

# Development and Evaluation of a Prototype Electronic Vertical Situation Display

by

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## **ABSTRACT**

Automation mode awareness problems have been experienced on many air transport aircraft and have been reported to the Aviation Safety Reporting System (ASRS) database. An examination of current generation AutoFlight Systems and a review of the ASRS database highlighted a lack of feedback in the vertical channel of aircraft automation. It was hypothesized that many of the incidents involving mode awareness problems could be mitigated by increased feedback in the vertical channel through an Electronic Vertical Situation Display (EVSD).

Functional requirements for an EVSD were developed and a implementation of the display was prototyped on a part task flight simulator. To evaluate the utility of the display, an experimental set of test scenarios were developed based on a representative set of known mode awareness problems. Commercial airline pilots were used as subjects in this experiment. This thesis presents the subjective and objective results of this evaluation of the display.

Certain types of scenarios showed a statistically significant improvement when the EVSD was available. In scenarios where another display explicitly showed the relevant information, availability of the EVSD was not correlated with improved performance. The EVSD was not observed to hamper pilot performance in any of the scenarios. A rating of the subjects' understanding of the scenarios showed a statistical improvement when the EVSD was available. Subjective surveys of the subjects rated elements of the EVSD as useful and helpful.

Thesis Supervisor: R. John Hansman  
Title: Professor of Aeronautics and Astronautics



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## List of Acronyms

ADI	Attitude Determination Indicator
AFP	Alpha Protection Floor
AFS	AutoFlight System
A/P	AutoPilots
ASL	Aeronautical Systems Laboratory
ASRS	Aviation Safety Reporting System
ATC	Air Traffic Control
CDU	Control Display Unit
CFIT	Controlled Flight Into Terrain
CWS	Control Wheel Steering
EHSI	Electronic Horizontal Situation Indicator
EVSD	Electronic Vertical Situation Display
FBW	Fly By Wire
FCU	Flight Control Unit
FD	Flight Director
FLCH	Flight Level Change
FMA	Flight Mode Annunciator
FMC	Flight Management Computer
G/A	Go Around
ILS	Instrument Landing System
LNAV	Lateral Navigation
MAP	Mode Awareness Problem
MCP	Mode Control Panel
MCT	Maximum Continuous Thrust
MIMO	Multiple Input-Multiple Output
PF	Pilot Flying
PFD	Primary Flight Display
PNF	Pilot Not Flying
SISO	Single Input-Single Output
T/D	Top of Descent
VNAV	Vertical Navigation
V/S	Vertical Speed mode





# Chapter 1

## Introduction

Current advanced commercial transport aircraft, such as the Boeing B777/B747-400, the Airbus A320/A340 and the McDonnell Douglas MD-11, rely on AutoFlight Systems (AFS) for flight management, navigation and inner loop control. These systems have evolved from straightforward autopilots into multiple computers capable of sophisticated and interrelated tasks. These tasks span the range from high level flight management to low level inner loop control. In addition, these systems provide envelope protection to prevent pilots from committing mistakes such as stalling the aircraft or lowering flaps at high speeds.

Unfortunately, as these systems have become more complex and interconnected, a new class of problems has developed associated with pilots' interaction with the automation. Many incidents have been reported where there exists some confusion between the pilots' expectations of the AFS and what the system is actually doing (Corwin, 1995). This confusion has been termed a Mode Awareness Problem (MAP).

After a description of the AFS, a formal definition of mode awareness problems is presented in Section 1.3 followed by representative incidents in which mode awareness problems are suspected as being a contributory factor.

### 1.1 AutoFlight System Description

The AFS in modern aircraft has three distinct mechanisms which correspond loosely to the time constants associated with the differing types of control. At the lowest level are a set of inner loop controllers, especially in Fly By Wire (FBW) systems, which improve the handling

characteristics of the aircraft by modifying the dynamics to which the pilot is exposed and provide aircraft attitude control. Above these are a set of autopilots (A/P) which command the aircraft to a specific state by providing inputs to the lower level controllers, much as a pilot would do manually. Finally, the Flight Management Computer (FMC) is a high level planning tool which can be programmed by the pilot to fly a complex predefined trajectory. These levels are discussed in more detail below.

### 1.1.1 Fly By Wire and Inner Loop Controllers

Inner loop controllers fly the aircraft to a target flight attitude. For example, if an external disturbance caused an aircraft to roll, the controller would return the aircraft to a level state, but would not correct for the integrated effects of the roll, such as a change in heading, or a loss of altitude. In a similar manner, the controller which maintains the aircraft pitch would compensate for a disturbance causing the pitch to change, but would not return the aircraft to the commanded altitude.

In addition, these controllers also perform a secondary role in Fly By Wire (FBW) aircraft, such as the Airbus A320/A340. Even the most basic flight control devices, such as the yoke (or side stick), pedals and throttle do not provide raw inputs directly to the control surfaces in FBW aircraft. Instead, the inputs are filtered and modified in a manner designed to provide a consistent set of dynamics to the pilot. This is intended to improve the safety of the aircraft by providing consistent responses to pilot inputs (Fishbein, 1995).

Even in aircraft which are not FBW, a set of low level inner loop systems may exist to control certain aircraft modes. The most well known of these is the yaw damper that is used on commercial jet transports (Weiner, 1988). Other aircraft have systems which modify input from

the standard control mechanisms to allow more flexibility in flight. For example, Control Wheel Steering (CWS) is available in the MD-11 and allows the pilot to directly control the roll angle of the aircraft.

### 1.1.2 Simple Autopilots

Simple autopilots control the aircraft at a level higher than the low level controllers by allowing the pilot to command the aircraft into a specific target state, such as holding at a commanded altitude, heading, or speed, or descending at a commanded rate. The autopilot system controls the aircraft around the commanded input of the pilot by providing inputs to the low level controllers to fly the aircraft to the designated path and speed (Fishbein, 1995).

In most cases, the A/P is also minimally capable of switching targets, and switching which specific A/P is currently controlling the aircraft. This capability allows the automation to make simple transitions to fly individual legs of segmented trajectory. For example, a system designed to control around a vertical speed may also include the logic necessary to stop the descent at a commanded altitude. When the aircraft levels out, a different A/P mechanism would control the aircraft to maintain that altitude.

The input to the autopilot is usually a Mode Control Panel (MCP), also referred to as a Flight Control Unit (FCU), which provides mechanisms to dial in various aircraft targets (altitude, vertical speed, airspeed, heading, etc.). The pilot then explicitly engages the A/P to capture the target. Limiting the complexity and capability of the autopilot system is the fact that only one target is associated with an individual autopilot system.

### 1.1.3 Flight Management System

The FMS is the strategic interface to the aircraft which drives the set of low level autopilots. The FMS has onboard an extensive database of navigation aids, waypoints, and standard arrival and departure procedures. Pilots use the FMS with a flight plan route to drive the set of low level autopilots. Pilots program the flight plan, consisting of waypoints and constraints into the FMS by interacting through a keypad-based Control and Display Unit (CDU). Using the flight plan, inputs from multiple navigation receivers and the database, the FMS provides inputs to the low level autopilots to flight the route automatically (Curran, 1992). The FMS can determine the most economical climb profiles, cruise altitudes, speeds and descent points to meet economic and wind constraints.

At a conceptual level, the FMS functions by switching between different vertical and lateral autopilot modes during different phases of flight without any need for further intervention from the pilot. This is particularly useful in long, uneventful stages of flight, such as cruise, though the FMS in modern aircraft is capable of fully automatic flights, including autonomous landings.

## 1.2 AutoFlight System Architectural Overview

Intrinsically, the higher level AutoFlight System function consists of switching between different *modes* of aircraft automation with simple modes being strung together to create more complicated flight trajectories. The following sections begin with an overview of mode definitions and the various types of mode transitions. Next, differences between horizontal and vertical modes are examined in the context of currently available mode feedback mechanisms. Finally the basic types of AFS input-output relationships are discussed.

### 1.2.1 Mode Definition

In this context, a mode is defined as a state of the aircraft automation which has a particular set of target criteria, control characteristics and transition criteria. Target criteria are the values that are programmed by the pilot or by the automation to which the mode will control the aircraft. An example would be the target heading or altitude at which the aircraft is flown.

The control characteristics define the actuators and associated control laws that the automation will use to fly to the target criteria. An example is using the ailerons to control the roll angle of the aircraft to acquire and maintain a commanded heading.

Transition criteria define the situations in which the automation will switch from the active mode to a new mode. These criteria can be utilized to create complex flight trajectories. An example of a transition criterium is the commanded altitude when the aircraft is in a descending mode. When the aircraft reaches the commanded altitude the automation will switch the active mode from the one used for the descent to a mode that transitions smoothly to and maintains the commanded altitude. Another example is if the aircraft exceeded safety limits, the automation will switch the active mode to one which reduced the risk of exceeding those limits.

### 1.2.2 Types of Modes

Current AutoFlight Systems switch between two basic types of operating modes which have been termed base modes and macro modes.

#### *Base Modes*

Base modes are used in quasi-steady-state conditions and have an invariant set of targets. A base mode example would be a Vertical Speed mode where the aircraft attempts to maintain a specific vertical speed target by controlling pitch using the elevators and an airspeed by controlling the thrust.

## *Macro Modes*

Macro modes consist of a linked sequence of base modes. Each base mode in the macro mode sequence has its own set of targets, implying a set of targets which vary over the course of the macro mode. Transitions between the base modes are made based on the mode transition criteria, such as altitude or indicated air speed. An example of a macro mode is the Autoland sequence, which transitions (in the vertical channel) between Altitude Hold, Glide Slope Capture, Flare, and Rollout with a different set of targets in each base mode.

### **1.2.3 Mode Transitions**

There are three types of transitions between modes. A *commanded transition* is active as soon as the selection is made. An example is pressing the Vertical Speed button, and thereby activating the Vertical Speed mode. An *uncommanded transition* is one that is not directly activated by the pilot. These transitions are usually some type of envelope protection. An example is a transition caused by overspeed protection. Finally, *automatic/conditional transitions* occur when, after arming, a mode engagement occurs at a transition criterium. An example is the use of Glide Slope Capture to transition to a descent mode after the aircraft intersects with the ILS glide slope signal.

### **1.2.4 Horizontal and Vertical Modes**

The AFS in a modern aircraft typically separates the guidance into uncoupled horizontal and vertical components. A simple example of a horizontal guidance base mode is using the MCP to command the aircraft to acquire and maintain a selected heading or track. A more complicated macro mode would be to use the CDU to program the FMS to fly a segmented trajectory in Lateral Navigation (LNAV). In this mode, the aircraft flies between preprogrammed waypoints defined by terrestrial navigation aids.

Typical vertical guidance modes include using the MCP to fly level in an Altitude Hold mode, or maintaining a selected vertical speed with Vertical Speed mode. In each of these modes the aircraft is controlled to a vertical path and the commanded airspeed. The FMS is also capable of flying complex Vertical Navigation (VNAV) trajectories, programmed by the pilot through the CDU, however, this mode is limited in use as LNAV mode must also be engaged. This is required because VNAV mode consists of adding altitude and speed restrictions to the horizontal waypoints. These restrictions would not have any context without the horizontal references.

### 1.2.5 Mode Feedback

The Flight Mode Annunciator on the Primary Flight Display (PFD) of modern aircraft is normally the primary location of mode status information. FMAs typically display the current mode configuration of the aircraft in a text format. The mode configuration consists of both the active mode and any additional modes that may have been armed, such as glide slope or localizer capture modes.

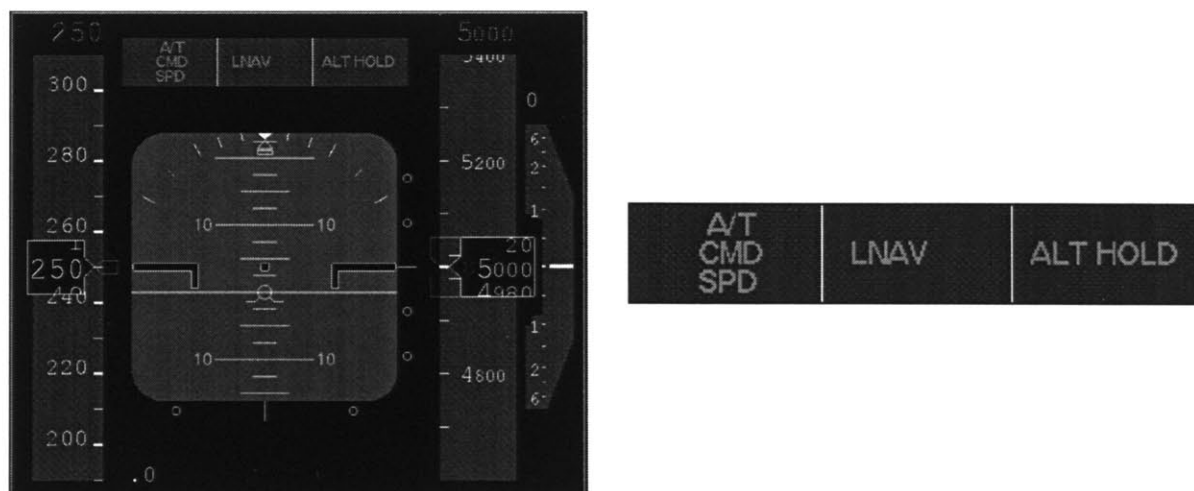


Figure 1.1: Primary Flight Display and Flight Mode Annunciator on B747-400

Both a PFD and a FMA from the Boeing B747-400 are shown below in Figure 1.1. As can be seen, the FMA is located in the middle of the display directly above the artificial horizon. The FMA symbology shows that the aircraft's Auto Throttle (A/T) mechanism is engaged and is being controlled by the autopilot (CMD) to follow a speed (SPD). In addition, the aircraft is in Lateral Navigation mode (LNAV) and currently holding altitude (ALT HLD) at 5000 ft.

### 1.2.6 AFS Input-Output Relationships

Two basic types of AFS input-output relationships can exist. The simpler is a quasi-steady-state model where each output state is controlled by a single input: Single Input-Single Output (SISO). A typical Vertical Speed mode engages two independent SISO controllers: the aircraft's pitch controls the vertical speed and the thrust controls the air speed. SISO models appear to be functionally adequate for most base modes.

The second type of relationship is one utilizing a Multiple Input-Multiple Output (MIMO) controller, where each output variable is controlled by more than one input. Some mode transitions appear to utilize a MIMO relationship. These transitions are typically of short duration and they do not appear to be modelled in detail by flight crews. An example of a complex mode transition is the 0.05g capture used in an Altitude Capture transition of the MD-11: when the aircraft is approaching a selected flight altitude, the intercept maneuver limits the normal acceleration to 0.05g.



## **1.3 Mode Awareness Problems**

A mode awareness problem exists when there is confusion between the pilots' expectations of the AFS and what the system is actually doing. Previous research (Sarter and Woods, 1992) has categorized mode awareness problems based on their underlying themes, such as problems related to VNAV modes, data entry, uncommanded mode transitions, infrequently used modes and features of the AFS etc.

In this work, mode awareness problems will be categorized in a less specific manner into three classically defined error categories: commission, omission and incorrect action (Sheridan, 1992). These are errors as viewed from the standpoint of the pilot: when the pilot believes that the AFS has committed an error. This allows a broader categorization, independent of the specific AFS mechanisms in question and instead focussing on the generic cause of mode confusion. In this research, mode awareness problems are said to have occurred when the aircraft AutoFlight System

1. executes an unexpected action - commission
2. fails to execute an expected action - omission
3. executes an action in an unexpected way - incorrect action

The next section will provide descriptions of three incidents which are examples of the types of mode awareness problems in this categorization.

### **1.3.1 Incidents Suspected to have Involved Mode Awareness Problems**

A few specific incidents are described below in order to give examples of actual cases of mode awareness problems. The first example is an error of commission: an A300 at Nagoya was inadvertently put into a go-around mode (Mecham, 1994) resulting in the crew fighting the

unexpected result. The second example illustrates an error of omission when an A320 in Bangalore was set in an incorrect mode (Lenorovitz, 1990) during approach that caused it to fail to add power to maintain a sufficient airspeed. The final example is one of an incorrect action. Vertical path control confusion on an Airbus A320 at Strausbourg (Sparaco, 1994) caused a Controlled Flight into Terrain as the crew was unable to detect an incorrect mode selection.

*Commission: Pitch Control in Go Around*

On April 26, 1994, an Airbus A300 landing at Nagoya Airport was inadvertently put into Go Around (G/A) mode by the pilots. G/A mode is used in situations where a landing needs to be aborted, and the aircraft needs to be reconfigured to leave the runway airspace and gain altitude quickly in order to attempt another landing. The mode attempts to pitch the aircraft into a nose up attitude and add power in order to climb.

The inadvertent engaging of G/A mode led to the crew using the aircraft flight controls to fight the automation in an attempt to keep the aircraft in a descent for landing. The aircraft's horizontal stabilizer was being trimmed for a nose up attitude as the automation attempted to overcome the pilots' using the elevators to place the aircraft into a descent configuration. When the pilots finally decided to abort the landing and to perform a G/A maneuver, they reconfigured the elevators for a climb configuration, which, when combined with the trim state of the horizontal stabilizer, caused the aircraft to pitch up sharply, stall at low altitude and crash (Mecham, 1994).

*Omission: Incorrect Mode Selection*

In February of 1990, an A320 crashed in Bangalore. The incident is suspected to have been caused by the crew incorrectly setting the descent mode during the approach. The A320 has an "idle open descent" mode in which the autothrust system keeps the engines at idle power. This mode is designed to be used for fuel efficient descents from altitude. However, since, in this

mode, the autothrust system limits the throttle to idle power, the mode does not allow the aircraft to necessarily maintain a commanded speed. In most high altitude descents, the pitch of the aircraft is used to maintain the commanded airspeed.

On this flight, an inexperienced first officer was flying the landing with the captain observing performance. According to the accident investigation, the crew entered the final approach phase of flight in a Vertical Speed mode (a “speed protected mode” which maintains the commanded speed) but then switched to the “idle open descent” mode (which does not maintain the commanded speed). The crew commented on the mode of the aircraft, and discussed how to disengage it, but did not actually do so. Neither crew member appeared to be monitoring the speed of the aircraft as it slowed to 25 kts below the 132 kts approach speed. It is speculated that the crew expected the AFS to automatically add power to the aircraft as it would do in a speed protected mode, such as the Vertical Speed mode normally used during approach.

This particular incident could be viewed as an error of omission. The crew expected that the aircraft was controlling the airspeed and relied on throttles to add power. The active mode of the aircraft did not allow this to occur.

*Incorrect Action: Vertical Path Confusion*

On January 20, 1992, an A320 aircraft crashed during a non-precision approach into Strausbourg airport. The aircraft was estimated to be descending at 3300 fpm, a much steeper rate than the approach was designed for. The approach to the airport specifies a gradual step-down with numerous level-off altitudes and short descent legs. Many pilots who land at Strausbourg realized that this complex approach trajectory could be safely approximated with a flight path angle of 3.3°. This descent rate came sufficiently close to matching the multiple altitude waypoints on the descent profile detailed in the approach plate.

It is speculated that the flight crew's intent was to descend on this simplified path, but instead placed the aircraft into the wrong descent mode: Vertical Speed instead of Flight Path Angle. In Vertical Speed mode, the indication for 3300 fpm looks almost identical to a descent in Flight Path Angle mode of 3.3°. The only indication of the engagement of an incorrect mode was text on the Flight Mode Annunciator and a decimal point on the target display. At the ground speed of the aircraft, 3300 fpm was twice the intended descent rate. The crew did not recognize the problem until too late and the much higher descent rate resulted in a Controlled Flight Into Terrain (CFIT).

## **Chapter 2**

### **Background and Motivating Research**

The fundamental motivation for this research is to reduce the number of aircraft incidents related to mode awareness problems. Toward this end, incidents in which mode awareness issues are suspected to have been a contributing factor have been examined. A review of the reports contained within the Aviation Safety Reporting System (ASRS) database was conducted along with a set of focussed interviews with flight crews and an examination of the feedback mechanisms in modern AutoFlight Systems.

#### **2.1 Aviation Safety Reporting System**

The Aviation Safety Reporting System allows pilots to detail safety problems or incidents with a degree of amnesty. A search was performed on the ASRS database by researchers at the Aeronautical Systems Laboratory (Vaneck and Midkiff, 1994) from the years 1990-94 with a set of keywords designed to elicit problems related to mode awareness. The keywords consisted of the following: annunciation, annunciator, FMC, flight management computer, FMS, flight management system, CDU, mode, capture, arm, automatic flight system, vertical, horizontal, and program.

A total of three hundred ASRS reports were returned by the keyword search. After analysis, 184 were categorized as mode awareness problems using the definition in Section 1.3.

