Institute of Cognitive Science

Technical Report

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A New Conceptual Model for Avionics Annunciation

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Abstract

This paper introduces and utilizes a new conceptual model of the avionics, the Cockpit System Model (Sherry, 1994), to analyze operational issues associated with flight mode annunciation documented in the literature. The Model decomposes the mission of flying a modern airliner from origin to destination into five asynchronous tasks: flightplanning, navigation, guidance, control, and stability augmentation. FMAs and MCPs in current glass cockpit aircraft use annunciation schemes that are generalizations of designs that were originally developed for an earlier generation of avionics systems that only automated control and stability augmentation tasks.

There are numerous operational consequences of extending annunciation schemes and conceptual models appropriate to avionics that automated control and stability augmentation tasks to modern avionics systems that automate all five tasks. Pilots have to utilize effortful, cognitive processes to construct useful representations of the current state of the avionics. A cause of automation surprises and other operational issues with modern avionics is lack of annunciation and training on the guidance task.

Annunciation in the cockpit should be explicitly based on the Model providing the flight crew information about the operation of each of the five tasks. This information enables the flight crew to monitor the avionics systems operation during fully automated operation, to evaluate the effect of engaging automated operation, and to perform tasks manually with the advice of the automated systems.

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1. Introduction

This paper introduces and utilizes a new conceptual model of the avionics, the Cockpit System Model (Sherry, 1994), to analyze operational issues associated with flight mode annunciation documented in the literature. The Cockpit System Model describes the operation of the avionics systems for modern, highly automated aircraft (e.g., the MD-11) that are required to perform a commercial air transport mission. The Model consists of five asynchronous tasks: flightplanning, navigation, guidance, control, and stability augmentation. Each of these complex operationally embedded tasks (Sherry, 1994) is represented as hybrid symbolic/continuous control system. The application of this model leads to improved methods for flight mode annunciation, for the training of flight-crews, and for the design of avionics systems. The model can also serve as the foundation for improved dialogue between operators, researchers, and designers.

1.1 Operational Issues

Recent articles on the operation of avionics systems have described the complexity of the control modes and flight mode annunciation (Corwin 1995; Degani, Shafto, & Kirlik, 1995; Eldredge, Mangold, & Dodd, 1992; Hutchins, 1993; Mangold & Eldredge, 1995; Sarter & Woods, 1992, 1994; 1995a,b; Wiener, 1988, 1989; Vakil, Hansman, & Midkiff, 1995; Vakil, Hansman, Midkiff, & Vaneck, 1995a,b). The results of this research have identified human interface issues ranging from lack of necessary feedback to the pilot to discrepancies between pilots' understanding and the actual operation of the complex subsystems that make up the avionics system.

Numerous researchers (e.g., Vakil, et al, 1995b) and pilots have pointed out that pilots are not provided with a comprehensive model of the avionics during training and that they may evolve incomplete and potentially incorrect models from their line experience. None of the articles sighted above base their analyses on complete models of the avionics.

1.2 Proposal

The Cockpit System Model is used to analyze issues raised in the articles cited above. This paper describes new forms of annunciation and feedback from avionics to the crew based on the model. These new forms of annunciation are used as tools in our analyses. Some of the operational issues discussed in the papers cited are due in part to existing schemes for annunciation that do not provide full coverage of all the tasks in the Cockpit System Model: flightplanning, navigation, guidance, control and stability augmentation.

The five task are further decomposed in subtask called *operational procedures*. This construct will be used as the conceptual foundation for annunciation. Sherry (1994) shows that operational procedures provides the basis for a complete, consistent, and understandable description of the operation of avionics software. The Cockpit System Model enables us to focus on details of specific interactions between the avionics and the crew and not just present high-level descriptions issues involved in feedback from the avionics to the crew (Billings, 1991).

Our primary assumption is that a common conceptual model must describe the actual structure of the avionics system, designers' models of the system, the pilots models of the operation and behavior of the system, and the model of the system providing the conceptual and organizational structure of training materials. Only such a shared model can provide the foundations for successful annunciation.

Aircraft in the early phases of development, such as the High Speed Civil Transport, may be able to take advantage of the specification of the operation of avionics systems, the simplified mode structure, and new schemes for annunciation discussed in this paper.

1.3 Outline of Paper

Section 2 selectively summarizes the current literature on operational issues dealing with modes, mode annunciation, and mode awareness for the current generation of avionics systems. We focus on pilots' understanding of avionics systems and operational requirements for annunciation. The Cockpit System Model and the concept of operational procedures are presented in Section 3. The guidance task and its associated vertical and lateral operational procedures are described in detail. Section 4 presents an overall analysis of annunciation from the perspective of the model. Section 5 introduces a new scheme for annunciation of the vertical guidance task based on the model. We also discuss proposals for vertical situation displays. Section 6 presents our conclusions.

2. Modes and Flight Mode Annunciation

The Flight Mode Annunciator (FMA) is one of the many user-interfaces between the avionics systems and the flight crew. The FMA provides information about the configuration of the avionics, the modes and targets selected by the flight crew, and the modes and targets selected by the avionics. This section describes current forms of annunciation found in modern cockpits, discusses operational issues, and identifies requirements for successful annunciation.

2.1 Current Forms of Annunciation

The intent of FMAs is to provide pilots with feedback concerning the operation of the avionics and the delegation of tasks between avionics and crew. Operationally, airline standard operating procedures (SOPs) call for monitoring of the FMA to confirm flight- crew commands to the avionics or avionics programming actions made via the Mode Control Panel (MCP), and to detect uncommanded mode changes caused by the envelope protection or automated operation of the Flight Management System (FMS).

Three major avionics programming actions are performed on the MCP and verified on the FMA. The first is configuration of the avionics: turning the flight directors on or off, setting the autothrottles on or off, engaging or disengaging the autopilot, and engaging or disengaging the FMS. There are a large number of combinations of these mixed configurations of operation. Polson, Irving, and Irving (1993) showed that there are approximately 36 achievable configuration combinations for the avionics for the Boeing 737-300 and 16 of them are used in line operations.

The second is manually programming the autopilot when the FMS is disengaged. Autopilot mode selections and target values are entered using knobs and switches on the MCP. The resulting control mode is annunciated on the FMA. Target values are displayed in windows on the MCP, on the FMA, or on speed and altitude tapes on the Primary Flight Display (PFD), or some combination of the preceding.

The third is heads-up programming of the FMS flightplan. Flightplan definition and the subsequent modification of the flightplan to fulfill ATC instructions generates a four dimensional trajectory in space from origin to destination. The flightplan is based on an optimum trajectory designed to satisfy the pilot entered Cost Index (fuel burn in $/time) and generates economy targets. Targets and control-modes selected by the FMS may be overridden by pilot selected targets for altitude and speed (e.g., speed intervention).

FMAs all use text abbreviations in different locations and colors to provide a description of the operation of the avionics. Location is used to distinguish the major categories of information being annunciated. A large number (10-15) of different abbreviations can appear at each of 3 to 5 locations. In the Airbus and

Boeing aircraft the categories are: configuration of the avionics (e.g., flight director on or off, autopilot on or off), autothrottle/speed control mode, roll axis mode, and pitch axis mode. Corwin (1995) presents an review of current forms of annunciation including descriptions of the FMAs and MCPs for current Airbus, Boeing, Concorde, Fokker, and McDonnell-Douglas glass cockpit transport aircraft.

2.2 Automation Surprises

Vakil, Hansman, Midkiff, and Vaneck (1995b) performed a study of mode awareness problems described in pilot reports to the Aviation Safety Reporting System (ASRS) submitted during the years 1990 to 1994. They found 184 reports in which the crew experienced an automation surprise which Vakil (1995b) attributed to mode awareness/understanding problems. Thirty four percent of the incidents described some kind of failure like disparities in the data base or hardware failures. The remaining categories of attributed causes were: insufficient knowledge of the avionics system (18%), pilot mistakes in programming (entry) of the FMS flightplan through the Control and Display Unit (CDU) (46%), failure to detect or anticipate a mode transition (20%), and crew coordination (14%). The percentages add up to more than 100% because approximately 30% of the incidents were classified in more than one category.

Observe that mode awareness problems can be caused by system failures, failures to adequately monitor the system, flightplan programming mistakes, or lack of knowledge of the system leading to misunderstanding of mode annunciation and mistakes in programming the flightplan. Thus, it is very difficult to separate mode awareness problems with more general issues concerning FMS flightplan programming skills, crews' understanding of the avionics, and situation awareness.

2.3 Incomplete Understanding of the Avionics

Other investigators have attributed operational issues with flight automation to inconsistencies between pilot's understanding of, and expectations for, the operation of the avionics, and the actual operation of the avionics. Wiener's (1988, 1989) studies revealed that even highly experienced pilots felt that they had gaps in their knowledge of how the automation functioned, frequently reporting being startled into asking "What is it doing now?" and wondering "Why is it doing that?" or "What is it going to do next?"

Eldredge, Mangold, & Dodd (1992) present the results of a detailed analysis of operational problems reported by pilots. They analyzed 99 incidents submitted to the ASRS during 1988 and 1989. They concluded that 60 out of the 99 incidents were caused by discrepancies between the pilot expectations and the operation of the avionics. In a recent review, Mangold and Eldredge (1995) argue that the different levels of automation cannot be effectively used by flight crews in revenue service operation, that flight crews may be unfamiliar with some of the functionality of the avionics, and that limitation in the annunciation of the state of the avionics and the state of the flightplan results in some uncertainty on the part of flight crews.

Sarter & Woods (1992, 1994) studies have shown that pilots' expectations for the behavior of the avionics systems on the Boeing 737-300 do not completely reflect the actual operation of the avionics, especially in rare but potentially critical emergency situation like a low speed abort on takeoff. Many of these cases are the result of differences between the pilots and the avionics strategies for handling these situations and can be resolved by improved dialogue between operators, trainers, and designers.

Woods and his colleagues (e.g., Woods, et al., 1994) have repeatedly made the point that the avionics systems may be too complex for human cognitive abilities due to the large number of different options for performing maneuvers, of different modes, especially those involving changes in speed and altitude. Many of the accidents and incidents describe by Corwin (1995) were attributed to a divergence between pilots' expectations and the operation of the avionics due to the complexity of avionics systems.

2.4 Limitations in Feedback to Pilots

Woods, et al. (1994) use the term *keyhole effect* to describe communication from a computer-based system to the human operator. Typical forms of feedback to the crew on the state of the automation like the FMA, Control and Display Unit (CDU) pages, and the Navigation Display (ND) are keyhole views of large and complex data structures that control the behavior of the avionics. In order to monitor or understand the current state of the system, the operator must integrate information from any different displays (e.g., FMA, ND, and numerous CDU pages). The CDU display, limited to 26 lines of less than 60 characters, and the FMA are classical example of keyholes.

