-7.5° Glide Slope
400 ft RAlt
MDA RAlt 200 ft
STOL RWY 35
NRC
ELEV 140
10
9
8
7
6
MSL
MSL

AUGMENTOR WING STI REFERENCE FLIGHT PATH 4 (MODERATE WORKLOAD)

WAYPOINT	LOCATION X (ft)	LOCATION Y (ft)	HEIGHT ABOVE AIRPORT Z (ft)	EAS (kt)	FLIGHT DATA ANGLE (deg)	TURN RADIUS (ft)
MCE	-33883	214879		--		
1	-39713	103470	2860	120		
2 VOLTA	-42628	47766	2860	120		
3 STOMAR	11983	21131	2860	120		
NRC	-2025	-1000	--	120		
4	-4798	-6000	1860	120		
5	-9419	-6000	1860	85		-3000
6	-12419	-3000	1860	74	-7.5	-3000
7	-9419	0	1240	74	-7.5	
8	-6077	0	800	69	-7.5	
9	-3039	0	400	69	-7.5	
10	-1520	0	200	69	-7.5	
11	950	0	200	120		
12	1450	0	200	120		-14630
13	15418	-12000	2860	120		
14	24534	-53859	2860	120		5500
15 WESTLEY	29166	-58052	2860	120		4193
16	28289	-49711	2860	120		
17	15187	-51088	2860	120		4193
18	16064	-59429	2860	120		
SCK	147960	-45458	136	--		

APPENDIX D

EDITED PILOT COMMENTS

PILOT NUMBER 1

- Flying curved Flight Plan 2 using the HSI and the EADI without the flight director and without the MFD seems unrealistic, because of the extremely high workload with wind in pursuing curved courses. I use the course predictor on the MFD to set the bank angle for curves when I don't have the flight director. [Editor's note: flying curved paths using the HSI and EADI would be a realistic backup, if the flight director failed and the aircraft did not have an MFD; therefore, the MFD provides a more graceful degradation to situation information alone if the flight director fails, although it is a much more costly backup than the HSI.]

- It's hard to keep track of where I'm going with the HSI. I need a waypoint number display with the HSI, although the bearing pointer helps. I need to keep the DME counter in my scan frequently when using the HSI, because it re-initializes often when the waypoints are closely spaced.

- Flight Plan 2 is possible with the flight director and the HSI but a lot easier with the flight director and the MFD, because a glance at the MFD tells me immediately where I am without having to correlate DME and bearing on the HSI with my memory of the waypoints passed over.

- Throttle director bar and the speed error bug have the opposite sense in relation to throttle activity between frontside and backside operation. Let's change the sense of the speed error bug on the EADI to be fast, DOWN and slow, UP. This agrees with the sense of the IAS needle at 95 kt and helps the throttle action to be consistent with the display on front and backside operation. [Editor's note: this sense of the speed bug operation is opposite to that provided in some ADIs for jet transport operation.]

PILOT NUMBER 3

- When using the flight director I tend to fixate too much, sometimes, on the flight director and not enough on situation. In fact, I spiraled into a crash on Flight Plan 2 and just before waypoint 11 even though I had the displacement window and flight director on the EADI and was using the MFD with the HSI covered.

- I am gaining more confidence in the MFD with each flight. I'm now getting better used to the MFD and its course predictor than when I first encountered it. I didn't pay much attention at all to the MFD last week.

- When using the HSI, an additional source of information must be available, i.e., a map or chart.

- The HSI is very good but takes more concentration when flying on raw data. The green bearing pointer (No. 2) helps to anticipate turns to waypoints.

- The high turbulence level (5 ft/sec RMS) causes excessive flight director activity.

- I prefer to use the MFD in its north-up orientation, because I can keep the direction of the prevailing winds more confidently in mind in relation to the flight plan.

- The flight director makes the task so easy that I don't have to check the HSI as long as I have the EADI window. [Editor's note:

flying Flight Plan 1 with all three primary displays during training.]

- While flying Flight Plan 1 with just the HSI supported by the EADI I missed waypoint 5 and the reference flight path mode disconnected. After that the HSI presented misleading guidance and I had to revert to the RMI to recover on final approach course. While flying with the HSI alone and the EADI on Flight Plan 2 I lost waypoint 4 and turned south prematurely and ended up flying in a circle.

- While using the MFD and the flight director without the HSI I ended up in a spiral crash just prior to waypoint 11 on the glide slope in Flight Plan 2. I think I developed tunnel vision on the flight director and forgot to monitor the situation until I was in trouble.

- I forgot to start the let-down at waypoint 8 in Flight Plan 3 when using the HSI alone with the EADI.

- When I have both the HSI and the MFD available I like to check the MFD for arrival at waypoints and to anticipate course changes and altitude changes but I still use the HSI for tracking the straight courses and I use the course predictor on the MFD for setting the bank angle on curved courses.

- When I was using the flight director with both the HSI and MFD, I checked the curved course predictor on the MFD and it was right on; it gives an impression of confidence.

[The following comments by Pilot 3 are made regarding Flight Plan 4]

- Easy to fly with either HSI or MFD; low workload.

- Am getting more used to the MFD and glancing at it more, but the HSI is also very easy to fly because the green bearing pointer moves automatically to indicate the direction of the next course segment prior to turns.

- The flight director works satisfactorily.

- Provided all of the enroute and approach plate information were available on call on the MFD, I could throw away my paper maps and get used to the MFD.

- I wasn't as precise without the flight director.

- I prefer to use the north-up MFD to maintain proper orientation of wind with respect to course. I prefer the RMI over the programmable heading display on the EADI for heading when using a north-up MFD and the HSI is covered. I like the heading-up MFD only on final approach course. Since NRC RWY 35 is already practically north, I don't bother changing MFD to heading-up on final approach.

- I like the flight director; when using the HSI alone without the flight director the workload feels much greater.

- When using the MFD alone without the flight director, I didn't have to use the STOLAND mode select panel for the missed approach at all. I used the MFD in north-up orientation, used course predictor to set bank angle for missed approach, and used the course history dots on the south-bound leg of the missed approach course to determine the distance off-set and the course for correcting wind drift. In this respect, the course history dots were very helpful in the missed approach when not using the reference flight path mode.

PILOT NUMBER 4

- The heading-up map on the MFD is not helpful for initial acquisition. I prefer north-up map first, then I may switch to heading-up at a convenient point of low workload in the approach.

- I used the HSI primarily for deviations and course changes but checked the MFD for waypoints when I had both displays available.

- When using the HSI with flight director and situation in following Flight Plan 1 I almost forgot where I was at the waypoint 6. This is an extremely difficult task using the HSI. While slowing to 75 kt approaching waypoint 6 I steepened my turn and almost lost the airplane. I was so busy I forgot to do the caution advisory task.

- When using the MFD and the flight director and situation, I was confused by the throttle director again on backside operation. The pitch director called for nose-up because I was fast, and I couldn't bring myself to bring the power back even though I was high. The map on the MFD gave me much more confidence about progress among waypoints than the HSI. I lost the airplane in roll while I was typing waypoint 1 [Editor's note: this is typical of the problems encountered in a simulation with workload for pilot and copilot when only the pilot is available to do all of the tasks which the copilot should be doing.]

- HSI - red number 1 bearing seems a distraction even though parked at north. One bearing pointer with multiple selections preferred.

- For some reason, probably long-time use of HSI-type instrument, I felt more comfortable during the HSI run than with the MFD. I feel as though I can acquire lateral and vertical displacement in less time from HSI, although MFD seems to have more information available.

- With use of HSI, I have changed my mind about the quality of information available from the green bearing pointer. I find it very useful in HSI-alone maneuvers.

- The presentation of vertical deviation on the HSI is analog and easier to assimilate than numerical altitude on the MFD.

- I am seldom conscious of the digital heading on MFD.

- In a tight turn (20-30 deg) the heading tape on the MFD moves so fast, I have to get away from the tape until I roll out. The movement of the heading-up chart on the MFD is adequate until less than 15 deg bank, then I can use the tape again. I like the compass on the HSI better but this may be due to my familiarity with the HSI.

- The MFD chart seems demanding because I have to look in two places to confirm altitude and lateral/longitudinal displacement, although I acknowledge that the MFD is much easier to keep track of progress among waypoints than the HSI. I don't have to develop a mental picture with the MFD.

- I'm not getting the quality of information from the window on the EADI that I am from the CDI/VDI on the HSI.

PILOT NUMBER 5

- When using the HSI with flight director and situation, I questioned whether the glide slope actually started at waypoint 7 in Flight Plan 1. There was no clear announcement of the start of glide slope. [Editor's note: this is a problem unique to the reference flight path mode of operation and has been noted by another pilot as well.]

- When using the MFD with flight director and situation, I misread the altimeter on final approach and went around at 1340 ft instead of 340 ft.

- It is unrealistic to require precision tracking in holding patterns. The holding patterns should be deleted from the MFD and just shown schematically on approach plates with arrows showing the direction of the turn. If the missed-approach route is shown on the MFD it should be terminated at the holding fix-point.

- HSI is preferable to the MFD for straight-course following, probably because of familiarity. The STOLAND reference flight path mode coupled to the HSI, CDI, VDI, and DME gives everything a pilot needs to fly standard terminal arrival routes. The map on the MFD offers a visual analog which helps to anticipate waypoints and turns but DME is adequate on the HSI.

- The EADI displacement window replaces the function of the CDI and VDI but doesn't have the familiar compass format. The map provides the heading-up format when the HSI is missing but doesn't have as desirable a compass format as the HSI. There is no real advantage of the MFD in piece-wise straight-course following.

- The MFD is far superior in turning maneuvers such as holding patterns, missed approaches, and curved approaches but one should not depend on measuring tracking errors and excess control capacity; rather one should depend on the pilot rating, eye-point-of-regard, and pilot opinion for comparing the MFD and HSI in these maneuvers.

- I prefer to use the MFD heading-up.

- Flight director makes control tolerable using the HSI alone, because it tells how much bank to command, and I just have to check the HSI for situation.

- The MFD course predictor also tells how much bank to command but it is not as relieving of workload as the flight director.

- The HSI alone is possible to use with the EADI but extremely difficult to keep track of waypoints. HSI requires intense concentration, whereas a glance at the MFD provides immediate horizontal position orientation.

- I don't like the clutter of the course and two bearing pointers when flying north.

- The pitch flight director and the window on the EADI are very noisy.

- The automatic flight mode is not a crucial test of differences between the HSI and MFD.

- When using the HSI, EADI, and raw data in making the final approach on Flight Plan 2 I thought I was still above the runway when I crashed on the glide path intercept point, because I was so busy correcting for the crosswind.

- While using the excess control capacity measurement task with Flight Plan 2 I could not do the caution advisory task in turns because the workload was so high.

[The following comments by Pilot 5 are made regarding Flight Plan 1 and MFD]

- The course line is <u>extremely</u> useful on straight courses. Makes it very easy to stay on course in presence of crosswind. It is the most desirable feature on the MFD.

- Heading information was hard to read and the digital heading was of no value. Poor heading information was my major complaint.

- The course predictor was very useful for curved path tracking. I did not use it on straight course as I tended to overcontrol; course line was sufficient on straight path. I would prefer to remove course predictor on straight paths as it tends to clutter the display.

- On the final approach there are two courses and I could not figure out what to track. Also seems cluttered at waypoints. I need a good clear picture of course and airplane to make intercept -- had too much lettering in the way.

- The most help came from course line on straight path, course predictor on curved path, and flight path angle for altitude.

[The following comments by Pilot 5 are made regarding Flight Plan 1 and HSI]

- I had no course line or course predictor which is a serious deficiency for curved path tracking and objectionable for straight line tracking, due to very large crab angles required at low speed.

- Green arrow covered up heading information.

- Difficult to impossible to keep oriented on HSI during curved path tracking.

- RMI heading scale has too many graduations, making it useless.

[The following comments by Pilot 5 are made regarding Flight Plan 2 and MFD with flight director off]

- This is <u>infinitely</u> better than HSI without flight director, however, this task is not acceptable for routine flight without at least a flight director.

- Workload is very high, especially in turns - 100%.

[The following comments by Pilot 5 are made regarding Flight Plan 2 and HSI with flight director off]

- I was semi-"lost" for most of the run; it was like following a white line in the fog. I thought I was still in a curved path when I hit the ground at the airport. I tracked the glide slope but had no time to crosscheck altimeters.

- Workload was 100% +

- This would classify as an extreme emergency in flight.

[The following comments by Pilot 5 are made regarding Flight Plan 2 and MFD with flight director on]

- MFD is a must for complex paths such as this one. I can tell orientation in a glance leaving adequate time to keep flight director bars centered and do side tasks.

- I need more information to
  - a) Warn of impending glide slope capture
  - b) Advise pilot of safety margins

- Flight director frequently gave erroneous cues during glide slope capture and tracking, e.g., it said to fly up and reduce power when already at 50 kt; this increases workload considerably.

[The following comments by Pilot 5 are made regarding Flight Plan 2 and HSI with flight director on]

- Curved path tracking without MFD is unacceptable because of problems with orientation in the turn.

- The flight director was very busy and required constant attention to keep centered.

EDITED PILOT COMMENTS DURING SECOND PHASE OF EXPERIMENT EMPHASIZING GEOGRAPHIC ORIENTATION

PILOT NUMBER 1

- The HSI provides no look-ahead capability and no direct display to ascertain correct bank angle in following or establishing curved courses like that on the MFD. It is difficult to keep up with progress on the approach plate when using the HSI, and there is insufficient raw data on the HSI to monitor progress of turns in off-nominal situations when using the flight director. I find it hard to integrate DME, course deviation, and vertical deviation. The HSI is very seriously deficient in status information to provide for a confident capture of a reference flight path. [Editor's note: capturing a reference flight path with only the HSI and EADI was a traumatic experience for all — both pilots and investigators — who participated in this experiment; there is reason to believe that the STOLAND capture criteria were partly at fault in the cases of both VOR/TACAN radial courses and reference flight paths.]

- The MFD provides no vertical look-ahead capability without cross-checking the chart, there is no DME, and the vertical situation is not well presented. There is an awful lot on the MFD which is hard to read sometimes but not necessarily confusing. If correct map scale is selected, the clutter is not too bad, but I must remove certain items (e.g., runway) occasionally to eliminate clutter. For final approach I would like increased resolution on the MFD. I don't use the heading tape on the MFD very much — I prefer the heading vector in front of the airplane symbol. However, the MFD offers the advantage of uniform displacement sensitivity in a holding pattern, whereas the HSI's angular course displacement sensitivity on VOR or TACAN at WESTLEY (Flight Plan 4) is lower.

- Although I tried the course-select mode of the roll flight director on the north-bound leg and the heading-hold mode on the south-bound leg of the holding pattern at WESTLEY (Flight Plan 4), I like using the raw data better than this flight director — it's too active. It's sufficient just to use the pitch director for maintaining altitude. Another problem with this roll flight director in the course select mode occurs after I acquire the north-bound leg of the holding pattern at WESTLEY. Then the roll command develops a stand-off on the downwind side of the course, and when I null the director command, it develops a displacement stand-off on the same side of the course. [Editor's note: this stand-off problem was eventually eliminated by removing the signal from the director representing the integral of VOR or TACAN course deviation; this problem arose, because autopilot signals were improperly applied as flight director commands in the design of the STOLAND software.]
- This fixed-base simulation of the airplane is marginally controllable, and the attitude display is almost completely demanding of the attentional workload, because of the spiral divergence above 100 kt and the oscillatory artifact in pitch. The airplane itself is easier to fly. [Editor's note: the oscillatory artifact in pitch is caused by an excessive cycle time in the EAI 8400 computer. Although several hours were devoted to try to correct the problem by modifying the pitch SAS, the restriction of airspeed to 120 kt or less proved to be the only partial remedy which worked.]

PILOT NUMBER 3

- When using the HSI and chart, I might refer back and forth several times just to check my position with respect to one waypoint or fix point, whereas with the MFD, one glance is sufficient to confirm my position with respect to a segment of the flight plan or a fix point.

- I prefer a north-up MFD to help me maintain the proper orientation of the wind with respect to the course. Then the only thing I have to be careful of is the direction of turning when headed toward southerly quadrants. I prefer the RMI over the numerical [programmable] heading display on the EADI when using the north-up MFD, and the HSI is covered. I would like a heading-up MFD only on the final approach course. Since NRC Runway 35 is practically north, I don't bother changing the MFD to heading-up on final.

- Flight director commands 25 or 30 deg bank angle at VOLTA (Flight Plan 4, Waypoint 2) for course change. I prefer to use MFD course predictor to start the turn earlier and make a shallower turn with 10 or 15 deg bank en route. Nevertheless, I like the flight director, especially in the terminal area and for the curved approach. When using the HSI and EADI without the flight director, subjective workload feels much greater. HSI requires more effort to remain oriented than the MFD and, in addition, the HSI requires constant reference to a chart.

- MFD eliminates the mental gymnastics required when using the HSI, especially in entering and maintaining holding patterns, which are considered the most difficult problem in using an HSI. Although it's much easier to remain oriented with the MFD than the HSI, it still may be necessary to have a compass and bearing pointers as on the RMI. [Editor's note: Pilot 3 never used the heading scale on the MFD, because the scale does not appear with the north-up orientation of the map.]

- VOR course displacement sensitivity seems lower than normal at WESTLEY (Flight Plan 4) which is 20 nm from SCK. [Editor's note: VOR/TACAN course displacement sensitivity throughout experiment was 5/6 of normal in order to provide 12 (instead of 10) deg full scale displacement for off-course indication in the vicinity of NRC.]

- I would like a vertical profile of my approach chart as well on the MFD, if I were to use it on final approach, but I don't need so many waypoints on final — just 1000 ft (altitude), glide slope capture point, 1000 ft (altitude), and minimum decision altitude. These should help to reduce the clutter on the final approach course on the MFD. Map scales of 5.0, 2.5, and 1.0 nm/inch might be more useful. I don't use the 0.5 nm/inch scale, except sometimes on final approach; but as long as I have the window box on the EADI, I don't really need to use 0.5 nm/inch on the MFD. It might also reduce clutter on the MFD by presenting only the waypoints where the pilot has to change course, altitude, or speed and just the holding fix point, although more charts now show the holding pattern. Putting the course angles on the MFD along segments between waypoints might also reduce the clutter beside the waypoints.

- If the MFD in operational aircraft could be shared with the weather radar display at the forward end of the console between pilots, a moving map might be provided at no extra cost in panel space. HSI bearings, DME, and deviations would seem to be an essential backup, even for a moving map. I would think you'd want both HSI and MFD, if the MFD could be shared with the weather radar display. In some ways the HSI is like a radar map of the ground — you know how cluttered that is? It's virtually useless, if you don't already know about where you are. Ground-mapping radar confirms your position, but you have to know where you are to use it. In a similar way the HSI improves my confidence in the moving map on the MFD.

- When using the MFD alone without a flight director on the EADI, I didn't have to touch the STOLAND Mode Select Panel at all for the missed approach. I kept the MFD north-up, used course predictor to set bank angles for missed approach course to fix point and for turns in the holding pattern, and used track history dots on south-bound leg after left turn from STOMAR (Flight Plan 3) to determine distance offset from V-109 and course for correcting wind drift. The MFD should offer much better precision in holding than is possible with the HSI.

PILOT NUMBER 4

- When using HSI on Flight Plan 2, I seem to maintain a lower gain, because I'm not as impressed with my lateral deviations as on the MFD. I feel more comfortable with HSI. When using MFD, I seem to fixate too long, and the roll axis gets away more. The green (waypoint) bearing pointer on HSI helps me to predict how to lead heading in turns to account for wind drift. On MFD I use course predictor for roll-in to turns and straight course line for roll-out of turns.

- When using HSI on Flight Plan 3 without flight director, I have no feeling of precision. I had to spend so much time in course-keeping and configuration-changing during the approach that my altitude-keeping suffered. Then during final approach the vertical deviation indicator on the HSI required too much attention for adequate vertical control on glide slope. I even reversed my sense of vertical perception at one point in descent! Throughout the initial approach in reference flight path mode on Flight Plan 3 I need a simple numerical counter to keep track of the next waypoint number toward which the green bearing needle on the HSI is pointing when the MFD is covered. I think the counter would reestablish confidence about position when cross-checking between HSI and chart. Also throughout the same initial approach, the heading reference bug on the HSI seemed too active without performing a useful role. [Editor's note: investigator responded to request for waypoint counter with HSI by permitting all pilots to view the next waypoint number presented on the MFD during the reference flight path mode. The map on the MFD was put out of view by using the slew switch whenever the MFD was not to be employed.]

C 3

- When using both HSI and MFD on Flight Plan 3 without flight director, there is no comparison between HSI and MFD in terms of locating my position: the MFD is far superior, although the HSI gives good displacement sensitivity for tracking.

- When using HSI on Flight Plan 3 with flight director, the STOLAND slew switch caused inattention to roll and pitch attitude while selecting heading to intercept course to STOMAR fix point on V-109 after go-around. Lost 900 ft altitude in graveyard spiral, but recovered at 440 ft. Used HDG SELECT flight director on southbound leg of holding pattern, but its turns are too tight, i.e., it calls for too much bank, especially in upwind turn. I prefer to fly the entire holding pattern on raw data, because of the distraction caused by the STOLAND button-pushing and slewing orgy even when trying to use just heading-hold and course-hold flight director modes on the straight legs.

- HSI VOR/MLS and WPT/TAC selector knobs must be scanned to confirm function of HSI bearing pointers and DME. Failing to check these knobs in the terminal area can get you into trouble. If knob positions were more clearly identifiable, they might attract my attention better during a scan. It would also be preferable to have the heading and course selection knobs on the HSI.

- Can't remember referring to glide slope needle during one final approach on Flight Plan 3, so assume an inappropriate dependence on the throttle and pitch flight directors!

- When using HSI on Flight Plan 4, I was so overloaded that a copilot was necessary for tuning radios and entering keyboard data. I seemed to accept lower precision than earlier HSI runs as best attainable.

- When using MFD on Flight Plan 3 without flight director, I think MFD is far superior to HSI, because MFD allows more time for vertical task. In holding patterns the MFD is a great help, because upwind turn must be quite shallow in high wind to protect downwind turn for radial capture to return to fix point. Otherwise you reach the bank limit of the aircraft in the downwind turn. However, I would like to see a trend vector (i.e., course predictor) with more sections of shorter length each for better intercept data. Also, the trend vector is too sensitive on the 0.5 nm/inch scale; would prefer a shorter course predictor to reduce its activity. I usually orient MFD heading-up for approach, north-up for go-around, and heading-up for holding pattern.