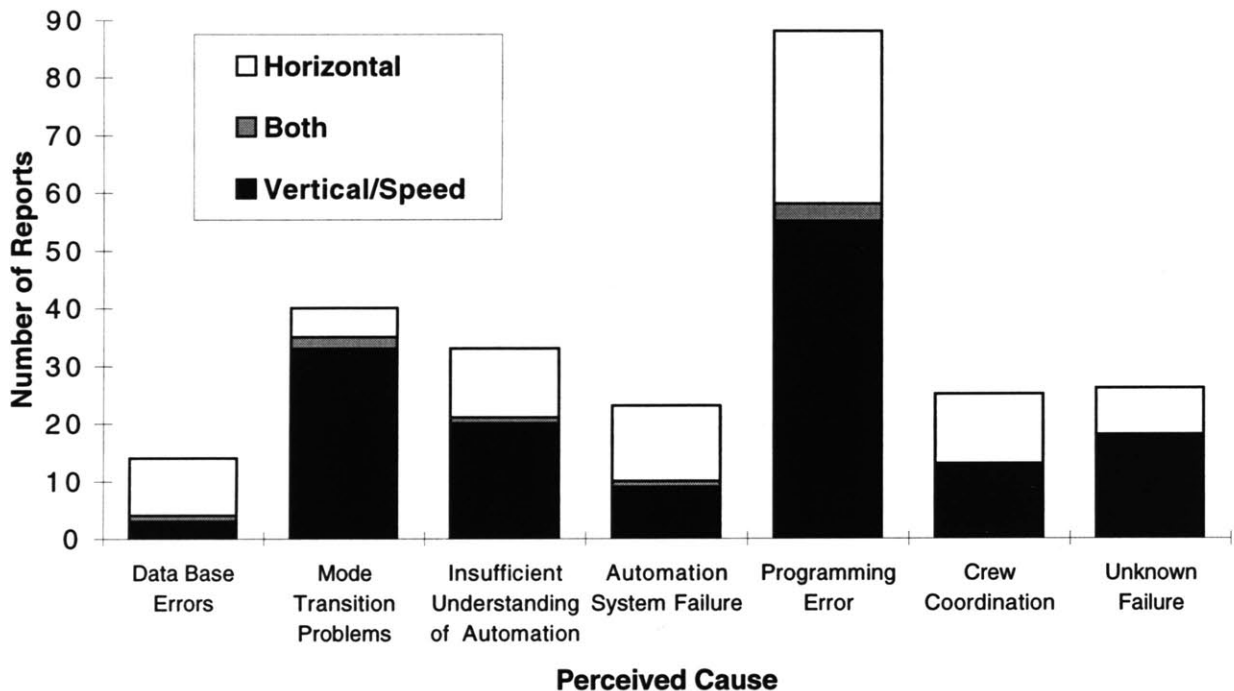


Figure 2.1: Breakdown of ASRS reports into Perceived Causes and Flight Domain

As shown in Figure 2.1, these reports were then categorized by the perceived cause of the problem and by the flight path (vertical/speed, horizontal or both) that was impacted. Since the vertical flight path and the speed are implicitly coupled, problems with either were grouped together. In instances where the problems spanned multiple causal categories, the reports were counted in each relevant category.

In Figure 2.1, it can be seen that vertical/speed problems dominate many of the categories. A total of 62.7% of the reports were vertical/speed related. In particular, the Mode Transition Problems category is dominated by vertical/speed problems. The data classified into the Insufficient Understanding of Automation also suggests a deficiency in knowledge of the vertical domain automation.

It should be noted that there exists a potential for over-reporting vertical deviations. Since Air Traffic Control (ATC) radar has very precise surveillance of altitude versus position, there may be more cause to report vertical/speed incidents due to the amnesty clause in the ASRS.

## **2.2 Feedback Mechanisms in Current AutoFlight Systems**

Feedback mechanisms in current aircraft AutoFlight Systems were examined to determine whether the feedback available concerning the active mode and the characteristics of that mode was sufficient (Midkiff, 1994). In addition the underlying aircraft automation architecture was examined to see whether it was a contributing factor in mode awareness issues. The aircraft examined included the Boeing B757/B767, the McDonnell Douglas MD-11 and the Airbus A300-600R.

An inventory of Flight Mode Annunciation (FMA) schemes was also completed by reviewing training manuals and a review of the open literature. The intent was to examine the feedback available on the Primary Flight Display through the FMA - the primary source of feedback for the automation state. The display conventions used in the FMA were compared across a larger set of aircraft, including the Boeing B737-500/600, B757, and B767, McDonnell Douglas MD-11, MD-80, Fokker 100 and Airbus A300-600R.

### **2.2.1 Flight Mode Annunciators**

As detailed in Section 1.2.5, the Flight Mode Annunciator on the Primary Flight Display of modern aircraft is used as the primary indicator of mode status information. Most FMAs depict the current mode configuration of the aircraft in text along with any armed modes.

More recently designed FMAs include target states along with the name of the mode. An example of a target state value would be the value of the commanded vertical speed in Vertical Speed mode. The Fokker F100 and the MD-11 FMAs also display the control allocation in each mode. This information identifies which actuator is controlling a particular output. Knowledge of control allocation is particularly important in the vertical domain, since pitch and thrust can be used interchangeably to control the vertical path and speed. Note that the availability of control allocation in these FMAs implies a set of parallel SISO (Single Input, Single Output) controllers being used. Neither of these features appears on the Boeing B747-400 FMA example shown in Section 1.1.

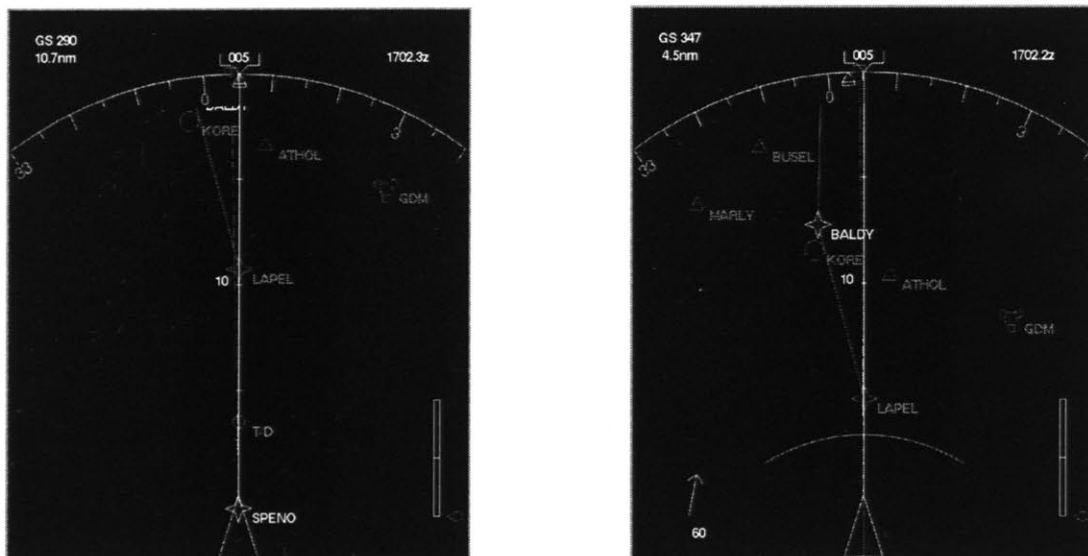


Figure 2.2: Electronic Horizontal Situation Display

### 2.2.2 Horizontal Channel Feedback

The primary feedback display for the horizontal channel is the Electronic Horizontal Situation Indicator (Map or Navigation Display) (EHSI) shown in Figure 2.2, which gives a full tactical and strategic view of the current and planned path of the aircraft. The position of the aircraft is



shown by a white triangle in the bottom center of the display. The aircraft is shown geographically relative to the inactive (blue) and programmed (magenta) waypoints in the vicinity. Programmed waypoints are those which have been entered as endpoints in segments of the FMS path (magenta line). The next active waypoint, the one that is actively being flown to, is shown in white. The current aircraft heading is shown on the compass arc on the top of the display. The second frame shows the same scene a few minutes later, after the descent to LAPEL has begun.

By displaying the area in front of the aircraft, this display allows pilots to quickly ascertain how the aircraft has been programmed and anticipate what it is expected to do. In particular, any deviation from the programmed path can quickly be seen by the aircraft symbol flying away from the magenta line.

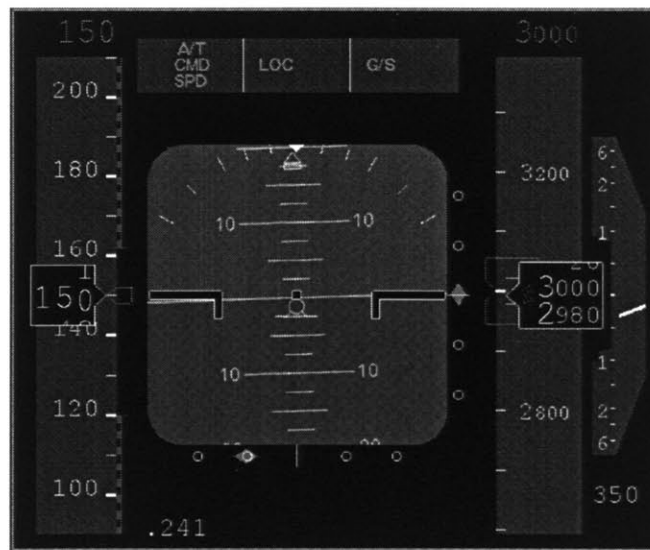


Figure 2.3: Primary Flight Display

### 2.2.3 Vertical Channel Feedback

The primary source of vertical channel feedback is the textual display in the Flight Mode Annunciator, in the top middle of the PFD shown in Figure 2.2. In this figure, the aircraft is tracking the ILS glide slope. To the right of the Attitude Determination Indicator, the magenta diamond shows the aircraft deviation above or below the glide slope, indicating, in addition to textually, that the current mode is Glide Slope Tracking. To the right of the altitude tape, the vertical path indicator shows the current descent rate of the aircraft, independent of active mode.

A few graphical elements related to the vertical path are displayed also on the EHSI. The first frame in Figure 2.2 shows a Top of Descent pseudowaypoint about 3 nmi in front of the aircraft. During the descent, an Altitude Intercept Arc (as seen in the second frame) indicates where the aircraft is expected to reach its commanded altitude. The programmed VNAV path is implied by the Top of Descent point, but this actual path is only displayed as a series of text based altitude and speed restrictions on the CDU. Pilots can use the keypad on the CDU to flip through pages of flight segments with associated restrictions and build a mental picture of the aircraft flight path. Unfortunately, in total, the various feedback mechanisms available for the vertical channel do not provide immediate graphical feedback.

### 2.2.4 Feedback Mechanism versus Channel Complexity

There is also an discrepancy between the feedback available in the vertical channel and the horizontal channel. Though the vertical channel is functionally more complex, there is less feedback to the pilots than in the horizontal. The vertical channel is more complex than the horizontal channel for two reasons: multiple targets and multiple control mechanisms for those targets.

As shown in Table 2.4, the horizontal flight of an aircraft is limited to using a single method to control a single target state: controlling the heading of the aircraft by using the ailerons to for roll authority.

**Table 2.4: Representative Horizontal Modes in the MD-11**

Horizontal Modes	Control Allocation
Heading	Roll
Track	Roll
NAV	Roll
ILS Localizer Tracking	Roll

In contrast, the vertical flight of an aircraft requires control of both the speed of the aircraft and its vertical path, since speed and vertical path are interrelated. This leads to the vertical flight of an aircraft having many more potential target states: vertical speed, altitude, preprogrammed vertical flight paths, airspeed, thrust level, aircraft pitch, angle of attack and so on. In addition, each of these targets can be controlled to by a combination of the aircraft pitch and the thrust level. Table 2.5 shows a tally of vertical and speed based flight modes drawn from the MD-11 Cockpit Pilot’s Guide.

As an example, in a simple base mode, such as the Altitude Hold mode, the aircraft speed would be controlled by the throttle and the vertical path (in this case, the altitude) would be controlled by the pitch of the aircraft with the elevators. Another base mode, Flight Level Change mode, sets the throttle at a limit value to control the vertical climb rate, and controls the speed of the aircraft with the pitch.

**Table 2.5: Representative Vertical and Speed Modes in the MD-11**

<b>Vertical and Speed Modes</b>	<b>Speed Control Allocation</b>	<b>Path Control Allocation</b>
Altitude Hold	Throttle	Elevator
Altitude Capture		Mixed (MIMO transition)
FMS Altitude Hold	Throttle	Elevator
FMS Profile Descent	Elevator	IDLE Throttle
Vertical Speed (MCP)	Throttle	Elevator
Vertical Speed (FMS)	Throttle	Elevator
Flight Path Angle	Throttle	Elevator
Flight Level Change	Elevator	IDLE or CLIMB Throttle
Glide Slope Tracking	Throttle	Elevator
Flare	Throttle	Elevator
Go Around	Elevator	CLIMB Throttle
Low Speed Protection	Elevator	Throttle
High Speed Protection	Elevator	Throttle

### 2.3 Focussed Interviews

Information was gathered via focussed interviews from a variety of informal sources, including direct flight deck observations, discussions with flight crews, and discussions with simulator check airmen about their observations of crews during recurrent training.

Two major conclusions were drawn from these interviews. The first was that the lack of a simple model for the AutoFlight System prompts pilots to create their own ad hoc models. The second was that the vertical channel poses many more problems than the horizontal channel, due to lack of feedback and its greater complexity.

Based on the analysis of the structure of current AutoFlight Systems, there do not appear to be any simple, consistent, global models for any current AFSs. Such models are not available in flight manuals which instead focus on crew interface and procedures. In the absence of a simple consistent model, pilots appear to develop their own ad hoc models of the AFS as independent parallel SISO control loops. As such, these models may not accurately represent AFS operation, especially in transitions between modes, particularly during automatic transitions. Transitions to and from envelope protection modes also appear to be particularly troublesome.

Since the vertical channel is intrinsically more complex than the horizontal channel, the problems associated with pilot models become exacerbated. In addition since the vertical flight path can be controlled by both pitch and thrust and is linked with the speed of the aircraft, many of the transitions used by in vertical flight involve MIMO control techniques. Pilots do not appear to model MIMO transitions in detail, relying instead on an understanding of the final target state and some smoothness criteria to monitor the AFS performance.

## **2.4 Improvement of Vertical Channel Feedback**

The background research has identified the lack of feedback and a high degree of automation complexity in the vertical channel as a possible source of mode awareness problems. The ASRS report analysis (Section 2.1) showed a majority of incident reports in the vertical/speed mode. The Flight Mode Annunciator (shown in Figure 1.1) depicts the minimal level of feedback currently available for the vertical channel. Finally, the focussed interviews with check airmen (Section 2.3) highlight the complexity of the vertical flight channel. Based on this information it was hypothesized that adding feedback to the vertical channel would mitigate some of the reported and suspected mode awareness problems.



## **Chapter 3**

### **Electronic Vertical Situation Display**

Background research highlighted the vertical channel as an area in need of improved feedback. Based on this hypothesis, a set of crew information requirements was developed. This set of requirements was incorporated into an Electronic Vertical Situation Display (EVSD) to mitigate some of the identified problems.

#### **3.1 EVSD Design**

The Electronic Vertical Situation Display is envisioned to provide an analog to the Electronic Horizontal Situation Indicator, which is currently available in glass cockpits. The display is designed to show the programmed vertical path of the aircraft and the modes associated with that path.

The information requirements for the EVSD were created based on operator requirements and on known mode awareness problems. The information requirements have four major components: the current mode, any anticipated modes, transitions into anticipated modes, and the consequences of the current state of aircraft automation. The four requirements also provide answers to the most commonly asked questions asked in glass cockpits: “What is it doing?”, “Why did it do that?” and “What will it do next?” (Wiener, 1989). These major aspects of the EVSD are overviewed below, and presented in much greater detail in Section 3.2.

### **3.1.1 Current Mode**

The current mode of the automation needs to be identified along with any of the specific attributes of the mode such as target state values and control allocation. If possible these should be displayed in a graphical format.

### **3.1.2 Anticipated Modes**

Anticipated modes consist of the future modes into which the automation expects the aircraft to transition. Based on some extrapolation of the current aircraft and automation state, the system needs to be able to anticipate future mode transitions and the associated future modes. This determination may be straightforward for many preprogrammed macro modes, but it may be inaccurate for uncommanded mode changes. For example, the highly accurate prediction of entering an envelope protection mode downstream is difficult. Issues associated with anticipation are discussed in Section 3.4.

### **3.1.3 Mode Transitions and Consequences**

Anticipation of the consequences of the current state of the automation is necessary. A predictive profile based on the current automation state should display the locations of anticipated mode transitions and their consequences on the flight path. Determining the location of these transitions requires making assumptions about both the intentions of the pilots and factors external to the aircraft, such as weather and air temperature. Closely related to this is the ability to anticipate mode changes. Since there may not be warning of certain types of mode changes, especially those which are selected by the crew, this may not be possible in all situations.

The consequences of a mode change are based on an extrapolation of the current state of the aircraft automation. A predictive profile based on the current automation state is shown to display the locations of anticipated mode transitions and their consequences on the flight path.



### 3.2 EVSD Format

Figure 3.1 shows the prototype EVSD. The display has four distinct areas. At the top of the display is the mode display window, showing the current and anticipated modes, control allocations and target states. At the left is a scalable altitude tape. The bottom window can either display the path distance (if in LNAV mode), or the range directly ahead of the aircraft. Finally, the main window shows the aircraft vertically in relation to the upcoming waypoints and mode transition points.

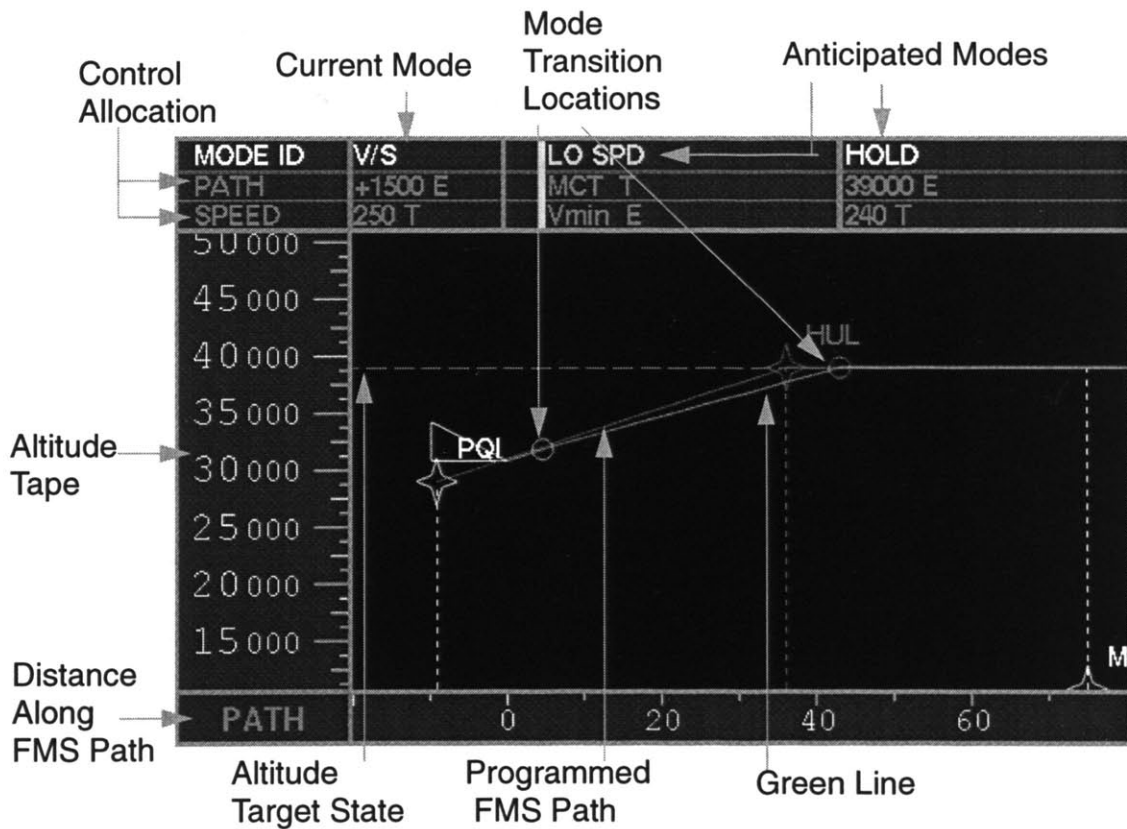


Figure 3.1: EVSD during Vertical Speed Climb, reaching an envelope protection limit

### 3.2.1 Current Mode

In Figure 3.1, the current mode is identified in the top window in green text, directly above the aircraft symbol. Underneath are the control allocations and the target states for the active mode. In this example, the aircraft is in Vertical Speed mode (V/S) with the vertical path controlled by elevator (E) and the speed controlled by throttle (T). An example of a transition criterium is the dashed magenta line at 39 000 ft, which is the altitude dialed into the Mode Control Panel.

### 3.2.2 Anticipated Modes

On the EVSD, the anticipated mode is shown in the top window above the point where it is predicted to be engaged. The anticipated target state and control allocations are depicted in a manner similar to the current mode. In Figure 3.1, the system is predicting an envelope protection violation and a mode transition to the Low Speed mode (LO SPD). In this mode, the display shows that the vertical path will be controlled by the throttles to Maximum Climb Thrust (MCT), and the speed will be controlled by elevators to  $V_{min}$ . Note that both the target states and the control allocation change when the new mode is engaged.

Another mode change is anticipated once the aircraft reaches the MCP altitude of 39 000 ft, approximately 40 nmi ahead of the aircraft. The aircraft will switch to Altitude Hold mode (HOLD). Once the automation switches to this mode, the altitude becomes a target state, as shown in the box underneath the HOLD text.