The intended function of the FMA is to provide pilots with feedback on the operation (and state) of the avionics system. There have been numerous discussions on the limitations of current schemes of feedback to the pilots of the operation of the avionics systems and automation in general (Woods, et al, 1994). Billings (1991), in his discussion of the principles of human centered automation, presents a series of design guidelines for feedback to pilots. Vakil, et al (1995b) showed that there were significantly more mode awareness problems with vertical as compared to horizontal (lateral) navigation. Recent proposals to enhance the feedback provided to pilots focus on designs for vertical situation displays (Hutchins, 1992, 1994; Vakil, Hansman, & Midkiff, 1995).

However, what is missing from all of these discussions of feedback and presentations of high level design principles (e.g., Billings, 1991) is the kind of detailed design guidance that would be need to develop and certify a new forms of feedback. This paper concludes that evaluations of the current FMAs and designs of new displays have to be based on complete models of how the avionics works and the operational requirements of pilots for information about the operation of the avionics.

2.5 Current Models of the Avionics

Vakil et al. (1995b) summarize models of modern avionics systems held by pilots and researchers studying cockpit automation (e.g., Hutchins, 1993; Mangold & Eldredge, 1995; Sarter & Woods, 1995a). These models are generalizations of the deterministic, linear models with feedback terms described in classical control theory texts (e.g., McRuer, Ashkenas, and Graham, 1973) reflecting the fact that modern avionics systems have evolved from autopilots.

2.5.1 Base-modes and Macro-modes

The trajectory is described by a flightplan entered into the Flight Management Computer (FMC) by the crew through the CDU. The avionics selects lateral and vertical control modes to fly the path described by the flightplan. The specification of a mode includes a set of targets (heading, track, speed, vertical speed, flight path angle, etc.) and a set of actuators (elevators, thrust, ailerons) that are used to control the aircraft.

Vakil et al. (1995b) partition the modes into base-modes that maintain a quasi-steady-state controlling to fixed targets, and macro-modes that are a sequence of base-modes. Examples of base-modes include heading hold which flys a fixed heading using roll commands and flight-level-change (FLCH) which climbs or descends the aircraft at max or idle thrust and pitches to a speed using the elevators. Examples of macro-modes are modes that climb or descend and level off at a target altitude or flying a descent path computed by the FMS (e.g., VNAV-PATH). Modern avionics systems have evolved by defining new base-modes like flight-path-angle and a large number of new macro-modes.

2.5.2 Mode Transitions

The pilots tasks in using such a system are to select and engage the correct base- or macro-mode and to monitor mode transitions. The engaged and armed modes are displayed on the FMA. Vakil et al. (1995b) assert that there are three types of transitions: commanded, uncommanded, and automatic/conditional. A commanded transition is one that occurs immediately on a pilot action. Examples of automatic/conditional transition include the execution of a sequence of base-modes under the control of a macro-mode and modes that are first armed and then engage after achieving a target state. Envelope protection functions are the usual source of uncommanded mode changes.

Recent analyses of the operation of modern avionics systems have emphasized the number and complexity of the base- and macro-modes of modern avionics systems and the complex pattern of transitions between these modes (Degani, Shafto, & Kirlik, 1995; Hutchins, 1993; Mangold & Eldredge, 1995; Woods et al. ,1994; Sarter & Woods, 1995a). For example, Hutchins (1993) analysis of the mode structure for pitch and thrust control in the Boeing 747-400 shows that there are 9 pitch and 6 thrust control modes generating 56 potential combinations. He then introduces a conceptual model that generates constraints necessary to define the 24 actual combinations. Sarter and Woods (1995a) describe conceptual and operational problems caused by the number of modes and uncommanded mode transitions.

2.5.3 Pilots' Models of the Avionics

Vakil et al. (1995 b) conclude that "there does not appear to be a simple, consistent, global model of current AutoFlight Systems." (page 4). They point out that no such model is presented in flight manuals which just describe basic avionics operating procedures and the crew-avionics interface. Numerous other researcher have made similar observations.

In interviews with pilots, Vakil et al. (1995b) found that pilots models are based on frequent situations that occur in normal operations. Pilots describe the system in terms of their understanding of the behavior of the base-modes and the more common macro-modes. They characterize the behavior of a given base-mode in terms of single-input, single-output control loops (SISO). Transitions between some elements of macro-modes and uncommanded mode changes are not well understood. Sarter and Woods (1992, 1995b) present data from questionnaires and studies of pilot performance in flight simulators illustrating pilots' limited understanding of the behavior of the avionics in infrequently occurring situations.

Vakil et al. (1995b) argue that incorporating a comprehensible, complete model of the avionics into pilot training would dramatically improve the current situation. Pilots try to induce the underlying structure of complex system from a very limited sample of its behavior (e.g., frequently occurring situations in normal operations). The avionics system is too complex for this method of instruction to be completely successful

2.5.4 A New Model of the Avionics

We agree that many of these observations about the issues associated with the operation and training of complex modern avionics systems are the result of the absence of a universally acceptable "consistent, global model of current AutoFlight systems." Our solution is to propose such a model, the Cockpit System Model (Sherry, 1994, Sherry and Polson, In Preparation), that includes constructs to manage the complexity and to facilitate the development of complete models of the operation of the avionics by the flight crew . This model is presented in Section 3.

2.6 Operational Requirements for Annunciation

Mangold and Eldredge (1995) present an excellent summary of the issues concerning annunciation and feedback to pilots about the operation of the avionics. They partition the general problem of annunciation into three views: 1) the instantaneous state of the aircraft, 2) the expected behavior of the aircraft for the next several minutes, and 3) the strategic view of the overall mission. Mangold and Eldredge (1995) make specific suggestions about both content and representation of displayed information for each view. We only discuss content.

View 1 provides pilots with information about the instantaneous state of the aircraft, including relationships of the current state of the aircraft to target values, operational limits, and envelope limits. Including envelope limits enables pilots to anticipate mode changes caused by envelope protection functions. This view also provides information about the current sources of speed, heading, and altitude targets enabling pilots to anticipate the immediate behavior of the aircraft or account for unexpected behaviors. FMAs are intended to provide such information, but this form of feedback is not completely successful. Mangold and Eldredge (1995) list many deficiencies.

View 2 provides pilots with a representation current flight segment including the expected path, target values and limits, and feedback on whether the aircraft will actually achieve target values. Eldredge, et al (1992) point out that many incidents described in ASRS reports were caused by the fact that pilots had no way to determine whether an aircraft trajectory will meet a crossing restriction or some other constraint included in the current clearance. Because it is very difficult for humans to predict near-term aircraft trajectories, pilots could not anticipate and then intervene in time to correct the situation. This circumstance can easily be solved by introducing short-term predictions of aircraft trajectory in the vertical and longitudinal axes.

View 3 is a long-term strategic view of the flightplan in the context of graphical locations identified by waypoints. The ND already provides crews with such information about the lateral flightplan. Mangold and Eldredge's proposals focus on the vertical flightplan. Other proposals for annunciation of the vertical flightplan have been made by Hutchins (1992, 1994) and Vakil, Hansman, Midkiff (1995) and will be reviewed in Section 5.

3. A Complete Model of the Avionics

This section presents the Cockpit System Model, a detailed description of the structure and functions of the avionics systems for highly automated modern airliners (e.g., the MD-11). The avionics is represented as a closed-loop control system. Unlike traditional flight control systems (McRuer, Ashkenas, and Graham, 1973) with deterministic, linear, control laws, the control laws of this closed-loop system are a hybrid of linear control laws and situation-action pairs found in rule based expert systems. The Cockpit System Model is based on a decomposition of the tasks involved in performing a commercial air transport mission and on a technique for describing the structure and operation of complex operationally embedded functions (Sherry, 1994). Also see Sherry, Youssefi, and Hynes (1995).

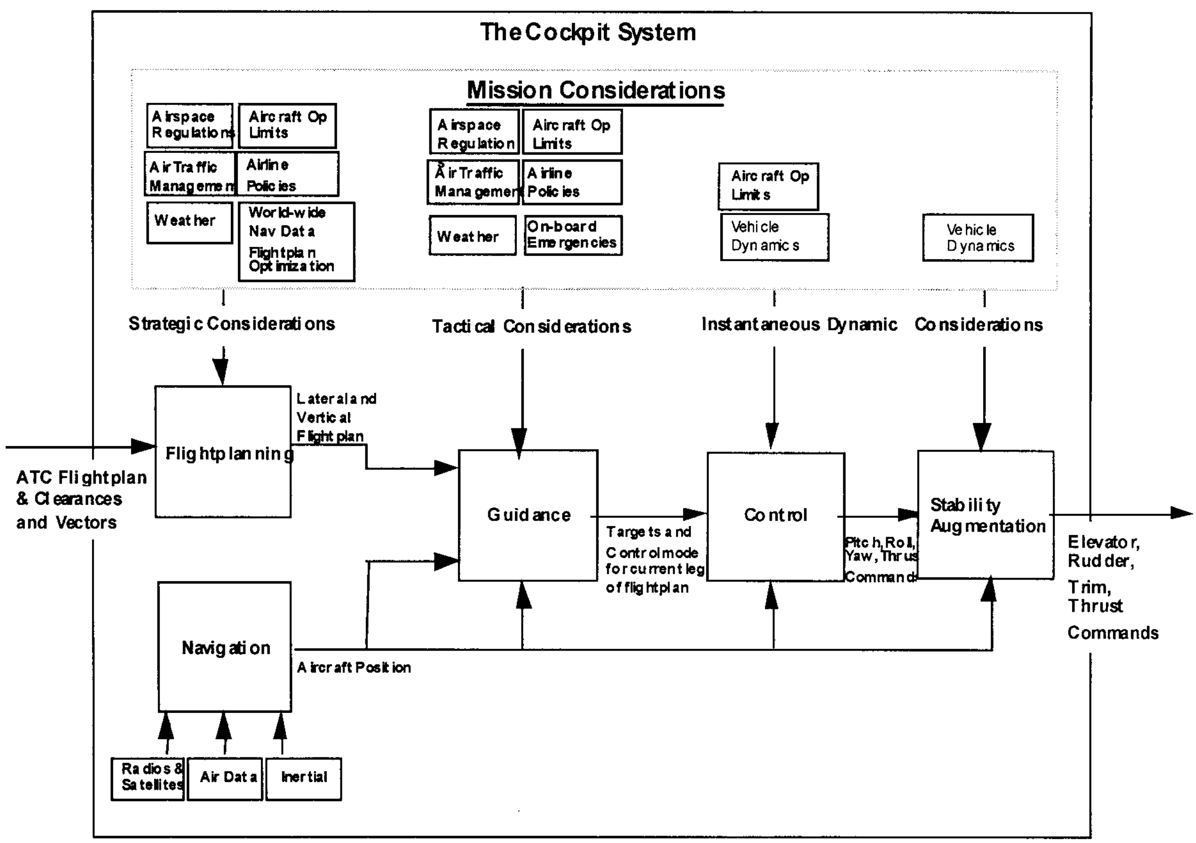

Figure 1. The Cockpit System Model

3.1 The Cockpit System

The structure and operation of the avionics software is determined by the tasks and the environment in which those task are performed, the mission of safely flying the aircraft from origin to destination. The Cockpit System Model (Sherry, 1994) is based on a decomposition of the tasks involved in performing a commercial air transport mission: Flightplanning, Navigation, Guidance, Control, and Stability Augmentation. The model is shown in Figure 1. The operation of each of the five tasks is described by a collection of mutually exclusive and exhaustive subtasks called operational procedures.