- Flight director allows overshoot on turn to final approach with 20 kt tail wind on base leg and 74 kt true air speed. Workload can be reduced in use of flight director by turning to desired heading or course using raw data (especially MFD) and then engaging appropriate holding mode of flight director. Turns can be shallower and better controlled, and you don't have to struggle with slew switches as much.

- When using MFD on longer straight courses in Flight Plan 4 in heading-up orientation, the course vector, trend vector, and map course line all merge and leave a sense of losing course information for short periods of time. MFD heading scale doesn't have a clear bold lubber line — very hard to use.

- EADI "window box" presents difficulties, because I find it unnatural to relate displacements in space to the nose of the aircraft symbol. Instead, I prefer to relate displacements in space to case-fixed points on the frame of the display which I associate with the center of gravity of the airplane behind me. There is too much confusing pitch activity by the horizon and pitch scale which distracts from (i.e., clutters) interpretation of the window. The horizon does not interfere with the interpretation of case-fixed displacement indicators on a conventional attitude director indicator.

PILOT NUMBER 6

- When HSI limits its deviation, you don't know how far off course you are. MFD overcomes this limitation of HSI. On "downwind" and base legs and final approach, the waypoints are so close that DME resets itself too frequently and offers few clues to progress among waypoints. The reference flight path mode doesn't give a significant glide slope capture cue. The HSI presents inadequate navigation status information on downwind leg and in final turn. The available number of choices (e.g., WPT/TAC and VOR/MLS) in the use of bearing and distance on the HSI leads to a sense of clutter and additional thought while searching the panel for additional information. The display attentional workload is completely demanding between the HSI and approach chart due to the uncertainty of position status on downwind leg, final turn, and descent. HSI is less demanding in other flight phases. Precision with HSI is inadequate in terminal area approach task, but satisfactory in holding pattern. Yet precision with HSI may actually be better than with MFD, because you must track HSI very closely in order to maintain understandable horizontal situation.
- The flight director is significantly better only in final turn and descent where it reduces workload and improves precision somewhat. However, the final turn is still not too easy to control. Must work hard to discern progress in position around the turn by checking heading against course. I turned off the roll flight director during go-around to intercept course to STOMAR in Flight Plan 3 for holding fix. After indirect entry to holding pattern, I used roll director to track north-bound course to STOMAR, then turned left without using director and resumed heading-hold director on south-bound course.
- Even with the MFD the base leg turn to final approach with the 20 kt tail wind on the base leg is still the most demanding part of the task — more so than the holding pattern, which is normally

hard to establish in a crosswind, but which is greatly aided by the MFD. However, the heading-up MFD is disorienting in turns at low speeds, because of the relatively high turn rates. I've noticed the same effect in the airplane when the MFD map swings around the airplane symbol. I might prefer north-up MFD, except on final approach. I also had problems with scaling and resolution on the 1.5 nm/inch scale — 0.5 nm/inch might have been better. Both MFD and EADI seemed quite cluttered — I had to use the EADI more than when the HSI was available.

- EADI is cluttered with both "window box" and flight director in use. However, in the base leg turn to final approach course on Flight Plan 3 with flight director commands displayed, I experience less of a problem trying to use the window box as a director, and my precision is better.

- Vertical situation information is insufficient for descent and deceleration with MFD and EADI. Although lateral precision in final turn is better with flight director, glide slope acquisition cues are still deficient. Precision on straight final approach is better with flight director in both lateral and vertical tracking.

- Even at high sensitivity, the MFD does not induce good tracking around final turn without a flight director — of course, neither does the HSI. Suggest that stronger associated heading information as on HSI might help the MFD, which has a poor heading scale.

- Clutter on the MFD is especially noticeable during final turn and final approach — too many waypoint numbers — hard to find aircraft symbol. Dislike heading-up MFD at high sensitivity in high rate turns. Sometimes I have to reposition map north-up.

- The heading reference required to hold the desired course is much easier to pick off the HSI rather than the MFD heading scale.

- When using the MFD, I prefer to disregard the roll flight director in the holding pattern. Even with the pitch director to help maintain altitude in the holding pattern, I use inertial flight path angle as well.

- Sensitivity of HSI course displacement in holding patterns is too low. HSI compass motion is also disorienting in turns. The HSI is definitely a rectilinear flight instrument.

- When using both HSI and MFD on Flight Plan 4 without a flight director, I use HSI for en route tracking but check MFD for progress. On the base leg turn to final approach the turning course needle on the HSI is disorienting. Although the 20 kt headwind on the base leg helped to slow the turn and to give me more time to capture the glide slope, I paid too much attention to the window box on the EADI rather than the MFD on the 0.5 nm/inch scale. If the VOR/MLS and WPT/TAC knobs on the HSI aren't set properly, the DME and bearings on the HSI will lead you astray. I used the MFD to set up the holding pattern, especially in the turns and the south-bound leg, but I used the HSI for tracking the north-bound course to the fix point at WESTLEY.

- The flight director makes me work too hard on the first straight leg from waypoint 1 to 2 in Flight Plan 4; the roll director has too much quickening for me.

- When using the MFD and EADI without the flight director on Flight Plan 4, capture of reference flight path at Waypoint 3 is easier than with the HSI. I don't have to guess so much where I am. The clutter on the MFD is significant when crossing over the NRC TACAN and when on final approach course.

COLLECTED RECOMMENDATIONS FOR STOLAND DISPLAY MODIFICATIONS BASED ON PILOT COMMENTS

The EADI "window box" presented difficulties for two of the pilots, apparently because of its central location. One perceived it as a flight director and had to suppress this impression repeatedly. The other perceived it beyond the "nose" of the airplane symbol and experienced confusion between displacement and pitch angle cues. A recommendation would be to compare the "window box" with the "pole track" or "channel" displacement symbol in another experiment.

(N.B. There is a project called "pole track MFD" in the STOLAND simulator files.) Pilot 4 expressed a preference for presenting displacement information at the bottom and right margins of the EADI, because he is accustomed to associating the marginal locations with the spatial position of his own aircraft, whereas he associates the central location with the pitch of his aircraft.

Slewing switch operation proved clumsy. Overshoots in turns occurred while trying to select a new course and there were instances of loss of both attitude and altitude awareness while trying to operate a slewing switch. Only the two pilots most familiar with the keyboard mnemonics chose to use keyboard entry instead of slewing switches. A recommendation would be to put the course and heading select controls back on the HSI as displacement controls rather than rate controls.

The VOR/MLS and WPT/TAC selector switches might remain as knobs or rings concentric with the course and heading selection controls on the HSI; however, annunciation for the VOR/MLS and WPT/TAC switches must be much clearer than at present. The positions of these two function selectors were not sufficiently apparent to several of the pilots, even though they knew they should be scanning the switches when functions were being changed. At least a green label for WPT/TAC and a red label for VOR/MLS would be a help, but a more startlingly apparent display of each selected switch position is apparently needed.

It should not be necessary both to select radio navigational stations for STOLAND and to select radio frequencies for the receivers. One set of selections should suffice. A recommendation would be to arrange for STOLAND to read whatever frequencies are selected for the receivers and to display the appropriate station identities on the MFD after using an internal table look-up routine.

The space on the MFD which is presently devoted to the heading scale would better be devoted to presenting a vertical approach profile.

Shorten the length of the curved course predictor on the MFD when the 0.5 nm/inch scale is selected so as to reduce its apparent sensitivity.

Color-code the DME windows on the HSI red and green to improve the clarity of their association with the bearing pointers and function selectors.

APPENDIX E

EYE-POINT-OF-REGARD DATA REDUCTION

A digital computer program has been written to reduce the EPR data to scanning statistics. The output consists of dwell time statistics and histograms for each instrument, summations for all instruments, and one way link transitions between instruments. This program could easily be changed to include more positions in the visual field, but for illustration this section describes the results in terms of pilot scanning behavior for an eight position display field. The ninth position is for blinks.

Some definitions of the properties of the raw and reduced EPR data are needed. For a given run of T_R sec duration:

- M is the number of instruments
- N_i is the number of fixations on instrument i
- N_M is the total number of fixations on all instruments
- N is the total number of fixations on instruments, elsewhere, blinks, etc.

It follows that

$$N_M = \sum_{i=1}^{M} N_i$$

The duration of a look at a given instrument is called the dwell time, T_d, and

$T_{d_{i_k}}$ is the duration of the kth dwell on instrument i

$$T_i = \sum_{k=1}^{N_i} T_{d_{i_k}} \text{ is the total time fixating i}$$

$$T_R = \sum_{i=1}^{M} T_i + T_{other}$$

where T_{other} includes blinks and looks elsewhere than at the defined instruments. For data reduction convenience we assigned a number to blinks and other regions of the panel so that all time during the run was subscripted and allocated.

Average properties of the data are important. The mean dwell time on instrument i is

$$\bar{T}_{d_i} = \frac{1}{N_i} \sum_{k=1}^{N_i} T_{d_{ik}} = \frac{T_i}{N_i}$$

The "scan rate" over all instruments on the panel is the average number of fixations per second, given by

$$\bar{f}_s = \frac{N}{T_R}$$

The scan rate on a given instrument is called the "look rate," given by

$$\bar{f}_{s_i} = \frac{N_i}{T_R}$$

The fraction of fixations on the ith instrument, ν_i, is called the "look fraction,"

$$\nu_i = \frac{N_i}{N}$$

The "dwell fraction" is the fraction of time spent on instrument i, given by

$$\eta_i = \frac{T_i}{T_R}$$

This is also called the "fractional scanning workload." The "look interval" is the inverse of the look rate, i.e.,

$$\bar{T}_{s_i} = \frac{1}{\bar{f}_{s_i}}$$

The look interval is a measure of the recycle time, and it can also be computed from the individual scan intervals (the time between successive looks at an instrument). The following quantities were printed for each instrument:

	SYMBOL
• Maximum and minimum dwell times	TMX, TMN
• Total dwell time, T_i	TD
• Number of fixations, N_i	N(I)
• Mean dwell time, $\overline{T}_{d_i}$	TB
• Dwell time standard deviation, σ_{T_i}	SD
• Dwell fraction, η_i	DF
• Look fraction, ν_i	LF
• Look rate, $\overline{f}_{s_i}$	LR
• Dwell time histogram at 0.25 sec intervals	
• Look interval, $1/\overline{f}_{s_i}$	LI

The data for all instruments included:

• Total dwell time, $\sum T_i$	
• Total number of fixations, N_M	N
• Scan rate, $\overline{f}_s$	SR
• One way transition links	

Summaries of definitions for the symbols used in the typed tables of EPR statistics are presented in Tables E-1 and E-2. Table E-3 then presents the run identification for the reduced EPR data which follows in Tables E-4 through E-11 in this appendix and Figs. 24 and 25 in the text. The histogram and link matrix portions of the output require some additional mention as to their interpretation. Primary link values are listed in Tables E-4 through E-7, and the complete transition link matrices follow in Tables E-8 through E-11.

The ordinate of the histogram (Figs. 24 and 25 in the text) has 0.000 representing the dwell times from 0.000 to 0.249 sec, 0.250 representing 0.250 and 0.499 sec, and so on. The numbers to the right of the dwell time intervals are the number of occurrences falling within this interval. The abscissa represents this number as a percent of the total dwells.

The transition links are read as the looks <u>FROM</u> instrument I (on the left side of the matrices in Tables E-8 through E-11) <u>TO</u> instrument J (along the top of the matrices) ($I \neq J$). This number is expressed as a percent of the total number of transitions. The total may not add to 1.000 because only primary link values are listed in Tables E-4 through E-7 and because of roundoff in the complete matrices.

The complete scan transition link matrices in Tables E-8 through E-11 show occasional evidence of slight asymmetry among the one-way link values for the primary displays as well as the conventional instruments. Different one-way link values between the same pair of instruments are indicative of circulatory determinism in scan patterns. Transition links appearing between instrument 3 (MFD) and 5 (HSI) are indicative of direct cross-checking between the primary horizontal displays. Such links, although rare, are predominantly unidirectional from HSI to MFD by Pilots 1, 3, and 4 when using raw situation data.

TABLE E-1. SYMBOLS FOR EPR STATISTICS

SYMBOL	DEFINITION
P	Pilot X
R	Run Y
C	Case Z
WP	Waypoint Interval A to B and Date
TR	Total run time, sec
N	Total number of dwells
SR	Scan rate = N/TR, sec^{-1}
I	Instrument number: I=1 = IVSI 2 = EADI 3 = MFD 4 = Barometric Altimeter 5 = HSI 6 = IAS 7 = To the right of the primary instrument panel (i.e., function switches and engine instruments) 8 = Above the primary instrument panel (i.e., the flight plan) 9 = Blinks (not counted)
N(I)	Number of fixations, N_i
TD	Total dwell time, T_i
TMX, TMN	Maximum and minimum dwell times
TB	Mean dwell time, $\overline{T}_{d_i}$
SD	Standard deviation of dwell time, σ_{T_i}
DF	Dwell fraction, η_i
LF	Look fraction, ν_i
LR	Look rate, $\overline{f}_{s_i}$
LI	Look interval, $1/\overline{f}_{s_i}$

TABLE E-2. DEFINITION OF WAYPOINT GROUPINGS

CASE NO.	FLIGHT PLAN	(WP) WAYPOINTS	DEFINITION
C2--	2	4 → 6	Turn at constant altitude.
↓	↓	8 → 9	Straight, decelerating flight.
↓	↓	9 → 11	Decelerating turn.
C2--	2	12 → 14	Final approach.
C3--	3	8 → 9	Straight, descending leg.
↓	↓	12 → 15	Decelerating turn to final approach.
↓	↓	15 → 18	Final approach.
↓	↓	18 → 21	Go-around leg. Climbing, accelerating flight.
↓	↓	21 → 22	Turn to holding pattern.
↓	↓	22 → 25	Enter holding pattern.
C3--	3	25 → 29	Holding pattern.

TABLE E-3

RUN IDENTIFICATION FOR THE REDUCED EYE-POINT-OF REGARD DATA

RUN NO.	PILOT	FLIGHT PLAN	LEVEL OF DISPLAY	CASE NO.	TABLE NO.
R148	3	3	Situation (raw data)	C301	D-8a
149	3	3	Flight director and situation	302	D-8b
154	1	3	Situation	301	D-7a
155	1	3	Flight director and situation	302	D-7b
156	1	2	Situation	201	D-6a
157	1	2	Flight director and situation	202	D-6b
261	4	2	Situation	201	D-5a
257	4	2	Flight director and situation	202	D-5b

TABLE E-4. EPR STATISTICS

a. Run 261

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR$_{-1}$ SEC	LI SEC	TRANSITION LINKS
P4 R261 C201	1	2	1.3	0.7	0.6	0.7	0.1	.01	.02	.02	50.5	2-->3 = .200
WP 4-6 20MAR	2	46	35.9	2.1	0.4	0.8	0.4	.36	.41	.46	2.2	3-->2 = .300
	3	36	42.4	2.9	0.5	1.2	0.5	.42	.32	.36	2.8	2-->5 = .036
TR=101.0 SEC	4	1	0.4	0.4	0.4	0.4	0.0	.00	.01	.01	101.0	5-->2 = .018
N = 111	5	4	3.2	1.2	0.4	0.8	0.3	.03	.04	.04	25.3	2-->4 = .000
SR= 1.10 1/SEC	6	18	13.6	1.0	0.4	0.8	0.2	.13	.16	.16	5.6	4-->2 = .000
	7	4	4.2	1.7	0.7	1.1	0.4	.04	.04	.04	25.3	2-->7 = .009
	8	0										7-->2 = .009
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR$_{-1}$ SEC	LI SEC	TRANSITION LINKS
P4 R261 C201	1	2	1.9	1.0	0.9	0.9	0.1	.04	.03	.04	25.4	2-->3 = .169
WP 8-9 20MAR	2	27	22.8	2.6	0.4	0.8	0.5	.45	.45	.53	1.9	3-->2 = .186
	3	13	9.9	1.1	0.4	0.8	0.2	.20	.22	.26	3.9	2-->5 = .051
TR= 50.7 SEC	4	0										5-->2 = .034
N = 60	5	3	3.2	1.4	0.5	1.1	0.5	.06	.05	.06	16.9	2-->4 = .000
SR= 1.18 1/SEC	6	13	11.4	1.3	0.4	0.9	0.3	.22	.22	.26	3.9	4-->2 = .000
	7	2	1.5	0.9	0.6	0.8	0.2	.03	.03	.04	25.4	2-->7 = .017
	8	0										7-->2 = .017
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR$_{-1}$ SEC	LI SEC	TRANSITION LINKS
P4 R261 C201	1	15	8.9	1.0	0.4	0.6	0.2	.11	.16	.19	5.4	2-->3 = .226
WP 9-11 20MAR	2	42	39.7	3.1	0.4	0.9	0.5	.49	.45	.52	1.9	3-->2 = .258
	3	25	19.5	1.0	0.5	0.8	0.1	.24	.27	.31	3.2	2-->5 = .011
TR= 80.6 SEC	4	0										5-->2 = .000
N = 94	5	1	0.7	0.7	0.7	0.7	0.0	.01	.01	.01	80.6	2-->4 = .000
SR= 1.17 1/SEC	6	6	5.4	1.3	0.5	0.9	0.3	.07	.06	.07	13.4	4-->2 = .000
	7	5	6.5	3.2	0.7	1.3	1.0	.08	.05	.06	16.1	2-->7 = .032
	8	0										7-->2 = .032
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR$_{-1}$ SEC	LI SEC	TRANSITION LINKS
P4 R261 C201	1	8	7.1	1.4	0.4	0.9	0.3	.12	.16	.13	7.5	2-->3 = .122
WP 12-14 20MAR	2	24	36.8	5.2	0.4	1.5	1.2	.61	.48	.40	2.5	3-->2 = .163
	3	8	8.4	1.7	0.7	1.0	0.3	.14	.16	.13	7.5	2-->5 = [illegible]
TR= 60.0 SEC	4	0										5-->2 = .122
N = 50	5	6	4.9	1.0	0.5	0.8	0.2	.08	.12	.10	10.0	2-->4 = .000
SR= 0.83 1/SEC	6	2	1.3	0.6	0.6	0.6	0.0	.02	.04	.03	30.0	4-->2 = .000
	7	2	1.6	0.9	0.8	0.8	0.1	.03	.04	.03	30.0	2-->7 = .041
	8	0										7-->2 = .041
	9	0										

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TABLE E-4 (Concluded)

b. Run 257

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR_{-1} SEC	LI SEC	TRANSITION LINKS
P4 R257 C202	1	1	0.5	0.5	0.5	0.5	0.0	.01	.01	.01	98.7	2-->3 = .272
WP 4-6 20MAR	2	44	61.4	4.5	0.4	1.4	1.1	.62	.47	.45	2.2	3-->2 = .293
	3	29	22.9	1.2	0.4	0.8	0.2	.23	.31	.29	3.4	2-->5 = .022
TR= 98.7 SEC	4	0										5-->2 = .022
N = 93	5	2	1.4	0.7	0.6	0.7	0.0	.01	.02	.02	49.4	2-->4 = .000
SR= 0.94 1/SEC	6	12	8.2	1.0	0.4	0.7	0.1	.08	.13	.12	8.2	4-->2 = .000
	7	5	4.3	1.0	0.8	0.9	0.1	.04	.05	.05	19.7	2-->7 = .054
	8	0										7-->2 = .022
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR_{-1} SEC	LI SEC	TRANSITION LINKS
P4 R257 C202	1	5	4.2	1.0	0.8	0.9	0.1	.08	.11	.10	10.1	2-->3 = .205
WP 8-9 20MAR	2	22	30.3	4.1	0.5	1.4	0.8	.60	.49	.44	2.3	3-->2 = .192
	3	9	7.7	1.3	0.5	0.9	0.3	.15	.20	.18	5.6	2-->5 = .000
TR= 50.4 SEC	4	0										5-->2 = .000
N = 45	5	0										2-->4 = .000
SR= 0.89 1/SEC	6	2	1.6	1.0	0.6	0.8	0.3	.03	.04	.04	25.2	4-->2 = .000
	7	7	6.6	1.3	0.6	0.9	0.2	.13	.16	.14	7.2	2-->7 = .136
	8	0										7-->2 = .159
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR_{-1} SEC	LI SEC	TRANSITION LINKS
P4 R257 C202	1	8	6.2	1.1	0.5	0.8	0.2	.08	.15	.10	10.1	2-->3 = .269
WP 9-11 20MAR	2	23	53.6	7.2	0.3	2.3	2.0	.67	.43	.29	3.5	3-->2 = .250
	3	15	11.0	1.1	0.5	0.7	0.1	.14	.28	.19	5.4	2-->5 = .000
TR= 80.4 SEC	4	0										5-->2 = .000
N = 53	5	0										2-->4 = .000
SR= 0.66 1/SEC	6	1	0.7	0.7	0.7	0.7	0.0	.01	.02	.01	80.4	4-->2 = .000
	7	6	9.0	2.9	0.8	1.5	0.8	.11	.11	.07	13.4	2-->7 = .019
	8	0										7-->2 = .058
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR_{-1} SEC	LI SEC	TRANSITION LINKS
P4 R257 C202	1	3	1.8	0.6	0.6	0.6	0.0	.03	.17	.05	20.0	2-->3 = .000
WP 12-14 20MAR	2	9	49.5	17.0	0.5	5.5	5.5	.82	.50	.15	6.7	3-->2 = .059
	3	1	3.0	3.0	3.0	3.0	0.0	.05	.06	.02	60.0	2-->5 = .000
TR= 60.0 SEC	4	0										5-->2 = .000
N = 18	5	0										2-->4 = .000
SR= 0.30 1/SEC	6	0										4-->2 = .000
	7	5	5.7	1.8	0.8	1.1	0.4	.09	.28	.08	12.0	2-->7 = .294
	8	0										7-->2 = .235
	9	0										