### 3.2.3 Mode Transitions and Consequences

Mode transition alerting has several elements. The first is the text of the anticipated mode translating across the top window, arriving at the current mode slot when engaged. The second is an Aircraft Path Line, commonly referred to as the “green line” which shows the path that the

aircraft will travel based on the current state of the automation. In Figure 3.1, the green line is shown deviating from the solid magenta line as the automation anticipates the aircraft being unable to maintain the commanded climb rate. In this case, an elbow in the path also highlights where the transition is calculated to occur.

The green line also has a set of circles which highlight where the aircraft is going to undergo a mode transition. Green circles depict when the aircraft is going to undergo a programmed mode transition, such as levelling at a commanded altitude as seen in Figure 3.1 near the 40 nmi point. These circles align with the green bars in front of programmed modes shown in the upper window. Yellow circles depict uncommanded or automatic mode changes that occur due to envelope protection violations. In Figure 3.1 the yellow circle at the bend of the elbow highlights the transition at the 5 nmi point to the Low Speed mode (LO SPD). These circles also align with the yellow bars in front of automatic modes in the upper window.

#### **3.2.4 Additional Symbology**

A solid magenta line connecting waypoint crossing restrictions is a graphical display of the current vertical path programmed into the FMS. Shown in the main section of the EVSD screen are the waypoints programmed into the FMS. In a manner consistent with the EHSD, programmed waypoints are magenta, and the active waypoint (the one the aircraft is flying to) is white. Non-programmed waypoints are not shown.

Altitude crossings are shown by the altitude of the waypoint symbol. Waypoints without restrictions are placed on the ground, or on the bottom edge of the screen if the ground is not visible. Dashed lines descend to the path scale on the bottom of the display to allow the distance to future waypoints to be easily determined. The horizontal scale is defined by the path distance between each waypoint.

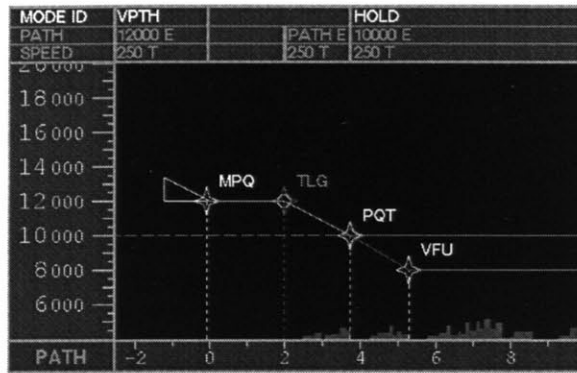


Figure 3.2: EVSD in VNAV Descent

The example shown in the Figure 3.2 is a Vertical Navigation macro mode (VNAV) descent. The aircraft is shown on the first segment of a descent profile using the VNAV mode to maintain an altitude of 12 000 ft. Near the TLG waypoint, the aircraft is anticipated to remain in the VNAV macro mode, but to change the target state at the Top of Descent point (a transition criterium) to a path-based descent. The Aircraft Path Line highlights another mode change that will occur near PQT at 10 000 ft as the aircraft intersects the preprogrammed MCP altitude transition criterium and switches out of VNAV and into an Altitude Hold mode.

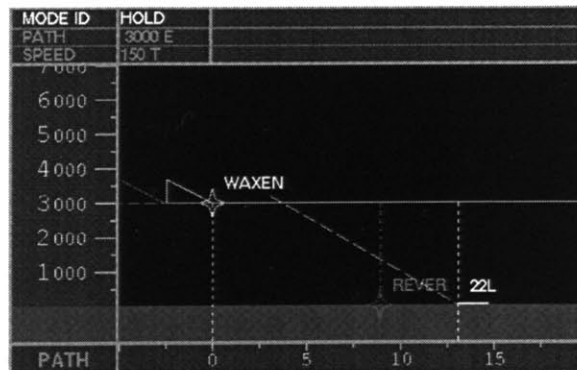


Figure 3.3: EVSD Near Approach

Figure 3.3 shows an aircraft close to approach with the additional symbology required near landing. The dashed white line is an indication of the location of the ILS glide slope. At the end of the glide slope is the runway, shown at the correct altitude and length. The difference between waypoints with and without an altitude restriction is also apparent. WAXEN has an altitude restriction associated with it, and is shown at that altitude of 3000 ft. Since there is no altitude restriction associated with the REVER waypoint, it is placed at ground level.

Finally, the very bottom of the main window in the Figure 3.2 has terrain information. While this capability was not used in the experimental evaluation, it has been prototyped on the EVSD.

### **3.3 EVSD Design Issues**

There were several issues which were taken into account in the design of the EVSD. The first was that several assumptions had to be made about the underlying AFS that for which the EVSD was providing feedback. In a related manner, a set of consistent colour symbology had to be selected. Finally, the anticipation capability required for the depiction of future modes had to be carefully designed.

#### **3.3.1 Implementation Assumptions**

Three major assumptions were made about the structure and capabilities of the underlying automation. The first was that the underlying architecture of the AFS was able to be represented with a SISO model. Earlier analysis has shown that the AFS appears to be functionally representable by a SISO model for most operating conditions. SISO models also appear to be consistent with pilot models and are currently used on FMAs in some aircraft.

The second assumption was that the system needed to maintain a level of consistency with the current technology level. In order to create a near term solution for current AFS problems, the display was designed to be consistent with current display system limitations and conventions. This also allows pilots to be trained on this display with minimal effort, and with maximum carryover from existing training. This assumption also lead to a set of colour conventions consistent with the Boeing B747-400 Electronic Horizontal Situation Indicator as shown in Table 3.2. Note that the Aircraft Path Line is symbology that is not currently available on the EHSI. This symbology, described in detail in Section 3.2.3, was created in order to have a mechanism to display anticipated mode changes, a capability not currently supported under Boeing conventions.

**Table 3.4: Color Conventions**

<b>Information Element</b>	<b>Graphical Representation</b>
MCP Input	Dashed Magenta Line
FMS Path	Magenta Line
Programmed Waypoint	White Symbol
Current Waypoint	Magenta Symbol
Mode Transition Point	Green Circle
Uncommanded Mode Transition Point	Yellow Circle
Aircraft Path Line	Green Line

In a related topic, in order to display anticipated modes, the ability to predict future automation states based on the current flight vector and automation state was assumed. This is covered in more detail in Section 3.3.2.

### 3.3.2 Anticipation Issues

There are several issues to consider when implementing anticipatory capabilities into aircraft. The biggest concern with reliable anticipation is the varying nature of the flight environment, both externally (winds, temperature) and internally (aircraft weight, configuration, pilot input).

There are also concerns about the non-linearities of aircraft dynamics during mode changes which may make the problem computationally difficult or not readily possible on current generation AutoFlight Systems. At the very least, aircraft may require better sensors, or better noise filtering capabilities. For this implementation of the EVSD, the specific anticipation techniques used are detailed in Section 4.5.

It is important to realize that modern aircraft currently have some level of anticipation capability. Both the altitude capture arc and the flight time determination by FMS involve estimates of the current and future state of the aircraft and provide pilots with input and feedback. Even with limitations, this input is found to be useful. Pilots realize the limitations of the automation (FMS calculates landings late, altitude capture arc moves) and adapt to them. An important consideration is that linear extrapolations improve as the aircraft approaches the transition point. These estimates improve primarily because environmental conditions are closer to those at transition point and the likelihood of unanticipated conditions decreases.





## Chapter 4

### Prototype EVSD Implementation

The prototype Electronic Vertical Situation Display was implemented on the Aeronautical Systems Laboratory's Advanced Part Task Simulator. This chapter covers the capabilities of the simulator facility and how they were used in this experiment. The experiment involved using a set of envelope protection features as part of a robust and realistic of AFS architecture. The chapter ends by covering the specifics of the mode anticipation implementation.

#### 4.1 Part Task Simulator Facilities

The experiment was conducted at the MIT Aeronautical Systems Laboratory using the Advanced Part Task Simulator. This facility has been developed over the last seven years by numerous MIT students involved in various aviation human factors and system design experiments.

##### 4.1.1 Simulator Setup

The heart of the simulator facility was a Silicon Graphics, Inc. (SGI) Indigo<sup>2</sup> Extreme Workstation. This machine is interfaced to a Mode Control Panel from a Boeing B737 cockpit, a sidestick controller, a Control Display Unit, and a set of standard aircraft input levers - throttles, landing gear, flaps and speed brakes. A schematic of this setup is shown in Figure 4.1.

The Mode Control Panel was used by the pilot flying as the primary input to the aircraft. The sidestick controller was used by the subject to provide input to the sidetask (detailed in Section 5.4.1). The CDU was primarily used as a mechanism to display altitude restrictions that had previously been programmed into the AutoFlight System. This was important for

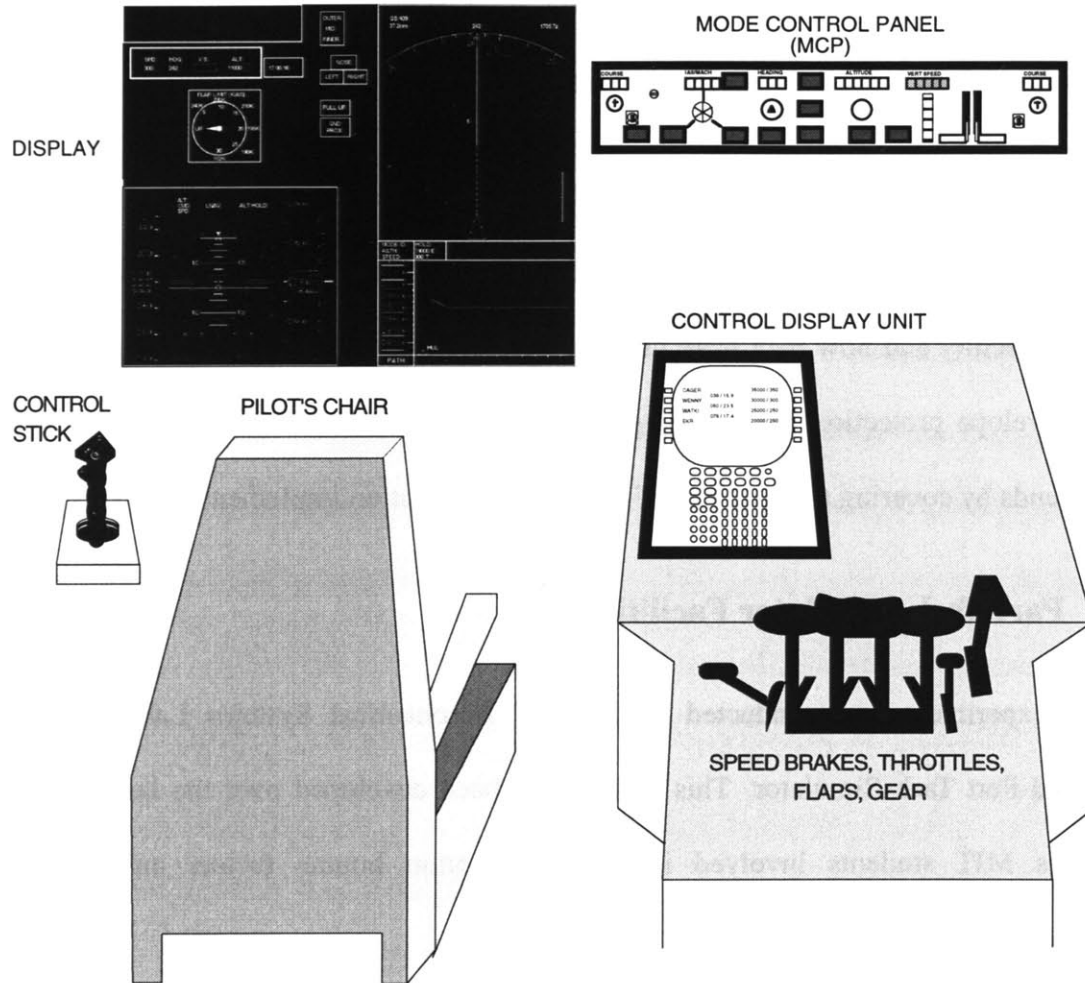


Figure 4.1: Prototype Part Task Simulator Facility

experimental runs in which the EVSD was not available as a graphical depiction of this information. Finally, the flap lever on the center panel was used in a number of scenarios to simulate low speed situations during approach scenarios.

#### 4.1.2 Screen Layout and Display Geometry

As can be seen in Figure 4.2, the prototype EVSD was placed on the simulator screen directly below the EHSI (map mode) display. It was scaled to be as wide as the EHSI and approximately half as tall.

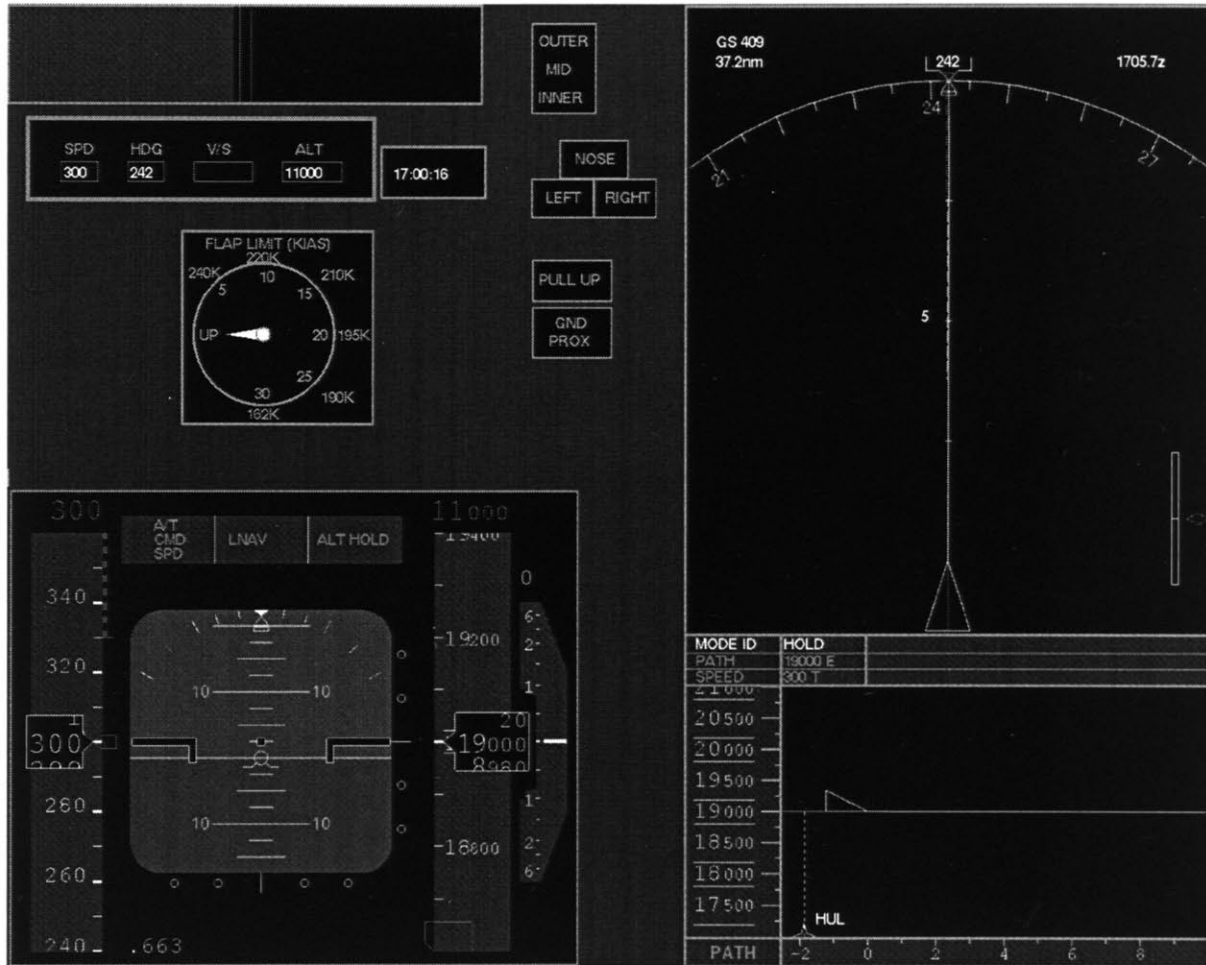


Figure 4.2: Simulator Screen Shot

A side task is located on the top left of the screen. The side task consisted of centering the position of a moving horizontal gray bar by using a side stick controller. Additional symbology available on the screen was a copy of the Mode Control Panel information (directly below the side task), a flap settings dial and various elements associated with landing: marker lights, gear lights and GPWS warnings. When scenarios were run without the EVSD a blank rectangle appeared where the display was normally located.

## 4.2 AutoFlight System Capabilities

Since this experiment explored pilot interaction with the simulator AutoFlight System, this section enumerates the capabilities that were available on the simulator which were used for this experimental evaluation.

### *Standard Modes*

The Advanced Part Task simulator is outfitted with a set of AFS modes designed around the terminal area operations for which it has historically been used. In particular, the simulator is outfitted with the vertical modes shown in Table 4.3. Since all of the scenarios were run in an automatic LNAV mode, the lateral modes were not relevant to the experiment.

**Table 4.3: Standard Simulator Modes**

<b>Mode Name</b>	<b>Functionality</b>
VNAVPATH	Vertical Navigation along a preprogrammed path
FLCH	Flight Level Change to the commanded altitude
ALT_HOLD	Hold the current commanded altitude
VS	Maintain the commanded Vertical Speed
GS	Follow the ILS glide slope
GS_ARM	Arm for capture of the ILS glide slope
GA	Abort the approach and Go Around

The simulator is capable of performing changes in altitude in three distinct ways. The first is to have a preprogrammed VNAV path to fly which has an altitude change along the path. The second is to climb at a “climb” throttle setting, or descend at “idle” thrust setting while maintaining an airspeed with appropriate pitch to the altitude dialed in the MCP as used in the

Flight Level Change mode. The final mechanism is to command a Vertical Speed (V/S). This vertical speed could fly away from the altitude dialed into the MCP and cause an open descent or climb.

In each case, when the path of the aircraft approaches the MCP altitude, a 0.05g capture maneuver is initiated to smoothly capture the target altitude and automatically transition into an Altitude Hold mode. While in this mode, the simulator uses a variation of the 0.05g arc to maintain the commanded altitude.

The final important mode was the glide slope arming mode, where the AFS was actively searching for a glide slope signal. As soon as the glide slope signal became available, the AFS would engage the Glide Slope (GS) mode.

#### *Envelope Protection Modes*

In order to create scenarios with automatic mode transitions due to overspeed and underspeed conditions, two envelope protection modes were used. The first was a High Speed mode, which protected the aircraft from overspeeding by switching the AFS into a speed on pitch, throttle at idle setting similar to the Flight Level Change mode explained in Section 2.2.4. This caused the descent rate of the aircraft to decrease to the maximum descent rate possible on idle throttle while not gaining speed. This mode was only available in modes where the aircraft was not *speed protected*, i.e. modes in which the speed was allowed to vary in order to capture a specific path or vertical rate. In particular, the envelope protection mode was not available or necessary for the Flight Level Change mode. This mode had a primary speed target and was not constrained to any particular path.

The Low Speed mode was very similar, but switched the aircraft into a speed on pitch, throttle at Maximum Continuous Thrust (MCT) setting again similar to the Flight Level Change mode. The MCT represents the maximum sustainable thrust at altitude.

Finally, a VNAV Speed mode was used to handle situations in which the vertical navigation logic was incapable of flying the programmed path without deviating from the commanded speed by more than 10 knots. This mode placed the aircraft into either a Low Speed or a High Speed equivalent mode depending on whether the AFS was being asked to climb or descend.

### *Simulator Automation Architecture*

It was anticipated that the experimental evaluation of the EVSD would have sessions limited to a few hours per subject. To enable this evaluation, the AFS architecture was designed to be explained quickly and clearly to the subject. Since all of the subjects were expected to have experience in highly automated, modern cockpits, this task was fairly straightforward. In order to create a simple structure, a small set of rules was created and applied to the AFS structure. The outcome of this set of rules detailed in Section 4.3 for the subset of the AFS that was modelled for this experimental evaluation.

## **4.3 Simulator AutoFlight System Architecture**

Designing and implementing a minimal set of rules which defined the AutoFlight System of the simulator solved a number of difficult situations for which satisfactory answers were not available in the open literature. The three rules involved the default state of the aircraft automation, the hierarchy of the constraints and targets input in various manners, and the actions of the envelope protection modes after the critical situation had passed.

#### 4.3.1 Default State

There were two basic default states for the aircraft automation, depending on whether the VNAV set of modes were engaged. If VNAV was engaged the AFS would default to VNAV Path, flying to and on the preprogrammed path as soon as it was capable. In situations where the system was forced into VNAV Speed mode, a reversion to VNAV Path would occur as soon as the aircraft levelled off. When not in any VNAV mode, and unless otherwise commanded, the aircraft would remain in its current mode.

#### 4.3.2 Constraint Hierarchy

The overall vertical navigation hierarchy dictated that more immediate modes would override those that were less immediate, or that inner loop modes would override outer loop modes. In particular, anytime the pilot overrode the AutoFlight System and took over manual control, the rest of the AutoFlight System disconnected itself. In addition, any time that a preprogrammed macro mode, VNAV in particular, intersected an inner loop restriction, such as the commanded MCP altitude or the glide slope, the AFS vertical mode would defer to Altitude Hold mode or Glide Slope mode, respectively.