3.1.1 Flightplanning

The goal of the flightplanning task is to generate a complete, detailed representation of the flightplan. The flightplanning task determines the four dimensional path that shall be flown by the aircraft. The crew enters the initial route and modifies it in response to ATC clearances. The crew also enters parameters for the aircraft performance model (e.g., gross weight, fuel reserves, etc.) and the winds model (e.g., predicted winds as various locations and altitudes along the route). The flightplanning task also takes into account the range and performance of the aircraft, the predicted weather, miscellaneous air space regulations, airline policies, and pilot preferences.

The flightplanning task software is a complex structure editor. It takes an initial symbolic description of the cleared flightplan and generates a detailed flight from origin to destination using various heuristics to fill in the missing segments, (e.g., STAR, approach, and landing runway).

3.1.2 Navigation

The navigation task determines the position of the aircraft in all four dimensions. The position is computed based on air data sensors, inertial sensors, and radio positions.

3.1.3 Guidance

The guidance task compares the desired flightplan from the flightplanning task with the actual position of the aircraft from the navigation task and generates inputs to the control task to achieve the trajectory defined by the current leg of the flightplan. The outputs of the guidance task are commands to the control task specifying lateral and vertical control modes with targets for the specified modes. Like the flightplanning task all the decision-making that takes place in the guidance task must account for international airspace regulations, airline policies, performance limits of the aircraft, passenger comfort and noise considerations, and weather information.

The guidance task may be automated or performed manually by the flight-crew. The authority for the avionics to provide automated guidance is issued by pilot selection of VNAV (PROF) modes. The guidance task may be performed manually by pilot selection of modes and targets on the MCP.

3.1.4 Control

The control task provides closed-loop control of the aircraft surfaces and engine thrust to achieve the targets defined by the guidance task. The inputs to the control task include altitude, speed, vertical speed, and heading/track targets for the current leg of the flightplan. The modes of the control task are the base-modes and some of the macro-modes described by Vakil, et al (1995b).

Examples of base control-modes on the lateral axis include heading control-mode or track control-mode. Examples of base control-modes in the vertical-longitudinal axis include the following pitch/thrust pairs; speed on elevators/maximum thrust on throttles, speed on elevators/idle thrust on throttles, vertical speed on elevators/ speed on throttles, and altitude hold on elevators/speed on throttles. To perform this operation, the control task must have complete knowledge of the dynamics of the aircraft and all of the aircraft systems.

The control task may be automated or performed manually by the flight crew. The authority for the avionics to provide automated control is issued by the pilot selection of the autoflight mode with the autopilot engaged. The control task may be performed by the flight crew manipulation of the yoke, rudder pedals and throttle levers.

3.1.5 Stability Augmentation

The stability augmentation task closes the loop on the vehicle dynamics to provide a stable (non-oscillatory and non-divergent) response to any inputs from the control task. The stability augmentation task must have complete knowledge of the dynamics of the aircraft and all of the aircraft systems.

3.2 A Hybrid Symbolic/Continuous Control System

McRuer, et al (1973) decompose the task of managing the mission of an aircraft into a collection of tasks similar in labels and definitions to the tasks for managing the mission of a commercial air transport defined by Sherry (1994): flightplanning, navigation, guidance, control, and stability augmentation. For example, guidance is described in McRuer, et al. (1973) as the selection of lateral and vertical control modes and their target values. This description is superficially similar to Sherry's (1994).

The aircraft. the response of the aircraft to control inputs (changes in aircraft surfaces and engine thrust), and the responses to external disturbances are modeled as a collection of linear differential equations with feedback terms, the control laws (McRuer, et al, 1973). These control laws in defined by linear input/output transformations only model the control and stability augmentation tasks, two of the five tasks involved in managing the mission. Flightplanning, guidance, and navigation are beyond the scope of the linear system formalisms of classical control theory.

The Cockpit System Model, however, cannot be represented by a collection of deterministic linear input/output transformations. The Cockpit System is an integrated combination of a rule-based model used in expert systems and continuous domain control laws used for traditional flight control. Sherry (1995) points out that 80% of the requirements in a system specifications for the flightplanning, guidance and navigation tasks are expert–system like, logical decision-making definitions. The remaining 20% of these requirements are linear system definitions in the form of control laws, filters, and other data manipulation algorithms. The same percentages were found in the software where the decision-making functions are represented as IF THEN/ELSE and CASE statements, and the linear system definitions are represented by algebraic or data manipulation statements.

Furthermore, Sherry (1995) found that the linear system portions of the tasks performed supporting roles that were independent of the overall mission of the system and required only knowledge of aircraft dynamics and the dynamics of aircraft systems. The decision-making portion of these systems, however, are integral parts of the overall operation of the mission and embody the strategies, and the tactics for controlling the aircraft throughout the mission, (i.e., is analogous to an rule-based system). The knowledge require to make these decisions includes: airspace regulations, airline policies, performance limits of the aircraft, passenger comfort considerations, and information about the weather.

3.2.1 Synthesis of Two Technologies

A modern avionics system is the synthesis of two technologies: a modern closed-loop control system and a rule-based, expert systems. The representations of control and stability augmentation are dominated by closed-loop control systems. Flightplanning, guidance, and navigation are versions of rule-based, expert systems that are dominated by decision-making logic.

In a closed-loop control system, the model is a set of differential equations describing the dynamics of the controlled system. It is a continuous system, that is, small changes in an input generate small changes in an output.

A rule-based system is a symbolic system. Each rule is made up of a situation and behaviors. If the situation description in a rule matches the current actual situation, the rule fires and executes its behaviors. Small changes in representation can generated large changes in behavior.

3.3 Operational Procedures

The concept of operational procedure was proposed by Sherry (1994) to describe the decomposition of software subtasks that accomplish each of the operationally embedded and reactive flightplanning, guidance, and navigation tasks. The software for these tasks have a structure that is analogous to rule-based expert systems. Their behavior is directly determined by their current representation of the mission which is a detailed representation of the task being performed by the system, that is, they are operationally embedded. These tasks are continuously evaluating their mission representations and changing their behavior as the representation changes, i.e., they are reactive.

3.3.1 Basic Definitions

Each operational procedure is defined by a set of *scenarios* and a *behavior* which are analogous to the situation and behavior of a rule. One or more scenarios are associated with a behavior. The scenarios are defined by a set of conditions or situations in the mission when the operational procedure should be performed.

Flightplanning, navigation, and guidance tasks have a common control structure. It is a task or data acquisition loop with inputs from other tasks and representations of the past operational procedures and scenarios (states) and possible future operational procedures and scenarios (states) of the task. Each possible pattern of inputs defines a scenario. One or more scenarios are associated with an operational procedure specifying its conditions for invocation. The code for each task is a complex case statement that is enclosed in the task acquisition loop.

3.3.2 Defined by Pilots' Representation of Mission

Operational procedures are based on pilots representations of the mission. The operational procedures decompose the computations involved in performing a task like guidance into a set of subtasks that are meaningful to pilots. This requirement is a powerful constraint on the structure of the rules that implement each of the tasks and their subtasks. This constraint is the basis for our claim that operational procedures should the basis for annunciation.

The following sections describe the decomposition of the guidance, flightplanning, and navigation tasks into operational procedures. Vertical guidance is described in detail. Later discussion of problems with current forms of annunciation and possible solutions will focus on vertical guidance. Vakil, et al (1995b) found that 62.7% of the automation surprises in their sample of ASRS reports involved vertical navigation.

3.4 Operational Procedures for Guidance

The guidance task takes as input the lateral and vertical flightplan from the flightplanning task and the position of the aircraft output by the navigation task. The outputs of the guidance task are commands to the control task specifying lateral and vertical control modes with targets for the specified mode.

The guidance task includes operational procedures for flying each leg of the flightplan. Like the flightplanning task, the guidance task may be decoupled into lateral guidance and vertical guidance. The operational procedures for the lateral guidance task identify the current leg in the flightplan and then select an appropriate lateral guidance operational procedure which issues a track or heading target to be flown by either a track or heading control-mode.

The operational procedures for the vertical guidance task identify the current leg of the flightplan and then select an appropriate vertical guidance operational procedure to achieve the objectives of the leg. A set of 10 vertical guidance operational procedures, representative of the vertical guidance operational procedures on the MD-11, are summarized in Table 1. The scenarios define all the possible combinations of situations in which the aircraft may be relative to the vertical flightplan.

Table 1

Summary of Objectives and Strategies of the Vertical Guidance Operational Procedures

Operational Procedure: Objectives and Strategies
Takeoff: Airmass-referenced ascent from Runway Threshold to Acceleration Altitude
Climb: Airmass-referenced ascent from Acceleration Altitude to the Cruise Flightlevel
Climb Intermediate Level: Level flight at Clearance Altitude or Climb Altitude Constraint
Cruise: Long-range level flight at the Cruise Flightlevel
Path Descent: Earth-referenced descent on the Descent/Approach Path
Descent Intermediate Level: Level flight at Clearance Altitude or Descent Altitude Constraint
Late Descent: Airmass-referenced descent with automated speed selection and airbrake extension to return the aircraft to the Descent/Approach Path
Early Descent: Airmass-referenced descent to reacquire the Descent/Approach Path
Path Descent Overspeed: Airmass-referenced deviation from the earth-referenced path to protect the speed envelope
Airmass Descent: Airmass-referenced descent without altitude, speed, time restrictions

3.4.1 Vertical Guidance

Flight management of the vertical profile is described by a set of vertical guidance operational procedures. These operational procedures specify the targets and control modes so that the aircraft maintains the desired aircraft trajectory in the pre-determined vertical Flightplan. The flight path of the aircraft is managed by the integrated control of the pitch axis, via commands to the control surfaces, and the thrust axis, via positioning of the throttle levers. These operational procedures are encoded with the explicit desired behavior of the aircraft such that the aircraft: observes the airspace regulations, observes Air Traffic Control clearances, responds in a prescribed manner to pilot entered commands, satisfies airline policies, and operate within the operational limits of the aircraft . Table 1 contains a brief description of the vertical guidance operational procedures.