TABLE E-5. EPR STATISTICS

a. Run 156

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC	TRANSITION LINKS
P1 R156 C201	1	0										2-->3 = .162
WP 4-6 3MAR	2	51	66.0	10.6	0.3	1.3	1.4	.66	.49	.51	2.0	3-->2 = .190
	3	21	18.7	1.6	0.4	0.9	0.3	.19	.20	.21	4.8	2-->5 = .000
TR=100.7 SEC	4	34	16.0	0.8	0.3	0.5	0.1	.16	.32	.34	3.0	5-->2 = .000
N = 106	5	0										2-->4 = .324
SR= 1.05 1/SEC	6	0										4-->2 = .286
	7	0										2-->7 = .000
	8	0										7-->2 = .000
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC	TRANSITION LINKS
P1 R156 C201	1	0										2-->3 = .212
WP 8-9 3MAR	2	26	33.7	4.4	0.3	1.3	1.2	.67	.49	.52	1.9	3-->2 = .250
	3	13	10.5	1.5	0.4	0.8	0.3	.21	.25	.26	3.9	2-->5 = .000
TR= 50.4 SEC	4	3	1.3	0.6	0.3	0.4	0.2	.03	.06	.06	16.8	5-->2 = .000
N = 53	5	0										2-->4 = .058
SR= 1.05 1/SEC	6	11	4.9	0.6	0.3	0.4	0.1	.10	.21	.22	4.6	4-->2 = .058
	7	0										2-->7 = .000
	8	0										7-->2 = .000
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC	TRANSITION LINKS
P1 R156 C201	1	0										2-->3 = .409
WP 9-11 3MAR	2	22	59.4	7.6	0.4	2.7	2.0	.75	.49	.28	3.6	3-->2 = .409
	3	19	15.4	1.8	0.4	0.9	0.3	.19	.42	.24	4.2	2-->5 = .023
TR= 79.4 SEC	4	0										5-->2 = .045
N = 45	5	2	1.2	0.6	0.5	0.6	0.1	.02	.04	.03	39.7	2-->4 = .000
SR= 0.57 1/SEC	6	0										4-->2 = .000
	7	2	3.5	2.4	1.0	1.7	1.0	.04	.04	.03	39.7	2-->7 = .045
	8	0										7-->2 = .045
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC	TRANSITION LINKS
P1 R155 C201	1	0										2-->3 = .050
WP 12-14 3MAR	2	21	46.8	6.9	0.6	2.2	1.6	.77	.51	.35	2.9	3-->2 = .050
	3	2	1.7	1.0	0.6	0.9	0.2	.03	.05	.03	30.3	2-->5 = .450
TR= 60.5 SEC	4	0										5-->2 = .450
N = 41	5	18	12.0	1.5	0.4	0.7	0.2	.20	.44	.30	3.4	2-->4 = .000
SR= 0.68 1/SEC	6	0										4-->2 = .000
	7	0										2-->7 = .000
	8	0										7-->2 = .000
	9	0										

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TABLE E-5 (Concluded)

b. Run 157

P1 R157 C202
WP 4-6 3MAR

TR=100.1 SEC
N = 35
SR= 0.35 1/SEC

I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC
1	0									
2	18	81.4	13.6	0.4	4.5	4.0	.81	.51	.18	5.6
3	10	10.0	2.7	0.4	1.0	0.9	.10	.29	.10	10.0
4	1	0.5	0.5	0.5	0.5	0.0	.00	.03	.01	100.1
5	0									
6	0									
7	6	8.2	2.0	0.8	1.4	0.4	.08	.17	.06	16.7
8	0									
9	0									

TRANSITION LINKS

2-->3 = .294
3-->2 = .294
2-->5 = .000
5-->2 = .000
2-->4 = .029
4-->2 = .029
2-->7 = .176
7-->2 = .176

P1 R157 C202
WP 8-9 3MAR

TR= 50.3 SEC
N = 19
SR= 0.38 1/SEC

I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC
1	0									
2	10	44.7	12.5	1.2	4.5	3.5	.89	.53	.20	5.0
3	6	3.2	0.6	0.4	0.5	0.1	.06	.32	.12	8.4
4	0									
5	0									
6	0									
7	3	2.3	0.9	0.6	0.8	0.1	.05	.16	.06	16.9
8	0									
9	0									

TRANSITION LINKS

2-->3 = .333
3-->2 = .333
2-->5 = .000
5-->2 = .000
2-->4 = .000
4-->2 = .000
2-->7 = .167
7-->2 = .167

P1 R157 C202
WP 9-11 3MAR

TR= 79.3 SEC
N = 21
SR= 0.26 1/SEC

I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC
1	0									
2	11	71.2	14.3	0.5	6.5	4.9	.90	.52	.14	7.2
3	4	2.3	0.7	0.4	0.6	0.1	.03	.19	.05	19.8
4	0									
5	4	2.4	0.6	0.5	0.6	0.1	.03	.19	.05	19.8
6	0									
7	2	3.4	2.6	0.9	1.7	1.2	.04	.10	.03	39.7
8	0									
9	0									

TRANSITION LINKS

2-->3 = .200
3-->2 = .200
2-->5 = .200
5-->2 = .200
2-->4 = .000
4-->2 = .000
2-->7 = .100
7-->2 = .100

P1 R157 C201
WP 12-14 3MAR

TR= 63.1 SEC
N = 15
SR= 0.24 1/SEC

I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC
1	0									
2	8	55.4	17.5	0.6	6.9	6.2	.88	.53	.13	7.9
3	3	2.7	1.1	0.8	0.9	0.2	.04	.20	.05	21.0
4	0									
5	0									
6	0									
7	4	5.1	2.4	0.7	1.3	0.8	.08	.27	.06	15.9
8	0									
9	0									

TRANSITION LINKS

2-->3 = .214
3-->2 = .214
2-->5 = .000
5-->2 = .000
2-->4 = .000
4-->2 = .000
2-->7 = .286
7-->2 = .286

TABLE E-6. EPR STATISTICS

a. Run 154

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC	TRANSITION LINKS
P1 R154 C301	1	0										2-->3 = .016
WP 6-9 3MAR	2	29	54.9	5.5	0.4	1.9	1.0	.51	.45	.32	3.1	3-->2 = .097
	3	5	6.6	1.5	0.5	1.1	0.4	.07	.10	.07	15.1	2-->5 = .419
TR= 90.4 SEC	4	0										5-->2 = .323
N = 63	5	26	27.5	2.3	0.4	1.1	0.5	.30	.41	.29	3.5	2-->4 = .000
SR= 0.70 1/SEC	6	0										4-->2 = .000
	7	1	0.9	0.9	0.9	0.9	0.0	.01	.02	.01	90.4	2-->7 = .016
	8	1	0.7	0.7	0.7	0.7	0.0	.01	.02	.01	90.4	7-->2 = .016
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC	TRANSITION LINKS
P1 R154 C301	1	0										2-->3 = .256
WP 12-15 3MAR	2	19	81.8	13.7	0.4	4.3	3.4	.51	.48	.19	5.3	3-->2 = .282
	3	12	12.4	2.0	0.5	1.0	0.5	.12	.30	.12	8.4	2-->5 = .179
TR=101.2 SEC	4	0										5-->2 = .154
N = 40	5	8	6.0	1.0	0.5	0.7	0.2	.08	.20	.09	12.7	2-->4 = .000
SR= 0.40 1/SEC	6	0										4-->2 = .000
	7	1	1.2	1.2	1.2	1.2	0.0	.01	.02	.01	101.2	2-->7 = .026
	8	0										7-->2 = .026
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC	TRANSITION LINKS
P1 R154 C301	1	0										2-->3 = .125
WP 15-18 3MAR	2	12	36.2	7.6	0.3	3.0	2.4	.72	.49	.24	4.2	3-->2 = .208
	3	5	6.5	2.3	0.6	1.3	0.6	.13	.20	.10	10.0	2-->5 = .292
TR= 50.1 SEC	4	0										5-->2 = .208
N = 25	5	7	5.7	1.1	0.5	0.8	0.2	.11	.28	.14	7.2	2-->4 = .000
SR= 0.50 1/SEC	6	0										4-->2 = .000
	7	1	1.8	1.8	1.8	1.8	0.0	.04	.04	.02	50.1	2-->7 = .042
	8	0										7-->2 = .042
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC	TRANSITION LINKS
P1 R154 C301	1	0										2-->3 = .128
WP 18-21 3MAR	2	18	37.4	7.6	0.4	2.1	1.9	.62	.45	.30	3.4	3-->2 = .205
	3	8	9.4	2.5	0.7	1.2	0.7	.16	.20	.13	7.5	2-->5 = .256
TR= 60.3 SEC	4	0										5-->2 = .154
N = 40	5	10	7.8	1.4	0.4	0.8	0.3	.13	.25	.17	6.0	2-->4 = .000
SR= 0.66 1/SEC	6	0										4-->2 = .000
	7	4	5.6	2.3	0.6	1.4	0.9	.10	.10	.07	15.1	2-->7 = .051
	8	0										7-->2 = .103
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC	TRANSITION LINKS
P1 R154 C301	1	0										2-->3 = .250
WP 21-22 3MAR	2	27	39.8	6.1	0.4	1.5	1.2	.49	.44	.34	3.0	3-->2 = .250
	3	19	19.5	2.6	0.5	1.0	0.6	.24	.31	.24	4.2	2-->5 = .117
TR= 80.6 SEC	4	0										5-->2 = .100
N = 61	5	7	7.0	1.5	0.5	1.0	0.4	.09	.11	.09	11.5	2-->4 = .000
SR= 0.76 1/SEC	6	1	0.5	0.5	0.5	0.5	0.0	.01	.02	.01	80.6	4-->2 = .000
	7	4	8.6	3.9	0.7	2.1	1.5	.11	.07	.05	20.1	2-->7 = .050
	8	3	5.3	2.2	1.5	1.8	0.4	.07	.05	.04	26.9	7-->2 = .050
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC	TRANSITION LINKS
P1 R154 C301	1	0										2-->3 = .159
WP 22-25 3MAR	2	33	31.9	2.8	0.3	1.0	0.6	.53	.47	.54	1.8	3-->2 = .174
	3	14	12.6	1.5	0.6	-0.9	0.3	.21	.20	.23	4.3	2-->5 = .014
TR= 60.7 SEC	4	10	5.2	0.7	0.4	0.5	0.1	.09	.14	.16	6.1	5-->2 = .000
N = 70	5	1	0.6	0.6	0.6	0.6	0.0	.01	.01	.02	60.7	2-->4 = .130
SR= 1.15 1/SEC	6	7	3.7	1.0	0.3	0.5	0.2	.06	.10	.12	8.7	4-->2 = .130
	7	5	6.7	2.0	0.8	1.3	0.5	.11	.07	.08	12.1	2-->7 = .058
	8	0										7-->2 = .058
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC	TRANSITION LINKS
P1 R154 C301	1	0										2-->3 = .153
WP 25-29 3MAR	2	79	85.9	2.9	0.3	1.1	0.5	.61	.48	.55	1.8	3-->2 = .178
	3	29	24.5	1.3	0.5	0.8	0.2	.17	.19	.21	4.8	2-->5 = .049
TR=140.4 SEC	4	9	3.5	0.5	0.4	0.4	0.1	.02	.05	.05	17.5	5-->2 = .049
N = 164	5	10	4.7	0.5	0.4	0.5	0.1	.03	.06	.07	14.0	2-->4 = .049
SR= 1.17 1/SEC	6	25	17.2	1.0	0.3	0.5	0.2	.12	.21	.25	4.0	4-->2 = .043
	7	3	4.7	2.0	1.0	1.6	0.5	.03	.02	.02	46.8	2-->7 = .018
	8	0										7-->2 = .012
	9	0										

TABLE E-6 (Concluded)

b. Run 155

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR_{-1} SEC	LI SEC	TRANSITION LINKS
P1 R155 C302	1	0										2-->3 = .214
WP 8-9 3MAR	2	15	76.6	24.6	0.4	5.1	5.7	.95	.52	.17	6.0	3-->2 = .214
	3	6	3.5	0.8	0.4	0.6	0.1	.04	.21	.07	19.1	2-->5 = .036
TR= 90.4 SEC	4	0										5-->2 = .036
N = 29	5	1	0.6	0.6	0.6	0.6	0.0	.01	.03	.01	90.4	2-->4 = .000
SR= 0.32 1/SEC	6	0										4-->2 = .000
	7	5	5.2	1.3	0.7	1.0	0.2	.06	.17	.06	19.1	2-->7 = .179
	8	2	4.3	3.5	0.9	2.2	1.9	.05	.07	.02	45.2	7-->2 = .179
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR_{-1} SEC	LI SEC	TRANSITION LINKS
P1 R155 C302	1	0										2-->3 = .444
WP 12-15 3MAR	2	10	44.2	24.8	0.9	9.4	7.1	.92	.53	.10	10.1	3-->2 = .444
	3	8	5.0	1.5	0.4	0.6	0.4	.05	.42	.08	12.6	2-->5 = .000
TR=101.1 SEC	4	0										5-->2 = .000
N = 19	5	0										2-->4 = .000
SR= 0.19 1/SEC	6	0										4-->2 = .000
	7	1	2.0	2.0	2.0	2.0	0.0	.02	.05	.01	101.1	2-->7 = .056
	8	0										7-->2 = .056
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR_{-1} SEC	LI SEC	TRANSITION LINKS
P1 R155 C302	1	0										2-->3 = .429
WP 15-19 3MAR	2	8	42.2	12.0	0.6	5.3	4.1	.85	.53	.15	5.2	3-->2 = .429
	3	6	7.2	2.0	0.8	1.2	0.5	.14	.40	.12	8.2	2-->5 = .071
TR= 49.9 SEC	4	0										5-->2 = .071
N = 15	5	1	0.5	0.5	0.5	0.5	0.0	.01	.07	.02	49.9	2-->4 = .000
SR= 0.30 1/SEC	6	0										4-->2 = .000
	7	0										2-->7 = .000
	8	0										7-->2 = .000
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR_{-1} SEC	LI SEC	TRANSITION LINKS
P1 R155 C302	1	0										2-->3 = .188
WP 18-21 3MAR	2	9	52.5	17.0	0.4	5.9	5.6	.88	.53	.15	6.7	3-->2 = .188
	3	3	2.4	1.2	0.4	0.5	0.4	.04	.18	.05	20.0	2-->5 = .000
TR= 59.9 SEC	4	0										5-->2 = .000
N = 17	5	0										2-->4 = .000
SR= 0.28 1/SEC	6	0										4-->2 = .000
	7	5	5.0	1.2	0.8	1.0	0.2	.08	.29	.08	12.0	2-->7 = .313
	8	0										7-->2 = .313
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR_{-1} SEC	LI SEC	TRANSITION LINKS
P1 R155 C302	1	0										2-->3 = .316
WP 21-22 3MAR	2	10	72.3	26.3	0.4	7.2	7.6	.90	.50	.12	8.0	3-->2 = .263
	3	6	4.1	1.0	0.4	0.7	0.2	.05	.30	.07	13.4	2-->5 = .000
TR= 80.3 SEC	4	0										5-->2 = .000
N = 20	5	0										2-->4 = .000
SR= 0.25 1/SEC	6	0										4-->2 = .000
	7	4	4.0	1.3	0.6	1.0	0.3	.05	.20	.05	20.1	2-->7 = .211
	8	0										7-->2 = .211
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR_{-1} SEC	LI SEC	TRANSITION LINKS
P1 R155 C302	1	0										2-->3 = .500
WP 22-25 3MAR	2	9	54.9	16.5	0.8	6.1	6.1	.91	.52	.15	6.7	3-->2 = .500
	3	8	5.6	1.0	0.4	0.7	0.2	.09	.47	.13	7.6	2-->5 = .000
TR= 60.4 SEC	4	0										5-->2 = .000
N = 17	5	0										2-->4 = .000
SR= 0.28 1/SEC	6	0										4-->2 = .000
	7	0										2-->7 = .000
	8	0										7-->2 = .000
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR_{-1} SEC	LI SEC	TRANSITION LINKS
P1 R155 C302	1	0										2-->3 = .313
WP 25-29 3MAR	2	17	129.2	25.8	0.8	7.6	7.8	.92	.52	.12	8.3	3-->2 = .313
	3	10	5.7	1.0	0.4	0.5	0.2	.04	.30	.07	14.1	2-->5 = .000
TR=140.5 SEC	4	0										5-->2 = .000
N = 33	5	0										2-->4 = .000
SR= 0.23 1/SEC	6	0										4-->2 = .000
	7	6	5.6	1.4	0.6	0.9	0.3	.04	.19	.04	23.4	2-->7 = .188
	8	0										7-->2 = .188
	9	0										

TABLE E-7. EPR STATISTICS

a. Run 148

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR_{-1} SEC	LI SEC	TRANSITION LINKS
P3 R148 C301	1	3	2.0	0.7	0.6	0.7	0.0	.02	.02	.03	36.9	2-->3 = .156
WP 8-9 1MAR	2	52	45.9	2.0	0.4	0.9	0.4	.42	.42	.47	2.1	3-->2 = .156
	3	25	25.5	2.4	0.4	1.1	0.5	.24	.20	.23	4.4	2-->5 = .156
TR=110.3 SEC	4	6	4.4	1.2	0.5	0.7	0.3	.04	.05	.05	18.4	5-->2 = .197
N = 127	5	27	22.1	1.5	0.4	0.9	0.2	.20	.22	.24	4.1	2-->4 = .033
SR= 1.12 1/SEC	6	5	4.4	1.5	0.4	0.9	0.4	.04	.04	.05	22.0	4-->2 = .025
	7	5	5.2	1.3	0.6	1.0	0.5	.05	.04	.05	22.0	2-->7 = .033
	8	0										7-->2 = .033
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR_{-1} SEC	LI SEC	TRANSITION LINKS
P3 R148 C301	1	2	1.3	0.3	0.5	0.4	0.2	.01	.02	.02	50.2	2-->3 = .084
WP 12-15 1MAR	2	37	50.5	4.4	0.2	1.6	1.2	.50	.44	.37	2.7	3-->2 = .108
	3	12	13.2	1.9	0.4	1.1	0.4	.13	.14	.12	8.4	2-->5 = .217
TR=100.4 SEC	4	4	2.0	0.5	0.4	0.5	0.1	.02	.05	.04	25.1	5-->2 = .217
N = 84	5	21	15.7	1.4	0.2	0.7	0.3	.16	.25	.21	4.8	2-->4 = .048
SR= 0.84 1/SEC	6	1	0.4	0.4	0.4	0.4	0.0	.00	.01	.01	100.4	4-->2 = .036
	7	7	7.4	3.1	0.5	1.0	0.9	.07	.08	.07	14.3	2-->7 = .060
	8	0										7-->2 = .048
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR_{-1} SEC	LI SEC	TRANSITION LINKS
P3 R148 C301	1	0										2-->3 = .047
WP 15-18 1MAR	2	22	34.3	3.5	0.4	1.6	0.9	.67	.50	.43	2.3	3-->2 = .047
	3	2	1.6	0.9	0.7	0.8	0.1	.03	.05	.04	25.8	2-->5 = .372
TR= 51.5 SEC	4	1	1.0	1.0	1.0	1.0	0.0	.02	.02	.02	51.5	5-->2 = .395
N = 44	5	17	13.3	1.2	0.5	0.8	0.2	.26	.29	.33	3.0	2-->4 = .023
SR= 0.85 1/SEC	6	0										4-->2 = .023
	7	2	1.4	0.8	0.6	0.7	0.1	.03	.05	.04	25.8	2-->7 = .047
	8	0										7-->2 = .047
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR_{-1} SEC	LI SEC	TRANSITION LINKS
P3 R148 C301	1	1	0.6	0.6	0.6	0.6	0.0	.01	.02	.02	59.5	2-->3 = .115
WP 18-21 1MAR	2	26	33.2	4.6	0.4	1.5	1.2	.54	.49	.44	2.3	3-->2 = .135
	3	7	9.6	4.2	0.6	1.4	1.3	.16	.12	.12	8.5	2-->5 = .269
TR= 59.5 SEC	4	4	2.7	0.8	0.5	0.7	0.1	.04	.05	.07	14.9	5-->2 = .250
N = 53	5	14	8.0	0.9	0.4	0.6	0.1	.13	.26	.24	4.2	2-->4 = .077
SR= 0.89 1/SEC	6	1	0.4	0.4	0.4	0.4	0.0	.01	.02	.02	59.5	4-->2 = .058
	7	0										2-->7 = .000
	8	0										7-->2 = .000
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR_{-1} SEC	LI SEC	TRANSITION LINKS
P3 R148 C301	1	0										2-->3 = .106
WP 21-22 1MAR	2	41	43.6	3.2	0.4	1.1	0.6	.53	.48	.50	2.0	3-->2 = .118
	3	11	9.6	1.5	0.6	0.9	0.2	.12	.13	.13	7.4	2-->5 = .200
TR= 81.6 SEC	4	5	3.5	0.8	0.6	0.7	0.0	.04	.05	.06	16.3	5-->2 = .176
N = 85	5	17	13.6	1.9	0.4	0.8	0.4	.17	.20	.21	4.8	2-->4 = .059
SR= 1.05 1/SEC	6	2	1.1	0.7	0.4	0.6	0.2	.01	.02	.02	40.8	4-->2 = .035
	7	9	9.4	2.8	0.5	1.0	0.7	.11	.10	.11	9.1	2-->7 = .082
	8	1	0.9	0.9	0.9	0.9	0.0	.01	.01	.01	81.6	7-->2 = .106
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR_{-1} SEC	LI SEC	TRANSITION LINKS
P3 R148 C301	1	2	0.8	0.5	0.3	0.4	0.1	.01	.02	.03	31.1	2-->3 = .046
WP 22-25 1MAR	2	41	29.7	1.7	0.4	0.7	0.3	.48	.47	.66	1.5	3-->2 = .080
	3	7	5.7	1.0	0.6	0.8	0.1	.09	.08	.11	8.9	2-->5 = .276
TR= 62.1 SEC	4	3	1.5	0.6	0.4	0.5	0.1	.02	.03	.05	20.7	5-->2 = .264
N = 88	5	26	18.5	1.4	0.4	0.7	0.2	.30	.30	.42	2.4	2-->4 = .034
SR= 1.42 1/SEC	6	3	1.7	0.6	0.5	0.6	0.0	.03	.03	.05	20.7	4-->2 = .034
	7	6	4.3	0.8	0.6	0.7	0.1	.07	.07	.10	10.4	2-->7 = .057
	8	0										7-->2 = .057
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR_{-1} SEC	LI SEC	TRANSITION LINKS
P3 R148 C301	1	4	2.7	1.0	0.4	0.7	0.3	.02	.03	.03	35.6	2-->3 = .081
WP 25-29 1MAR	2	78	77.5	2.9	0.3	1.0	0.6	.54	.48	.55	1.8	3-->2 = .081
	3	14	14.3	1.6	0.7	1.0	0.2	.10	.09	.10	10.2	2-->5 = .269
TR=142.5 SEC	4	6	4.1	1.6	0.4	0.7	0.4	.03	.04	.04	23.8	5-->2 = .262
N = 161	5	44	33.1	1.4	0.4	0.9	0.2	.23	.27	.31	3.2	2-->4 = .038
SR= 1.13 1/SEC	6	9	5.8	1.0	0.3	0.6	0.3	.04	.06	.06	15.9	4-->2 = .031
	7	4	2.8	0.9	0.6	0.7	0.1	.02	.02	.03	35.6	2-->7 = .019
	8	2	2.1	1.3	0.8	1.0	0.3	.01	.01	.01	71.3	7-->2 = .025
	9	0										