#### 4.3.3 Envelope Protection Modes

Whenever the aircraft AFS was forced into an Envelope Protection mode, it remained in that mode until it intersected a constraint that would allow it to transition to another mode. While in VNAV Speed mode, the aircraft would remain in a descent or climb until it intersected either the commanded MCP altitude (when it would revert to Altitude Hold mode), or until it intersected a level section of the programmed path (when it would revert to VNAV Path mode). When not in VNAV mode, the aircraft would continue on its flight vector until it intersected the commanded MCP altitude.

## 4.4 Anticipation Capability Implementation

The current implementation of the anticipation capability uses a simplified linear extrapolation to determine what the aircraft is expected to do. The linear extrapolation is based on the current aircraft automation state and operating environment.

The first segment of the linear extrapolation is created based on the instantaneous flight vector of the aircraft until it intersects one of the target states (MCP altitude, VNAV path). Further extrapolation looks forward to a mode change point caused by either an interception of target state (reaching the programmed altitude or waypoint, or interception of the glide slope signal) or anticipates a speed violation based on the acceleration of the aircraft.

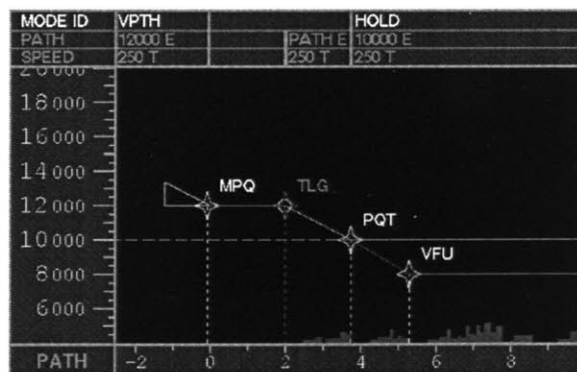


Figure 4.4: Anticipation using Programmed Path

Figure 4.4 shows an example of the former type: the aircraft path line continues straight and level until it reaches a target - the waypoint labelled TLG. At that point, it linearly anticipates the next stage of flight, the descent from TLG to POT. At POT, the next target point, the altitude dialed into the Mode Control Panel overrides the VNAV system, and levels the aircraft at 10 000 ft.



In contrast, Figure 4.5 shows the envelope protection type of anticipation. The speed of the aircraft is dropping as it is forced into an unusually steep climb at a high altitude. This leads to the AutoFlight System anticipating a envelope protection transition into the Low Speed mode relatively soon. From that point forward, the well defined Low Speed mode operating characteristics are used to anticipate the next segment of the aircraft's flight.

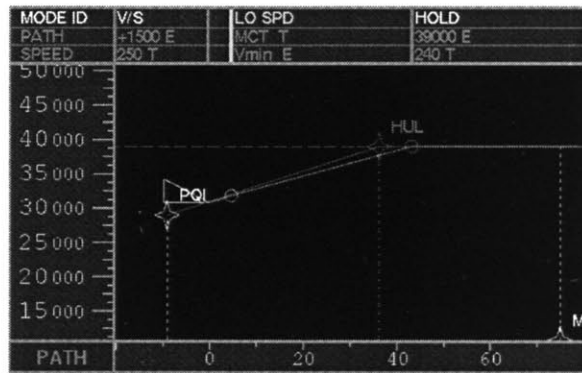


Figure 4.5: Anticipation using Envelope Protection Limits



## **Chapter 5**

### **Experimental Design**

The performance of AutoFlight System monitoring with a standard set of displays was compared to the performance when standard displays were augmented with the Electronic Vertical Situation Display by performing an experiment using the Aeronautical Systems Laboratory's (ASL) Part Task Simulator. This chapter described the experiment design and the data analysis used in this study. Both performance and subjective measures were used in the evaluation process. The experimental overview is presented followed by the procedural protocol and the performance measures.

#### **5.1 Experiment Overview**

The overall approach to this experiment was to have subject (current "glass cockpit" airline) pilots act as Pilot Not Flying (PNF) and observe a set of scenarios running on the ASL Part Task Simulator. While subjects observed the scenarios, the researcher acted as Pilot Flying (PF), interacting with the simulated aircraft automation and responding to prerecorded Air Traffic Control directives. Both the subject and the researcher were located in front of identical displays (shown in Figure 4.2) to simulate the set of instruments available to the captain (subject) and first officer (researcher) in an actual cockpit. Both displays were electronically slaved together to show identical information at all phases of the experiment. If during the course of the scenario the subject felt that some sort of mode event (as detailed in Section 5.3.1) occurred, they pressed a button on the side stick controller and articulated their concern. This audio data was later analyzed for timing and content.

During experimental design it was found that simply monitoring the displays was an unrealistic representation of the workload in actual cockpit operations. To correct this, subjects were given an unrelated side task to monitor.

This evaluation methodology is very similar to the SAGAT situational awareness technique (Endsley, 1995) with some implementation differences. In contrast with SAGAT evaluations, where the subjects actively interact with the simulator, the EVSD evaluation scenarios were completely passive for the subjects. The only interaction was for the subjects to articulate concerns at any point during the evaluation that they felt necessary.

## **5.2 Test Matrix**

The design of the test matrix included only one independent variable: the availability of the EVSD. This led to each scenario being run at least twice, once with and once without the display.

In order to prevent pilots from recognizing a scenario the second time they were exposed to it, two full sets of scenarios were constructed. At a minimum, scenarios that address the same mode awareness problem were set in a different geographic airspace with different associated altitudes, ATC clearances, timing conditions and waypoints.

In addition, to prevent pilots from expecting every scenario to have a mode error, some scenarios were created which did not have mode events. These “placebo” scenarios, which made up one third of the scenarios, were scattered throughout the experimental run.

To minimize learning effects, subjects were initially trained with the simulator and with the display. Half of the subjects were run through the scenarios first with the EVSD, and secondly without the EVSD. The other half of the subject were exposed to the scenarios in the reversed

order. In addition, to minimize problems with varying the scenario order between runs, half of the subjects had one set of scenarios first; the second half had the other set first. As shown in Table 5.1, the total of eight subject allowed two complete test matrices to be filled.

**Table 5.1: Test Matrix**

Subject Number	First Scenario Set	EVSD	Second Scenario Set	EVSD
1	1	Y	2	N
2	2	N	1	Y
3	1	N	2	Y
4	2	Y	1	N
5	1	Y	2	N
6	2	N	1	Y
7	1	N	2	Y
8	2	Y	1	N

### 5.3 Performance Measures

Three separate performance measures were used in this study. The first was an objective measure of the time it took subjects to respond to the incident. Secondly, a questionnaire was filled out by each subject after each scenario. Finally, after all the scenarios had been completed, subjects filled out a summary questionnaire as an overall evaluation of the EVSD.

#### 5.3.1 Subject Input

During the scenario, the subject had access to a Push to Talk button which signaled the computer to record their voice as well as the time at which the signal was sent. Subjects were instructed to signal the computer at any time they would normally discuss a problem with the

other pilot, or any time they felt it necessary to discuss the operation and performance of the aircraft. Pilots were explicitly instructed to signal they computer when they felt that a *mode event* occurred as defined as either:

1. An uncommanded mode transition had occurred
2. An error had been made in interfacing with the FMS
3. An unsafe or nonprocedural operation had taken place

At this point, subjects were instructed to articulate the reason that the button was pressed and explain the situation to the best of their ability. Subjects were instructed to use the Push to Talk button as a tool to communicate problems to ATC, or to the PF. In addition to recording timing information, this mechanism also recorded the subject's statements for future analysis. The scenario continued during and after the recording, until the scenario was completed. After the scenario was completed, the display blanked and the subject answered a series of questions designed to determine the level of mode and situational awareness.

### **5.3.2 Objective Measures**

The objective measures were based on the elapsed time between the mode event and the pilot response or, when relevant, the net altitude deviation the aircraft from the intended path. The latter indication was used when the altitude deviation of the aircraft was the relevant factor in the incident.

### 5.3.3 Subjective Measures

After each scenario, subjects were asked questions which addressed the cause of the mode transition, the consequences of the new mode state and the cues used by the subject to determine that an incorrect automation state was reached.

1. Why did you stop the scenario?
2. What caused the event? Why did it happen?
3. What cues did you use to determine that the event occurred?
4. What would have eventually happened if you had not stopped the scenario?

These questionnaires were then rated to determine the level of the subject's understanding of the problem. Each rating corresponded with differing levels of comprehension:

1. Did not react to or understand mode event
2. Reacted procedurally to mode event
3. Understood mode event

In order to determine in an objective manner whether pilots understood the underlying cause of the incident, each scenario had a key element that was deemed to be indicative of understanding. These elements are detailed in Section 6.2 along with the scenarios themselves.

### 5.3.4 Post Experiment Questionnaire

In addition, after the experiment was completed, subjects filled out a survey comparing the EVSD enhanced AutoFlight system to the regular AutoFlight System. An example of this survey is shown in Appendix A.

## 5.4 Subject Selection and Training

Subjects were local pilot volunteers who had experience flying highly automated glass cockpit aircraft, in particular the Boeing B757/B767. Since subjects were volunteering time to the experiment and were a self-selected group, results may be skewed in the favour of pilots who are interested in new technology in the cockpit.

To train subjects, they were first given an overview of the basic instrumentation on the simulator, including the map display (EHSD), the primary flight display, and the B737 Mode Control Panel. Subjects were also trained to the specifics of the AutoFlight System simulated on the computer. These specifics included the inclusion of envelope protection and the VNAV Path to VNAV Speed mode change if the aircraft varied more than 10 kts from the target speed in VNAV mode.

Since the simulator is not aircraft specific, subjects were allowed to familiarize themselves with the mixed display conventions. They were also shown how to use the control stick to interact with the side task, and how and when to use the Push to Talk button to record mode events. In addition, subjects were given a complete demonstration of the capabilities and display conventions of the EVSD in detail, to allow familiarization. Subjects were then flown through a set of three training scenarios.

Before each scenario, subjects were briefed on the state of the aircraft and automation. An example of this briefing would be: “The aircraft is straight and level at FL210, and is waiting on a climb directive from ATC to FL 350. We’re in LNAV, and Altitude Hold. Airspeed is 300 kts and the next active waypoint is LUX”. Subjects had the opportunity to ask for clarification of the aircraft state at any time before the scenario began. Appropriate diagrams were available for those scenarios in which landing plates were used.



Once the scenario began, subjects were instructed to always use the Push to Talk button to interact with the researcher (Pilot Flying), or with ATC to assure that any conversations were recorded for later analysis. The researcher acted as the sole PF and responded to the prerecorded Air Traffic Control cues that occurred at various times during the scenarios. The PF also handled all of the interaction with the MCP and scaled the displays to ensure that the relevant information was always available.

#### **5.4.1 Side Task**

In order to maintain a level of pilot workload, subjects are also given a side task. The side stick controller is used to provide input to an indicator bar as it varies based on a Markov turbulence model. This side task is located on the top left corner of Figure 4.2. The goal was to keep the grey bar centered within the green level lines.

The intent of the sidetask was to increase the workload of the pilot to a more realistic level by requiring them to break their regular scan pattern in order to deal with the varying indicator bar. Subjects were instructed to attend to the side task when they felt they had time, but not at the expense of monitoring the aircraft.

### **5.5 Scenario Design**

In order to evaluate the effect of the prototype EVSD on mode awareness a representative series of experimental scenarios were developed based on a sampling of common mode awareness problems that were found in the ASRS review and in the open literature. The scenarios are described in Chapter 6 along with the results of the evaluation.



## **Chapter 6**

### **Scenario Descriptions and Evaluation Results**

The purpose of this experiment was to investigate the relative differences in pilot performance when an Electronic Vertical Situation Display augmented a standard glass cockpit and when such as display was not available, in terms of both performance and subjective evaluations. This chapter reports the results of the experiment: profiles of the subjects, results of individual scenarios, and finally the overall subjective evaluation of the display.

#### **6.1 Profile of Subjects**

A total of eight subjects participated in this experimental evaluation. The subject ranged in ages from 39 to 53 with a mean age of 47. First officers comprised 62.5% of the subjects; the remaining 37.5% were captains. 37.5% were initially trained as civil pilots, while the remainder were initially trained by the military.

Subjects had between 4000 and 15870 hours of civilian flight experience with a mean of 8646 hours. Between 200 and 5000 of these hours were in glass cockpits, with a mean of 2263 hours. Estimated flight hours in 1995 ranged between 250 and 800 with a mean of 533 hours.

#### **6.2 Scenario Descriptions and Results**

The bulk of the scenarios have results based on objective timing information. Two of the scenarios (Target Error by Pilot Flying during Non-precision Approach and the Altitude Capture Failure during Altitude Change) use the net altitude deviation as a more relevant measure, as it is of greater merit. In this context, negative altitude deviations refer to pilots reporting the incident

before they reached the point at which an altitude deviation would occur. Similarly, negative times refer to pilots anticipating the incident and reporting it before it would occur, with the absolute value of the time indicating the anticipation time.

### 6.2.1 Glide Slope Transmitter Failure during Approach

This scenario simulated the loss of the ground based glide slope transmitter during an AFS flown Instrument Landing System (ILS) approach.

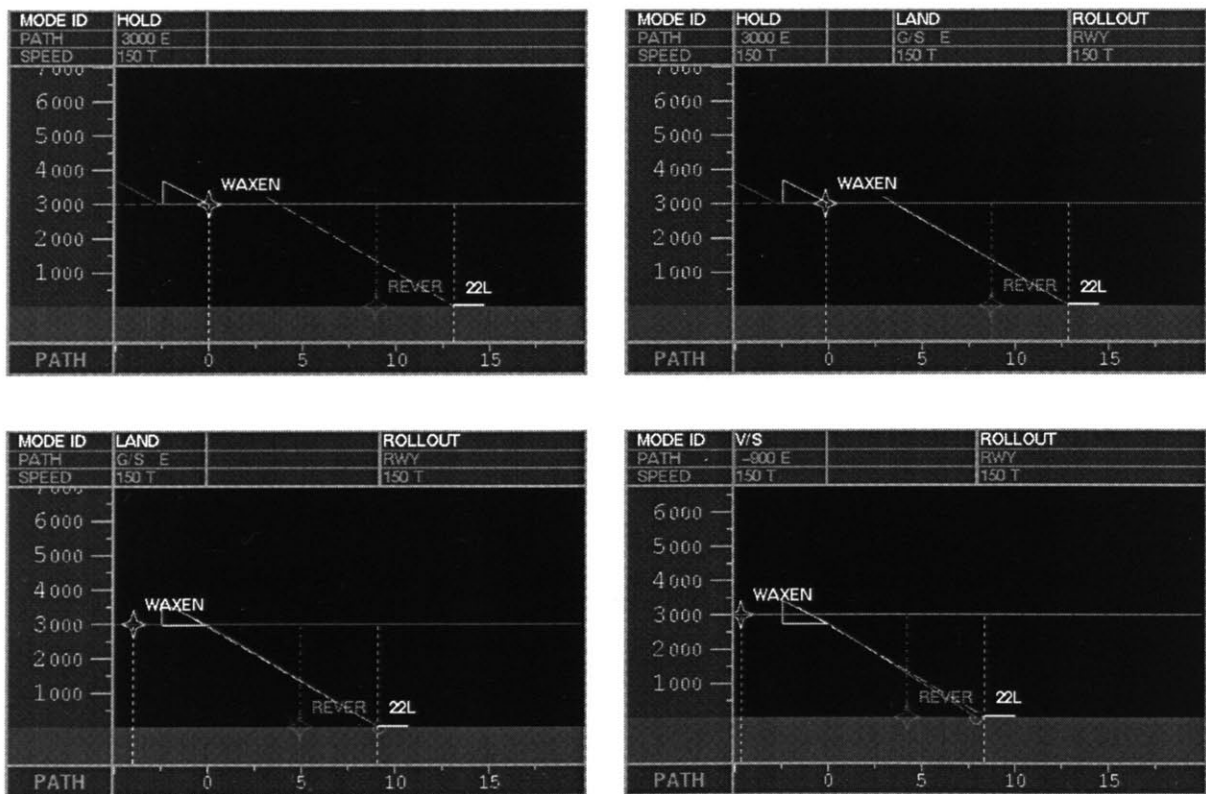


Figure 6.1: Glide Slope Transmitter Failure during Approach

### *Description*

As shown in the first frame of Figure 6.1, the aircraft starts this scenario close to the airport, at a low altitude, and with flaps in a semi-extended setting (15°). In the second frame, the Pilot Flying engages both the Glide Slope Capture and the Localizer Capture logic in the AFS. A few seconds after the glide slope is captured in the third frame, the ground based transmitter fails. This failure results in a loss of signal to the aircraft system, causing a mode reversion to Vertical Speed mode with the current (instantaneous) vertical speed as the target criterium as seen in the final frame.

This mode reversion is common in AFS designs because it maintains the instantaneous speed to allow easy recapture of the glide slope in situations where the signal is momentarily interrupted due to ground reflections or shadowing by other aircraft. The cues that normally show that the aircraft's receiver has failed (crosses over the glide slope information areas on the PFD) are not shown, because the aircraft based equipment continues to function normally. After the aircraft transitions into Vertical Speed mode and the flight path trajectory intersects the ground short of the runway threshold.

### *Mode Event Cues*

EVSD-specific cues include a change in the mode header and the green path prediction line indicating the dangerous flight path as shown in the final frame of Figure 6.1.

Without the EVSD, cues include the disappearance of the magenta diamond on the glide slope indicator, and the FMA and the MCP reverting to a vertical speed mode. In the first frame of Figure 6.2, the PFD is shown just before the glide slope signal is lost. In the second frame, the

loss of signal is shown by the lack of a magenta glide slope tracking diamond on the scale to the left of the Attitude Determination Indicator (ADI), and by the change in the active mode of the aircraft from G/S to V/S.

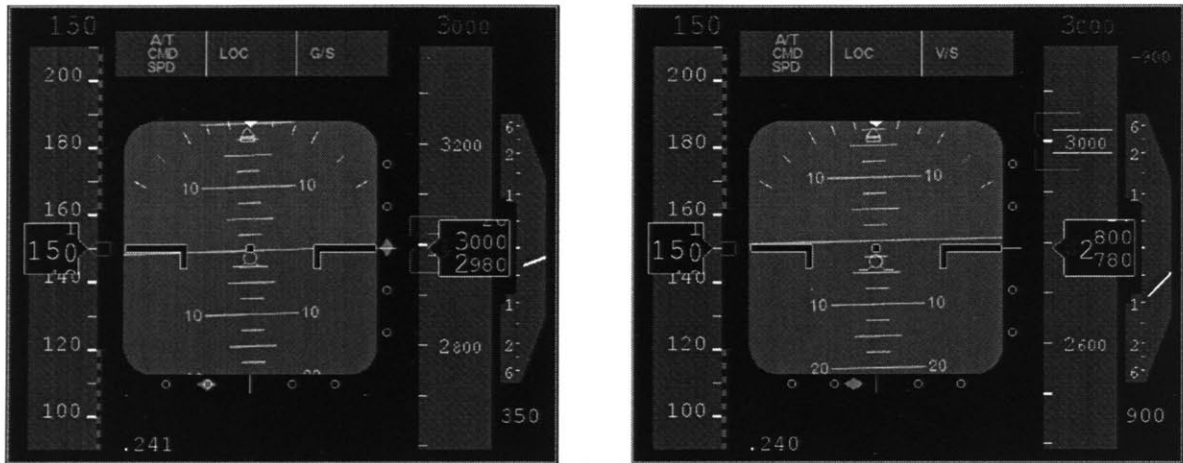


Figure 6.2: Glide Slope Transmitter Failure during Approach: Non-EVSD Cues

The key element to understanding this scenario was for the subjects to realize that an equipment failure occurred and that the glide slope signal had been lost and that the new flight path landed short of the runway.

### *Results*

Figure 6.3 shows that by using the EVSD, subjects noticed and reacted to this mode event 17.2 seconds sooner than without at a confidence level of 80%. This is interesting in that the only changes on the EVSD during this scenario are the shift in the green line and the flashing and alteration of the text displayed in the mode header.

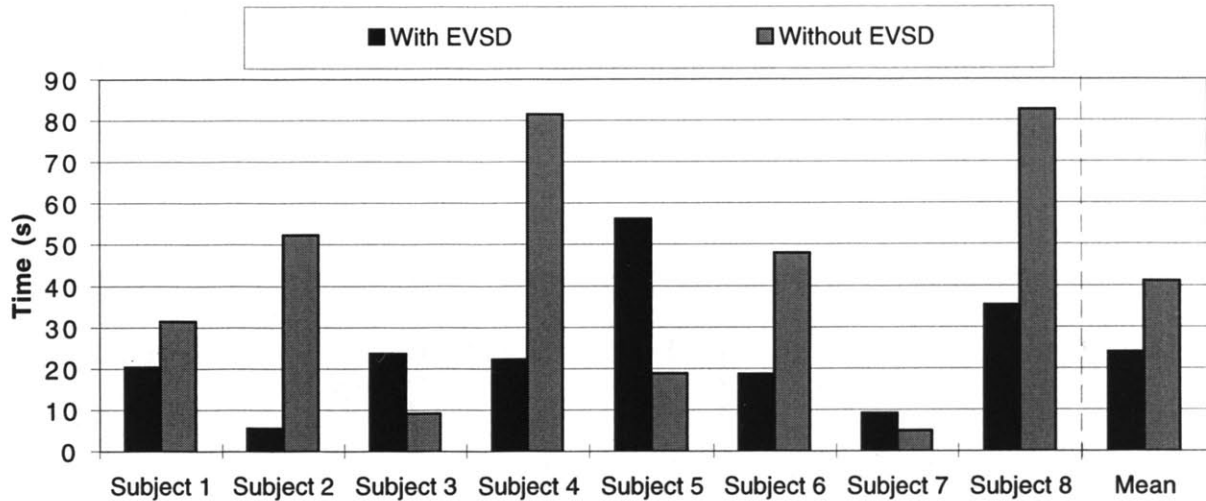


Figure 6.3: Glide Slope Transmitter Failure during Approach: Timing Results

Pilot understanding of the scenario was slightly different with the EVSD as seen in Figure 6.4. One subject recognized the reversion to a Vertical Speed mode, but completely failed to notice the event in terms of landing short of the runway. While the subject called for a Go Around due to loss of glide slope, he failed to realize the immediate implications of the mode event.