Each vertical guidance operational procedure is identified by an associated set of attributes described below:

Objective (and Strategy): Each operational procedure is characterized in terms of it's objective and strategy and answers the "why ?" question. This description must be comprehensible to pilots. The objectives and strategy of the operational procedure represent the goals or the specific maneuver that can be achieved by this operational procedure and its manner of operation. Each operational procedure is defined by a different combination of objectives and strategies.

Scenario: The scenario identifies the situation in the mission when the operational procedure shall be invoked. The scenario must define a meaningful component of the mission (e.g., cruise or profile descent). The scenario takes into account the objective of this leg of the flightplan (e.g., climb to cruise altitude), the position of the aircraft relative to the flightplan, pilot selected speed and altitude restrictions, operational limits of the aircraft, and the status of the equipment.

Targets: Each operational procedure defines a set of targets that must be maintained or acquired by the aircraft to satisfy the objectives of the operational procedure. The targets may be defined by pilot entered speed or altitude restrictions from the MCP, constraints associated with a waypoint, values computed by the avionics (e.g., an optimum speed such as ECON climb or cruise speed), or values determined by the objectives of the maneuver. The targets are altitude, speed, vertical speed, and descent/approach path. The descent/approach path target is the altitude/speed/distance rate trajectory defined relative to the destination runway.

Integrated Pitch/Thrust Control Mode: Each operational procedure defines an integrated pitch/thrust control mode and the target parameters of the mode that shall be acquired and maintained by the control task via the elevators and throttles. The control modes are defined as a tuple of the form a/b where a is the parameter controlled by the elevators and b is the parameter controlled by the throttles. The control modes fall into one of the following two categories:

Airmass-referenced control modes maintain airspeed or vertical speed relative to the surrounding airmass: speed/max-thrust, speed/idle-thrust, and vertical speed/speed. Earth-referenced control modes maintain a fixed path relative to the earth: path/speed, path/idle-thrust, altitude capture/speed, altitude capture/idle-thrust, altitude hold/speed, and altitude hold/idle-thrust.

Behavior: The behavior summaries the changes in control mode, the target values, and resulting changes in pitch and thrust. The behavior answers the "What?" question

The vertical guidance Operational Procedures are described in more detail in the following sections.

3.4.1.1 Takeoff Operational Procedure

The Takeoff operational procedure performs airmass-referenced ascent subject to obstacle clearance and takeoff noise restrictions. The operational procedure is invoked by advancing the throttles for acceleration from the runway threshold and is no longer active once the aircraft has sequenced (climbed above) the takeoff acceleration altitude. In the automation of this operational procedure the automation typically assumes authority once the aircraft sequences 400ft above ground level (AGL).

The takeoff operational procedure accelerates the aircraft down the runway through V_1 decision speed to the rotate speed of V2 + 10 knots. Following rotation, the aircraft climbs controlling speed relative to the airmass with high fidelity. The throttles are set at maximum allowable thrust rating (takeoff thrust). When the aircraft sequences the thrust reduction altitude, the thrust is cutback (reduced) to a lower thrust rating (climb thrust) for the remainder of the climb.

3.4.1.2 Climb Operational Procedure

The Climb operational procedure performs airmass-referenced ascent to the cruise flightlevel. The operational procedure is invoked when the aircraft sequences the takeoff acceleration altitude or when the aircraft is cleared for continuation of the climb from an intermediate level. The climb operational procedure is terminated when the when the aircraft captures an intermediate level altitude or the cruise flightlevel. The progress of the aircraft to the cruise flightlevel is restricted by intermediate level-offs that occur due to ATC clearance that specify intermediate altitudes, or by altitude constraints incorporated in the flightplan (i.e. at, or at or below altitude constraints)..

The climb operational procedure ascends controlling speed relative to the airmass via the elevators (pitch) and with the throttles at the optimum climb thrust rating (climb or alternative thrust). The speed targets used for control are based FAA regulations (250knots/FL100), airline policies, ATC clearances containing speed restrictions, or an economy (optimum) speed profile for climbout computed by the flightplanning task.

Current automation of the climb operational procedure does not typically include changes of speed to ensure that the aircraft at or above altitude constraints incorporated into the flightplan are satisfied. The guidance task computes predictions of the aircraft trajectory and will annunciate this situation warning the crew that the aircraft will not comply with the altitude constraint. The pilot is required to resolve the inconsistency between aircraft performance and the flightplan restrictions.

3.4.1.3 Climb Intermediate Level Operational Procedure

The Climb Intermediate Level operational procedure performs level flight at the reference altitude defined by ATC clearance that specify intermediate altitudes or altitude constraints incorporated in the flightplan. The operational procedure is invoked when the aircraft achieves the altitude below the reference altitude at which the capture maneuver is initiated. The climb intermediate level operational procedure is terminated when the aircraft is cleared for continued climbout or when sequencing (or deleting) the altitude constraint or the waypoint associated with the altitude constraint

3.4.1.4 Cruise Operational Procedure

The Cruise operational procedure performs level flight at the cruise flightlevel. This operational procedure is geared towards long range cruise. The operational procedure is invoked when the aircraft achieves the altitude below the cruise altitude at which the capture maneuver is initiated. The cruise operational procedure is terminated when the aircraft sequences the top of descent or when the cruise flightlevel is raised or lowered.

The cruise operational procedure captures and maintains level flight at the cruise flightlevel by controlling altitude via the elevators (pitch) and speed via the throttles. The altitude target is the cruise flightlevel. The speed target is the economy cruise mach or other pilot selected speeds. The speed target is limited to the applicable climb or descent speed limits and the speed envelope.

3.4.1.5 Path Descent Operational Procedure

The Path Descent operational procedure provides earth-referenced descent on the fixed descent/approach path. The path defines an altitude, speed, and thrust setting (idle thrust or speed on throttle) based on the distance to the destination. This path is computed using the flightplan altitude and speed constraints, the specified descent speed schedule, wind and other environmental information, and an aero/engine model of the dynamics of the aircraft. The path is fixed unless a change to the flightplan or speed is made, and is subject to the accuracy of the aero/engine model and the environmental data entered by the flight crew.

The path descent operational procedure is invoked when the aircraft sequences the top of descent. The operational procedure is terminated when the aircraft levels off at an intermediate altitude or is commanded to deviate from the path by MCP selections by the flight crew.

The operational procedure captures and maintains the fixed descent/approach path controlling altitude via the elevators (pitch) and with the throttles fixed at an Idle thrust rating or actively controlling speed. The speed target is defined based on the speed specified for the distance-referenced segment of the descent/approach path. When the distance-referenced path segment calls for idle thrust, the actual speed of the aircraft is determined by the flight-path angle of the segment. The flight-path angle is earth-referenced and does not account for transient behavior of the airmass. A reversion to active speed control via the throttles takes place when the aircraft is more than 10 knots slow of the desired speed. Airbrakes may be applied to avoid an overspeed. The control of the airbrakes is the responsibility of the flight-crew. Application of the airbrakes results in a reduction of speed. No change in flight-path angle will result since the aircraft is being controlled to the fixed, earth-referenced path.

3.4.1.6 Late Descent Operational Procedure

The Late Descent operational procedure performs airmass-referenced descent to recapture the descent/approach path. The rate of descent, determined by the speed target and the application of airbrakes, is adjusted to recapture the path and to satisfy all flightplan altitude and speed constraints. The progress of the aircraft may be restricted by intermediate level-offs at the clearance altitude.

The late descent operational procedure is invoked when the aircraft is above the distance-referenced segment of the descent/approach path and the clearance altitude is lowered. The operational procedure is terminated when the aircraft captures the descent/approach path segment or when the aircraft captures an intermediate level altitude at the clearance altitude.

The operational procedure descends controlling speed relative to the airmass via the elevators (pitch) and with the throttles at the an idle thrust rating. The speed target used for control is based on the relative position of the aircraft to the descent/approach path and flightplan altitude and speed constraints. When the descent must be expedited to satisfy an altitude constraint, the speed target is set to the V_{MAX} and a message recommends extension of airbrakes. When a more leisurely return to the path is feasible, the speed target may be set to the speed defined for the distance-referenced descent/approach path segment + 20 knots, or the path speed may be used with airbrakes. When the speed of the aircraft is constrained by speed constraints or speed limits, the path speed is selected and the airbrakes must be extended.

Current automation of the late descent operational procedure does not typically include changes of speed to ensure that the aircraft satisfies flightplan altitude constraints. The guidance task computes predictions of the aircraft trajectory. Messages displayed on the CDU annunciate that the aircraft will not meet the flightplan altitude constraint. The pilot is required to resolve the inconsistency between aircraft performance and the flightplan restrictions.

3.4.1.7 Early Descent Operational Procedure

The Early Descent operational procedure performs airmass-referenced descent to recapture the descent/approach path from a position short of the path. The rate of descent is selected to recapture the path with an appropriate level of aggressiveness. The progress of the aircraft may be restricted by intermediate level-offs that occur due to an ATC clearance or by altitude constraints incorporated in the flightplan.

The early descent operational procedure is invoked when the aircraft is below the distance-referenced segment of the descent/approach path. This may occur when the automation is engaged or when the flightplan is changed and the aircraft is now short of the path. The operational procedure is terminated when the when the aircraft captures the distance-referenced descent/approach path segment or when the aircraft captures an intermediate level altitude

The early descent operational procedure descends controlling vertical speed via the elevators (pitch) and speed with the throttles. The control will revert to speed control via the elevators and idle thrust on throttles to avoid violation of the speed envelope due to excessive vertical speed. The speed target is speed desired for the distance-referenced path segment. The speed target is limited to flightplan speed constraints, the speed limit, and the operational (speed) envelope.

3.4.1.8 Descent Intermediate Level Operational Procedure

The Descent Intermediate Level operational procedure performs level flight at the reference altitude defined by ATC clearance that specify intermediate altitudes or by altitude constraints incorporated in the flightplan. The operational procedure is invoked when the aircraft achieves the altitude above the reference altitude at which the capture maneuver is initiated. The operational procedure is terminated when the aircraft is cleared for continued descent by lowering the clearance altitude, sequencing (or deleting) the altitude constraint or the waypoint associated with the altitude constraint.