TABLE E-7 (Concluded)

b. Run 149

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC	TRANSITION LINKS
P3 R149 C302	1	2	1.1	0.5	0.5	0.5	0.0	.01	.03	.02	44.9	2-->3 = .147
WP 9-9 1MAR	2	34	66.1	7.1	0.3	1.9	1.5	.74	.49	.38	2.6	3-->2 = .147
	3	11	7.6	1.0	0.3	0.7	0.2	.08	.16	.12	9.2	2-->5 = .147
TR= 99.7 SEC	4	2	1.3	1.0	0.4	0.7	0.4	.01	.03	.02	41.8	5-->2 = .162
N = 69	5	11	5.5	0.9	0.3	0.5	0.1	.06	.16	.12	9.2	2-->4 = .029
SR= 0.69 1/SEC	6	0										4-->2 = .029
	7	9	6.1	1.5	0.5	0.9	0.3	.09	.13	.10	10.0	2-->7 = .132
	8	0										7-->2 = .118
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC	TRANSITION LINKS
P3 R149 C302 WP	1	2	0.9	0.5	0.4	0.4	0.1	.01	.02	.02	50.4	2-->3 = .100
12-15 1MAR	2	37	69.2	13.4	0.3	1.9	2.3	.69	.46	.37	2.7	3-->2 = .088
	3	10	11.8	2.4	0.3	1.2	0.5	.12	.12	.10	10.1	2-->5 = .200
TR=100.8 SEC	4	7	3.8	0.7	0.4	0.5	0.1	.04	.09	.07	14.4	5-->2 = .213
N = 81	5	19	11.3	1.0	0.4	0.6	0.2	.11	.23	.19	5.3	2-->4 = .075
SR= 0.80 1/SEC	6	1	1.0	1.0	1.0	1.0	0.0	.01	.01	.01	100.8	4-->2 = .075
	7	5	4.0	1.0	0.6	0.5	0.1	.04	.06	.05	20.2	2-->7 = .050
	8	0										7-->2 = .050
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC	TRANSITION LINKS
P3 R149 C302	1	0										2-->3 = .095
WP 15-18 1MAR	2	11	42.0	8.4	0.6	3.8	2.8	.84	.50	.22	4.5	3-->2 = .095
	3	2	1.5	1.0	0.4	0.7	0.4	.03	.09	.04	24.9	2-->5 = .238
TR= 49.8 SEC	4	0										5-->2 = .238
N = 22	5	5	3.0	0.8	0.4	0.6	0.1	.06	.23	.10	10.0	2-->4 = .000
SR= 0.44 1/SEC	6	0										4-->2 = .000
	7	4	3.3	0.9	0.7	0.8	0.1	.07	.18	.08	12.5	2-->7 = .143
	8	0										7-->2 = .190
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC	TRANSITION LINKS
P3 R149 C302	1	0										2-->3 = .250
WP 18-21 1MAR	2	13	49.3	12.5	0.8	3.8	3.9	.82	.52	.22	4.6	3-->2 = .250
	3	6	5.3	1.5	0.6	0.9	0.4	.09	.24	.10	10.0	2-->5 = .083
TR= 60.3 SEC	4	0										5-->2 = .083
N = 25	5	2	0.9	0.4	0.4	0.4	0.0	.01	.08	.03	30.1	2-->4 = .000
SR= 0.41 1/SEC	6	0										4-->2 = .000
	7	4	4.7	1.7	0.8	1.2	0.4	.08	.16	.07	15.1	2-->7 = .167
	8	0										7-->2 = .167
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC	TRANSITION LINKS
P3 R149 C302	1	2	1.3	1.1	0.3	0.7	0.6	.02	.03	.02	40.1	2-->3 = .213
WP 21-22 1MAR	2	33	39.3	2.8	0.3	1.2	0.7	.49	.43	.41	2.4	3-->2 = .187
	3	19	18.1	2.2	0.5	1.0	0.4	.23	.25	.24	4.2	2-->5 = .053
TR= 80.2 SEC	4	9	6.6	1.0	0.4	0.7	0.3	.08	.12	.11	8.9	5-->2 = .053
N = 76	5	4	3.2	1.5	0.5	0.8	0.5	.04	.05	.05	20.0	2-->4 = .107
SR= 0.95 1/SEC	6	2	1.1	0.7	0.4	0.5	0.2	.01	.03	.02	40.1	4-->2 = .120
	7	6	10.0	4.2	0.6	1.7	1.4	.13	.08	.07	13.4	2-->7 = .053
	8	1	0.5	0.5	0.5	0.5	0.0	.01	.01	.01	80.2	7-->2 = .067
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC	TRANSITION LINKS
P3 R149 C302	1	1	0.6	0.6	0.6	0.6	0.0	.01	.02	.02	61.6	2-->3 = .186
WP 22-25 1MAR	2	30	30.9	3.4	0.4	1.0	0.6	.50	.50	.49	2.1	3-->2 = .186
	3	11	16.0	4.9	0.5	1.5	1.4	.26	.18	.18	5.6	2-->5 = .102
TR= 61.6 SEC	4	6	3.1	0.6	0.3	0.5	0.1	.05	.10	.10	10.3	5-->2 = .085
N = 60	5	6	3.2	0.6	0.4	0.5	0.1	.05	.10	.10	10.3	2-->4 = .102
SR= 0.97 1/SEC	6	0										4-->2 = .102
	7	5	7.1	2.6	0.5	1.4	0.9	.11	.08	.08	12.3	2-->7 = .085
	8	1	0.9	0.9	0.9	0.9	0.0	.01	.02	.02	61.6	7-->2 = .085
	9	0										

	I	N(I)	TD SEC	TMX SEC	TMN SEC	TB SEC	SD SEC	DF	LF	LR SEC^{-1}	LI SEC	TRANSITION LINKS
P3 R149 C302	1	2	1.0	0.6	0.4	0.5	0.2	.01	.02	.01	70.7	2-->3 = .202
WP 25-29 1MAR	2	57	97.4	7.4	0.4	1.7	1.3	.69	.50	.40	2.5	3-->2 = .211
	3	24	21.0	3.7	0.4	0.9	0.6	.15	.21	.17	5.9	2-->5 = .140
TR=141.3 SEC	4	10	6.9	0.9	0.4	0.7	0.2	.05	.09	.07	14.1	5-->2 = .132
N = 115	5	16	7.4	0.9	0.3	0.5	0.1	.05	.14	.11	8.8	2-->4 = .088
SR= 0.81 1/SEC	6	0										4-->2 = .088
	7	6	7.6	2.7	0.8	1.3	0.7	.05	.05	.04	23.6	2-->7 = .044
	8	0										7-->2 = .044
	9	0										

TABLE E-8a. TRANSITION LINK MATRICES FOR RUNS 261 AND 257

CONDITION : P4 R261 C201   WP 4-6 20MAR

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1			.009				.009	
2	.009		.200		.036	.155	.009	
3	.009	.300				.009	.009	
4			.009					
5		.018	.018					
6		.082	.064	.009			.009	
7		.009	.027					
8								

CONDITION : P4 R257 C202   WP 4-6 20MAR

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1		.011						
2	.011		.272		.022	.109	.054	
3		.293				.022		
4								
5		.022						
6		.120	.011					
7		.022	.033					
8								

TABLE E-8b

CONDITION : P4 R261 C201 WP 8-9 20MAR

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1		.034						
2	.034		.159		.051	.186	.017	
3		.186				.017		
4								
5		.034				.017		
6		.186	.017				.017	
7		.017	.017					
8								

CONDITION : P4 R257 C202 WP 8-9 20MAR

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1		.114						
2	.091		.205			.045	.136	
3	.023	.182						
4								
5								
6		.045						
7		.159						
8								

TABLE E-8c

CONDITION : P4 R261 C201 WP 9-11 20MAR

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1		.129				.011	.011	
2	.140		.226		.011	.043	.032	
3		.258					.011	
4								
5			.011					
6	.011	.043	.011					
7	.011	.022	.022					
8								

CONDITION : P4 R257 C202 WP 9-11 20MAR

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1		.096					.058	
2	.115		.269			.019	.019	
3		.250					.038	
4								
5								
6		.019						
7	.038	.058	.019					
8								

TABLE E-8d

CONDITION : P4 R261 C201   WP 12-14 20MAR

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1		.143	.020					
2	.163		.122		.102	.041	.041	
3		.163						
4								
5		.122						
6			.020		.020			
7		.041						
8								

CONDITION : P4 R257 C202   WP 12-14 20MAR

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1		.176						
2	.176						.294	
3		.059						
4								
5								
6								
7		.235	.059					
8								

TABLE E-9a. TRANSITION LINK MATRICES FOR RUNS 156 AND 157

CONDITION : P1 R156 C201 WAY PTS 4 TO 6 2MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.162	.324				
3		.190						
4		.286	.038					
5								
6								
7								
8								

CONDITION : P1 R157 C202 WAY PTS 4 TO 6 3MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.294	.029			.176	
3		.294						
4		.029						
5								
6								
7		.176						
8								

TABLE E-9b

CONDITION : P1 R156 C201 WAY PTS 8 TO 9 3MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.212	.058		.212		
3		.250						
4		.058						
5								
6		.192	.019					
7								
8								

CONDITION : P1 R157 C202 WAY PTS 8 TO 9 3MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.333				.167	
3		.333						
4								
5								
6								
7		.167						

TABLE E-9c

CONDITION : P1 R156 C201 WAY PTS 9 TO 11 3MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.409		.023		.045	
3		.409			.023			
4								
5		.045						
6								
7		.045						
8								

CONDITION : P1 R157 C202 WAY PTS 9 TO 11 3MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.200		.200		.100	
3		.200						
4								
5		.200						
6								
7		.100						
8								

TABLE E-9d

CONDITION : P1 R156 C201 WAY PTS 12 TO 14 3MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.050		.450			
3		.050						
4								
5		.450						
6								
7								
8								

CONDITION : P1 R157 C201 WAY PTS 12 TO 14 3MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.214				.286	
3		.214						
4								
5								
6								
7		.286						
8								

TABLE E-10a. TRANSITION LINK MATRICES FOR RUNS 154 AND 155

CONDITION : P1 R154 C301 WAY PTS 8 TO 9 3MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.016		.419		.016	
3		.097						
4								
5		.323	.081					.016
6								
7		.016						
8		.016						

CONDITION : P1 R155 C302 WAY PTS 8 TO 9 3MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.214		.036		.179	.071
3		.214						
4								
5		.036						
6								
7		.179						
8		.071						

TABLE E-10b

CONDITION : P1 R154 C201 WAY PTS 12 TO 15 3MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.256		.179		.026	
3		.282			.026			
4								
5		.154	.051					
6								
7		.026						
8								

CONDITION : P1 R155 C302 WAY PTS 12 TO 15 3MAR76

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.444				.056	
3		.444						
4								
5								
6								
7		.056						
8								

TABLE E-10c

CONDITION : P1 R154 C301 WAY PTS 15 TO 18 3MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.125		.292		.042	
3		.208						
4								
5		.208	.083					
6								
7		.042						
8								

CONDITION : P1 R155 CASE 302 WAY PTS 15 TO 18 3MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.429		.071			
3		.429						
4								
5		.071						
6								
7								
8								

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TABLE E-10d

CONDITION : P1 R154 C301 WAY PTS 18 TO 21 3MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.128		.256		.051	
3		.205						
4								
5		.154	.077				.026	
6								
7		.103						
8								

CONDITION : P1 R155 C302 WAY PTS 18 TO 21 3MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.188				.313	
3		.188						
4								
5								
6								
7		.313						
8								

TABLE E-10e

CONDITION : P1 R154 C301 WAY PTS 21 TO 22 2MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.250		.117	.017	.050	.017
3		.250					.017	.033
4								
5		.100	.017					
6		.017						
7		.050	.017					
8		.017	.033					

CONDITION : P1 R155 C302 WAY PTS 21 TO 22 2MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.316				.211	
3		.263						
4								
5								
6								
7		.211						
8								

TABLE E-10f

CONDITION : F1 R154 C301 WAY PTS 22 TO 25 3MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.159	.130	.014	.101	.058	
3		.174		.014			.014	
4		.130	.014					
5			.014					
6		.101						
7		.058	.014					
8								

CONDITION : F1 R155 C302 WAY PTS 22 TO 25 3MAR76

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.500					
3		.500						
4								
5								
6								
7								
8								

TABLE E-10g

CONDITION : P1 R154 C301 WAY PTS 25 TO 29 3MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.153	.049	.049	.209	.019	
3		.178						
4		.043	.006					
5		.049	.006			.006		
6		.196	.012		.006			
7		.012			.006			
8								

CONDITION : P1 R155 C302 WAY PTS 25 TO 29 3MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.313				.188	
3		.313						
4								
5								
6								
7		.188						
8								

TABLE E-11a. TRANSITION LINK MATRICES FOR RUNS 148 AND 149

ENTER DATA FILE NAME : HAAG

CONDITION : P3 R148 C301 WAY PTS 8 TO 9 1MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1		.008			.008	.008		
2	.016		.156	.033	.156	.025	.033	
3		.156		.008	.041			
4		.025	.008			.008	.008	
5		.197	.025					
6	.008	.008		.008	.016			
7		.033	.008					
8								

CONDITION : P3 R149 C302 WAY PTS 8 TO 9 1MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1		.029						
2	.029		.147	.029	.147		.132	
3		.147			.015			
4		.029						
5		.162						
6								
7		.118	.015					
8								

TABLE E-11b

CONDITION : F3 R148 C301 WAY PTS 12 TO 15 1MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1		.012					.012	
2	.024		.084	.048	.217	.012	.060	
3		.108			.024			
4		.036			.012			
5		.217	.024				.012	
6		.012						
7		.048	.036					
8								

CONDITION : F3 R149 C302 WAY PTS 12 TO 15 1MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1		.025						
2	.025		.100	.075	.200	.012	.050	
3		.088			.025			
4		.075			.012			
5		.213	.012				.012	
6		.012						
7		.050	.012					
8								

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TABLE E-11c

CONDITION : P3 R148 C301 WAY PTS 15 TO 18 1MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.047	.023	.372		.047	
3		.047						
4		.023						
5		.395						
6								
7		.047						
8								

CONDITION : P3 R149 C302 WAY PTS 15 TO 18 1MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.095		.238		.143	
3		.095						
4								
5		.238						
6								
7		.190						
8								

TABLE E-11d

CONDITION : P3 R148 C301 WAY PTS 18 TO 21 1MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1		.019						
2	.019		.115	.077	.269	.019		
3		.135						
4		.058						
5		.250	.019					
6		.019						
7								
8								

CONDITION : P3 R149 C302 WAY PTS 18 TO 21 1MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.250		.083		.167	
3		.250						
4								
5		.083						
6								
7		.167						
8								

TABLE E-11e

CONDITION : P3 R148 CS01 WAY PTS 21 TO 22 1MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1								
2			.106	.059	.200	.012	.082	.012
3		.118				.012		
4		.035					.024	
5		.176	.024					
6		.024						
7		.106						
8		.012						

CONDITION : P3 R149 CS02 WAY PTS 21 TO 22 1MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1						.013		.013
2	.013		.213	.107	.053		.053	
3	.013	.187				.013	.027	
4		.120						
5		.053						
6		.013	.013					
7		.067	.013					
8				.013				

TABLE E-11f

CONDITION : P3 R148 C301 WAY PTS 22 TO 25 1MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1		.023						
2	.011		.046	.034	.276	.034	.057	
3		.080						
4		.034						
5		.264	.023				.011	
6	.011	.011	.011					
7		.057			.011			
8								

CONDITION : P3 R149 C302 WAY PTS 22 TO 25 1MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1		.017						
2	.017		.186	.102	.102		.085	.017
3		.186						
4		.102						
5		.085						
6								
7		.085						
8		.017						

TABLE E-11g

CONDITION : P3 R148 C301 WAY PTS 25 TO 29 1MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1		.019						.006
2	.019		.081	.038	.269	.056	.019	
3		.081					.006	
4	.006	.031						
5		.262	.006					.006
6		.056						
7		.025						
8		.006			.006			

CONDITION : P3 R149 C302 WAY PTS 25 TO 29 1MAR76

ALL INSTRUMENTS

1-WAY TRANSITION LINKS

	1	2	3	4	5	6	7	8
1		.018						
2	.018		.202	.088	.140		.044	
3		.211						
4		.088						
5		.132					.009	
6								
7		.044	.009					
8								

APPENDIX F

INSPIRATIONS FOR EYE MOVEMENT STUDIES IN FLIGHT CONTROL AND MONITORING TASK

(From Ref. 1*)

The measurement of pilots' eye fixations and movements about the instrument panel within the cockpit has attracted research for over a quarter of a century (e.g., in Ref. 2, see Refs. 67-77, 82-85, 93, and 96). Not surprisingly, the motivation for the earliest available results seems to have been to compare pilot fatigue under instrument flight rules induced by differences in "scanning workload" among instruments between the Standard (circa 1944) Army Air Force and Royal Air Force instrument panels. To explain statistically significantly different experimental results on the two different panel arrangements, an embryonic display arrangement hypothesis was set forth in 1944: "Differences between the time spent on the various instruments in the two panel arrangements may be explained by the hypothesis that pilots tend to spend more time on the centrally located instruments, and particularly on the instrument located in the top center position. While not definite, this finding suggests that instrument panel designs should place the most important instrument for instrument flight in the top center position of the panel, and the next most important instrument in the lower center position." (From Ref. 67 in Ref. 2)

Other early studies of eye movements of flight personnel were concerned with open-loop signal detection, for example, searching for targets on radar scopes, monitoring multi-engine performance for threshold-exceedences, and establishing minimum visual angles external to the cockpit under visual flight rules.

However, the inspiration for much of this eye movement work was founded on the belief that the cues used by the pilot in controlling flight would be revealed by noting the (separated) instruments upon which the fovea of the eye was fixating inside the cockpit under instrument flight rules, and

*Unless otherwise noted, reference numbers in this appendix refer to reference list at the end of this appendix, page F-6.

by correlating the directions of fixations external to the cockpit with significant ground-based cues in landing approaches under visual flight rules. Information about the useful instrument flight control cues was believed to be fundamental to an understanding of the function served by flight instruments. It was expected that this understanding would, in turn, form a basis for improving the design of aircraft instruments, increasing the efficiency of instrument flight training, and simplifying the task of instrument flying.

Today we are still working to fulfill this expectation, because the premise on which it was founded twenty years ago has been shown to be only a partial truth for several reasons. Pilots develop an ability to operate effectively on parafoveally and peripherally perceived information (Ref. 3), albeit with some limitations (Ref. 4), and, of course, on reinforcing (i.e., nonconflicting) motion and aural cues. Further, there is considerable indirect evidence (e.g., Ref. 5) that in "stare mode" circumstances fixing the eye-point-of-regard serves merely to stabilize the eyeball for good parafoveal viewing, so that the fixation point may be unconnected with the information actually used, or even perceived, by the pilot. We cannot say that what is being fixated necessarily corresponds to an input.

The inspiration for the earliest pilots' eye movement studies — that scan patterns might be useful for workload measures — was revived more recently in Ref. 6. While scan patterns are indeed relevant to workload, the connection is not simple. The eye requires fixation to keep the eyeball stable, so there is a kind of Parkinson's Law for the eyeball — the sum of the fixation dwell times on the instruments expands or contracts to equal the time available (neglecting saccadic times). There is, of course, a minimum dwell time of about 0.4 sec per instrument, so it is possible to contrive saturated conditions where the control task demands pilot fixations on too many instruments too often in order to maintain control. But the interpretation of such results would often be ambiguous if one is looking for the pilot's inputs.

The early eye movement studies referenced above considered fixations as a function of the overall pilot-aircraft system task, such as landing approach, but completely apart from the controlled element dynamics. To get at the total "pilotability" problem, we proposed some years ago that pilot-aircraft system dynamic techniques be applied to the display area. Under coordinated NASA-ARC and JANAIR sponsorship we have in the last four years developed, refined, and elaborated a theory (Refs. 2, 7, and 8) applied it to a number of interesting situations (Refs. 7, 8, and 9), and have supported and augmented the theoretical development in crucial areas with experimental efforts (Refs. 9, 10, and 11).

SCANNING PHENOMENA TO BE DESCRIBED

Scanning of an instrument panel permits the displayed information to be sampled foveally. The foveal fixation dwell time interval is variable, but averages about one-half second among conventional separated flight instruments and one second or more among integrated or combined flight instruments. Information outside the foveal region may perhaps be observed parafoveally. One can measure the transition of foveal fixation between two instruments and the pause or dwell of the visual axis of fixation on an informative part of the instrument (for example, the tip of a pointer) before beginning the next transition. Measurements have shown variability in the time interval which elapses between successive fixations on the same instrument. This time interval is called the scan interval or sampling interval. It will, in general, exhibit a different ensemble average value for each point of fixation. Besides instrument-to-instrument scans, scanning may occur among the elements of combined displays, or between a display and a point of regard in the external visual field during IFR-to-VFR transition.

Besides instrument-to-instrument scans, scanning occurs between elements within combined or integrated symbolic and pictorial displays. For example, secondary fixation transitions within the two-axis attitude director on various symbols, indices, and scales have been observed in the experiments of Ref. 10. Among several pictorial examples of pilot's scanning patterns on different instrument panel arrangements in Ref. 5, there is shown an internal pattern on an integrated contact analog display. Obviously, one must speak of a foveal scanning pattern among "symbols" in the case of the contact analog or some other integrated display, rather than among "instruments" as we shall do in most of what follows.