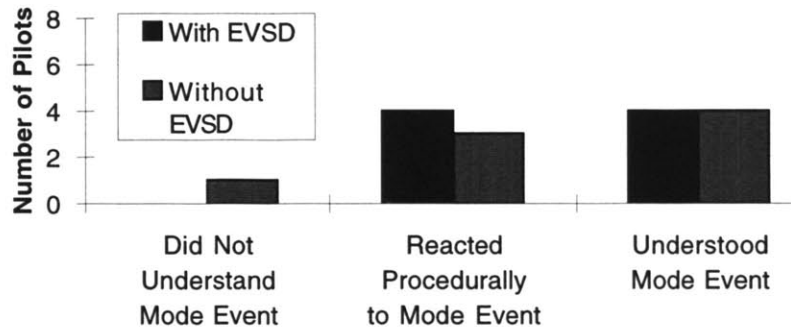


Figure 6.4: Glide Slope Transmitter Failure during Approach: Subject Understanding Ratings

## 6.2.2 Overspeed Envelope Protection during Altitude Change

A late ATC directive leads to a high vertical descent rate, which engages the envelope protection of the aircraft.

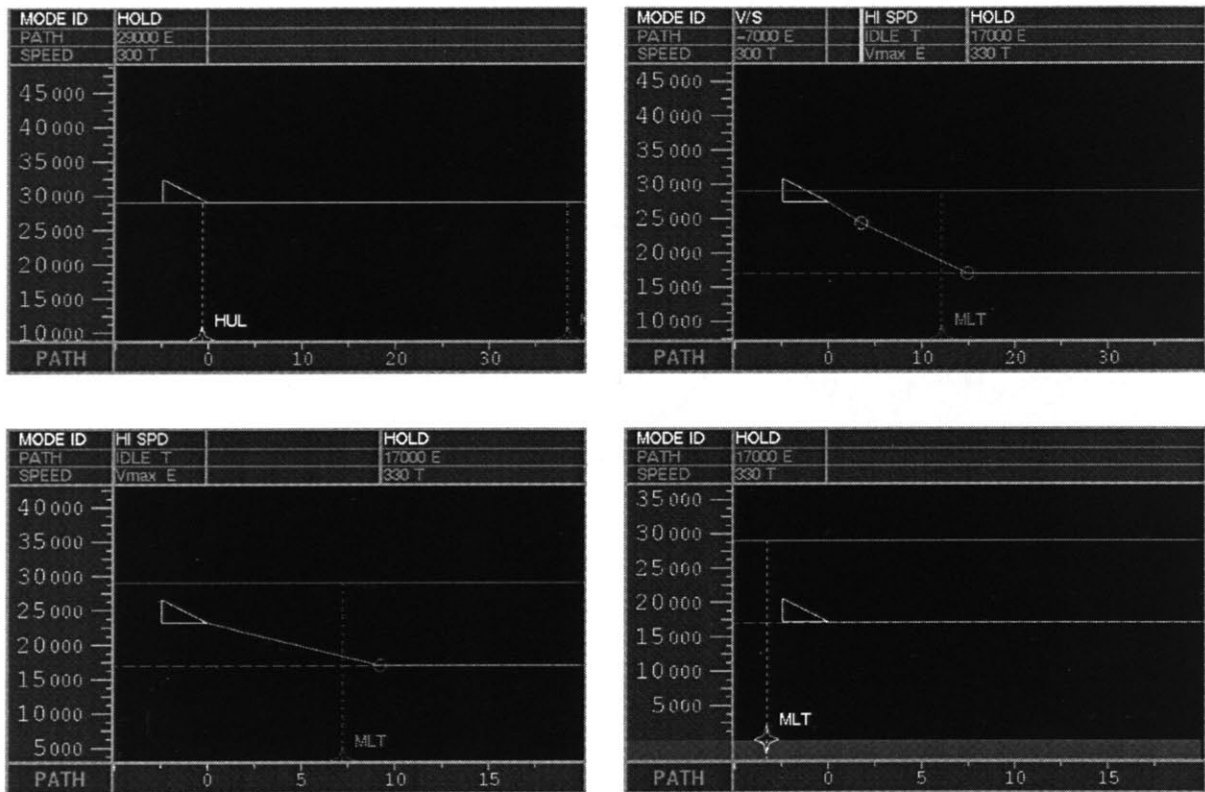


Figure 6.5: Overspeed Envelope Protection during Altitude Change

### Description

The first frame in Figure 6.5 shows the aircraft beginning the scenario at a high altitude and at reasonable speed. The subject is instructed that they are waiting for an ATC clearance to descend to the next waypoint. When the clearance is finally given, it is an urgent request (“ASL123,



immediate descent to 17 000 ft.”). After initially trying a Flight Level Change mode descent, it becomes clear that a high speed Vertical Speed mode descent will be necessary as shown in the second frame.

During this steep descent in vertical speed mode, the envelope protection limits of the aircraft are surpassed. The aircraft transitions to High Speed Protect mode in the third frame; AFS control allocation shifts from speed-on-thrust to speed-on-pitch to prevent the aircraft from overspeeding further. Finally, due to insufficient descent rate, the aircraft overflies the altitude crossing as seen in the final frame.

### *Mode Event Cues*

EVSD-specific cues include a mode header change and the green Aircraft Path line indicating an altered flight trajectory as apparent in the second and third frames of Figure 6.5. The second frame in Figure 6.5 shows how the EVSD predicted this mode change before it occurred, allowing the pilot to anticipate the change long before it is expected to occur. As shown in the first Figure 6.6, without the EVSD, the cues include the speed of the aircraft approaching the limits at which envelope protection will be engaged. The indication that the crossing restriction will not be achieved is the Altitude Capture Arc on the EHSI, as shown in the second frame.

The key element to understanding this scenario was for the subjects to realize that the aircraft was not capable of meeting both the speed and vertical descent rate targets, or that the aircraft had not been given enough time to make such an altitude change, as well as the fact that the crossing restriction would not be met.

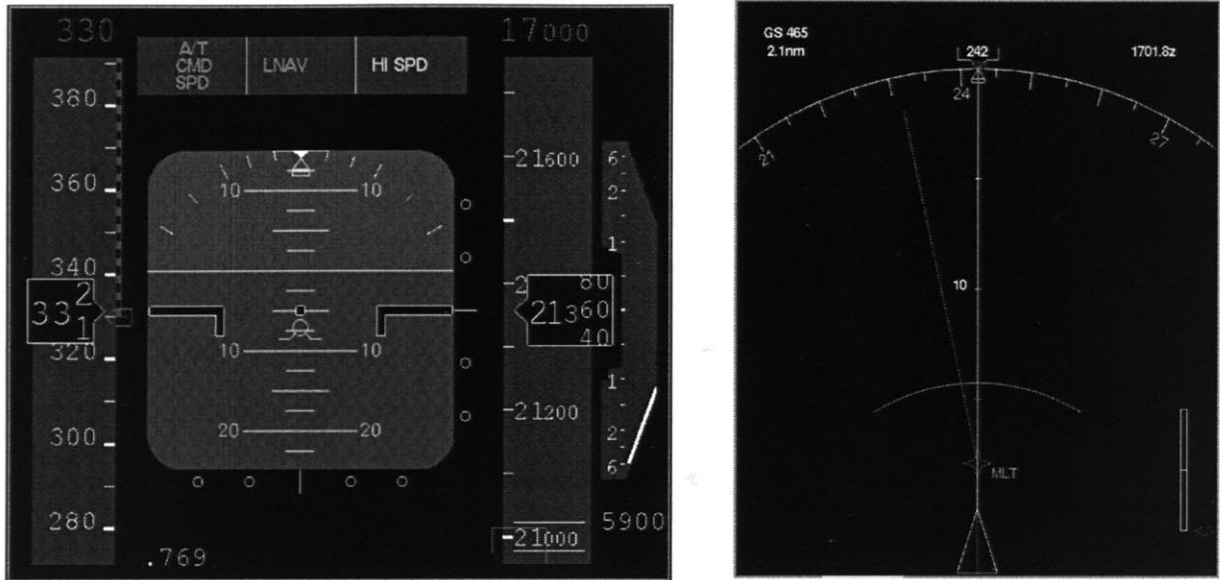


Figure 6.6: Overspeed Envelope Protection during Altitude Change: Non-EVSD Cues

### Results

Figure 6.7 shows that the anticipation capabilities of the EVSD allowed pilots to predict the overspeed situation 40.3 seconds sooner than they did without the display, at a confidence level of 95%. Note that negative times refer to the pilots anticipating the incident. It was clear during this experiment that the anticipation capability was directly responsible for the improvement as subject directly referenced the EVSD when calling ATC to report that they would be unable to make the crossing. Several subjects commented on the fact that the information was easily available in the graphical format. In addition, several subjects mentioned additional quantitative

information available on the display, such as the distance to the overspeed condition, the altitude at which the overspeed would occur, and the distance by which the altitude restriction would not be met.

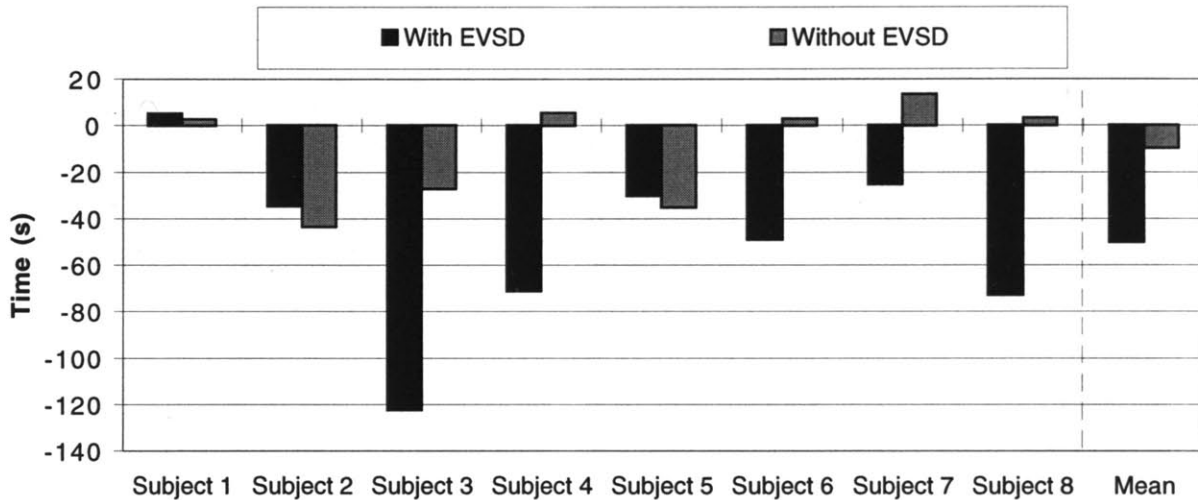


Figure 6.7: Overspeed Envelope Protection during Altitude Change: Timing Results

Figure 6.8 shows the ratings of pilot understanding. There was a very slight improvement in favour of the EVSD, as one subject did not notice the implications of the mode event to the larger flight plan, namely being high at the next waypoint.

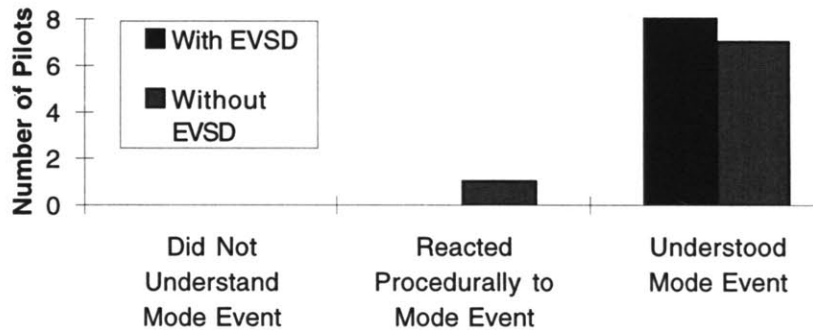


Figure 6.8: Overspeed Envelope Protection during Altitude Change: Subject Understanding Ratings

### 6.2.3 Altitude Capture Failure during Altitude Change

During a Flight Level Change Descent, the aircraft fails to level-off at the MCP altitude.

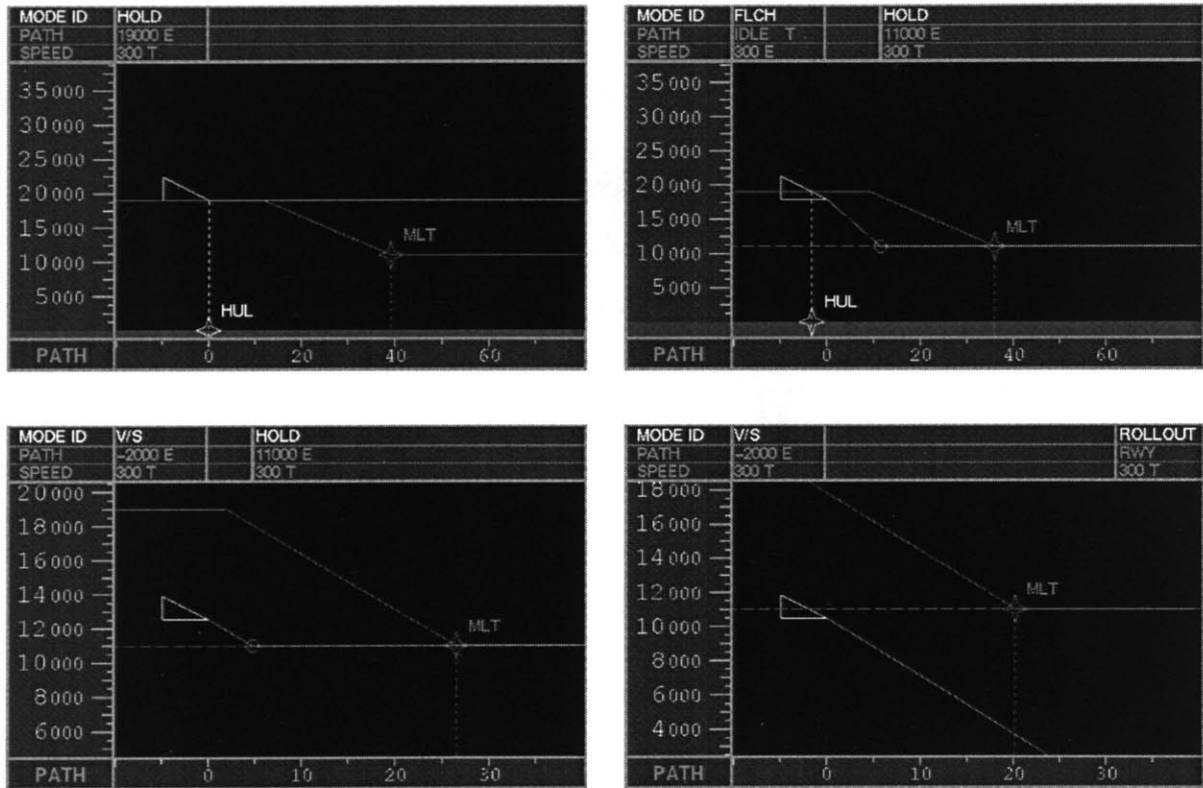


Figure 6.9: Altitude Capture Failure during Altitude Change

#### Description

Figure 6.9, frame one shows the aircraft at the start of the scenario at a high altitude and at reasonable speed. The subject is instructed that they are waiting for an ATC clearance to descend to the next waypoint, seen to be MLT. When the clearance is given the Pilot Flying initiates a Flight Level Change mode descent as seen in the second frame. Upon nearing the altitude

programmed into the MCP, the Pilot Flying decides to shallow the descent to “smooth out the ride in the back” by changing the descent into Vertical Speed mode and dialing in a shallower descent rate as seen in the third frame, to minimize the transition at the commanded level off altitude.

Instead of capturing the programmed altitude, the aircraft, the aircraft continues its descent at the commanded vertical speed target as seen in the final frame. Since the MCP altitude is now above the aircraft, the vehicle enters an open descent.

### *Mode Event Cues*

The final frame in Figure 6.9 shows the EVSD-specific cue after the event: the green path prediction line indicating the open descent. Without the EVSD, subjects had to monitor the altitude tape and verify that level off did not occur. As seen in Figure 6.6, the altitude tape clearly indicated the aircraft descending through the altitude of 11 000 ft dialed into the MCP.

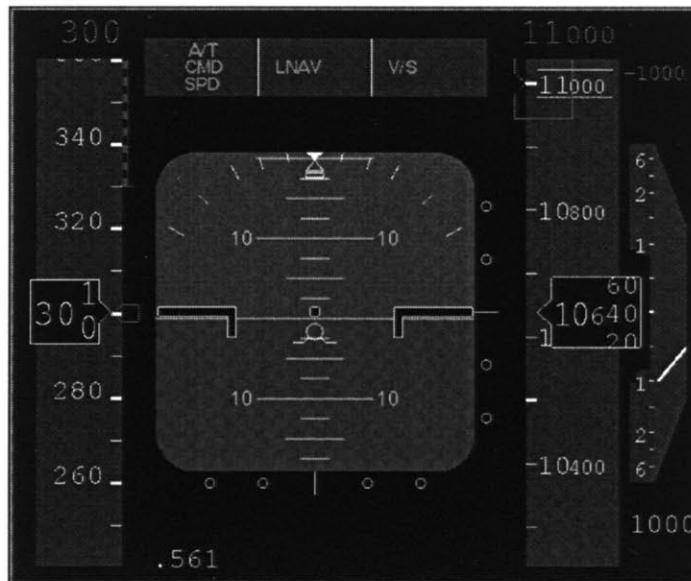


Figure 6.10: Altitude Capture Failure during Altitude Change: Non-EVSD Cues

The key element to understanding this scenario was for the subjects to realize that an equipment failure occurred and that the aircraft was placed into an open descent situation which could lead to Controlled Flight Into Terrain.

### Results

As seen in Figure 6.11, subjects were observed to deviate from the target altitude by 45.8 feet less with the EVSD than without, but this value had little statistical significance. In this scenario, the EVSD did not appear to help or hinder this type of inner loop monitoring in a significant manner. It was observed that subjects tended to watch the altitude tape on the Primary Flight Display rather than the EVSD.

This seems to imply that the EVSD may not be useful in situations where the information necessary to detect a mode event is explicitly available on a standard piece of cockpit automation. Alternately, the fact that pilot are trained to use specific display when dealing with high importance tasks which have dedicated feedback mechanisms may have overridden any use of the EVSD. Note that due to an anomaly in the simulation, one of the subjects was not tested in this particular scenario.

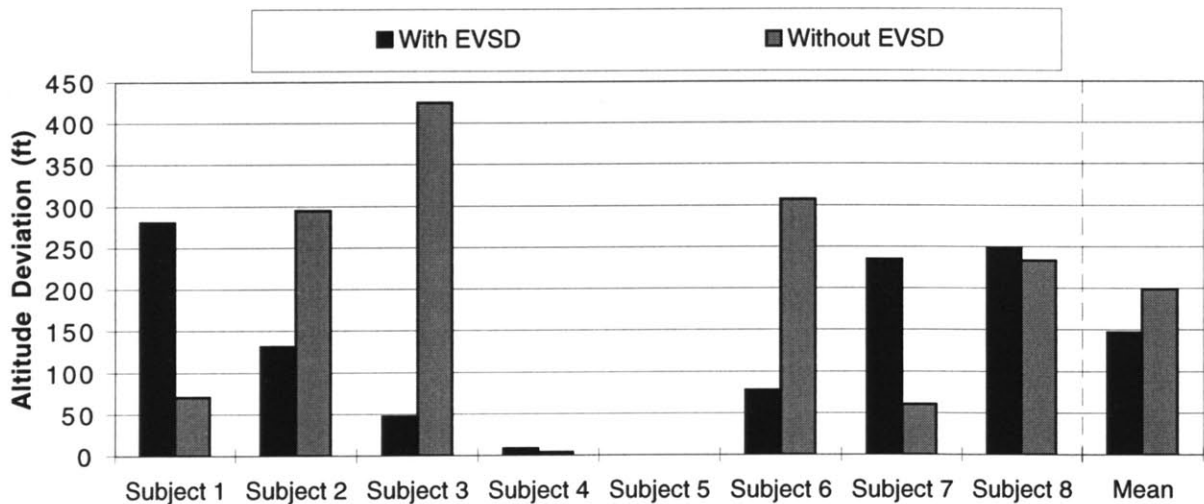


Figure 6.11: Altitude Capture Failure during Altitude Change: Altitude Deviation Results

The ratings of pilot understanding were again very similar. However, as seen in Figure 6.12, without the EVSD, fewer pilots recognized the full implications of the “altitude bust”.