The descent intermediate level operational procedure captures and maintains level flight controlling altitude via the elevators (pitch) and speed via the throttles The speed target is the speed for the distance-referenced path segment. The speed target is limited to flightplan speed constraints, the speed limit, and the operational (speed) envelope.

3.4.1.9 Path Descent Overspeed Operational Procedure

The Path Descent Overspeed operational procedure performs airmass-referenced deviation from the path to protect the speed envelope. The progress of the aircraft may be restricted by intermediate level-offs do to ATC clearance that specify intermediate altitudes or by altitude constraints incorporated in the flightplan.

The path descent overspeed operational procedure is invoked when the aircraft is capturing or maintaining the path and the aircraft speed is accelerating towards the maximum speed envelope. The procedure is terminated when the when the aircraft recaptures the distance-referenced descent/approach path segment, or when the aircraft captures an intermediate level altitude.

The operational procedure descends controlling speed relative to the airmass via the elevators (pitch) and with the throttles at the an idle thrust rating. The speed target is speed desired for the distance-referenced path segment. The speed target is limited to flightplan speed constraints, the speed limit, and the operational (speed) envelope.

3.4.1.10 Airmass Descent Operational Procedure

The Airmass Descent operational procedure performs airmass-referenced descent to an altitude specified in an ATC clearance or an altitude constraint incorporated in the flightplan. The procedure is invoked when the aircraft is cleared for continuation of the descent from an intermediate level when the path is not available (no destination, no gross weight). The airmass descent operational procedure is terminated when the aircraft captures an intermediate level altitude.

The airmass descent operational procedure descends controlling speed relative to the airmass via the elevators (pitch) and with the throttles at an idle thrust rating. The speed target used for control is based on FAA regulations (250knots/FL100), airline policies, ATC clearances containing speed restrictions, or a speed profile for descent computed by the flightplanning task.

Current automation of the airmass descent operational procedure does not typically include changes of speed to ensure that the aircraft satisfies flightplan altitude constraints. The guidance task computes predictions of the aircraft trajectory. Messages displayed on the CDU annunciate that the aircraft will not meet the flightplan altitude constraint. The pilot is required to resolve the inconsistency between aircraft performance and the flightplan restrictions.

3.4.2 Evolution of Vertical Guidance Operational Procedures

The vertical guidance operational procedures were developed using task analysis and knowledge engineering techniques based on the concept of an operational procedure. The participants in the process included senior pilots from four international airlines, flight test engineers responsible for commercial air transports, and avionics engineers with extensive jump-seat experience.

The first question that had to be resolved was a definition of what constitutes an operational procedure for the task of vertical guidance. The solution was to define the boundaries between flightplanning, guidance, and control in terms of inputs and the outputs of the vertical guidance task. The inputs for vertical guidance are all associated with the relative position of the aircraft to the flightplan, the status and availability of aircraft systems, and the state of the aircraft relative to the environment (ATC instructions, traffic, weather). The outputs for vertical guidance are the integrated pitch/thrust control mode, altitude target, speed target, vertical speed target, and earth-referenced path flight path angle.

The next step in the design process was to identify and come to consensus on an initial set of operational procedures. The dialogue was performed iteratively by asking two questions: (1) What should the automation do in this scenario ? (2) When does the automation perform a given action ? Question 1 defines the behavior given a scenario. Question 2 defines the scenario given a behavior. This second phase generated over 350 operational procedures.

The number of vertical guidance operational procedures generated required that the operational procedures be organized into a hierarchy to facilitate the formulation of mental-models by the pilot operators. In organizing the operational procedures into a hierarchy, a trade-off had to be made between the number of operational procedures at any level and the visibility of the operational procedures. Pushing a set of operational procedures down to a lower level hides their behavior. Leaving the operational procedures at the higher level extends the list of operational procedures at this level.

An example of this process is the design of the late descent operational procedure. The group of operator experts made the decision to provide one operational procedure for the late descent at the top level of the hierarchy and to hide the selection of speed targets for the nominal late descent and the expedite late descent to make a flightplan altitude constraint to a lower level in the hierarchy. The alternative is to have two operational procedures at the top level: late descent and expedite late descent.

The critical point to realize is that operational procedures are not an arbitrary, rule-based (nested IF THEN/ELSE) implementation the vertical guidance task. Individual operational procedures are meaningful to pilots subtasks of the task of vertical guidance during all phases of the mission. The task of vertical guidance is complex , and thus the knowledge engineering process generated a large number of rules. The rules were then organized into a hierarchy to enable pilot to understand them in spite of their large number. The top-level operational procedures are the foundation for effective annunciation and effective communication.

3.4.3 Lateral Guidance

Lateral guidance is provided for terminal area and enroute operations including SIDs, STARs, holding patterns, lateral offsets, procedure turns, and Direct to a Waypoint. Lateral guidance steering commands are computed based on the lateral flightplan and the current aircraft position. The lateral guidance operational procedures are classified into three groups: operational procedures for maintaining a leg, operational procedures for transitioning between legs, and operational procedures for acquiring and capturing lateral legs.

Table 2

Lateral Leg Types Defined by ARINC 424-7

A F- Fly a DME Arc To a Fix (Waypoint)	HF - Fly a Holding Pattern To a Fix (Waypoint)
CF - Fly a Course To a Fix (Waypoint)	HM - Fly a Holding Pattern To Manual Termination
CA - Fly a Course To an Altitude	IF - Initial To a Fix (Waypoint)
CD - Fly a Course To a DME Distance	PI - Procedure Turn To Intercept a Course
CI - Fly a Course To Intercept another Course	TF - Track To (Great Circle) a Fix (Waypoint)
CR - Fly a Course To Intercept a VOR Radial	VA - Heading (Vector) To an Altitude
DF - Direct To a Fix (Waypoint)	VD - Heading (Vector) To a DME Distance
FA - Fly a Course From a Fix To an Altitude	VI - Heading (Vector) To Intercept a Course
FM - Fly a Course From a Fix To Manual Termination	VM - Heading (Vector) To Manual Termination
HA - Fly a Holding Pattern To a Fix (Waypoint)	VR - Heading (Vector) To Intercept a VOR Radial

3.4.3.1 Operational Procedures for Maintaining Lateral Legs

The lateral flightplan is composed of a string of waypoints from origin runway to destination runway. The string of waypoints are connected by one of 20 lateral leg types defined by ARINC 424-7. The operational procedure for each leg is defined by path control type (track or heading) and a set of conditions for terminating the leg. The complete set of lateral leg types is presented in Table 2. The leg types are represented by a two letter code. The first letter indicates the contour of the leg; there are nine possible leg contours. The second letter identifies the condition for termination; there are six possible termination types. Only 20 of the 56 combination define legal lateral leg types

3.4.3.2 Operational Procedures for Transitioning Between Legs

The operational procedures for transitioning between legs are determined by the course change between the legs, the type of the next leg, and any additional waypoint attributes such as a requirement to fly-by or overfly the waypoint. A representative set of six operational procedures are described below.

There are three operational procedures for transitioning between legs at a waypoint that is designated a "fly-by" type. When the course change between legs is less than 3 degrees the operational procedure simply picks up the course (or heading) for the next leg. When the transition requires a course change of greater than 3 degrees and less than 135 degrees, the operational procedure flies a circular path defined to be tangential to the current and next legs. For course changes greater than 135 degrees, the operational procedure flies a circular path that is tangential to the current leg and a line normal to the next leg. This path is extended to provide 45 degree intercept to the next leg.

There are three operational procedures for waypoints designated as "fly-over". All the transitions occur at the fix that is overflown. If the next leg is a TF, the operational procedure captures the course of the next leg. If the next leg is heading leg (i.e. VA, VD, VI, VM or VR), the operational procedure captures the heading of the leg. If the next leg is DF, the operational procedure flies a transition path consisting of turn and straight leg to the next waypoint tangential.

3.4.3.3 Operational Procedures for Recapturing a Lateral Leg

The operational procedures for recapturing a lateral leg are determined by the abeam distance between the aircraft's current position and the leg and the relationships between the aircraft's course and the heading or track of the current leg and possibly future legs in the flightplan.

The automation that is provided in modern aircraft is relatively straightforward. The aircraft makes no attempt to recapture the lateral path if the aircraft is more that 10 nm of the leg when LNAV (lateral guidance) is engaged. The aircraft will continue to fly it's current heading. In typical avionics systems, the automation remains armed until the aircraft is with in 10 nm offset of the lateral leg. With 10 nm lateral offset of the lateral leg a set of operational procedures return the aircraft to the lateral leg with various angular intersects.

The absence of annunciation of the scenario (situation of the aircraft relative to the flightplan) and the subsequent behavior of the operational procedures can sometimes result in surprise behavior of the aircraft. This type of surprise occurs on the sequence of the 10 nm lateral offset.

3.5 Operation Procedures for Flightplanning and Navigation

It is not possible to provide a detailed description of the flightplanning and navigation tasks in terms of operational procedures. Although these tasks are implemented using rule-like architectures (nested if-then-else's), individual rules do not necessarily describe a subtask that would be meaningful to pilots. In this section, we sketch out designs for these tasks based on hypothetical operational procedures.

3.5.1 Flightplanning

The operational procedures for the flightplanning task generate a complete, detailed representation of the flightplan, the four dimensional path that shall be flown by the aircraft. The operational procedures create and modify the string of legs that constitute the flightplan based on a large set of rules for stringing lateral legs, input from the crew entered on the CDU, the current state of the flightplan, and the current position of the aircraft provided by the navigation task.

The crew creates and modifies the flightplan by entering identifiers for various elements including takeoff runways, standard instrument departures (SIDs), waypoints, airways, company routes, standard arrivals (STARs), approaches, and landing runways. The associated operational procedures map these symbolic entries into sequences of waypoints defined by latitude/longitude, and in some cases, altitude and/or speed constraints.

Other operational procedures deal with uncertainties in the target flightplan. The preplanned route is typically incomplete (e.g. lacking the approach and landing runway). These operational procedures compensate for the uncertainties in pre-flight by making assumptions about missing flightplan elements that yield sufficiently accurate computations of expected time of arrival (ETA), fuel-burn, and other predictions. The flightplanning operational procedures also include decisions based on the predicted performance of the aircraft.

The in-flight ATC instructions are more difficult to deal with. In-flight changes to the flightplan, the result of weather, air traffic, and the operation of on-board aircraft systems add to uncertainty. They are typically executed in high-demand terminal area, are made without detailed knowledge of the preplanned target flightplan, and are themselves inherently incomplete in that they are provided segment by segment only (e.g. terminal area vectors prior to approach). These operational procedures make assumptions on the outcome of the intermediate maneuvering and plan a conservative trajectory that leaves room for the worst-case scenario.