Furthermore, an observable foveal scanning pattern may be accompanied by a parafoveal scanning pattern of awareness which is not directly observable by measuring eye movements. However, the presence of parafoveal awareness is indirectly observable by its influence on the pilot's describing function.

Although we shall be speaking primarily about the visual modality, the pilot can also choose to use or ignore motion and aural cues. While this is not quite like sampling, the more or less continuous use of the vestibular or aural modality is akin to a process of selection when these cues reinforce the visual modality.

The proportion of the total number of fixations which fall upon a particular instrument is called the average look fraction for that instrument. Its upper bound is one-half, which implies that every other fixation or look is on that instrument having a look fraction equal to one-half. The look fraction represents the ensemble probability of fixation for each instrument, and the sum of all look fractions on the instrument arrangement must equal unity.

The proportion of the total time during which fixations dwell on a particular instrument is called the average dwell fraction for that instrument. Since the cumulative sum of all dwell fractions, including blinks and distractions, must also equal unity, by definition, the dwell fraction is also termed "fractional scanning workload" or "temporal probability of fixation."

The proportion of all fixation transitions which go in the same direction between a pair of instruments is called the "one-way link-value" in the specified direction. The sum of the two one-way link-values between a pair of instruments is called the "two way" link value. In 1950, new research extended the display arrangement hypothesis of 1944 to suggest that the pattern of link values between instruments is indicative of the goodness of different panel arrangements. Since, in point of fact, the scanning statistics are quite stationary over measurement intervals as short as 100 sec, different one way link values between the same pair of instruments are also indicative of determinism in scan patterns. The results in Ref. 10 show no evidence of circulatory determinism in scanning traffic. This simplification proves useful in making predictions of scanning behavior.

The pilot using a flight director or automatic system for control wants to spend a certain amount of time monitoring the confidence-inspiring situation information. This is how he gains and maintains confidence in the flight director or automatic system. We speak of this time that he spends monitoring the situation information as his monitoring workload margin. It can be expressed either as a fraction of time, the dwell fraction, or as the fraction of the number of looks, the look fraction. Sufficient monitoring margin is essential to the pilot to perceive exceedence of tolerances or specified values related to the task. Most of the pilot's status displays present the flight motion variables which are constituents of the automatic and flight director commands. Other status displays are common to engine or radar instrument monitoring, where the effects of manual control are not displayed.

One purpose in the research reported in Refs. 12 and 13 has been to improve the models for predicting the partition of the pilot's time between the monitoring margin and the fraction of time required for control. Estimates of average monitoring display threshold exceedence frequencies in terms of a level of pilot confidence in his situation, coupled with two conservative principles, viz., the conservation of look fraction and of dwell fraction, provide the basis for the partition of scanning workload for monitoring and control. The results of the partition provide estimates of the average scanning frequencies, dwell intervals, look intervals, link values, and other scanning parameters for monitoring and control.

The principal cost of the pilot's scanning behavior is an increased "remnant" which depends on the scanning frequency, variations therein, and the fixation dwell interval, as well as the variance of the displayed (and perceived) signal. The remnant acts like an injected noise and is the real cause of saturation in using multi-instrument displays, because it may conspire to compromise the pilot's confidence in his situation, to compromise his performance, or both, so that his subjective impression of the overall task workload will be high. So, as we said at the outset, the measurement of eye fixation is certainly connected with pilot inputs and workload, but the connection is by no means a simple one.

REFERENCES FOR APPENDIX F

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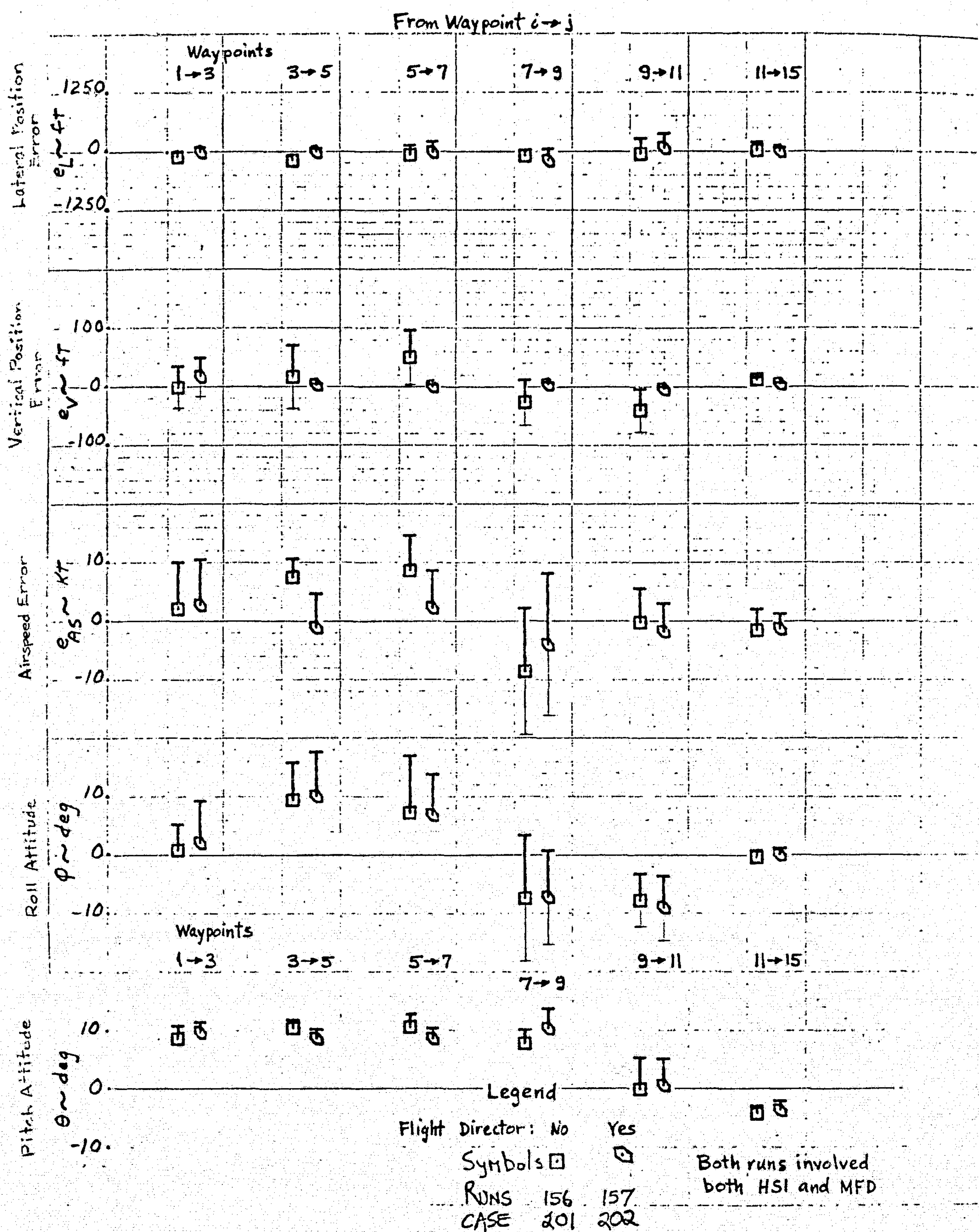
9. Allen, R. W., and H. R. Jex, An Experimental Investigation of Compensatory and Pursuit Tracking Displays with Rate and Acceleration Control Dynamics and a Disturbance Input, NASA CR-1082, June 1968.

10. Weir, David H., and Richard H. Klein, The Measurement and Analysis of Pilot Scanning and Control Behavior During Simulated Instrument Approaches, NASA CR-1535, June 1970.

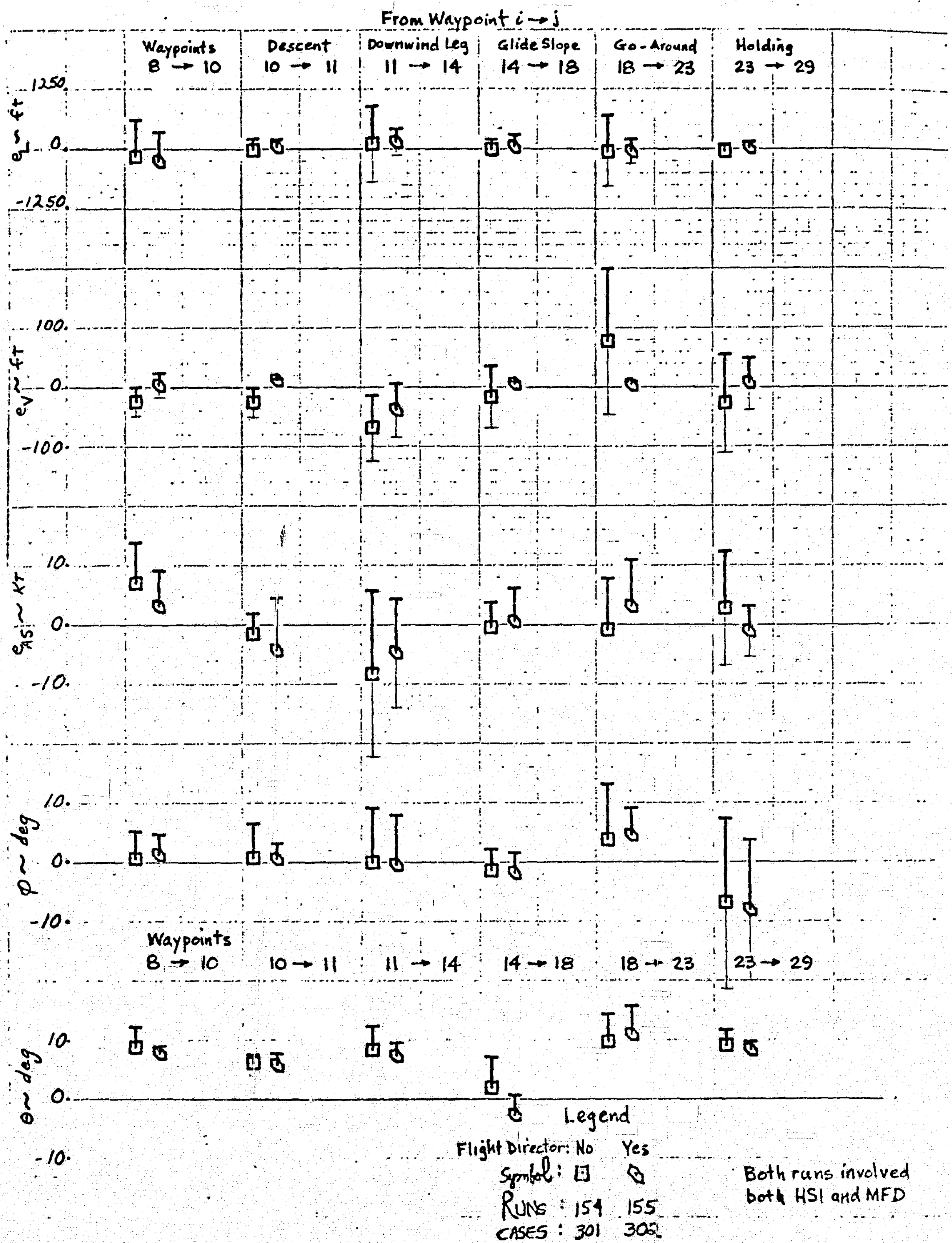
11. Allen, R. W., W. F. Clement, and H. R. Jex, Research on Display Scanning, Sampling, and Reconstruction Using Separate Main and Secondary Tracking Tasks, NASA CR-1569, July 1970.

APPENDIX G

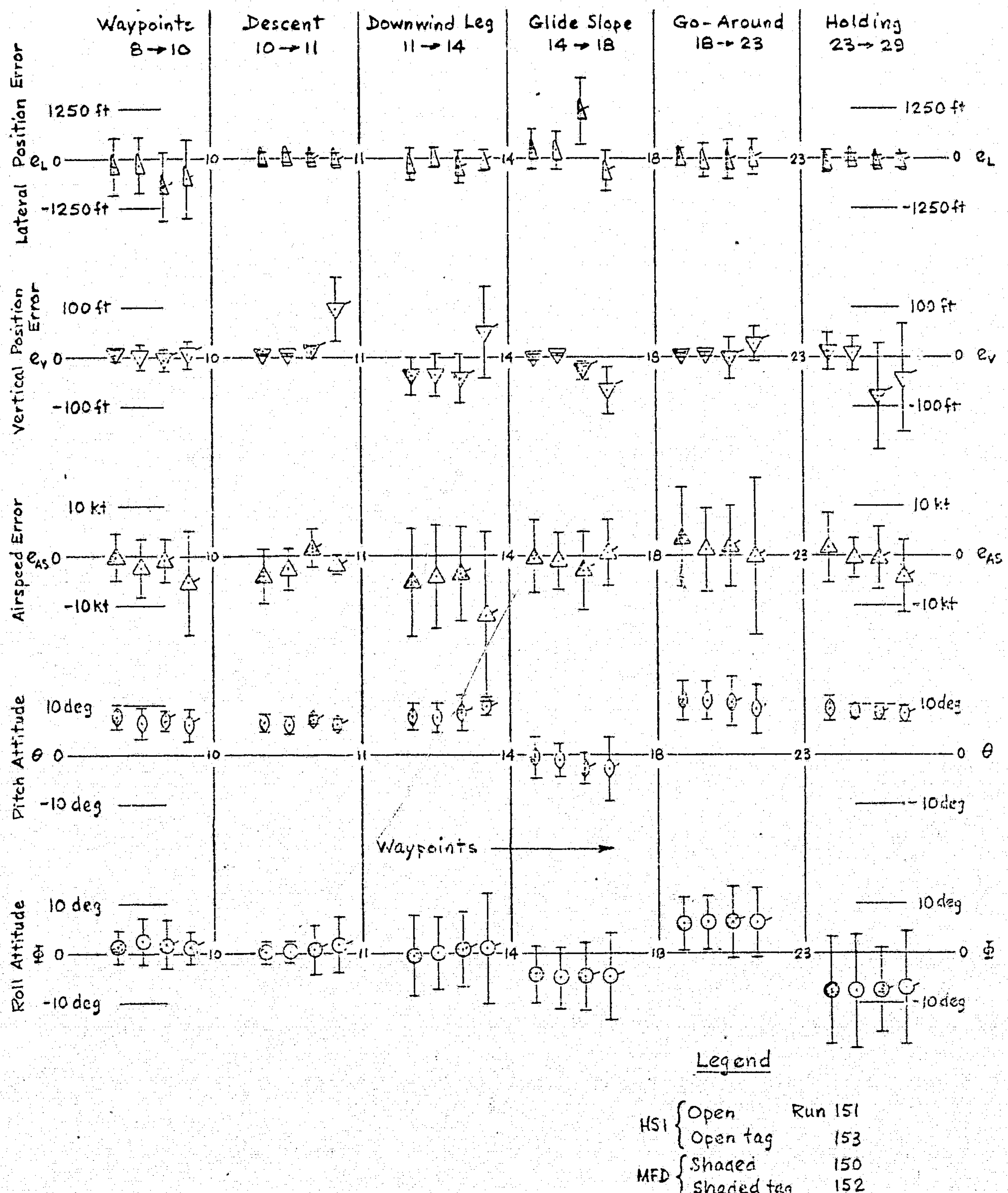
GRAPHICAL SUMMARIES OF SAMPLED TRACKING ERROR STATISTICS



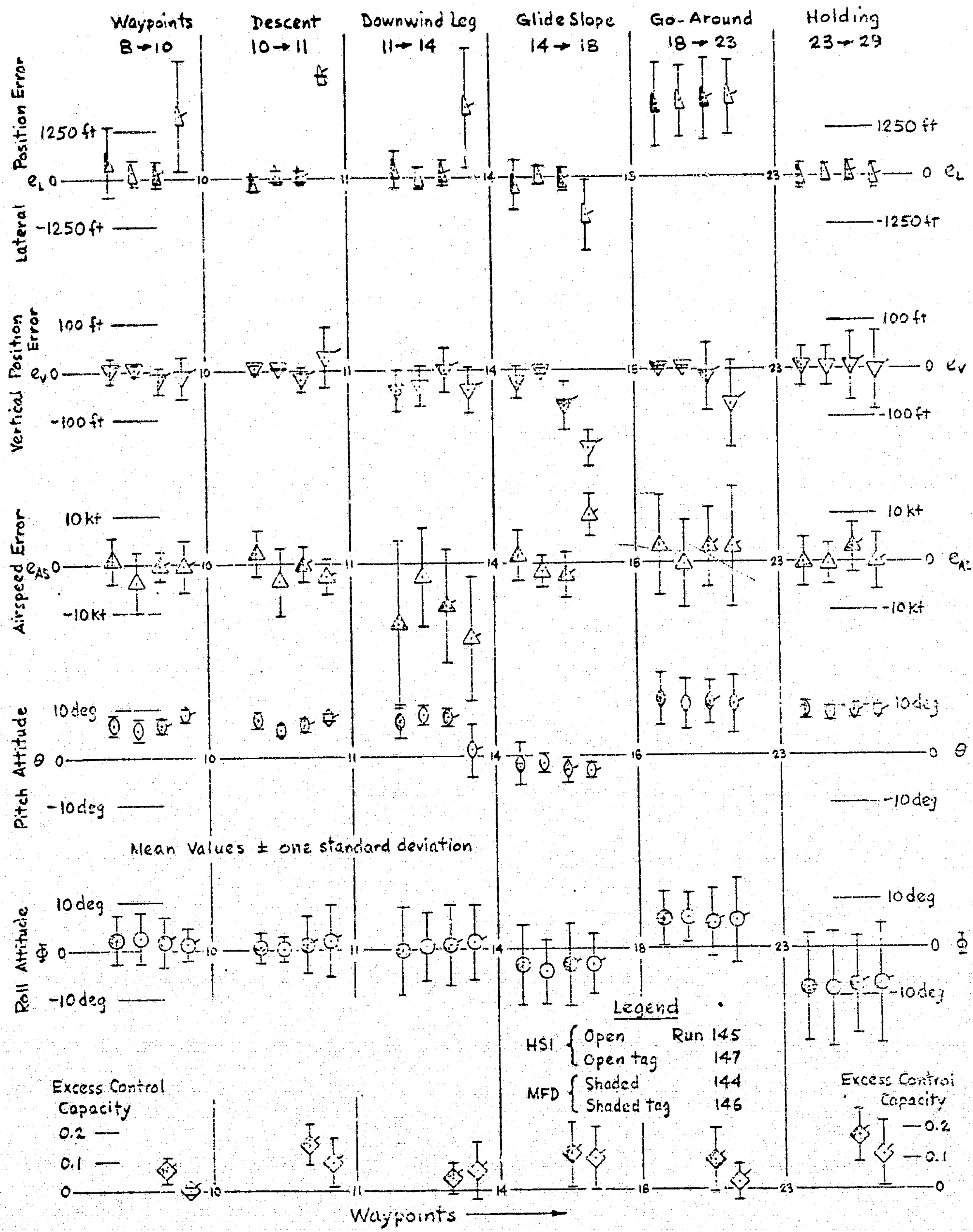
Sampled Statistics for Flight Plan 2 with Pilot 1
Mean Values Plus One Standard Deviation



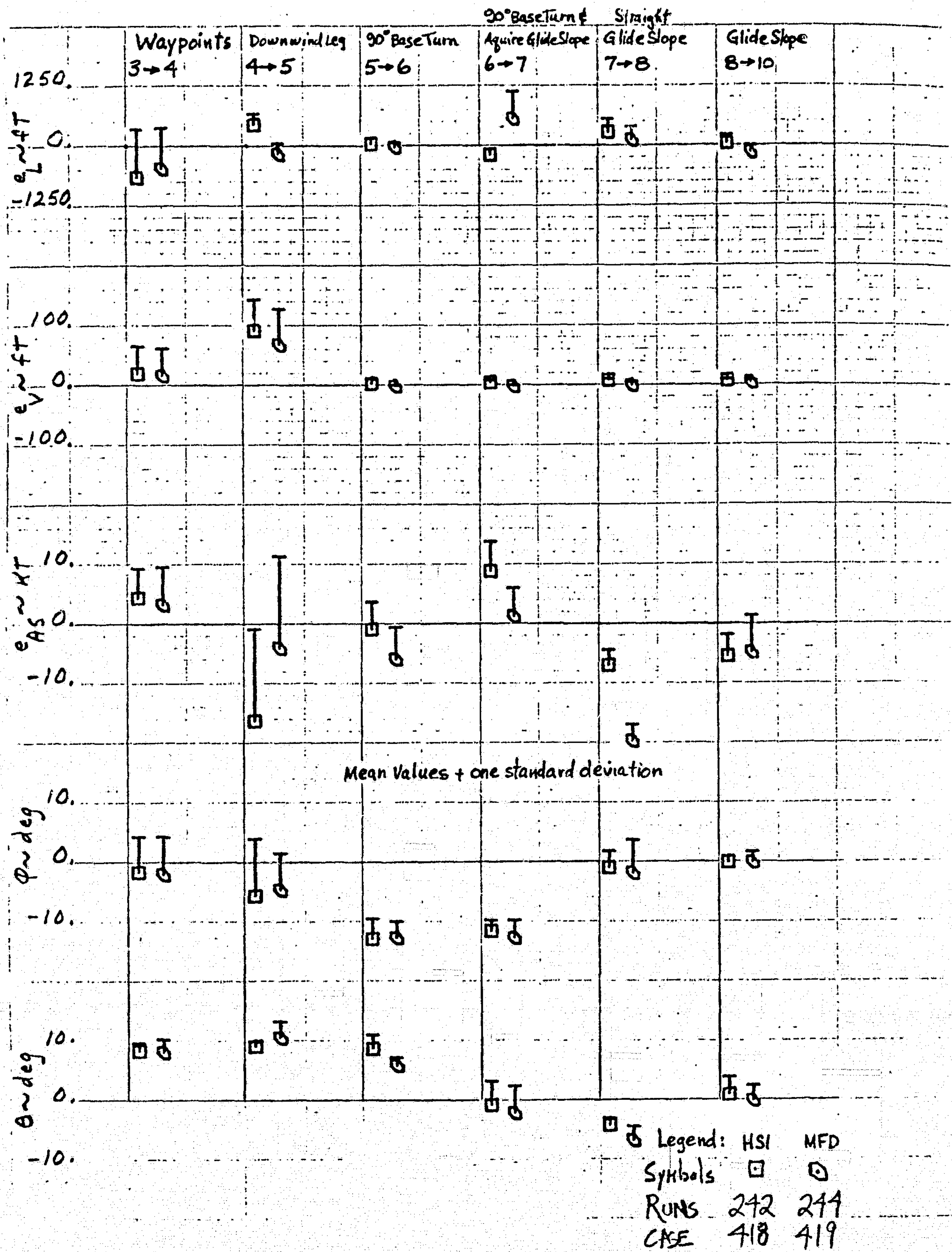
Sampled Statistics for Flight Plan 3 with Pilot 1
Mean Values Plus One Standard Deviation