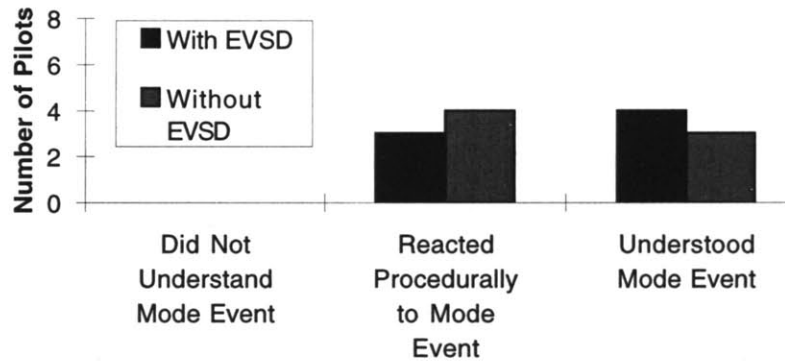


Figure 6.12: Altitude Capture Failure during Altitude Change: Subject Understanding Ratings

### 6.2.4 VNAV Path to VNAV Speed Transition due to High Winds

During a VNAV flight profile, unanticipated wind conditions cause the aircraft to switch to an envelope protection VNAV SPD mode in order to prevent the aircraft from varying too far from the speed target.

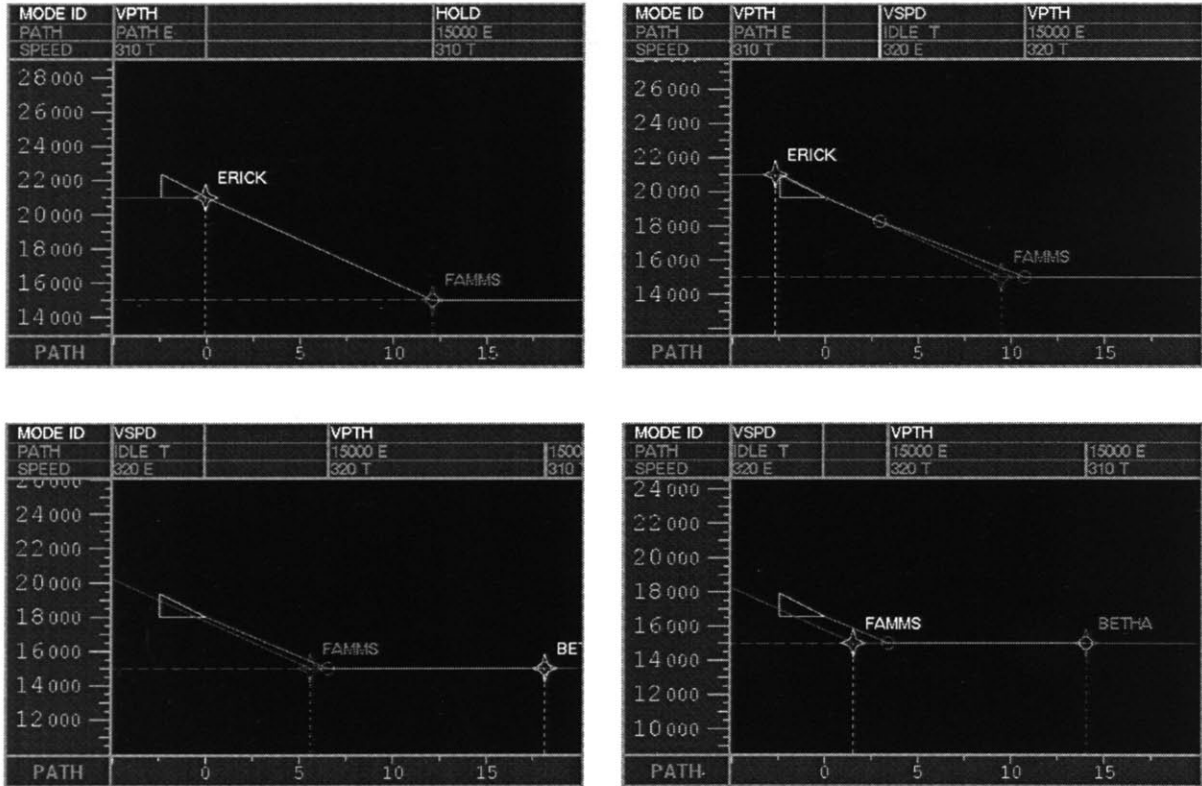


Figure 6.13: VNAV Path to VNAV Speed Transition due to High Winds

#### Description

As seen in the first frame of Figure 6.13, the aircraft begins the scenario at a high altitude and at a reasonable speed. The aircraft is in VNAV mode to meet the altitude restrictions imposed by the procedure. All of the restrictions are already programmed into the flight computer. Soon after reaching the Top of Descent point and starting the descent, unanticipated tail wind conditions



result in a higher vertical speed than planned. This causes the aircraft to fly off of the programmed path and the speed to increase while the AFS attempts to recapture the path as seen in the second frame. The AFS is designed to switch to VNAV Speed mode that when the speed in VNAV Path mode reaches the critical value of commanded speed  $\pm 10$  kts which has just occurred in the third frame. In VNAV Speed mode, the vertical path is sacrificed to maintain the speed target. As seen in the final frame, diverging from the programmed path causes the aircraft to overfly the next altitude restriction.

*Mode Event Cues*

The second and third frame of Figure 6.13 show the EVSD-specific cues of a mode header change, green path prediction line indicating change of descent trajectory and the point of MCP altitude intercept moves downstream of the next waypoint.

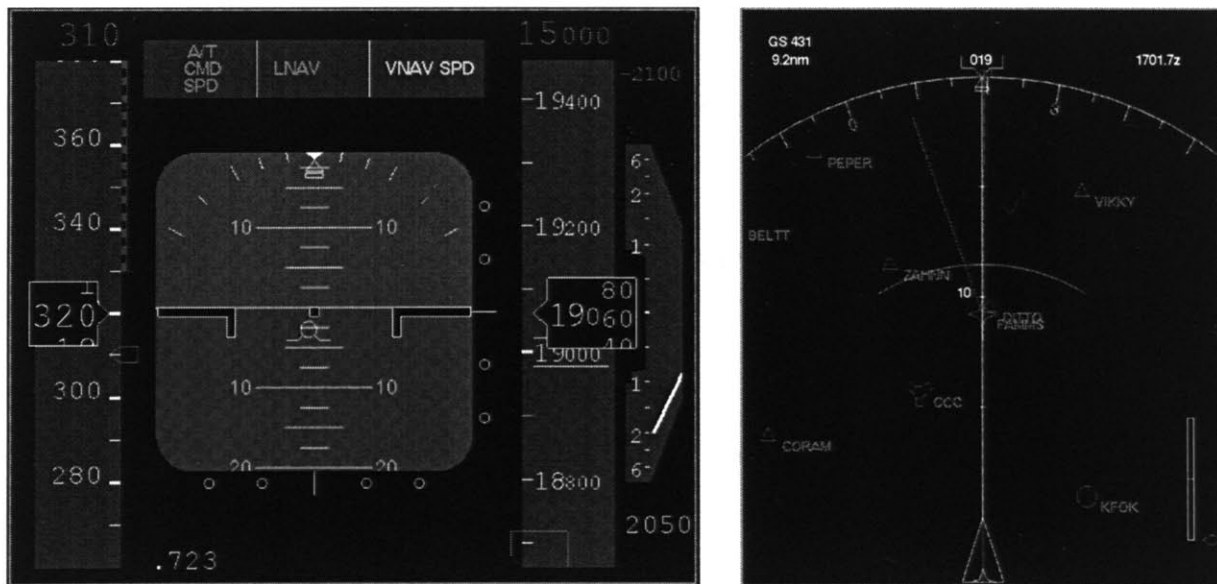


Figure 6.14: VNAV Path to VNAV Speed Transition due to High Winds: Non-EVSD Cues

Without the EVSD, the cues include the mode change being indicated in the Flight Mode Annunciator as seen in the first frame Figure 6.14 and the altitude tape on the PFD can be seen climbing towards the 10 knot threshold, though the transition point is not noted on the tape. In addition the second frame shows that the green Altitude Capture Arc on the EHSI shows the intersection with the programmed altitude occurring too late.

The key element to understanding this scenario was for the subjects to notice that the speed of the aircraft was increasing because of the wind conditions.

### Results

Figure 6.15 shows that subjects reacted to this mode change 4.7 seconds faster with the EVSD than without. However, this value is not statistically significant with the small number of subjects tested. This result was unexpected since the same anticipation capabilities that were used effectively in two other scenarios were available to the subjects. In fact, only one pilot appeared (Subject 7) to use the anticipation capabilities by directly referencing the EVSD when calling ATC to report that the aircraft would be unable to make the crossing. It is hypothesized that a

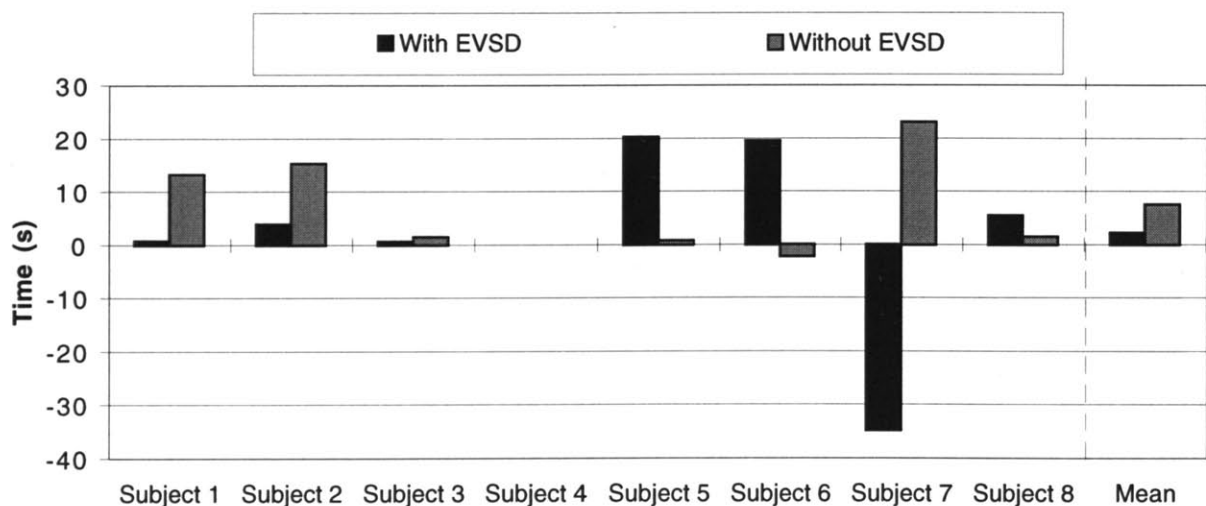


Figure 6.15: VNAV Path to VNAV Speed Transition due to High Winds: Timing Results

lack of experience with the VNAV system may have been a contributing factor. Note that due to a simulator anomaly, the timing results for subject 4 were rendered invalid and so were not included in the analysis.

Figure 6.16 shows that the pilot understanding ratings did not show any difference whether or not the EVSD was available. None of the pilots remarked on the increasing winds during the descent.

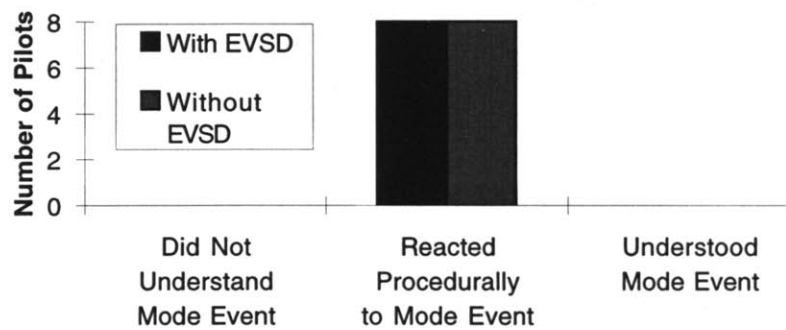


Figure 6.16: VNAV Path to VNAV Speed Transition due to High Winds: Subject Understanding Ratings

## 6.2.5 Target Error by Pilot Flying during Non-Precision Approach

In this scenario, the Pilot Flying misdials the MCP altitude and misses an intermediate waypoint.

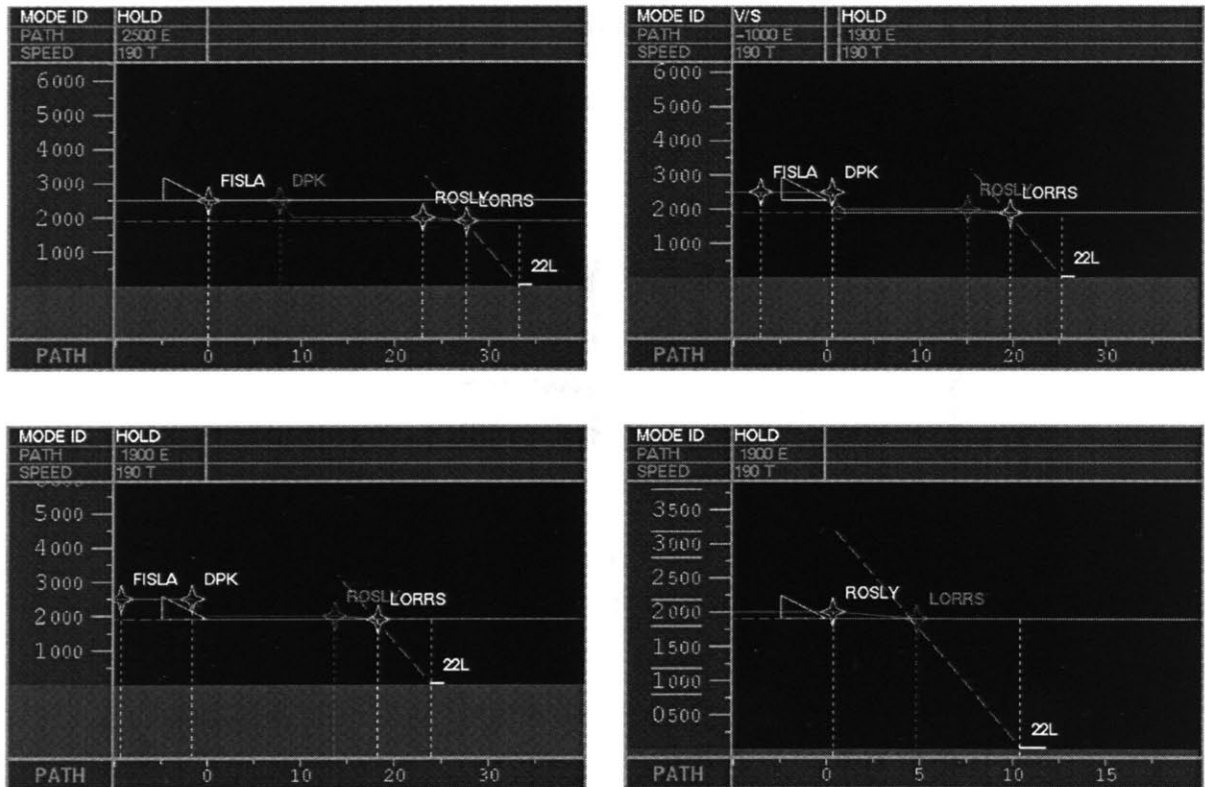


Figure 6.17: Target Error by Pilot Flying during Non-Precision Approach

### Description

The first frame in Figure 6.17 shows the aircraft starting this scenario close to the airport, at a low altitude, and with flaps fully retracted. During the non-precision approach, the researcher acting as Pilot Flying deals with slowing the aircraft by dialing the correct speed targets, and guiding the aircraft through each altitude restriction. The second frame shows that during one

such descent, an intermediate altitude target between the Final Approach Fix and the Missed Approach Point is inadvertently omitted by the Pilot Flying (researcher) causing an altitude deviation as seen in detail in the final two frames.

### *Mode Event Cues*

The last two frames of Figure 6.17 show the EVSD-specific cues of an inappropriate altitude target in mode header and the green path prediction line below the solid magenta programmed path, indicating the neglected intermediate step. In addition, as the MCP altitude is dialed into the AFS, the dashed magenta line depicting the commanded level off altitude is seen to be below the programmed path.

Without the EVSD, subjects relied on the altitude target box in the Primary Flight Display above the altitude tape as shown in the first frame of Figure 6.18 and on reading the value directly from the Mode Control Panel. A copy of the MCP output that was available on the screen is shown in the second frame. In some cases, subjects were noticed to be observing the Pilot Flying as the incorrect value was being dialed into the MCP.

The key element to understanding this scenario was for the subjects to realize that the Pilot Flying had misentered the altitude into the MCP.

### *Results*

Altitude deviation in this scenario was measured by how far below the correct altitude the aircraft was when the subject recognized that a mistake had been made by the Pilot Flying. In this context, a negative number represents that the subject realized the error before an altitude deviation occurred; a positive number represents an actual altitude deviation.

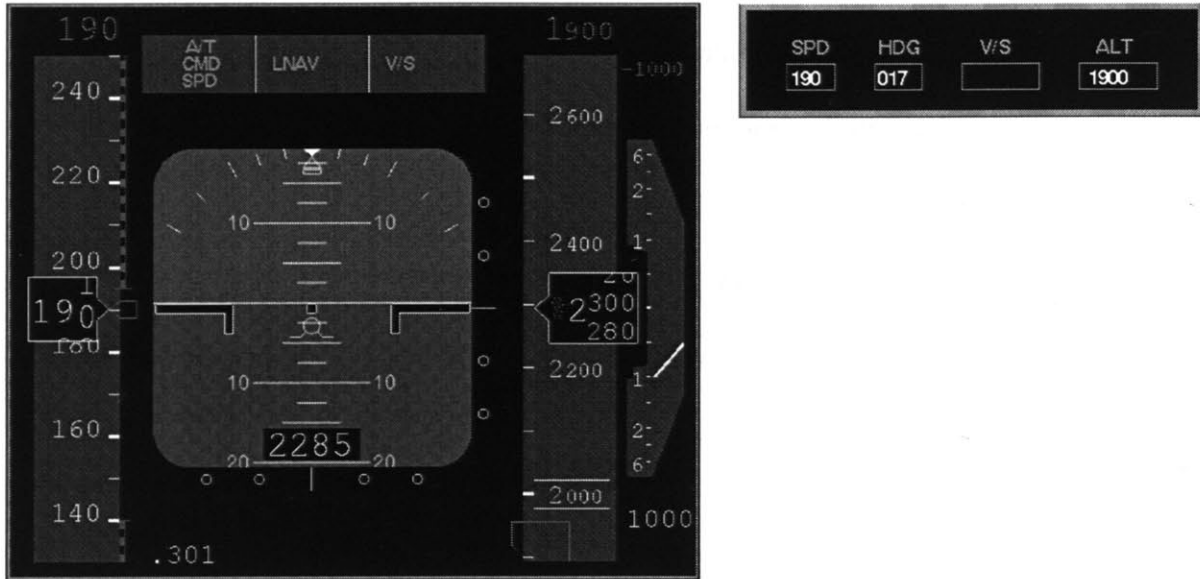


Figure 6.18: Target Error by Pilot Flying during Non-Precision Approach: Non-EVSD Cues

As seen in Figure 6.19, using the EVSD, subjects were found to deviate from the target altitude by 117.1 feet more than without, but this value has little statistical significance in light of the sample size. It was also observed that subjects watched the Pilot Flying dial the incorrect value in the MCP rather than observing the mistake elsewhere. One pilot commented on the fact that the EVSD was not the correct display to use to catch this error, and that good Cockpit Resource Management should prevent this type of mistake from occurring.

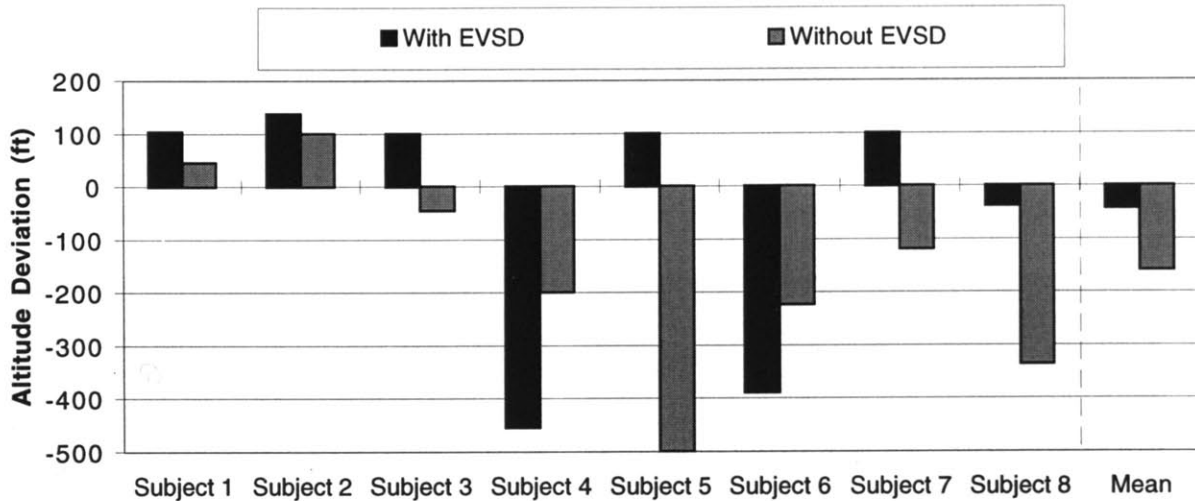


Figure 6.19: Target Error by Pilot Flying during Non-Precision Approach: Altitude Deviation Results

Without the EVSD, Figure 6.20 shows that one subject completely missed the altitude deviation. This subject flew at the lower altitude during that entire flight segment.