The flightplanning operational procedures are complex because they must be able to properly deal with an incomplete description of the route and with arbitrary modifications by the crew that may introduce additional uncertainties about the intended route of flight, that may be in error, or that may not define safe or comfortable trajectories. Also, there are interactions between modifications entered by the crew and the flightplan editing heuristics defined by operators, airframers, and designers that are programmed into the software.

One example documented in the literature is the operational procedure that deletes the altitude constraints for an approach when the destination runway is changed (Sarter & Woods: 1995b). In a large number of scenarios this is the correct behavior because the destination has changed (ex. alternate) or the type of approach (ILS Type A, B, or C, Localizer only, or VFR) has changed. There are however a small number of scenarios where the change is to a parallel runway with the same altitude constraints. In this case, it would be optimal if the constraints were not automatically deleted from the flightplan. To address this issue requires good communication between all parties, a complete and consistent definition of the operational procedures (scenarios and behaviors), and appropriate and clear annunciation.

3.5.2 Navigation

The navigation task takes input from numerous redundant data sources, selects a best combination of sources, and computes values for aircraft position, velocities, and accelerations. These values are provided to all other tasks and displayed to the crew. The navigation task furnishes the continuous real-time solutions for aircraft position (latitude, longitude, altitude), ground speed, flight path angle, track angle, and wind velocity and direction. The data is computed using the appropriate combinations of Inertial Reference Systems (IRS), Air Data Computers (ADC), DME Transponders, VOR/LOC Receivers, GPS Receiver, ILS Receiver.

The navigation operational procedures represent the different methods used to compute aircraft position, velocities, and accelerations combining the outputs of available sensors that generate the best estimates of these parameters. The scenarios that invoke the operational procedures are defined based on the sensor accuracy characteristics, the raw sensor data, the position of ground-based sensors (from the Navigation Data Base), the availability of individual sensors, pilot instructions and preferences, and rules for selecting the best combination of sensors. The behaviors for each operational procedure define the algorithms for computing and smoothing the position data. These algorithms correct the noise induced errors between sensors and bias the resulting position data.

The top-level navigation operational procedures, listed in order of preference, include:

Compute Position Using IRS/GPS/DME Data
Compute Position Using IRS/GPS Data
Compute Position Using IRS/DME
Compute Position Using IRS/DME/VOR (for Collocated DME/VOR)
Compute Position Using IRS/LOC/DME (for Localizer Update)
Compute Position Using IRS only
Compute Position Using Radio Only

When the navigation VHF radio receivers are available for automatic tuning, the automation selects and tunes the best combinations of available closest transmitting stations. The operational procedure for Radio Management include approximately 20 top-level operational procedures.

3.6 Control and Stability Augmentation

The operational procedures for the control and stability augmentation tasks are the modes. The operational procedures for the control task include the integrated pitch/thrust control modes and the heading/track lateral modes(described above). The scenario defines the conditions for engagement and initialization of the linear control laws. The behavior describes the input/output transfer function of the closed-loop control law.

4. Annunciation and The Cockpit System Model

This section presents an analyses of annunciation using the Cockpit System Model. We describe operational issues caused by discrepancies between the pilots expectations and the operation of the avionics. Discrepancies between pilots' and the avionics' representations of the situation and lack of shared expectations about the behavior of the aircraft cause automation surprises. As Wiener (1988, 1989) shows, the unexpected behavior of the aircraft startles pilots into asking to asking the questions "What is it doing now?", "Why is it doing that ?", and "What's it going to do next ?"

For example, Woods and his colleagues (e.g., Woods, et al., 1994) have repeatedly made the point that avionics systems are too complex with their large number of different options for performing maneuvers and different modes, especially involving vertical guidance. We claim many of the phenomena that they describe are caused by the fact that the guidance task is hidden in the current generation of glass cockpits. The guidance-control distinction is a critical element for the design of superior annunciation, for development of new training programs, and for understanding many of the operational issues discussed in Section 2.

Current glass cockpit aircraft use annunciation schemes are generalizations of designs that were originally developed for an earlier generation of avionics systems that only automated control and stability augmentation tasks. The aviation human factors literature and airline training has been system oriented (e.g., FMS, autopilot, CDU, etc.) rather than task/operational procedures oriented. In particular, pilots and researchers do not make sharp distinctions between guidance and control functions lumping them together under the topics of avionics modes, mode awareness, and annunciation.

4.1 Overview of Annunciation

Communication from the avionics to the crew involves providing annunciation or feedback about the avionics representation of the mission and control actions. This feedback must take three forms: (1) During manual operation, provide the flight crew with annunciation about the aircraft dynamics and the information necessary to perform the flightplanning, guidance, and control tasks. (2) During partially automated operation, provide the flight crew with annunciation of the aircraft dynamics and operation of the automated tasks as well as the information necessary to perform the manual tasks. (3) During fully automated operation, provide the flight crew with annunciation of the flightplanning, guidance and control tasks' representations of the situation and current and future behaviors.

4.2 Categories of Annunciation

Mangold and Eldredge's analysis of annunciation, summarized in Section 2.6, partitions the annunciation into three views:

View 1) the instantaneous state of the aircraft
View 2) the expected behavior of the aircraft for the next several minutes
View 3) the strategic view of the mission.

These three views map naturally onto the control, guidance and flightplanning tasks of the Cockpit System Model.

The Control view (View 1) provides pilots with information about the instantaneous state of the aircraft, including the current mode of the control task, relationships of the current state of the aircraft to target values, information about the current sources of speed, heading, and altitude targets, operational limits, and envelope limits. From the perspective of the Cockpit System Model, Mangold and Eldredge call for a more complete annunciation of the current modes of the control and stability augmentation tasks.

The Guidance view (View 2) provides pilots with a representation of the current segment (or leg) of the flightplan including the expected path, target values and limits. This view may also provide predictions of the near-term aircraft trajectory and possible violations of flightplan constraints. This annunciation is not explicit in the modern cockpit. Annunciating the operational procedures for the guidance task would provide this information.

The Flightplan view (View 3) is a long-term strategic view of the mission as represented by the flightplan. This view is distributed across the ND and various pages on the CDU in current glass cockpits.

4.3 Annunciation of the Operation of the Cockpit System Tasks

The Cockpit System Model provides a representation of all the tasks must be performed to complete a commercial air transport mission. As mentioned above, the decomposition into these five tasks was based on a task analysis of cockpit operations and reflects the way we found that pilots think about their responsibilities, the knowledge required to perform the mission, and the strategic nature of the mission. The operation of each task can be completely and consistently defined by a hierarchy of operational procedures. The annunciation of the operational procedures and outputs for each of the five tasks is summarized below.

4.3.1 Control and Stability Augmentation

The inner-most loop is the control and stability augmentation tasks. These tasks require knowledge of vehicle dynamics and are performed with a loop closure required to stabilize and control the aircraft. The annunciation of these tasks are included in View 1 of the Mangold & Eldredge model.

In modern cockpits the operational procedure for the control task, the control-mode, is annunciated specifically in the FMA portion of the PFD. The outputs of the control task, the pitch, roll and thrust commands, are not annunciated explicitly. The pitch and roll commands appear on the Flight Directors (if they are displayed). The commands can also be inferred from the actual pitch and roll of the aircraft displayed on the PFD which exhibits roughly a one second delay in response to the command and by the movement of the yoke and rudder pedals (if coupled). This annunciation has proven satisfactory. Although there are new ideas about the form of the annunciation, there appears to be a consensus that the current content is satisfactory.

4.3.2 Guidance

The next outer-loop control is the guidance task. This task requires mission level knowledge such as airline policies, airspace regulations, air traffic control instructions, and operational range and limits of the aircraft. The annunciation of this task are included in View 2 of the Mangold & Eldredge model.

In modern cockpits, the operational procedures for the guidance task are not annunciated. With deep knowledge of the scenarios and behaviors associated with the operational procedures, the objective and actions of the automated avionics systems can be inferred from the guidance targets (described below). The large, and complex nature of the decision making in the guidance task results in unexpected behavior and automation surprises.

The outputs of the guidance task, the altitude, speed, and track (heading) targets are well annunciated. These targets typically appear in altitude and speed displays (dials or tapes) and sometimes on the FMA. The track (heading) target may be displayed on the rolling compass. When these targets are manually selected they appear in the MCP windows. When these modes are generated from the automation, the MCP windows are typically dashed or display the armed targets.

What is completely missing is annunciation of the guidance task's objectives and the representations of the current and predicted situation (the operational procedures and their scenarios). Accurate information about the guidance task's objectives and current and predicted situation representation is required to understand the behavior of the avionics and to evaluate the reasonableness of a proposed maneuver. Here again, the current scenario can be constructed by scanning critical CDU pages and the ND. However, this takes time and the construction process may not be completed successfully.

4.3.3 Flightplanning

The next outer-loop control is the flightplanning task. This task requires mission level knowledge such as airline policies, airspace regulations, air traffic control instructions, and operational range and limits of the aircraft. The annunciation of this task is included in View 3 of the Mangold & Eldredge model.

In modern cockpits, the operational procedures for stringing the flightplan are not annunciated. With deep knowledge of the scenarios and behaviors associated with these operational procedures, the objective and actions of the automated avionics systems can be inferred from the resulting flightplan (described below). The complex nature of the decision-making processes during the flightplanning task can generate unexpected results and automation surprises. Some interfaces to the flightplanning task include a feature that alleviates this phenomena somewhat. The flight crew is able to review entries, that if found to be correct can be executed. This at least avoids the possibility of instantaneously introducing an incorrect flightplan but does not illuminate the decision-making logic underlying the construction of the flightplan.

The outputs of the flightplanning task, the lateral and the vertical flightplans are annunciated to varying levels. The lateral flightplan is displayed in complete graphical form on the ND. This information is also duplicated on the CDU flightplan pages. The vertical flightplan is not displayed graphically at all. A model of the flightplan can be formulated by inspection of the CDU flightplan pages (page 1 and page 2). For even simple flightplans, this is difficult.

4.3.4 Navigation

The navigation task services the flightplanning, guidance and control tasks. This task requires some mission level knowledge and more specific knowledge about the operation and accuracy (noise) characteristics of the navigation sensors.

In modern cockpits, the operational procedures for the navigation task are annunciated clearly. The ND and the CDU navigation pages display the active combination of sensors used to compute the aircraft position. The aircraft position is also clearly annunciated on the ND, and CDU Performance, Position, Flightplan, and Navigation pages.