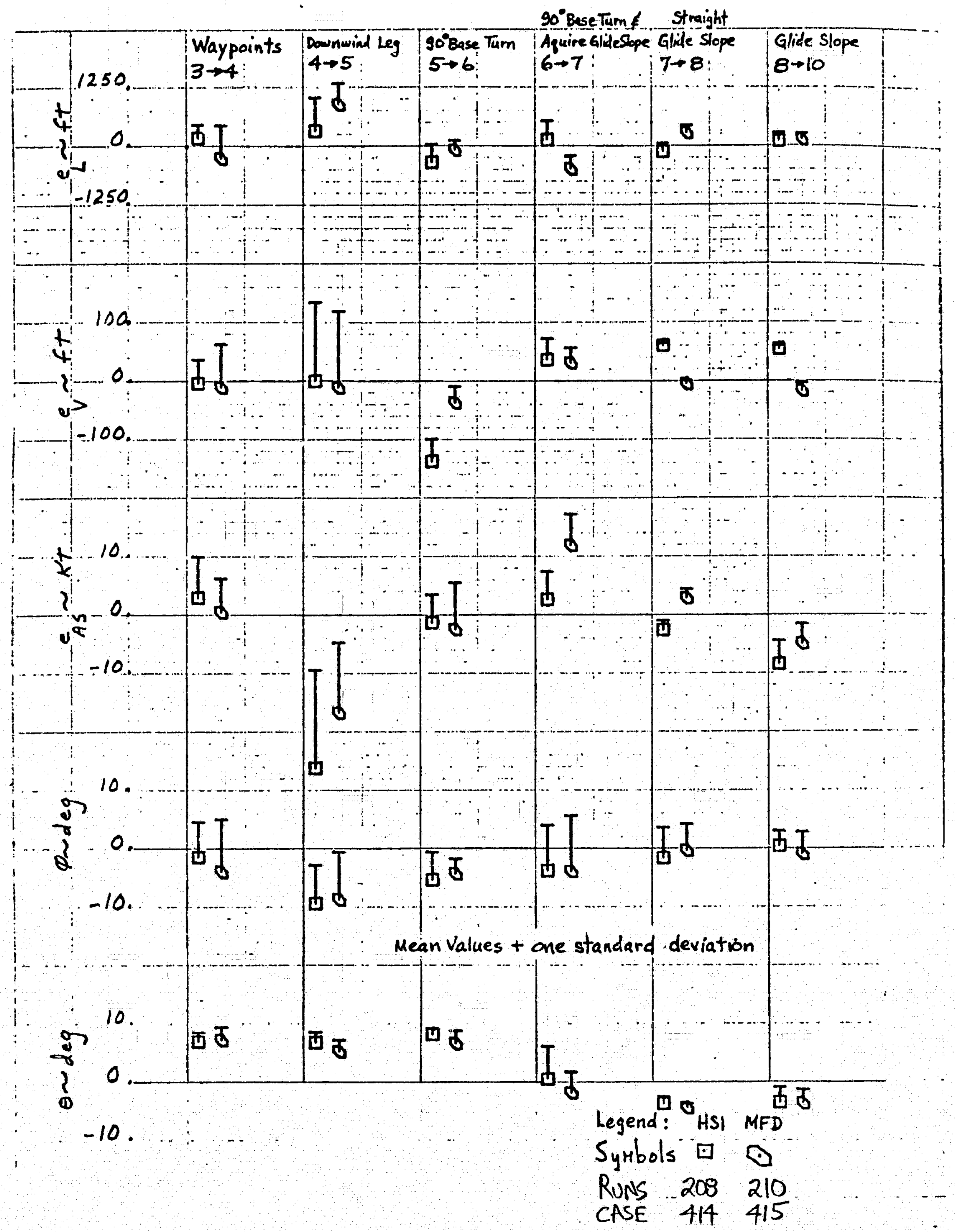
Sampled Statistics for Flight Plan 3 with Pilot 1
Tagged Runs with Raw Situation Data
Other Runs with Flight Director
Mean Values Plus or Minus One Standard Deviation



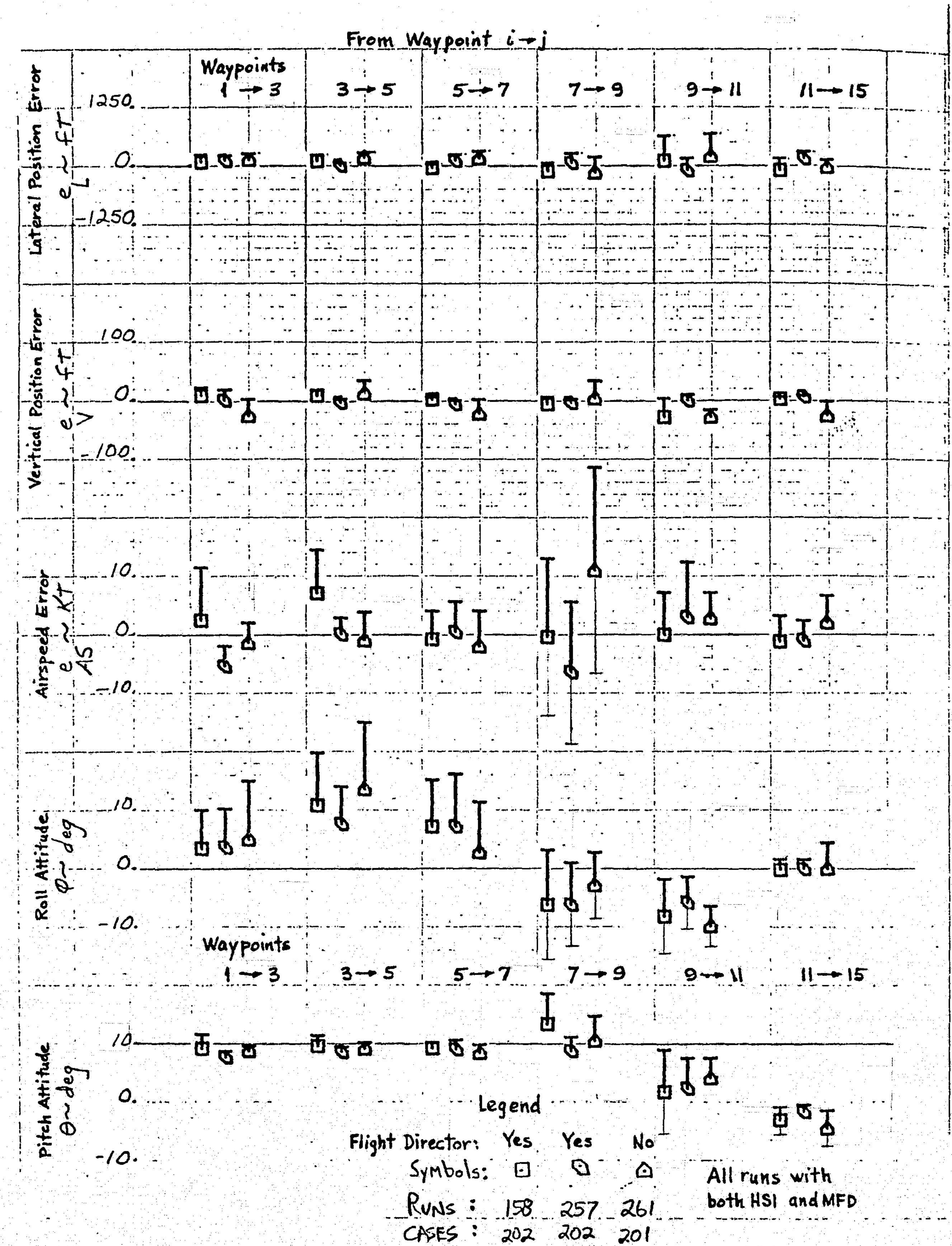
Sampled Statistics for Flight Plan 3. Tagged Runs with Raw Data
Other Runs with Flight Director by Pilot 3



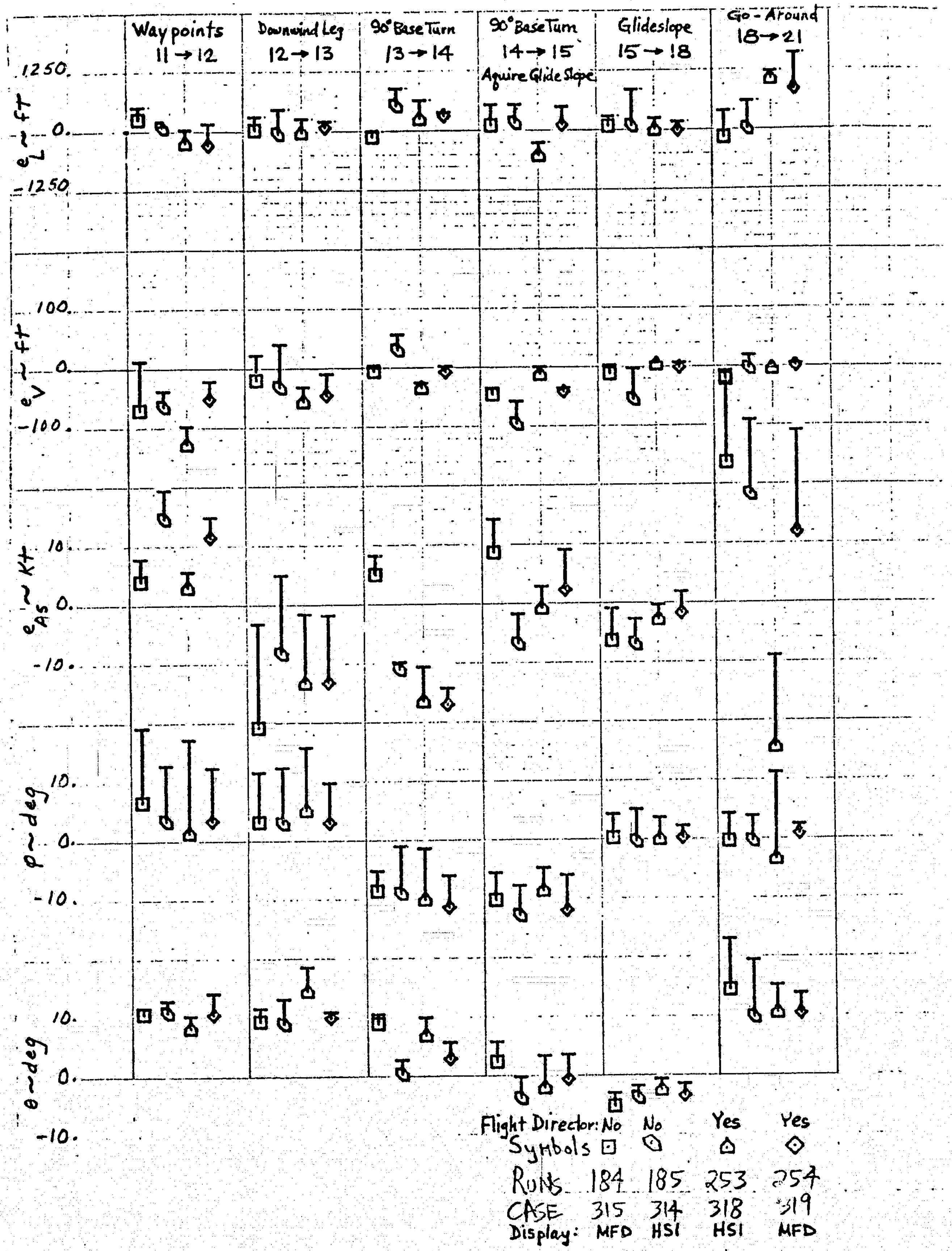
Sampled Statistics for Flight Plan 4 with Pilot 3
Both Runs with Flight Director



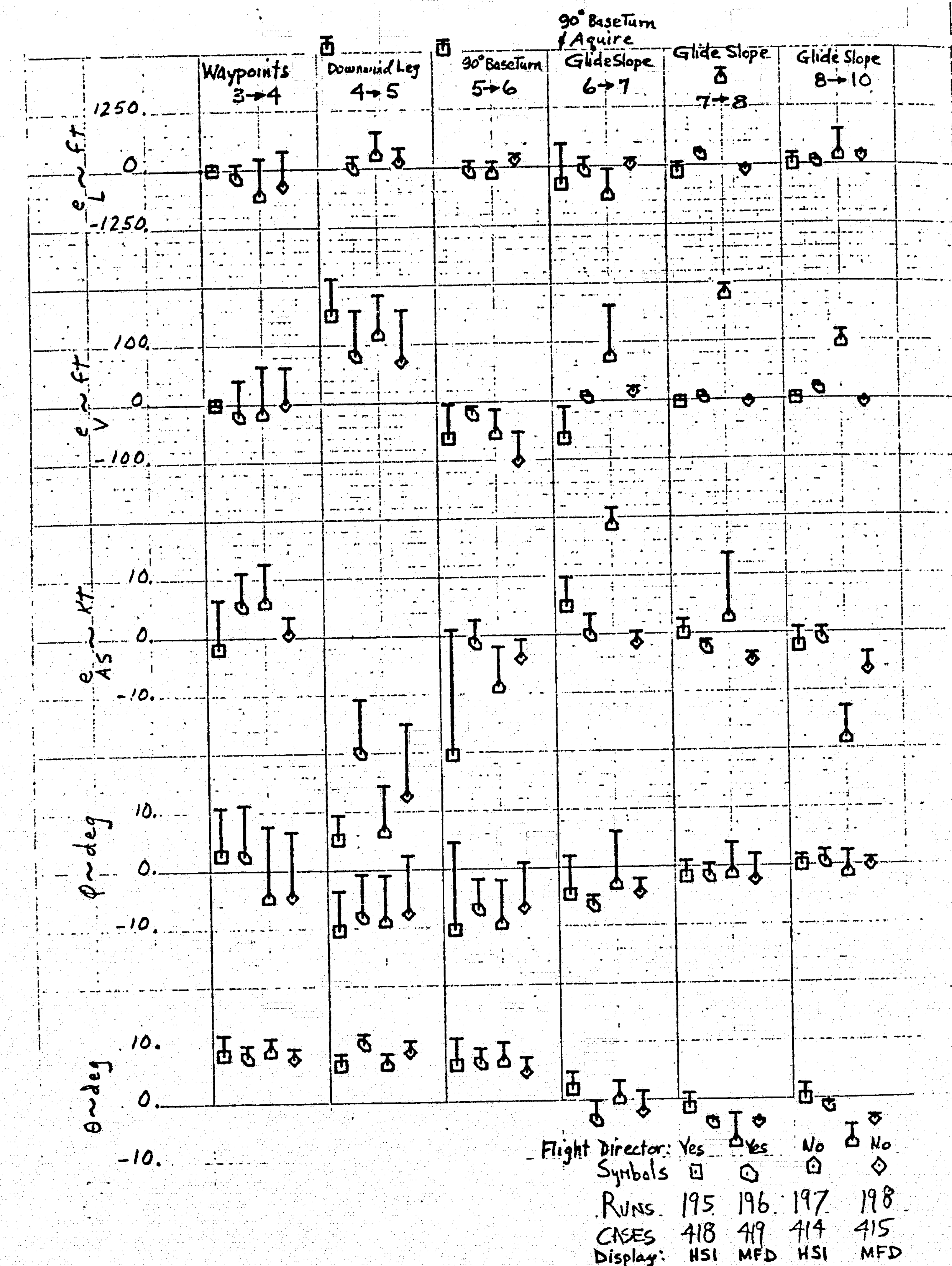
Sampled Statistics for Flight Plan 4 with Pilot 3
Both Runs with Raw Situation Data



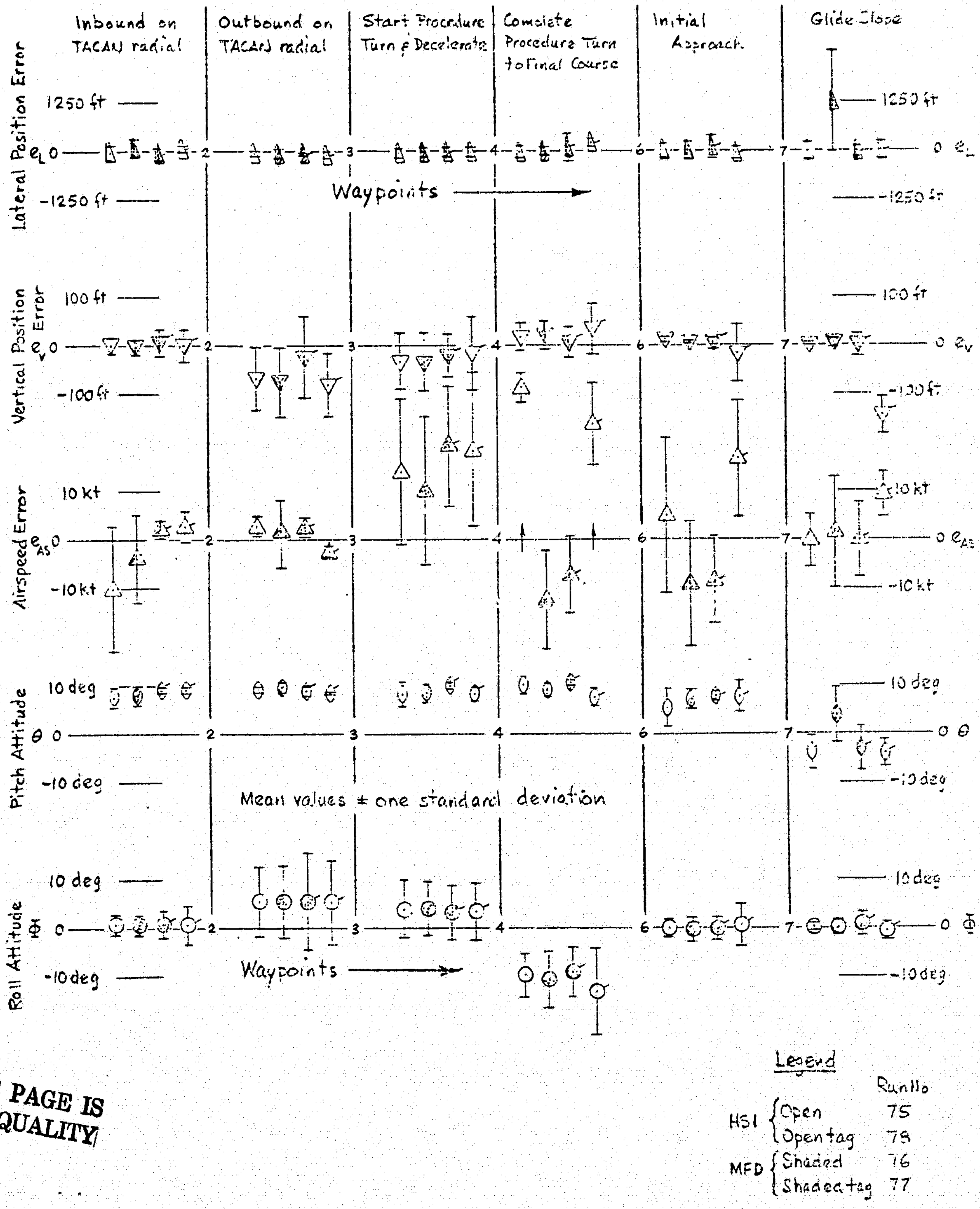
Sampled Statistics for Flight Plan 2 with Pilot 4
Mean Values Plus One Standard Deviation



Sampled Statistics for Flight Plan 3 with Pilot 4
Mean Values Plus One Standard Deviation



Sampled Statistics for Flight Plan 4 with Pilot 4
Mean Values Plus One Standard Deviation



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Sampled Statistics for Flight Plan 1 with Pilot 5
Tagged Runs with Raw Situation Data
Other Runs with Flight Director

APPENDIX H

ANALYSIS OF VARIANCE IN EXCESS CONTROL CAPACITY AND CAUTION ADVISORY RESPONSE TIME

TABLE H-1

TESTS OF SIGNIFICANCE IN DIFFERENCES BETWEEN MEAN EXCESS CONTROL CAPACITIES WITH FLIGHT PLAN 2 AND PILOT 1 ($E_c = 1.1$)

	DISPLAY RUN NUMBER	MFD 139	HSI 142	95% FIDUCIAL INTERVALS FOR DIFFERENCES	DISPLAY EXHIBITING GREATER MEAN XSCC
Waypoints 1 → 3	Number of Samples, n	784	741	$D_{.05} = 0.0086$ (Behrens)	HSI
	Mean XSCC, m_j	0.145	0.196	$m_{142} - m_{139} = 0.051$*	
	Standard Deviation, s_j	0.104	0.063	$D_{.05} = 0.0087$	
	Standard Error, $s_j/\sqrt{n}$	0.0037	0.0023	(Scheffe or Tukey)	
Waypoints 3 → 5	Same as above	412	387	$D_{.05} = 0.0083$ (Behrens)	Neither
		0.080	0.093	$m_{142} - m_{139} = 0.013$	
		0.047	0.070	$D_{.05} = 0.0082$	
		0.0023	0.0035	(Scheffe or Tukey)	
Waypoints 5 → 7	Same as above	486	488	$D_{.05} = 0.0103$ (Behrens)	Neither
		0.146	0.130	$m_{139} - m_{142} = 0.016$	
		0.062	0.098	$D_{.05} = 0.0103$	
		0.0028	0.0044	(Scheffe or Tukey)	
Waypoints 7 → 9	Same as above	604	667	$D_{.05} = 0.010$ (Behrens)	MFD
		0.105	0.076	$m_{139} - m_{142} = 0.029$*	
		0.098	0.086	$D_{.05} = 0.010$	
		0.0040	0.0033	(Scheffe or Tukey)	
Waypoints 9 → 11	Same as above	471	445	$D_{.05} = 0.011$ (Behrens)	Neither
		0.156	0.166	$m_{142} - m_{139} = 0.010$	
		0.062	0.096		
		0.0029	0.0046	$D_{.05}$ = 0.0104 (Scheffe) ≐ 0.0105 (Tukey)	
Waypoints 11 → 15	Same as above	411	472	$D_{.05} = 0.00416$ (Behrens)	Neither
		0.236	0.227	$m_{139} - m_{142} = 0.009$	
		0.0136	0.0432		
		0.00067	0.0020	$D_{.05} = 0.00436$ (Scheffe or Tukey)	

*Difference between means significant at 0.05 level based on Behrens', Scheffe's, or Tukey's tests (Refs. 25-27).