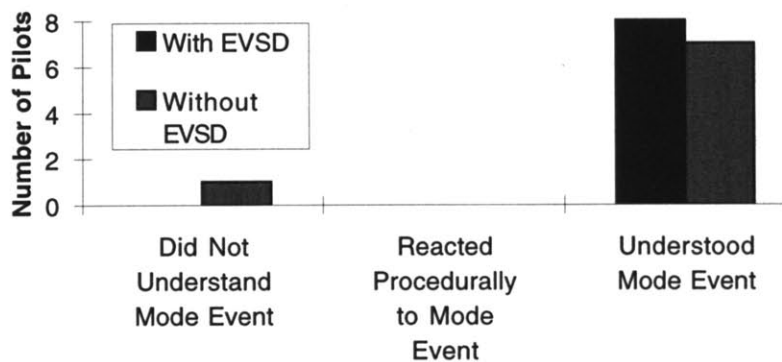


Figure 6.20: Target Error by Pilot Flying during Non-Precision Approach: Subject Understanding Ratings

## 6.2.6 Underspeed during Altitude Change due to ATC Directive

Overconstraining ATC directives cause the aircraft to lose speed to the point where the low speed envelope protection functionality of the aircraft is engaged.

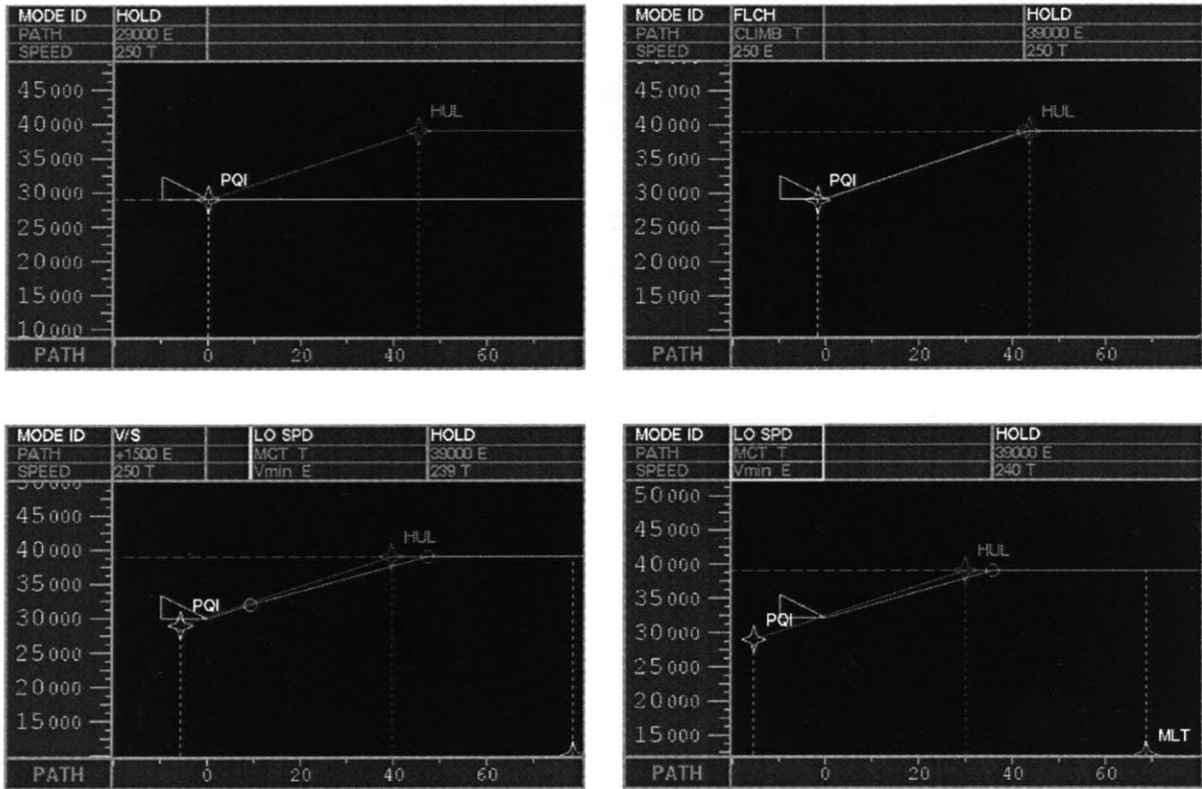


Figure 6.21: Underspeed during Altitude Change due to ATC Directive

### Description

The first frame in Figure 6.21 shows the aircraft starting the scenario at a high altitude and at a low speed. The subject has been instructed that they are waiting for an ATC clearance to climb to the next waypoint (in this case HUL). ATC issues a climb crossing restriction, and the Pilot Flying engages Flight Level Change mode to make the crossing, as seen in the second frame. A few minutes later an amendment is issued which asks that a vertical speed target be maintained



through 35 000 ft. After switching the aircraft into Vertical Speed mode, and dialing in the target speed, it becomes clear that the amendment results in a target that exceeds the climb performance capability of the aircraft, as shown by the segmented flight path in the third frame. The final frame shows that some time later, the aircraft envelope protection system engages and transitions to a Low Speed envelope protection mode. The lower climb rate in the envelope protection mode prevents the aircraft from making its crossing restriction, and from maintaining the vertical speed target.

*Mode Event Cues*

The final two frames of Figure 6.21 show EVSD-specific cues of the mode header change and the green path prediction line indicating that the aircraft will not make the restriction. Without the EVSD, the subjects had to watch the decreasing speed and the encroaching speed limits on the speed tape as shown in the first frame of Figure 6.18. In addition, as shown in the second frame, the Altitude Capture Arc provided information as to where the aircraft would level off.

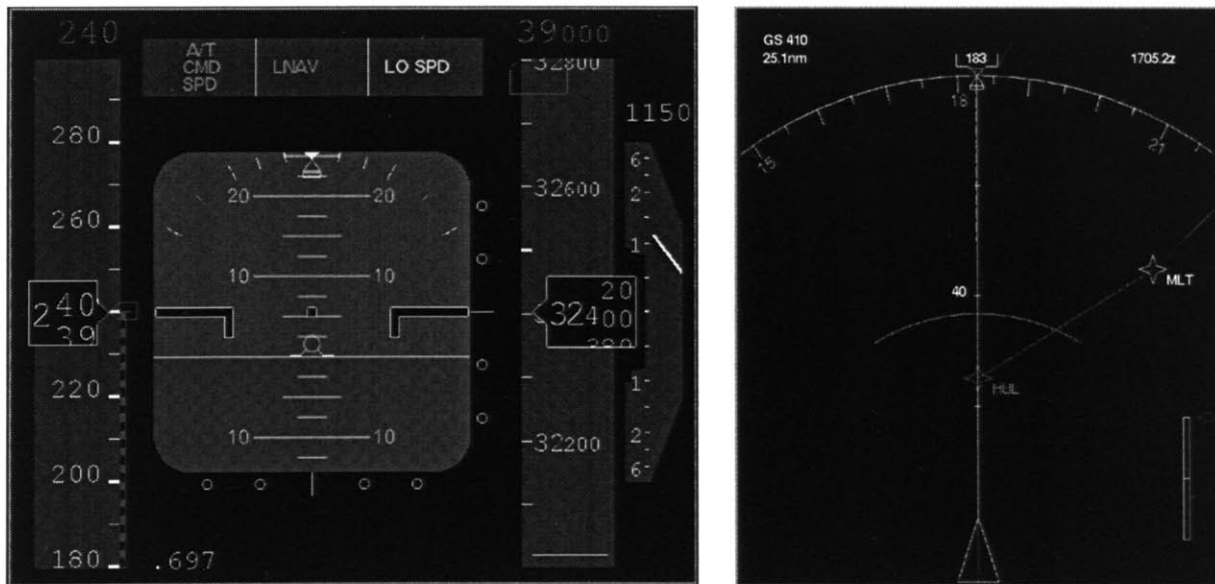


Figure 6.22: Underspeed during Altitude Change due to ATC Directive: Non-EVSD Cues

The key element to understanding this scenario was for the subjects to realize that the aircraft was not capable of meeting both the speed and vertical ascent rate targets. The aircraft had not been given enough time to make such an altitude change and therefore the crossing restriction would not be met.

*Results*

Figure 6.23 shows that the anticipation functionality of the EVSD allowed pilots to predict the underspeed situation 60.6 seconds sooner with the EVSD than without, at a confidence level of 95%. Note here that negative times refer to the pilots anticipating the incident before it actually occurs. In addition to catching the error, several subjects recorded the distance by which the crossing restriction would be missed and additional related information (i.e. the altitude at which the envelope protection mode would be engaged, the location at which the low speed mode would be engaged, etc.).

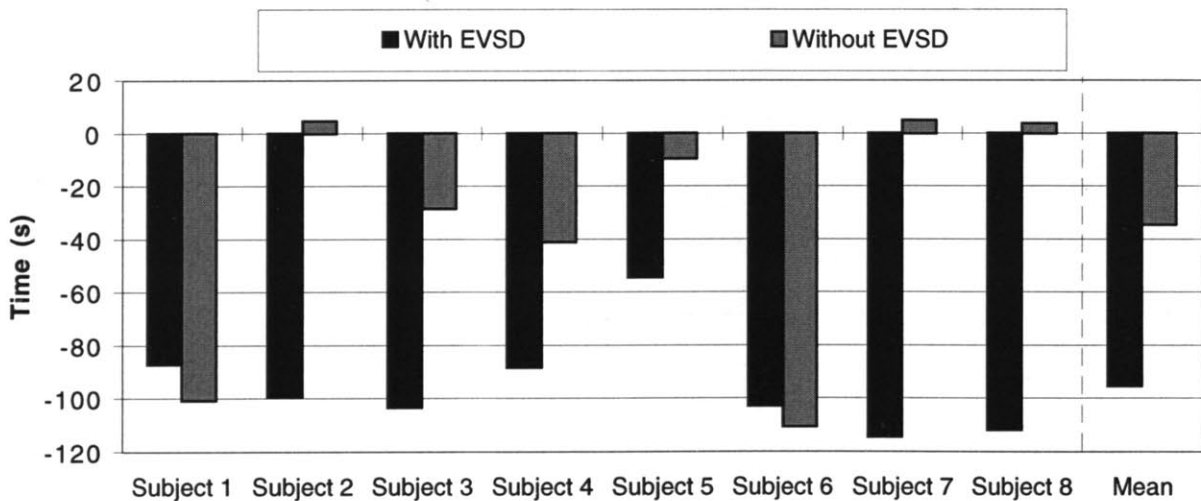


Figure 6.23: Underspeed during Altitude Change due to ATC Directive: Timing Results

The pilot understanding ratings for this scenario were very clearly skewed in favour of EVSD. The clear trend from Figure 6.24 was that the subjects better understood the implications of the mode event and the cause of the event when they had access to the EVSD display. It appears that the anticipatory capabilities of this display are seen to be particularly useful in situations where the pilot would have to do mental computations to determine where an envelope protection mode would be engaged.

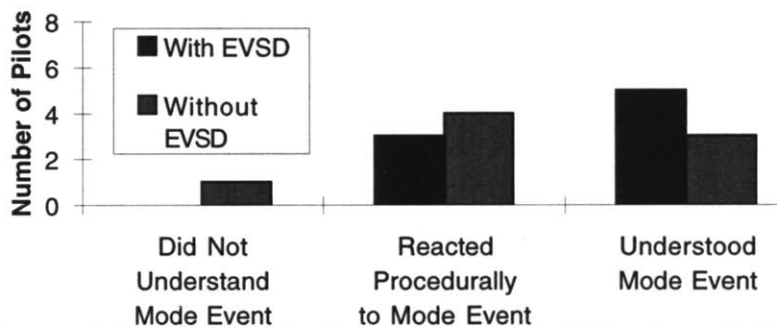


Figure 6.24: Underspeed during Altitude Change due to ATC Directive: Subject Understanding Ratings

## 6.2.7 Unexpected Climb during Approach due to Flap Overspeed

In this scenario, the aircraft attempts to climb to the Missed Approach Altitude due to a flap overspeed condition caused by Pilot Flying error.

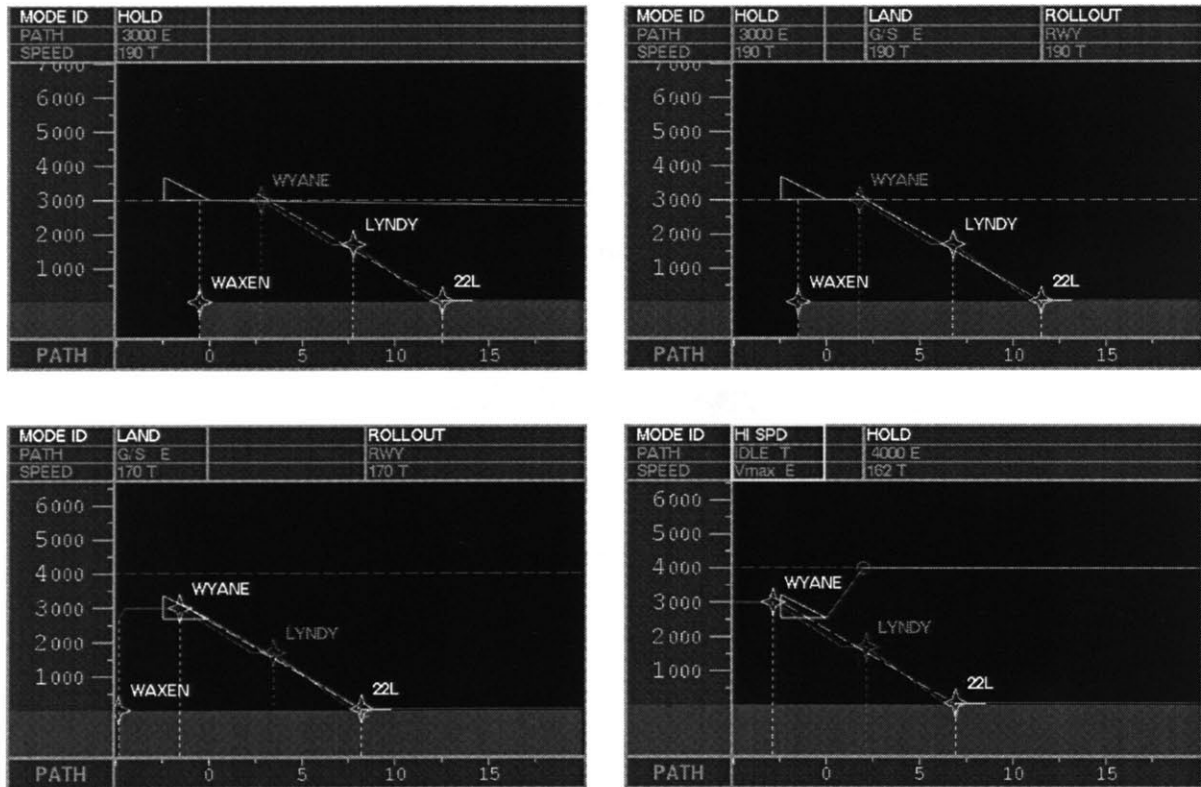


Figure 6.25: Unexpected Climb during Approach due to Flap Overspeed

### Description

The first frame of Figure 6.25 shows that the aircraft starts this scenario close to the airport, at low altitude, and with flaps in a semi-extended setting (15°). After capturing the glide slope and localizer (in the third frame) the Pilot Flying reduces the commanded airspeed and dials the Missed Approach Altitude into the Mode Control Panel. While lowering the flaps a few seconds too early, the PF engages the High Speed mode of the AFS. As seen in the final frame, since the

MCP is dialed to the Missed Approach Altitude (above the current altitude), the aircraft adds suddenly pitches up and adds power in an attempt to capture the higher altitude. This particular problem emulates an event that occurred on an A310 in Orly, France in September 1994.

### Mode Event Cues

As seen in the final frame of Figure 6.25, when the envelope protection mode becomes engaged the pitch-up of the aircraft is readily apparent on the EVSD. In addition, the acquisition of the MCP altitude is clearly shown. Even without the EVSD, the speeds limits are readily apparent on the Primary Flight Display at all times during the approach as seen in the first frame of Figure 6.26. After the flap speed has been exceeded, the PFD also shows the pitch up of the aircraft (on the ADI) and the engagement of the High Speed mode on the FMA as seen in of the final frame of Figure 6.26. The target altitude is available on both the MCP, in the box on the on the altitude tape of the PFD as the magenta numbering above the tape.

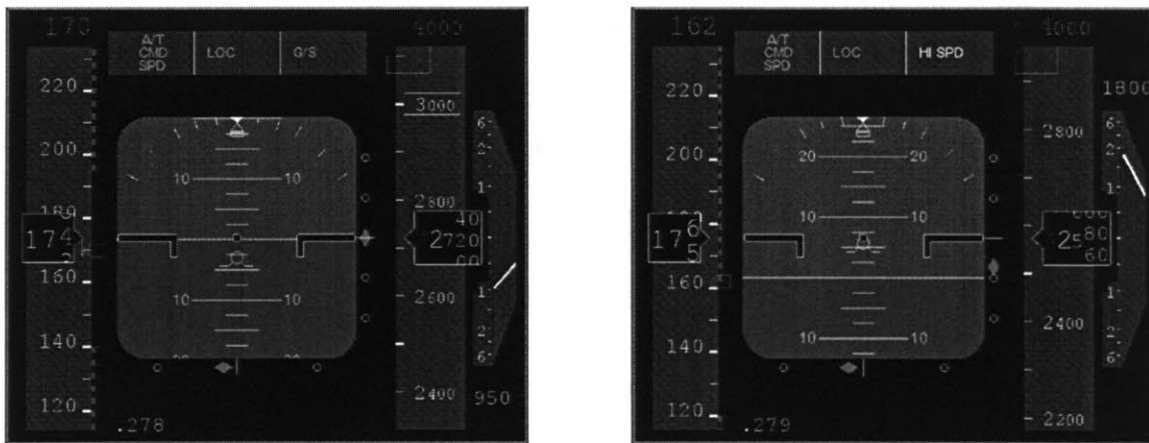


Figure 6.26: Unexpected Climb during Approach due to Flap Overspeed: Non-EVSD Cues

The key element to understanding this scenario was for the subjects to realize that the aircraft transitioned into the High Speed mode because of the overspeed condition and was flying to the Missed Approach Altitude.

*Results*

Figure 6.27 shows that the subjects reacted to the sudden climb 0.8 seconds slower with the EVSD than without, but the confidence level of this value is low. This value is also within the noise level of human reaction time. In this scenario subjects responded by viewing the pitch up of the aircraft in the PFD and immediately calling in a go-around condition to ATC. Once this was completed, subjects considered what caused the situation and examined the EVSD when it was available.

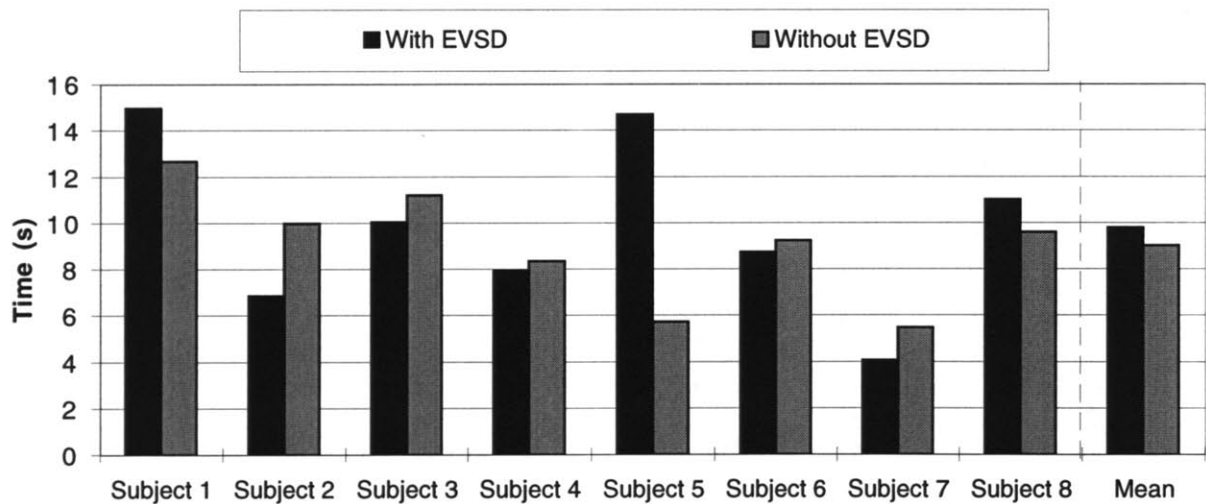


Figure 6.27: Unexpected Climb during Approach due to Flap Overspeed: Timing Results

The pilot understanding ratings for this scenario were very clearly skewed in favour of EVSD. The clear trend from Figure 6.28 was that the subjects better understood the implications of the mode event, and the elements that cause the event, when they had access to the EVSD

display. In particular, the fact that the aircraft had been inadvertently programmed to level off at the Missed Approach Altitude was noted by subjects when the EVSD was available. Finally, several subjects felt that the response of the aircraft to this rather minimal overspeed condition was unwarranted.