4.4 Annunciation of Patterns of Delegation

The authority for performing the tasks of the Cockpit System Model may be allocated to the avionics or performed by the flight crew. The three basic configurations include: complete manual control, automated control with manual flightplanning and guidance, and fully automated flightplanning, guidance and control.

The Cockpit System is in *Manual Control* when the flight-crew have elected to fly the aircraft via the yoke, throttles, and rudder pedals (with the assistance of the stability augmentation system). The flight-crew has assumed responsibility for flightplanning, guidance, and control functions. This configuration is typically annunciated by some form of indication that the autoflight system is not engaged such as toggle switches on the MCP or an indicator on the PFD.

The System is in *Automated Control and Manual Flightplanning and Guidance* when the flight-crew have elected to enter guidance targets and control modes manually and have delegated authority to the control task to acquire and maintain these targets. The flight-crew maintains responsibility for flightplanning and guidance functions. This configuration is annunciated on the FMA by indication that the autoflight system is engaged and that control-modes have been selected. Targets are also displayed in the MCP window and on the dials and tapes. In some aircraft the control-modes and targets may be annunciated in a color that differentiates this configuration from the fully automated configuration (described below).

The Cockpit System is considered to be in a *Fully Automated Mode of Operation* when the flight-crew have delegated full authority to the avionics to perform the flightplanning, guidance, and control tasks. This configuration is annunciated on the FMA by indication that the autoflight system is engaged and that control modes prefaced by "VNAV", or "P" indicating that the VNAV/LNAV, or PROF/NAV macro-modes have been engaged. In other aircraft the control modes may be annunciated in a different color to indicate the PROF or NAV macro-mode has been engaged. The targets are displayed on the dials and tapes and may take the form of a different shape or the same shape with a different color

The Cockpit System may be in any one of a number of mixed configurations. For example, in the control loop, the avionics system may be controlling the throttles (autothrottle) while the flight-crew control roll and pitch. Another example is in the guidance loop, where the avionics system may be performing flightplanning, guidance, and control tasks on the lateral axis, while the flight-crew are performing the flightplanning, guidance and control tasks in the vertical and longitudinal axes.

Mixed configurations of operation are particularly prevalent when the aircraft is being vectored by air traffic control. In this circumstance, the flight crew have a number of options. They can enter the ATC instruction into the flightplan and allow the Cockpit System to continue in fully automated configurations of operation, or they can enter the ATC instruction as a guidance target and shift portions of the operation of the Cockpit System into a manual guidance configuration of operation.

5. Annunciation for Vertical Guidance

This section presents a detailed analysis of the annunciation of the vertical guidance task. This task may be the cause of numerous ASRS reports. (See Section 2.). The guidance task is the least well annunciated of the five tasks in current glass cockpits. (See Section 4.3.) The analysis is performed by example. The examples discusses the operation of the automation when the flight-crew have delegated authority for flightplanning, guidance and control to the avionics.

The analysis is based on a proposed annunciation scheme for vertical guidance operational procedure and control mode annunciation. The new annunciation scheme is illustrated by three examples of automation surprises that would be eliminated by the scheme. The first example is an unexpected level-off during climb to cruise altitude. The second the third are automation surprises that occur during descent.

5.1 Annunciation Based on Operational Procedures

Table 3

Proposed Cockpit Annunciation

Why/What:	Current Operational Procedure Name
	Current Vertical Control Mode and Purpose
	<Speed Target> Speed Target Op Proc
	<Altitude Target> Altitude Target Op Proc
What is Next?	Next Operational Procedure Name
	Next Vertical Control Mode and Purpose
	<Next Speed Target> Speed Target Op Proc
	<Next Altitude Target> Altitude Target Op Proc

The annunciation scheme, shown in Table 3, displays the current and next vertical guidance operational procedure and their speed and altitude targets and vertical control mode. The next vertical guidance operational procedure is defined by the flightplan and predicted flight path. This annunciation scheme is presented to convey content only (not format) and answers the questions Why?, What now? and What next?, that is Wiener's (1988, 1989) questions. It combines information from Mangold and Eldredge's (1995) View 1 (control) and View 2 (guidance).

We first describe the representation used to present these examples and the complete descent profile in Appendix A. The examples, shown in Tables 4, 5, and 6, are described as situation-behavior pairs. We will assume that the avionics remains fully coupled with automated flightplanning, guidance, and control. The situation is defined by a position of the aircraft relative to the flightplan, or a pilot action. The situation is described only in general terms and should be applicable to all modern aircraft. The actual mechanization of these situations and pilot actions may vary and are not described in this report. The annunciation of this situation is also summarized in italics.

The behavior section describes the behavior of the aircraft, the operation of the avionics, and the flight mode annunciation. This description has also been generalized across aircraft types and is intended to be representative of modern commercial aircraft. The actual mechanization and operation differs between aircraft and is not discussed in this paper.

The underlined items in the flight mode annunciation identify what has changed from the previous situation-behavior pair. The pilot is required to have memorized the previous set of annunciations and then by noticing a change during continuous scanning, infer the operation of the automation. The description also includes a version of Table 3, the operational procedure representation of the vertical guidance task. This information represents the decision-making of the avionics and answers the "Why?", "What Now ?" and "What's Next ?" questions.

5.2 Unexpected Level-off

Situation: The aircraft is cleared to FL330, the programmed cruise altitude. The pilot flying dials up the altitude window on the MCPto the Cruise Flightlevel but does not remove the now unwanted altitude restriction at CCC.
***Current Cockpit Annunciation**: Pilot action.*

Behavior: Climb Operational Procedure. The aircraft continues climbing. A short time later, the aircraft unexpectedly starts to level off at FL180.

Current Cockpit Annunciation:
SPEED |CLIMB THRUST
PFD Altitude Target on Tape and FMA - Altitude Restriction at CCC
PFD Speed Target on Tape and FMA - ECON Climb CAS.

Proposed Cockpit Annunciation:
Why/What:- Climb Operational Procedure
- < SPEED |CLIMB THRUST> - Airmass- Ref. Climb
- <Speed Tgt> ECON Climb CAS
- <Alt Tgt> Altitude Restriction at CCC
What's Next:- Climb Intermediate Level Operational Procedure
- <ALTITUDE HOLD|SPEED> Earth-ref Level Flight
- <Speed Tgt> ECON Climb CAS
- <Alt Tgt> Level at Altitude Restriction at CCC

Table 4 Annunciation After Dialing Up Altitude Window Before Unexpected Level Off

When the crew performed the initial phases of the flightplanning task before take-off, they entered a company route that included an at or below FL180 altitude constraint at waypoint CCC, 60 nm from the airport. The aircraft was lightly loaded and would reach FL180 several nm before CCC. When passing through FL140, the aircraft is cleared to FL330, the programmed cruise altitude. The autopilot, LNAV, and VNAV are engaged, (i.e., fully automated flightplanning, guidance, and control.) The pilot flying dials up the altitude window on the MCP to the cruise flightlevel but does not remove the now unwanted altitude restriction at CCC. A short time later, the aircraft unexpectedly starts to level off. Our proposed annunciation, shown in Table 4 would display the following information to the crew before the unexpected level off occurs.

In this simple situation, the are several differences between the information annunciated and what the crew should expect if the aircraft were going to continue to climb to FL330. The target altitude for the current operational procedure is not 33,000 cruise flightlevel. The next operational procedure is not Cruise and the speed and altitude targets are incorrect too.

5.3 Automation Surprises During Descent

The next two examples are automation surprises occur when the aircraft when recapturing the computed descent/approach path from above. These examples are part of a complete hypothetical descent profile that starts at cruise flight level and ends at glide slope capture which is presented in Appendix A.

5.3.1 Unexpected Speed Target Following Clearance to Descend.

Situation:	The aircraft is cleared for descent. The pilot lowers the Clearance Altitude.
Current Cockpit Annunciation: *Pilot action.*	
Behavior:	Late Descent Operational Procedure. The aircraft noses down to initiate the descent. The speed target changes to the Descent CAS + 20 knots. This speed target ensures convergence to the path without airbrakes. The elevators control to the speed. The throttles retard and remain at an idle thrust setting.
Current Cockpit Annunciation:	
	IDLE THRUST|SPEED.
	PFD Altitude Target on Tape and FMA - Clearance Altitude
	PFD Speed Target on Tape and FMA - Descent CAS + 20 knots.
Proposed Cockpit Annunciation:	
Why/What:-	*Late Descent Operational Procedure*
-	*<SPEED|IDLE THRUST> Airmass-ref Descent*
-	*<280> ECON CAS + 20 knots*
-	*<Alt Tgt> Level at Clear Alt*
What's Next:-	*Path Descent Operational Procedure*
-	*<PATH|IDLE THRUST> Earth-ref Descent*
-	*<260> ECON Descent CAS*
-	*<Alt Tgt> Descent to Clear Alt*

Table 5. Description of situation, behavior, and proposed annunciation for example of unexpected speed target following clearance to descend.

In this situation, the aircraft is located long of (above) the optimum (ECON speed) path and is in level flight at the clearance altitude. The aircraft is cleared for descent.

The pilot lowers the clearance altitude by adjusting the altitude target on the MCP. The details of the situation, current cockpit annunciation, behavior, and proposed annunciation are given in Table 5.

The result of this action is that the guidance task switches operational procedures from descent intermediate level to late descent. The objective of the late descent operational procedure is return the aircraft to the optimum descent/approach path. This maneuver is performed in by an airmass-referenced descent controlling speed on elevators and with the throttles at idle. The altitude target is the clearance altitude.

In this scenario, the estimated point of intercept of the descent/approach path does not violate any altitude constraints and can be performed without an aggressive maneuver (see the example below for a more aggressive maneuver). As a result the automated guidance task selects the Economy Descent CAS + 20 knots.

In current forms of annunciation, this situation is annunciated by a change in pitch | thrust control-mode and by a change in speed target. The speed target value will not match (unless by coincidence) any speed targets computed by the automation or selected by the pilot. The heuristic simply calls for adding 20 knots to the speed that would normally be flown on the path.

Our proposed annunciation scheme provides feedback on both the avionics representation of situation as well as expected behavior of the aircraft. Displaying the current operational procedure(Why?/What?), Late Descent, informs the crew that they are long (high) on the computed descent/approach path and that the aircraft will descend at a speed of ECON CAS + 20 knots with idle thrust. Displaying the next operational procedure(Why?/What?), Path Descent, informs the crew that the avionics predicts that the aircraft will successfully capture the path from above with the commanded maneuver. Feedback on both Why?/What? and What's Next? enable the crew to understand the selected mode and speed target. Information about both the current and predicted relationship to the path and the behavior of the aircraft are required to prevent an automation surprise.