TABLE H-2

TESTS OF SIGNIFICANCE IN DIFFERENCES BETWEEN MEAN EXCESS CONTROL CAPACITIES WITH FLIGHT PLAN 2 AND PILOT 3 ($E_c = 1.2$)

a. HSI 59; MFD 60

	DISPLAY RUN NUMBER	HSI 59	MFD 60	95% FIDUCIAL INTERVALS FOR DIFFERENCES BASED ON BEHREN'S TEST	DISPLAY EXHIBITING GREATER MEAN XSCC
Waypoints 1 → 3	Number of Samples, n	783	721	$D_{.05} = 0.010$	
	Mean XSCC, m_j	0.165	0.167	$m_{60} - m_{59} = 0.002$	Neither
	Standard Deviation, s_j	0.093	0.102		
	Standard Error, $s_j/\sqrt{n}$	0.0033	0.0038		
Waypoints 3 → 5	Same as above	374	395	No test needed	
		0.240 (max)	0.240 (max)		Neither
		Not Applicable	Not Applicable		
Waypoints 5 → 7	Same as above	429	445	$D_{.05} = 0.010$	
		0.240 (max)	0.118	$m_{59} - m_{60} = 0.122$*	HSI
		Not Applicable	0.090		
			0.0043		
Waypoints 7 → 9	Same as above	534	520	$D_{.05} = 0.011$	
		0.141	0.062	$m_{59} - m_{60} = 0.079$*	HSI
		0.105	0.074		
		0.0045	0.0032		
Waypoints 9 → 11	Same as above	458	386	$D_{.05} = 0.0078$	
		0.182	0.086	$m_{59} - m_{60} = 0.096$*	HSI
		0.065	0.051		
		0.0030	0.0026		
Waypoints 11 → 15	Same as above	454	440	$D_{.05} = 0.0065$	
		0.046	0.019	$m_{59} - m_{60} = 0.027$	Neither
		0.064	0.029		
		0.0030	(Skewed distribution) 0.0014		

*Difference between means significant at 0.05 level based on Behren's test (Ref. 25).

TABLE H-2 (Concluded)

b. HSI 58; MFD 56

	DISPLAY RUN NUMBER	MFD 56	HSI 58	95% FIDUCIAL INTERVALS FOR DIFFERENCES BASED ON BEHREN'S TEST	DISPLAY EXHIBITING GREATER MEAN XSCC
Waypoints 1 → 3	Number of Samples, n Mean XSCC, m_j Standard Deviation, s_j Standard Error, $s_j/\sqrt{n}$	889 0.179 0.097 0.0033	833 0.169 0.100 0.0035	$D_{.05} = 0.0095$ $m_{56} - m_{58} = 0.010$	Neither
Waypoints 3 → 5	Same as above	361 0.240 (max) Not Applicable	1220 0.074 0.079 0.0023	$D_{.05} = 0.005$ $m_{56} - m_{58} = 0.166$*	MFD
Waypoints 5 → 7	Same as above	435 0.240 (max) Not Applicable	No Data		
Waypoints 7 → 9	Same as above	506 0.140 0.093	No Data		
Waypoints 9 → 11	Same as above	393 0.046 0.058	No Data		
Waypoints 11 → 15	Same as above	366 0.067 0.058	No Data		

*Difference between means significant at 0.05 level based on Behren's test (Ref. 25).

TABLE H-3

TESTS OF SIGNIFICANCE IN DIFFERENCES BETWEEN MEAN EXCESS CONTROL CAPACITIES WITH FLIGHT PLAN 3 AND PILOT 3 ($E_c = 1.1$)

	DISPLAY RUN NUMBER	MFD 146	HSI 147	95% FIDUCIAL INTERVALS FOR DIFFERENCES BASED ON BEHREN'S TEST	DISPLAY EXHIBITING
Waypoints 8 → 10	Number of Samples, n	759	834	$D_{.05} = 0.0034$	MFD
	Mean XSCC, m_j	0.067	0.003	$m_{146} - m_{147} = 0.064^*$	
	Standard Deviation, s_j	0.047	Not Applicable		
	Standard Error, $s_j/\sqrt{n}$	0.0017			
Waypoints 10 → 11	Same as above	486	487	$D_{.05} = 0.010$	MFD
		0.153	0.095	$m_{146} - m_{147} = 0.058^*$	
		0.084	0.080		
		0.0038	0.0036		
Waypoints 11 → 14	Same as above	621	587	$D_{.05} = 0.0088$	HSI
		0.038	0.063	$m_{147} - m_{146} = 0.025^*$	
		0.054	0.094		
		0.0022	0.0039		
Waypoints 14 → 18	Same as above	616	816	$D_{.05} = 0.011$	Neither
		0.117	0.102	$m_{146} - m_{147} = 0.015$	
		0.107	0.102		
		0.0043	0.0036		
Waypoints 18 → 23	Same as above	1195	1115	$D_{.05} = 0.007$	MFD
		0.094	0.025	$m_{146} - m_{147} = 0.069^*$	
		0.106	0.060		
		0.0031	(Skewed distribution) 0.0018		
Waypoints 23 → 29	Same as above	1630	1651	$D_{.05} = 0.0068$	MFD
		0.175	0.113	$m_{146} - m_{147} = 0.062^*$	
		0.087	0.109		
		0.0022	0.0027		

*Difference between means significant at 0.05 level based on Behren's test (Ref. 25)

TABLE H-4

TESTS OF SIGNIFICANCE IN DIFFERENCES BETWEEN MEAN EXCESS CONTROL CAPACITIES WITH FLIGHT PLAN 2 AND PILOT 4 ($E_c = 1.1$)

a. HSI 164; MFD 163

	DISPLAY RUN NUMBER	MFD 163	HSI 164	95% FIDUCIAL INTERVALS FOR DIFFERENCES BASED ON BEHREN'S TEST	DISPLAY EXHIBITING GREATER MEAN XSCC
Waypoints 1 → 3	Number of Samples, n	760	753	$D_{.05} = 0.0076$	MFD
	Mean XSCC, m_j	0.130	0.116	$m_{163} - m_{164} = 0.014^*$	
	Standard Deviation, s_j	0.107	0.113		
	Standard Error, $s_j/\sqrt{n}$	0.0039	0.0041		
Waypoints 3 → 5	Same as above	403	388	$D_{.05} = 0.0118$	MFD
		0.087	0.067	$m_{163} - m_{169} = 0.02^*$	
		0.098	0.068		
		0.0049	0.0035		
Waypoints 5 → 7	Same as above	429	425	$D_{.05} = 0.0122$	HSI
		0.113	0.136	$m_{164} - m_{163} = 0.023^*$	
		0.082	0.098		
		0.0040	0.0048		
Waypoints 7 → 9	Same as above	583	499	$D_{.05} = 0.0125$	HSI
		0.074	0.116	$m_{164} - m_{163} = 0.042^*$	
		0.101	0.107		
		0.0042	0.0048		
Waypoints 9 → 11	Same as above	565	469	$D_{.05} = 0.01$	MFD
		0.158	0.105	$m_{163} - m_{164} = 0.053^*$	
		0.090	0.070		
		0.0038	0.0032		
Waypoints 11 → 15	Same as above	413	432	$D_{.05} = 0.006$	MFD
		0.234	0.131	$m_{163} - m_{164} = 0.103^*$	
		Not Applicable	0.069		
			0.0033		

*Difference between means significant at 0.05 level based on Behren's test (Ref. 25).

TABLE H-4 (Concluded)

b. HSI 256; MFD 260

	DISPLAY RUN NUMBER	HSI 256	MFD 260	95% FIDUCIAL INTERVALS BASED ON BEHREN'S TEST	DISPLAY EXHIBITING GREATER MEAN XSCC
Waypoints 1 → 3	Number of Samples, n Mean XSCC, m_j Standard Deviation, s_j Standard Error, $s_j/\sqrt{n}$	740 0.152 0.098 0.0036	574 0.114 0.090 0.0038	$D_{.05} = 0.010$ $m_{256} - m_{260} = 0.038^*$	HSI
Waypoints 3 → 5	Same as above	345 0.053 0.067 0.0036	311 0.040 0.044 (Skewed distribution) 0.0025	$D_{.05} = 0.0086$ $m_{256} - m_{260} = 0.013$	Neither
Waypoints 5 → 7	Same as above	446 0.021 0.026 (Skewed distribution) 0.0012	533 0.086 0.087 0.0038	$D_{.05} = 0.0078$ $m_{260} - m_{256} = 0.065^*$	MFD
Waypoints 7 → 9	Same as above	612 0.058 0.071 0.0029	488 0.034 0.043 (Skewed distribution) 0.0018	$D_{.05} = 0.0066$ $m_{256} - m_{260} = 0.024^*$	HSI
Waypoints 9 → 11	Same as above	525 0.030 0.033 (Skewed distribution) 0.0014	362 0.112 0.070 0.0037	$D_{.05} = 0.0078$ $m_{260} - m_{256} = 0.082^*$	MFD
Waypoints 11 → 15	Same as above	388 0.060 0.050 0.0025	536 0.034 0.042 (Skewed distribution) 0.0018	$D_{.05} = 0.006$ $m_{256} - m_{260} = 0.026^*$	HSI

*Difference between means significant at 0.05 level based on Behren's test (Ref. 25).

TABLE H-5

TESTS OF SIGNIFICANCE IN DIFFERENCES BETWEEN MEAN EXCESS CONTROL CAPACITIES WITH FLIGHT PLAN 2 AND PILOT 5 (E_c = 1.1)

	DISPLAY RUN NUMBER	MFD 124	HSI 125	95% FIDUCIAL INTERVALS FOR DIFFERENCES BASED ON BEHREN'S TEST	DISPLAY EXHIBITING GREATER MEAN XSCC
Waypoints 1 → 3	Number of Samples, n Mean XSCC, m_j Standard Deviation, s_j Standard Error, $s_j/\sqrt{n}$	747 0.188 0.085 0.0031	815 0.215 0.058 0.0020	$D_{.05}$ = 0.0073 $m_{125} - m_{124}$ = 0.027*	HSI
Waypoints 3 → 5	Same as above	396 0.238 0.00640 0.000322	407 0.190 0.078 0.0039	No Test Needed $m_{124} - m_{125}$ = 0.048	MFD
Waypoints 5 → 7	Same as above	455 0.063 0.073 0.0034	521 0.058 0.050 0.0022	$D_{.05}$ = 0.008 $m_{124} - m_{125}$ = 0.005	Neither
Waypoints 7 → 9	Same as above	525 0.116 0.082 0.0036	580 0.086 0.095 0.0039	$D_{.05}$ = 0.0105 $m_{124} - m_{125}$ = 0.030*	MFD
Waypoints 9 → 11	Same as above	429 0.114 0.062 0.0030	652 0.093 0.094 0.0037	$D_{.05}$ = 0.0094 $m_{124} - m_{125}$ = 0.021*	MFD
Waypoints 11 → 15	Same as above	430 0.228 0.0240 0.00116	415 0.014 0.0248 0.00122	No Test Needed $m_{124} - m_{125}$ = 0.214	MFD

*Difference between means significant at 0.05 level based on Behren's test (Ref. 25).