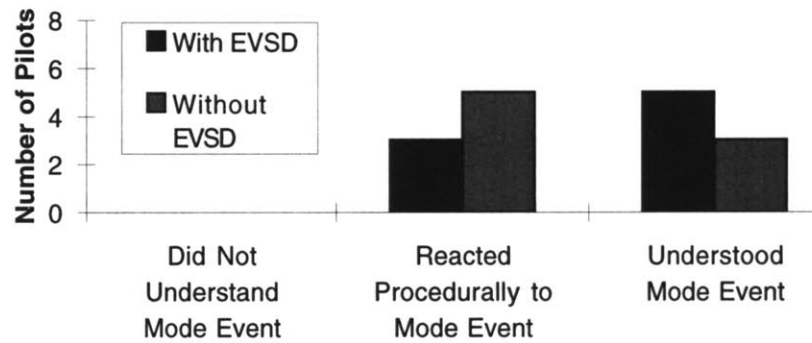


Figure 6.28: Unexpected Climb during Approach due to Flap Overspeed: Subject Understanding Ratings

### 6.3 Amalgamated Subject Understanding Ratings

Individual scenarios showed statistically minor differences in the subjects understanding of individual mode events. However, looking at the amalgamated results shown in Figure 6.29, there is a clear improvement in mode event understanding when the EVSD is available. A Willcoxon analysis to look at the statistical difference between the scenarios which had the EVSD and those which did not showed a difference at the 90% confidence level.

Note that a Willcoxon analysis does *not* measure the actual direction of the difference. However, it is clear from the data that the EVSD provided a difference that can be readily characterized as an improvement.

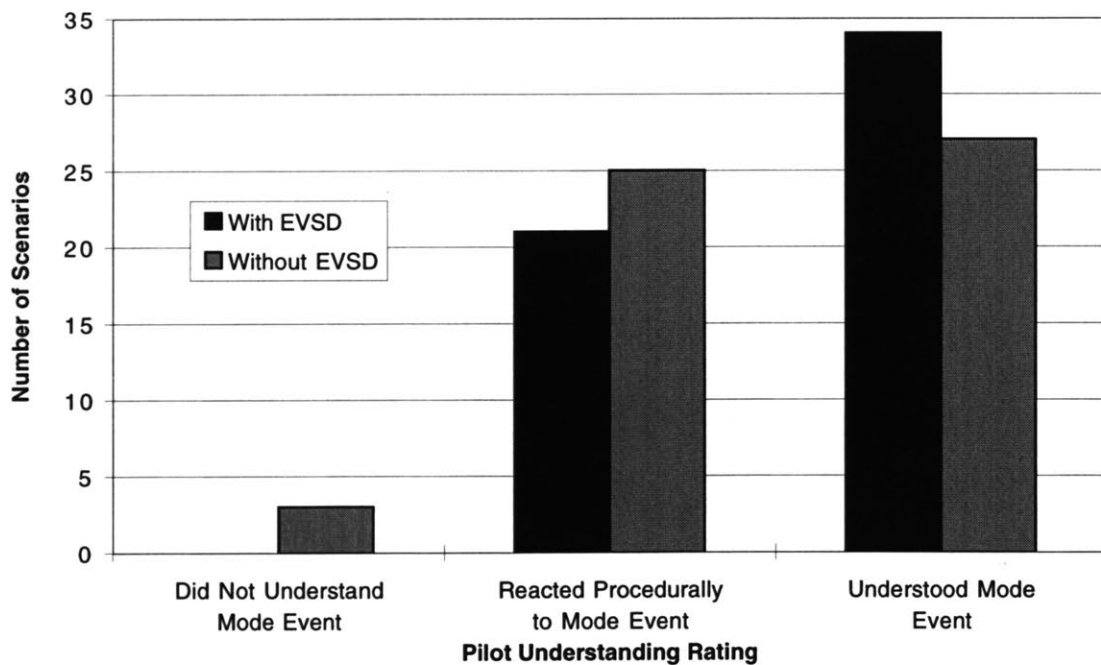


Figure 6.29: Amalgamated Pilot Understanding Histogram



## 6.4 Subjective Results

In addition to the scenario specific results, each subject was asked to fill out a survey to assess the usefulness of the EVSD in various situations and to determine the usefulness of specific elements of the EVSD.

### 6.4.1 Subjective Value of the EVSD

Subjects were asked to rate the value of the EVSD on a scale from *Very Valuable* to *Very Detrimental*. The results of this questionnaire are shown in Figure 6.30.

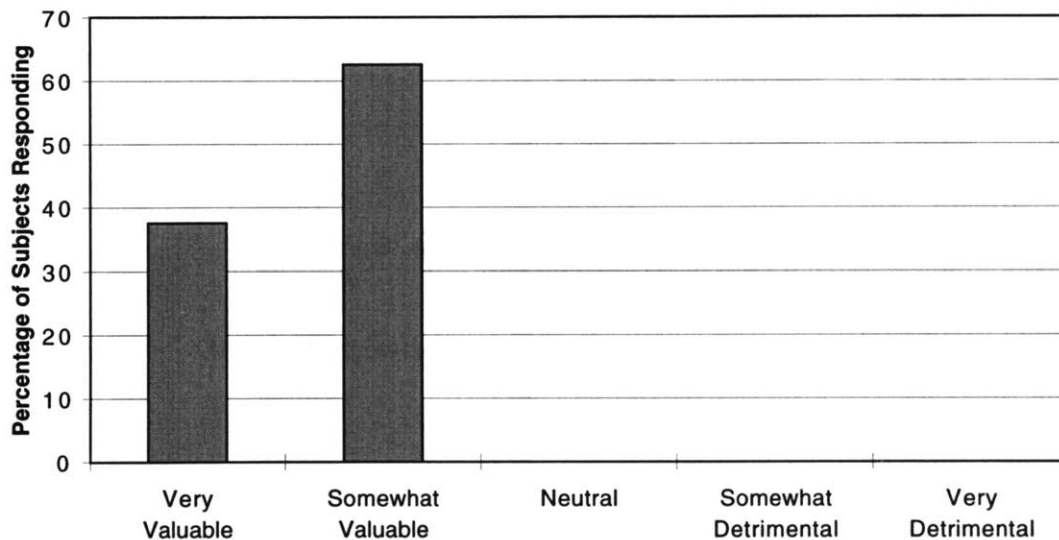


Figure 6.30: Subjective Questionnaire: How Valuable was the EVSD

As can be seen, all of the subjects felt that the display was at least somewhat valuable. It should be noted that the subjects were volunteers for this experiment, so that these results may be biased by having subjects which were predisposed to new technology in the cockpit.

### 6.4.2 Comparison of EVSD with Current AutoFlight System

Subjects were also asked to compare the EVSD to the current AFS for a variety of tasks on a scale from *Significantly Better* to *Significantly Worse* as shown in Figure 6.31.

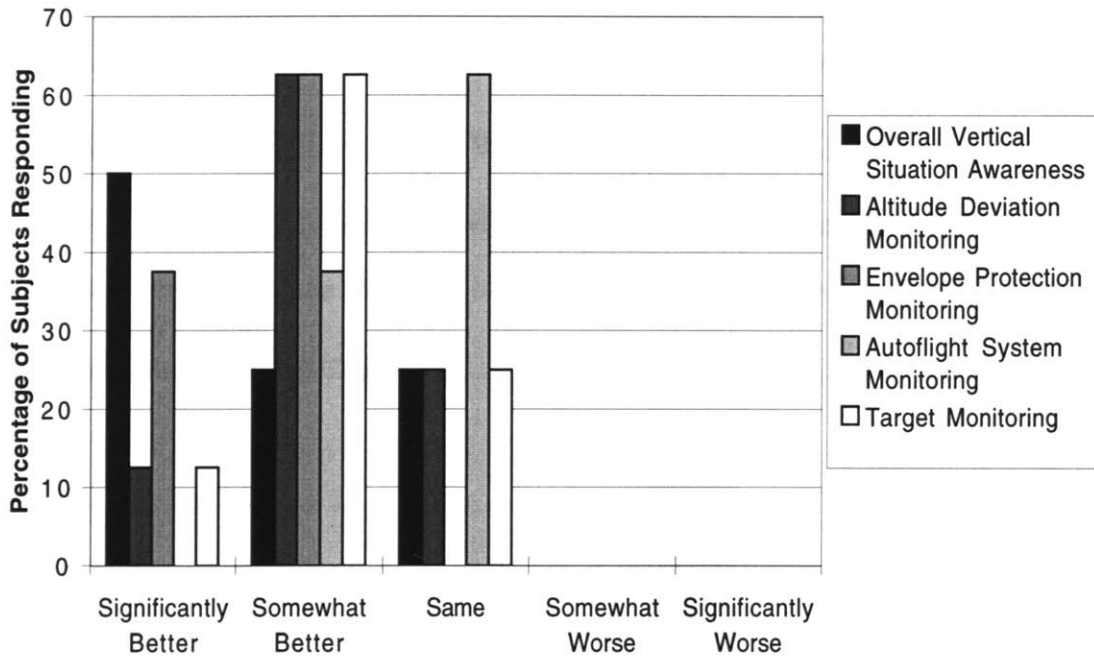


Figure 6.31: Subjective Questionnaire: Comparison between the EVSD and Current Vertical Feedback Mechanisms

These results show that the subjects found the EVSD useful in a wide range of tasks, from inner loop target monitoring to augmenting overall situation awareness. This is not consistent with the objective results, which seem to point to more effective usage in situations where there was a strategic advantage to the information on the EVSD. The display tended to be less useful in instances where another instrument provided the same information, especially when the task involved tactical types of inner loop monitoring.

### 6.4.3 Subjective Value of Elements of EVSD

Finally, subjects were asked to rate the usefulness of specific elements of the EVSD on a scale from *Very Valuable* to *Very Detrimental*. Each of these were scales with five levels, with the middle value being neutral. In addition, subjects were asked additional comments on the EVSD and features they felt were missing or required. The results of this questionnaire are outlined on Figure 6.32. Once again, for each question, the percentage of subjects responding in that category is shown.

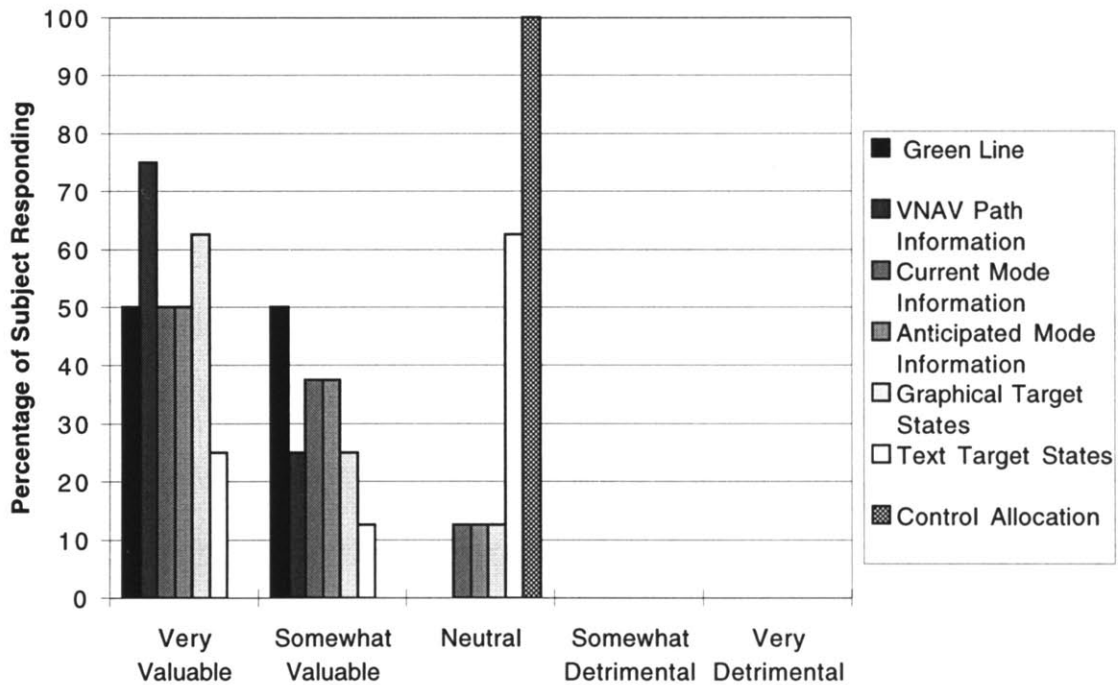


Figure 6.32: Subjective Questionnaire: Value of Specific EVSD Elements

Figure 6.32 shows that subjects were not concerned with the control allocation, or the redundant target state information provided in the top bar of the EVSD. The interaction of the Green (Aircraft Path) Line, the VNAV Path information and the graphical target states were cited as being even more useful than the individual elements.

Subjects were also given the opportunity to comment on features that they felt were missing on the prototype EVSD. 75% of the subjects were interested in seeing terrain information on the display and another 25% were interested in seeing vertical weather information. It should be noted that terrain information drawn from a database has been incorporated into the current EVSD design (as seen in Figure 3.2), but the feature was not considered mature and stable enough to incorporate into this experimental evaluation.

## Chapter 7

### Conclusions

Automation mode awareness problems have been reported by operators of many air transport aircraft. An examination of current generation AutoFlight Systems and a review of the ASRS database highlighted a lack of feedback in the vertical channel of aircraft automation. It was hypothesized that many of the incidents involving mode awareness problems could be mitigated by increased feedback in the vertical channel through an Electronic Vertical Situation Display.

An EVSD was prototyped which had four major display features: the current mode, anticipated modes, transitions into anticipated modes, and the consequences of the current state of aircraft automation. To evaluate the utility of the display, an experimental set of test scenarios was developed based on a representative set of known mode awareness problems from the ASRS review. Commercial airline pilots with glass cockpit experience were used as subjects in the experimental evaluation of the EVSD.

The Electronic Vertical Situation Display was found to significantly improve mode awareness understanding and the detection of mode awareness problems in both subjective and objective measures of subject response. Objective results were particularly strong when the anticipation functions of the EVSD could be used to foresee an event before it actually occurred. Amalgamated ratings of pilot understanding of mode awareness problems over the full set of scenarios increased in a statistically significant manner when the EVSD was available. In addition, subjects were much more specific when reporting problems to Air Traffic Control. For example, rather than simply reporting that they were unable to make a crossing restriction,

subjects would also report how far past of the waypoint the altitude would be acquired. Several subjects also mentioned the additional utility of having a vertical image of the aircraft's programmed flight.

The subjective survey results showed all of the subjects finding the display at least *Somewhat Valuable*. Display elements of the EVSD were also rated individually, with no elements being rated as detrimental and certain elements, such as the Aircraft Path Line and the vertical depiction of the VNAV trajectory being rated as *Very Valuable* by at least half the subjects. When subjects were asked to compare the EVSD with the mode feedback available in the cockpit available, they felt that overall situational awareness was improved, as was altitude monitoring and envelope protection monitoring.

Based on the positive results of this preliminary study, further evaluation of the EVSD concept appears warranted. Several issues remain to be addressed before a vertical display can be incorporated into current glass cockpits. For example an EVSD implementation must be designed to be compatible with specific AutoFlight Systems. Specific mode symbologies and names, scaling concerns, and colour conventions must be addressed, along with issues of retrofitting this display to current aircraft. This also entails finding an appropriate location for the EVSD in the valuable real estate of the modern cockpit.

In addition to continuing the development of the EVSD, other mechanisms to address mode awareness problems also should be pursued. In the short term, better training programs, specifically designed to promote understanding of the AFS should be undertaken to help make pilots aware of how to avoid and mitigate mode awareness problems. In the long term, the underlying structure of the AFS should be evaluated in the pursuit of providing a more consistent AutoFlight System architecture to pilots.

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# Appendix A Subjective Survey of EVSD

1. How valuable was the Electronic Vertical Situation Display:

Very Valuable	Somewhat Valuable	Neutral	Somewhat Detrimental	Very Detrimental

Why?

2. How does the EVSD compare with the current AutoFlight System for:

Overall Vertical Situation Awareness					
	Significantly Better	Somewhat Better	Same	Somewhat Worse	Significantly Worse
Altitude Deviation Monitoring					
	Significantly Better	Somewhat Better	Same	Somewhat Worse	Significantly Worse
Envelope Protection Monitoring					
	Significantly Better	Somewhat Better	Same	Somewhat Worse	Significantly Worse
Autoflight System Monitoring					
	Significantly Better	Somewhat Better	Same	Somewhat Worse	Significantly Worse
Target Monitoring					
	Significantly Better	Somewhat Better	Same	Somewhat Worse	Significantly Worse

3. What do you consider the

BEST feature of the EVSD:

WORST feature of the EVSD:

feature that is MISSING on the EVSD:

4. Please rate the value of each of the following features of the EVSD:

Green Line

--	--	--	--	--

Very Valuable      Somewhat Valuable      Neutral      Somewhat Detrimental      Very Detrimental

VNAV path information

--	--	--	--	--

Very Valuable      Somewhat Valuable      Neutral      Somewhat Detrimental      Very Detrimental

Current Mode Information

--	--	--	--	--

Very Valuable      Somewhat Valuable      Neutral      Somewhat Detrimental      Very Detrimental

Anticipated Mode Information

--	--	--	--	--

Very Valuable      Somewhat Valuable      Neutral      Somewhat Detrimental      Very Detrimental

Graphical Target States  
(MCP line / G/S line)

--	--	--	--	--

Very Valuable      Somewhat Valuable      Neutral      Somewhat Detrimental      Very Detrimental

Text Target States  
(in top window)

--	--	--	--	--

Very Valuable      Somewhat Valuable      Neutral      Somewhat Detrimental      Very Detrimental

Control Allocation

--	--	--	--	--

Very Valuable      Somewhat Valuable      Neutral      Somewhat Detrimental      Very Detrimental

5. Any additional comments or suggestions?

# **Appendix B Subject Scenario Questionnaire**

Scenario Number:

Pilot Number:

Why did you use the “press to talk” button?

What caused the event? Why did it happen?

What cues did you use to determine that the event occurred?

What would have eventually happened if you had not stopped the scenario?



## Appendix C Subject Briefing

The experimental methodology is to fly a series of “mini-scenarios”, each consisting of a short (about 5 minute) session of observation of the autoflight system maneuvering via the standard methods (EHSI display, ADI, MCP). Instead of actively controlling the aircraft, the subject, acting as pilot-not-flying will allow the researcher (acting as the First Officer and pilot flying) to react to all ATC commands and maintain tactical control of the aircraft. The subject is encouraged to ask for scale changes on the displays and other passive observations.

If at anytime during the scenario, the subject feels that they should query the Pilot Flying about the behaviour of the aircraft, or of any concerns about the performance of the PF, the subject should articulate this concern via the “Press to Talk” button. Situations in which the button should be used include, but are not limited to:

Inability to meet ATC directive, clearances or procedures.  
Any sort of unsafe condition.  
Any perceived fault with the aircraft.

Essentially, the subject CANNOT hit the button too often. Any situation which is of concern should be articulated.

In addition, the subject has another task, which is to keep a load centered. The display for this load is in the top left hand side of the screen. The side stick controller should be moved left to right to center the load. An error value based on the duration of the misbalancing and the degree of misbalancing will be recorded.

### Training Session

Flight Level Change - climb, descent

- Control Altitude
- Note Targets
- Note Control Allocation

Vertical Speed - climb, descent

- Control Altitude
- Note Targets
- Note Control Allocation

High Speed - climb, descent

- Control Altitude
- Note Targets
- Note Control Allocation
- Note mode change circle

Approach Mode

- Arming
- extrapolation vector

## The Simulator:

The Aeronautical System Laboratory's Advanced Part Task Simulator is a medium fidelity simulation of aircraft operations, with particular attention paid to displays and autopilot logic. However, since it does not emulate any single aircraft (it is a mixture of the B757/767/747-400 with a B737 MCP and some display conventions from the MD-11), a few of the characteristics it exhibits must be noted and understood.

1. The VNAV function consists of two modes, VNAV PATH (where the a/c tries to follow a specific path at the target speed) and VNAV SPD (the a/c tries to maintain a target speed during vertical maneuvers). The transition from VNAV PATH to VNAV SPD occurs when due to an unforeseen AFS target conflict, the a/c speed exceeds the target speed by 10 kts. This should be considered a legitimate reason to use the press to talk button.
2. Envelope protection boundaries are shown on the speed tape on the ADI. The red marker indicate Vmin and Vmax. If these boundaries are exceeded, the a/c autopilot will automatically switch to either a LOSPD or HISPD mode to maintain the Vmin or Vmax speed until it captures the target altitude.
3. The Altitude Capture Logic on the simulator flies a .05g arc when close to the target altitude. It sometime overshoots slightly. During this capture, the a/c will be in the ALT HLD mode.
4. The localizer capture/tracking logic is somewhat coarse: it overshoots the localizer several times before tracking down it tightly.
5. Some of the scenarios do *not* have anything worth reporting. These are inserted to keep the task interesting and make sure that the task does not become too easy. If the subject feels that the scenario did not have any problems, he or she should simply state so on the questionnaire.
6. A great deal of effort has been put into the fidelity of the simulation. Correct cues will be available from the MCP, the EVSD (if it is currently visible), the ADI, the CDU and the EHSI. The throttle (when on manual) , flap and landing gear are all functionally operational and may be used for additional information.

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