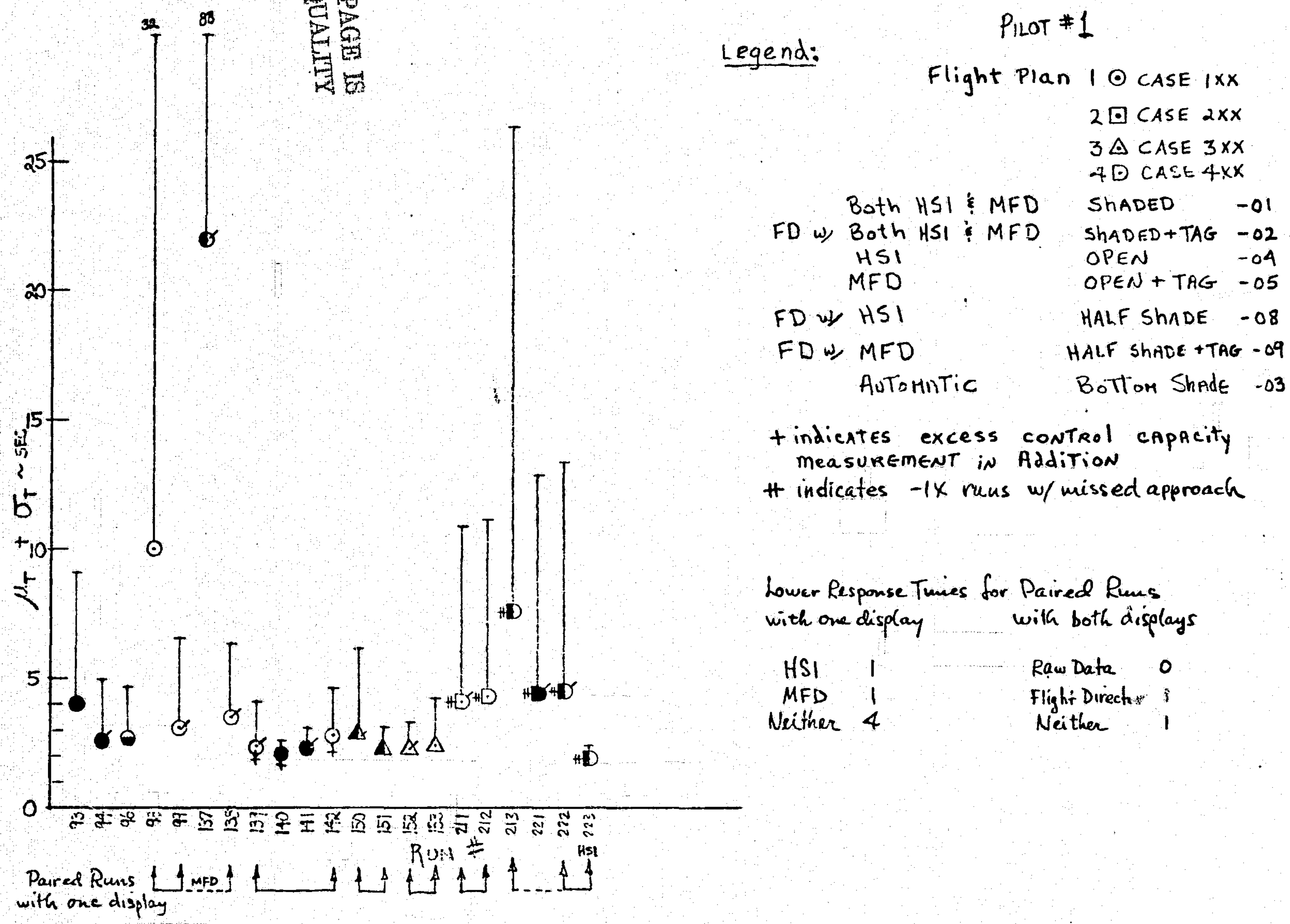

Figure H-1. Caution Advisory Task Response Times for Pilot 1

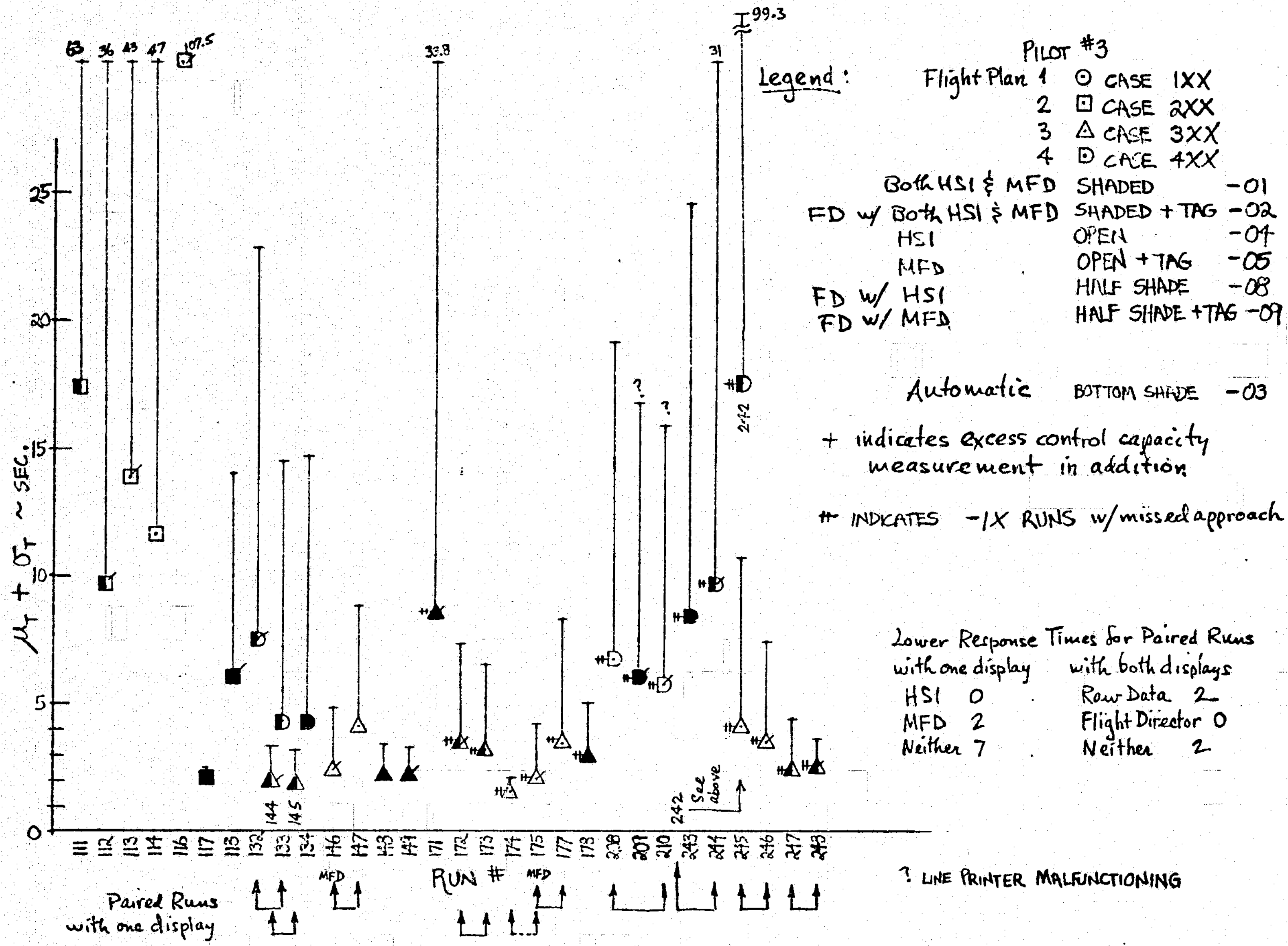

Figure H-2. Caution Advisory Task Response Times for Pilot 3

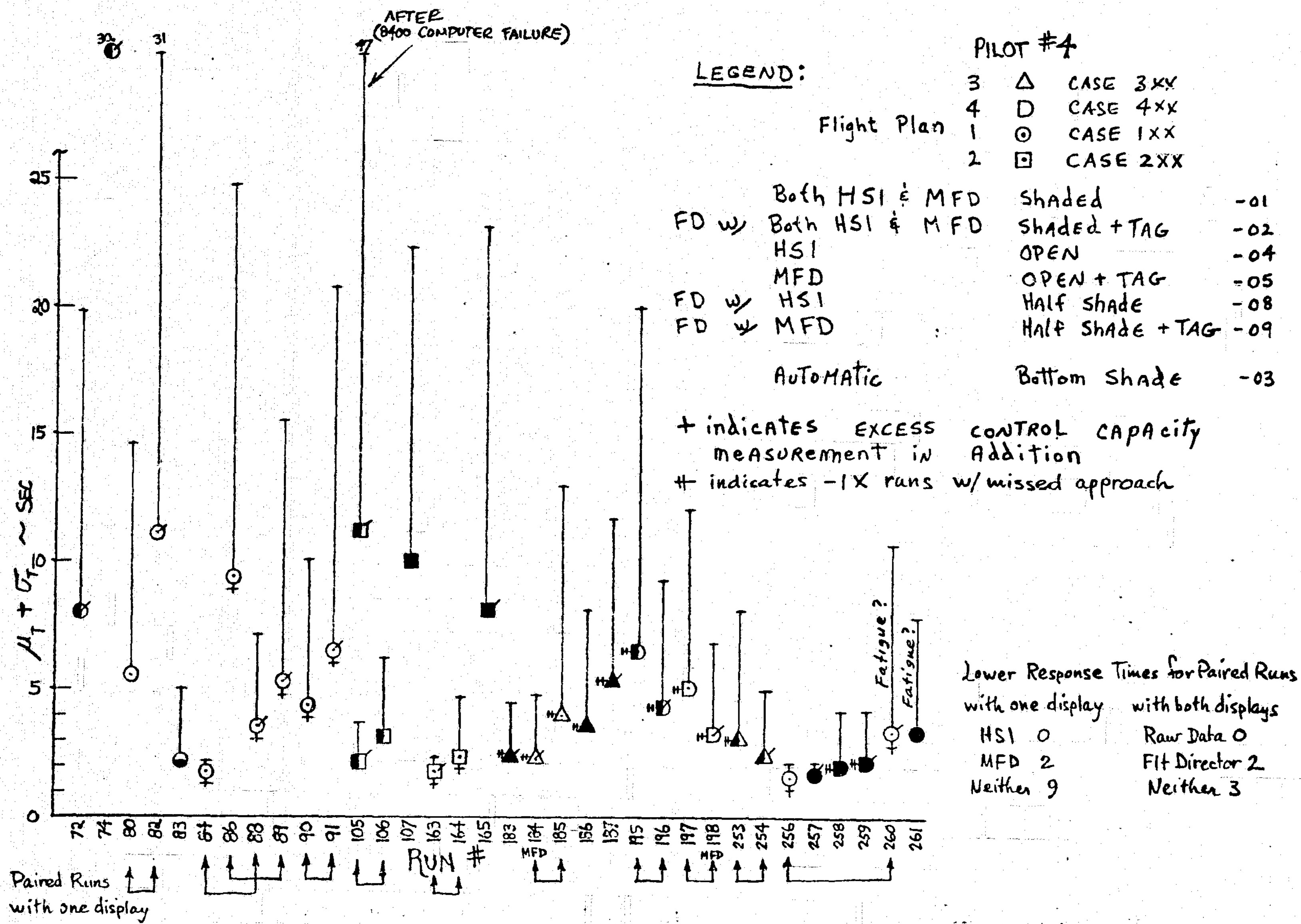

Figure H-3. Caution Advisory Task Response Times for Pilot 4

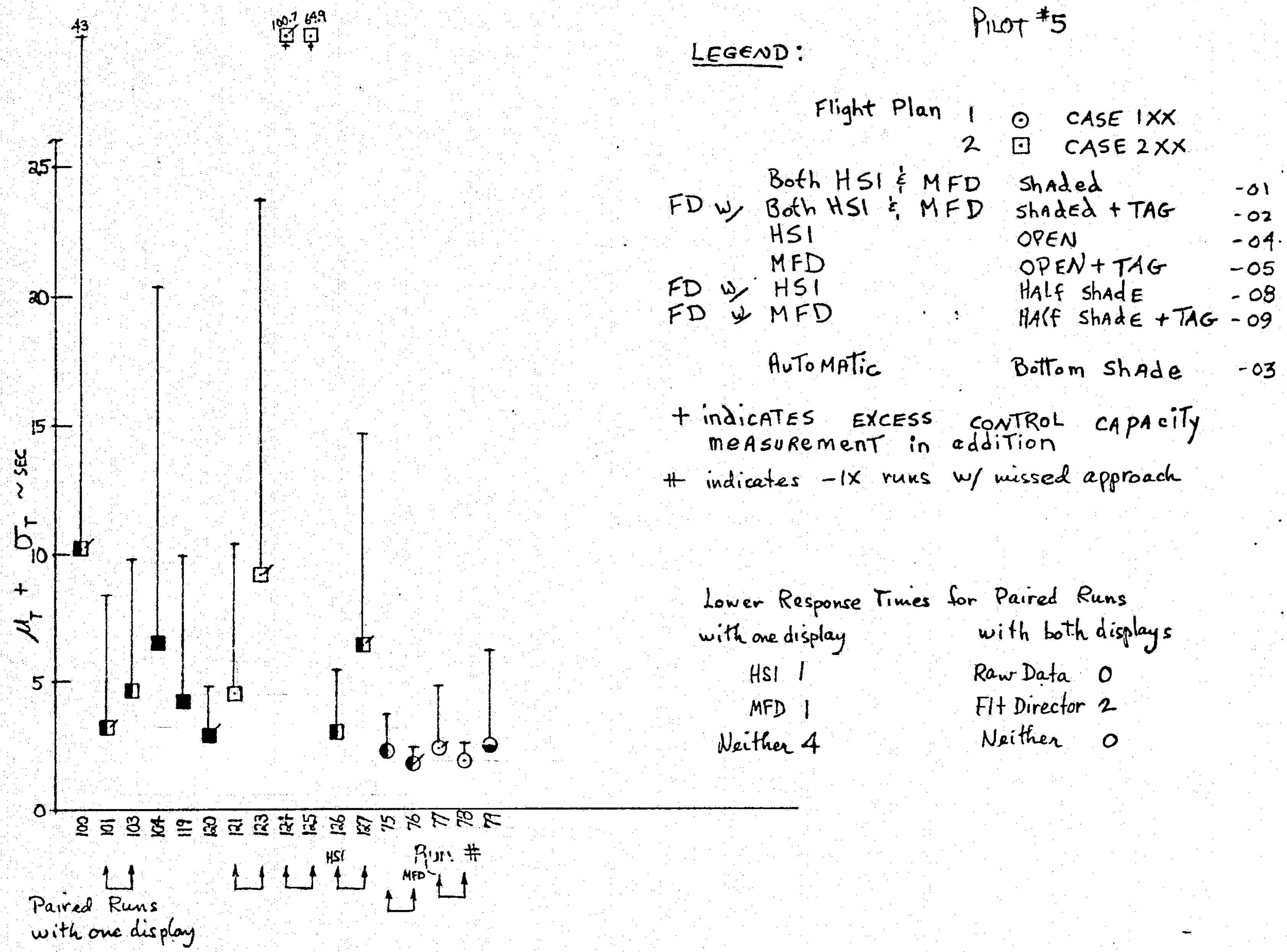

Figure H-4. Caution Advisory Task Response Times for Pilot 5

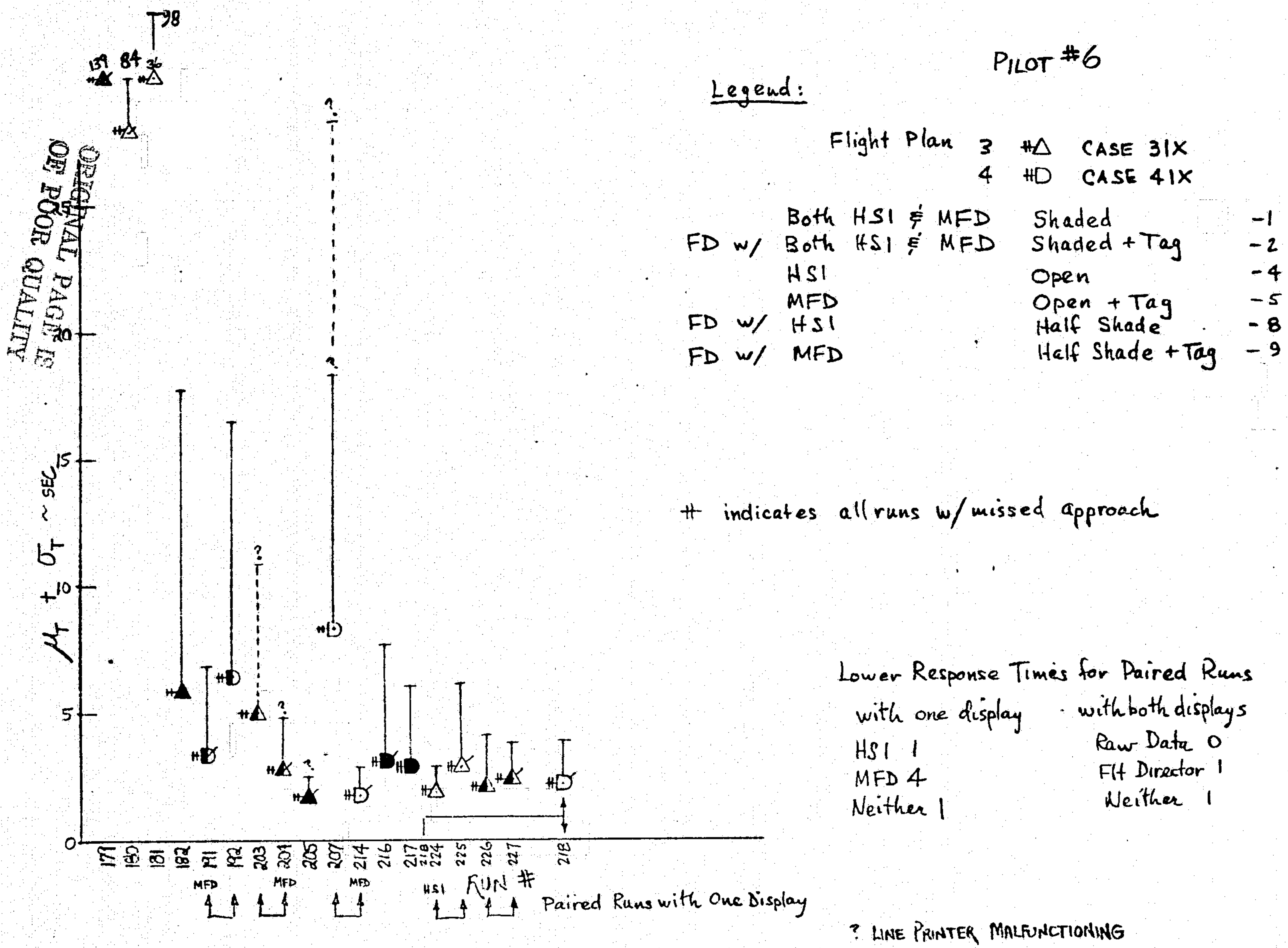

Figure H-5. Caution Advisory Task Response Times for Pilot 6

TABLE H-6. ANALYSIS OF VARIANCE FOR CAUTION ADVISORY RESPONSE TIMES BY PILOT 1

DISPLAY:	HSI	HSI	MFD	MFD	95% FIDUCIAL INTERVALS FOR THE DIFFERENCE BETWEEN MEANS BASED ON BEHREN'S TEST		DISPLAY HAVING LESSER MEAN RESPONSE TIME AND FLIGHT PLAN NUMBER
Run Number, R	98		99	138	$m_{98} - m_{99} = 6.9$*	$m_{98} - m_{138} = 6.5$	2
Number of Samples, n	12		11	11	$D_{.05} = 14.07$ (Behren's)	$D_{.05} = 14.01$	MFD
Mean, m_j (sec)	10.0		3.1	3.5	$D_{.05} = 14.03$ (Scheffe)	$D_{.05} = 13.99$	
Standard Deviation, s_j (sec)	22.1		3.4	2.8	$D_{.05} = 14.22$ (Cochran and Cox)	$D_{.05} = 14.16$	
Standard Error, $s_j/\sqrt{n}$ (sec)	6.38		1.0	0.84			
$s_j/\sqrt{n} \div 3$ =	2.13 (Corrected for skewness) →				$D_{.05} = 5.11$ (Behren's)		
Same as above	142		139		$m_{142} - m_{139} = 0.4$		2
	12		12		$D_{.05} = 1.55$		Neither
	2.8		2.4				
	1.8		1.7				
	0.52		0.49				
Same as above	151		150		$m_{150} - m_{151} = 0.6$		3/FD
	20		21		$D_{.05} = 1.51$		Neither
	2.3		2.9				
	0.8		3.2				
	0.16		0.70				
Same as above	153		152		$m_{153} - m_{152} = 0.1$		3
	21		21				Neither
	2.4		2.3				
	1.8		1.0				
Same as above	212		211		$m_{212} - m_{211} = 0.2$		4-1X
	30		31				Neither
	4.3		4.1				
	6.8		6.8				
Same as above	213	223	222		$m_{213} - m_{222} = 3.0$	$m_{222} - m_{223} = 2.6$*	4-1X FD
	31	30	30		$D_{.05} = 11.6$	$D_{.05} = 3.22$	HSI
	7.5	1.9	4.5			$D_{.25} = 1.87$	
	18.9	0.5	8.8				
	5.57	0.091	1.6				
	1.86		0.53 (Corrected for skewness) →			$D_{.05} = 1.1$	

*Difference between means significant at 0.05 level after correction for skewness.

TABLE H-7. ANALYSIS OF VARIANCE FOR CAUTION ADVISORY RESPONSE TIMES BY PILOT 3

				75% AND 95% FIDUCIAL INTERVALS FOR THE DIFFERENCES BETWEEN MEANS BASED ON BEHREN'S TEST				DISPLAY HAVING LESSER MEAN RESPONSE TIME AND FLIGHT PLAN NUMBER
Display		MFD	HSI					
Run Number, R		132	133	$m_{132} - m_{133} = 3.2$				4 FD
Number of Samples, n		27	30	$D_{.05} = 7.07$				Neither
Mean, m_j		7.5	4.3					
Standard Deviation, s_j		15.3	10.2					
Standard Error, $s_j/\sqrt{n}$		2.94	1.86					
		XSCC MFD	XSCC HSI		FD MFD	FD HSI		3/FD Neither
R		146	147	$m_{147} - m_{146} = 1.7$*	144	145	$m_{144} - m_{145} = 0.1$	3
n		21	21	$D_{.05} = 2.34$	21	21	Neither	MFD
m_j		2.4	4.1	$D_{.25} = 1.35$	2.0	1.9		
s_j		2.4	4.7		1.4	1.3		
$s_j/\sqrt{n}$		0.52	1.03					
$s_j/\sqrt{n} \div 3$			0.34 (Corrected for skewness) →	$D_{.05} = 1.28$				
		MFD	HSI					
		172	173	$m_{172} - m_{173} = 0.2$				3-1X FD
		20	21					Neither
		3.4	3.2					
		3.9	3.3					
	HSI	MFD	HSI					
R	177	175	174	$m_{177} - m_{175} = 1.4$*			$m_{175} - m_{174} = 0.5$	3-1X
n	20	21	21	$D_{.05} = 2.40$			$D_{.05} = 0.99$	MFD
m_j	3.5	2.1	1.6	$D_{.25} = 1.39$				
s_j	4.8	2.1	0.5					
$s_j/\sqrt{n}$	1.07	0.46	0.11					
$s_j/\sqrt{n} \div 3 = 0.35$ (Corrected for skewness) →				$D_{.05} = 1.2$				
		MFD	HSI		FD MFD	FD HSI		
R		210	208	$m_{208} - m_{210} = 1.0$	244	242	$m_{242} - m_{244} = 7.8$	4-1X
n		31	30	Neither	32	<31	Neither	
m_j		5.7	6.7		9.7	17.5		
s_j		$1\underline{0}.2$[†]	12.4		21.7	81.8		
		MFD	HSI		FD MFD	FD HSI		
R		246	245	$m_{245} - m_{246} = 0.6$	248	247	$m_{248} - m_{247} = 0.1$	3-1X
n		20	21	Neither	20	21	Neither	
m_j		3.5	4.1		2.5	2.4		
s_j		3.9	6.6		1.1	2.0		

*Difference between means significant at 0.05 level after correction for skewness
†Line printer omitted this digit; therefore, underlined digit is uncertain.

TABLE H-8

ANALYSIS OF VARIANCE FOR CAUTION ADVISORY RESPONSE TIMES BY PILOT 4

					95% FIDUCIAL INTERVALS FOR THE DIFFERENCE BETWEEN MEANS BASED ON BEHREN'S TEST	DISPLAY HAVING LESSER MEAN RESPONSE TIME AND FLIGHT PLAN NUMBER
Display		HSI	MFD			
Run Number, R		80	82		$m_{82} - m_{80} = 5.6$	1
Number of Samples, n		14	15			Neither
Mean, m_j		5.5	11.1			
Standard Deviation, s_j		8.6	20.2			
Standard Error, $s_j/\sqrt{n}$						
---	---	---	---	---	---	---
	HSI	HSI	MFD	MFD		
R	84	86	88	89		1 XSCC
n	15	14	14	15		Neither
m_j	1.8	9.4	3.6	5.3		(2 pair)
s_j	0.4	15.4	3.5	10.3		
---	---	---	---	---	---	---
		HSI	MFD			
R		90	91		$m_{91} - m_{90} = 2.1$	1
n		16	15			Neither
m_j		4.4	6.5			
s_j		5.7	14.3			
---	---	---	---	---	---	---
R		106	105		$m_{106} - m_{105} = 1.0$	2 FD
n		13	11		$D_{.05} = 2.06$	Neither
m_j		3.2	2.2			
s_j		3.0	1.5			
$s_j/\sqrt{n}$		0.83	0.45			
$s_j/\sqrt{n} \div 3 =$		0.28 (Corrected for skewness)	→	→	$D_{.05} = 1.15$	
---	---	---	---	---	---	---
R		164	163		$m_{164} - m_{163} = 0.6$	2
n		13	14		$D_{.05} = 1.43$	Neither
m_j		2.4	1.8			
s_j		2.3	0.6			
$s_j/\sqrt{n}$		0.64	0.16			

TABLE H-8 (Concluded)

Display	HSI	MFD	75% AND 95% FIDUCIAL INTERVALS FOR THE DIFFERENCE BETWEEN MEANS BASED ON BEHREN'S TEST	DISPLAY HAVING LESSER MEAN RESPONSE TIME AND FLIGHT PLAN NUMBER
Run Number, R	185	184	$m_{185} - m_{184} = 2.7^*$	3-1X
Number of Samples, n	20	20	$D_{.05} = 3.94$	MFD
Mean, m_j	5.0	2.3	$D_{.25} = 2.27$	
Standard Deviation, s_j	8.0	2.5		
Standard Error, $s_j/\sqrt{n}$	1.79	0.56		
$s_j/\sqrt{n} \div 3 =$	0.60 (Corrected for skewness)	→	$D_{.05} = 1.69$	
R	195	196	$m_{195} - m_{196} = 2.1$	4-1X FD
n	40	33	$D_{.05} = 4.74$	Neither
m_j	6.5	4.4		
s_j	13.6	4.9		
$s_j/\sqrt{n}$	2.15	0.85		
R	197	198	$m_{197} - m_{198} = 1.8^*$	4-1X
n	31	30	$D_{.05} = 2.89$	MFD
m_j	5.1	3.3	$D_{.25} = 1.68$	
s_j	7.0	3.5		
$s_j/\sqrt{n}$	1.26	0.64		
$s_j/\sqrt{n} \div 3$	0.42 (Corrected for skewness)	→	$D_{.05} = 1.57$	
R	253	254	$m_{253} - m_{254} = 0.7$	3-1X FD
n	21	20		Neither
m_j	3.1	2.4		
s_j	5.0	2.6		
R	256	260	$m_{260} - m_{256} = 1.8$	2 XSCC
n	13	13	$D_{.05} = 4.42$	Neither
m_j	1.6	3.4		
s_j	0.6	7.3		
$s_j/\sqrt{3}$	0.17	2.02		

*Difference between means significant at 0.05 level after correction for skewness.

TABLE H-9

ANALYSIS OF VARIANCE FOR CAUTION ADVISORY RESPONSE TIMES FOR PILOT 5

				75% AND 95% FIDUCIAL INTERVALS FOR THE DIFFERENCE BETWEEN MEANS BASED ON BEHREN'S TEST	DISPLAY HAVING LESSER MEAN RESPONSE TIME AND FLIGHT PLAN NUMBER
Display	HSI	MFD			
Run Number, R	75	76		$m_{75} - m_{76} = 0.5$*	1 FD
Number of Samples, n	14	14		$D_{.05} = 0.88$	MFD
Mean, m_j	2.3	1.8		$D_{.25} = 0.5$	
Standard Deviation, s_j	1.4	0.6			
Standard Error, $s_j/\sqrt{n}$	0.37	0.16			
$s_j/\sqrt{n} \div 3$	0.12 (Corrected for skewness)	→		$D_{.05} = 0.44$	
Display	HSI	MFD			
R	78	77		$m_{77} - m_{78} = 0.5$	1
n	15	16		73° $D_{.05} = 1.35$	Neither
m_j	1.9	2.4			
s_j	0.7	2.4			
$s_j/\sqrt{n}$	0.18	0.6			
Display	HSI	MFD	MFD		
R	103	101	100		2 FD
n	13	13	12		Neither
m_j	4.6	3.2	10.2		
s_j	5.2	5.2	33.4		
Display	HSI	MFD			
R	121	123		$m_{123} - m_{121} = 4.7$	2
n	13	12		$D_{.05} = 9.77$	Neither
m_j	4.5	9.2		$D_{.33} = 4.72$	
s_j	5.9	14.5			
$s_j/\sqrt{n}$	1.64	4.19			
Display	HSI	MFD			
R	125	124		"Couldn't do task in turns"	2 XSCC
n	7	6			Neither
m_j	64.9	100.7			
s_j	81.5	187.2			
$s_j/\sqrt{n}$	30.8	76.4			
Display	HSI	MFD			
R	126	127		$m_{127} - m_{126} = 3.4$*	2 FD
n	12	13		$D_{.05} = 5.23$	HSI
m_j	3.0	6.4		$D_{.25} = 2.98$	
s_j	2.4	8.3			
$s_j/\sqrt{n}$	0.69	2.3			
$s_j/\sqrt{n} \div 3$	(Corrected for skewness)	0.77 →		$D_{.05} = 2.24$	

*Difference between means significant at 0.05 level after correction for skewness.

TABLE H-10

ANALYSIS OF VARIANCE FOR CAUTION ADVISORY RESPONSE TIMES FOR PILOT 6

				75%, 90% AND 95% FIDUCIAL INTERVALS FOR THE DIFFERENCE BETWEEN MEANS BASED ON BEHREN'S TEST	DISPLAY HAVING LESSER MEAN RESPONSE TIME AND FLIGHT PLAN NUMBER
Display	HSI	MFD			
Run Number, R	192	191		$m_{192} - m_{191} = 3.0$*†	4-1X FD
Number of Samples, n	30	31		$D_{.05} = 3.98$	MFD
Mean, m_j	6.4	3.4		*$D_{.25} = 2.31$	
Standard Deviation, s_j	10.1	3.4			
Standard Error, $s_j/\sqrt{n}$	1.84	0.61			
R	203	204		$m_{203} - m_{204} = 2.2$*†	3-1X FD
n	21	20		$D_{.05} = 2.78$	MFD
m_j	5.0[a]	2.8		$D_{.25} = 1.61$	
s_j	5.7[a]	2.0[a]			
$s_j/\sqrt{n}$	1.24	0.45			
	HSI	MFD	MFD		
R	207	214	218	$m_{207} - m_{218} = 6.1$*†	4-1X
n	41	16	31	84° $D_{.05} = 6.25$	MFD
m_j	8.3	1.8	2.2	‡$D_{.10} = 5.22$	
s_j	19.9[a]	1.1	1.7		
$s_j/\sqrt{n}$	3.11		0.31		
R	224	225		$m_{225} - m_{224} = 1.0$*†	3-1X
n	20	20		$D_{.05} = 1.57$	HSI
m_j	1.9	2.9		*$D_{.25} = 0.91$	
s_j	1.0	3.2			
$s_j/\sqrt{n}$	0.22	0.72			
R	226	227		$m_{227} - m_{226} = 0.3$	3-1X FD
n	20	20			Neither
m_j	2.1	2.4			
s_j	2.0	1.4			
R	181	180		Pilot didn't attend to task closely	3-1X
n	<20	<20			
m_j	36.1	27.8			
s_j	62.1	56.6			

*Difference between means significant at 0.25 level.
†Difference between means significant at 0.05 level after correction for skewness.
‡Difference between means significant at 0.1 level.
[a]Line printer missed these characters; underlined digits are uncertain.

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