5.3.2 Unexpected Changes in Control-mode and Speed Target following Direct To.

In this situation the aircraft is located long of (above) the optimum (ECON speed) path and is performing an airmass-referenced descent to return to the path as described in the example above. During this descent the aircraft is vectored direct to a downpath waypoint CCC. The pilot performs the Direct To CCC on CDU and executes (reviews and confirms) the flightplan. We will assume that the avionics remains fully coupled with automated flightplanning, guidance and control. The details of the situation, current cockpit annunciation, behavior, and proposed annunciation are given in Table 6.

The result of this action is that the flightplan is shortened. The aircraft, previously long of (above) the path designed for an approach to the destination runway, is now even further long of (above) the same path. As it turns out there is an altitude constraint at waypoint CCC that now cannot be satisfied by simply descending at Descent CAS + 20 knots. A more aggressive maneuver is required. The automated guidance task, recognizing this scenario, increases the speed target to maximum speed (and may display an extend airbrakes message). The aircraft noses over and accelerates to the speed envelope.

As in the second example above, the pilot action results in a change to the aircraft trajectory resulting from a change to the control-modes and targets. These changes are difficult to anticipate. The effect of shortening the distance to the destination is not easily intuited from the available vertical flightplan information. Furthermore, the choice of speed target is radical and is not easily explained by the FMA.

Situation: The aircraft is cleared to the next waypoint. The pilot performs a Direct To the waypoint. The flightplan change shortens the distance to the destination, and causes a change of the position of the aircraft relative to the path. The aircraft now has less distance to achieve the AT altitude constraint at waypoint CCC.

Current Cockpit Annunciation: *Pilot action.*

Behavior: Late Descent Operational Procedure. The speed target is increased to V_{MAX} to increase the rate of descent. The aircraft noses down to capture the speed target The elevators control speed. The throttles are set at an Idle thrust rating.

Current Cockpit Annunciation:

SPEED|IDLE THRUST.
PFD Altitude Target on Tape and FMA - Clearance Altitude
PFD Speed Target on Tape and FMA - Maximum Speed.

Proposed Cockpit Annunciation:

Why/What:- *Late Descent Operational Procedure*
- *<SPEED|IDLE THRUST> Airmass-ref Descent*
- *<340> Max Speed to Expedite Descent*
- *<Alt Tgt> Level at Clear Alt*

What's Next:- *Path Descent Operational Procedure*
<PATH|IDLE THRUST> - Earth-Ref. Descent
- *<260> ECON Descent CAS*
- *<Alt Tgt> Descent to Clear Alt*

Table 6. Description of situation, behavior, and proposed annunciation for example of unexpected changes in control-mode and speed target following direct to.

In this case, the choice of speed target may be inferred, on aircraft equipped with NDs that display the path intercept point, by the path intercept point lying beyond the waypoint with an altitude constraint. This would only be obvious if the Waypoint option for the ND was selected displaying the altitude constraints at each waypoint in the display.

5.3.3 Differences of Opinion About Maneuvers

There are a number of different operational procedures for performing this maneuver that involve the extension of airbrakes without increasing speed, increasing speed only (as in this example), or both extending airbrakes and increasing speed. This paper does not advocate a position on the best operation. This paper does however suggest that the operation, be decided by a group of experienced operators, that the operation be applicable to all scenarios, and that the operation and it's objectives be clearly be annunciated to avoid unexpected behavior. Furthermore, this paper does not take a position on the value in returning to the optimum path computed with the Economy speeds when the aircraft initiated the descent from cruise. Again, the scenarios and appropriate behaviors must be specified and evaluated to determine the best operation. The following general comments are also results of the above analyses.

5.4 General Comments

The analysis above demonstrated the value of providing information about the situation that the aircraft is in and the effect of a flightplan change (or other pilot action). The analysis also demonstrates the value of the annunciating the current and next operational procedures to explain the operation of the automation. Appendix A includes a full profile from cruise to approach that provides some additional examples of the phenomena described above.

5.4.1 Not Distinguishing Between Guidance and Control

Recall that all modern transport aircraft use text abbreviations in different locations and colors to provide an incomplete description of the operation of the avionics. Location is used to distinguish the major categories of information being annunciated.

Our analysis of current annunciations schemes identifies three characteristics. 1) The distinction between the guidance and control tasks is not explicit, neither in the annunciation or training. 2) A single location is used to annunciate the mode of the control task or present some indication of the active vertical guidance operational procedures during automated guidance. 3) The same location is used to annunciate the pattern of delegation as well as the state of the guidance or control task.

The mnemonic LNAV annunciates automatic lateral guidance. The lateral control-mode (i.e. heading, or track) selected by automatic lateral guidance is not annunciated. Lateral guidance operational procedures are not annunciated explicitly, although they may be inferred by referencing the CDU flightplan pages and the ND when the aircraft is maintaining a lateral leg.

The vertical axis is similar. The same location is used to annunciate manually selected vertical control modes and automatic guidance, VNAV. In the Boeing 747-400 and 777, some information about the current vertical guidance operational procedure can be inferred from the mnemonics VNAV-PATH, VNAV-SPEED, and

VNAV-ALT combined with knowledge about the current phase of flight (climb, cruise, descent). VNAV-ALT is climb/descend intermediate level. In the descent phase, VNAV-PATH is the path descent operational procedure. The transition from VNAV-PATH to VNAV-SPEED is the transition from the path descent operational procedure to any of following operational procedures: early descent, late descent, path descent overspeed, or airmass descent.

5.4.2 Meta Buttons and Hidden Complexity

Hutchins (1992, 1994) has pointed out the LNAV and VNAV buttons on the MCP have very different functions from the other "mode" switches on the MCP like FLCH or V/S which engage a control mode. These control modes generate predictable and well described behavior. During climb, FLCH causes the throttles to go to climb thrust and control of speed to be on the elevators. The behavior of LNAV or VNAV depends on the operational procedure that is invoked. The behavior of the aircraft is not predictable because the crew has no direct indication of the next operational procedure that will be invoked.

Annunciating the guidance operational procedures solves the meta button problem. The display of the guidance operational procedures would provide the flight crew with information about the strategies and rules used to acquire and maintain the active segment (leg) of the flightplan. This information could be made available even when the crew has configured the system for manual guidance.

5.4.3 Apparent Complexity of the Control Task

The failure to distinguish between the guidance and control tasks has lead both researchers (Hutchins, 1993, Mangold and Eldredge, 1995) and developers of airline training materials to refer to the control modes of the control task and the guidance operational procedure as "modes." This confusion increases the apparent complexity of the control task and hides critical information about the operation of the guidance task.

Hutchins (1993) in a paper entitled "Mode Management Made Simple" includes VNAV-PATH, VNAV-SPEED, and VNAV-ALT in his analysis of the conceptual structure of vertical axis control "modes" for the Boeing 747-400. Hutchins (1993) shows that the Boeing training materials and the FMA annunciation lead to the inference that there are 9 pitch control-modes and 6 thrust control-modes involved in control of the vertical axis. However, recall that VNAV-PATH, VNAV-SPEED, and VNAV-ALT annunciate a subset of the vertical guidance operational procedures giving just 6 accessible pitch control modes.

The failure to distinguish between guidance and control leads to potential misunderstandings about the operation and underlying complexity of the control and guidance tasks. This layering hides the larger and complex strategies, rules, and situations embodied in the guidance task, and inhibits the feedback necessary to be able to necessary to anticipate the near term, next few minutes, behavior of the aircraft.

5.4.4 Tradeoff Between Useful Information and Complexity

As demonstrated by our three examples, significant information about the current and predicted situations and the behavior of the aircraft can be provided to the flight crew by the annunciation of the operational procedures. However, there are well motivated objections to our annunciation scheme shown in Table 3. The first is that the information presented is already available in the cockpit or can be inferred by the flight crew. The second is objection to the format of the displayed information.

The information displayed by our proposed annunciation scheme can be inferred from the FMA, PFD, ND, and relevant CDU pages. One of us (LS) does it all time when he is riding in the jump seat. However, it is instructive to briefly consider the visual scan patterns, skills, and knowledge required to make such inferences.

The current forms of annunciation require the pilot scan several displays to infer the current guidance operational procedure. In some cases (the FMA), the pilot must recall the previous state of a display and compare current and the recalled state. Changes in the state of the avionics are communicated only by recognizing a change of a text symbol at a physical location on a display. The necessary information, often encoded in cryptic symbols, is distributed across different locations of the FMA and various displays. Access of some of the information may require manipulation of the CDU keys to bring up the right pages on the CDU display. Construction of the representation of the avionics contained in our proposed annunciation scheme involves in scanning the relevant displays, encoding each piece of information, and then integrating the encoded data.

These processes are time consuming, effortful, subject to disruption, and unreliable. Skilled behavior has surprising high error rates, 10% to 30% (Kitajima & Polson, 1995). It is often impossible for a human to perform the computation necessary to predict the expected trajectory of the aircraft that defines the next situation. Making the necessary inferences also require deep knowledge of the operational procedures. Thus, we argue that our proposed annunciation scheme contains a great deal of useful information about the operation of the avionics that cannot be easily or reliably inferred from feedback provide in the current generation of glass cockpits.

We no have useful responses to objections about the format of our annunciation. The large amount of text that would be added to the PFD would increase the complexity of an already cluttered display. In the following sections, we review research projects that are developing graphical vertical situation displays that could be used to present the information contained in our proposed annunciation scheme.

5.4.5 Related Work

Vakil, Hansman, and Midkiff (1995) and Hutchins (1992, 1994) present alternative proposals to improve vertical annunciation that have many of the same objectives as our scheme. All have the goals of answering the questions Why?, What now? and What next? and combined information in Mangold and Eldredge's (1995) View 1 and View 2. However, neither is based on the Cockpit System Model, and thus they do not make the distinction between guidance and control.

Vakil, et al's and Hutchins' vertical situation displays provide a good representation of the situations described in the examples and the Profile in Appendix A. However, these displays must be enhanced to include the segments and points of the descent/approach path. These displays along with other mode annunciation schemes must be developed to summarize the operation of operationally embedded reactive systems than we have modeled using operational procedures.

5.4.5.1 The Electronic Vertical Situation Display

Vakil and his colleagues have developed an Electronic Vertical Situation Display (EVSD) that annunciates the current and next vertical guidance control modes with target values and control allocations and a graphical representation of the predicted sequences of current modes and targets. They also attempt to predict and annunciate uncommanded mode changes. The graphical representation displays the predicted vertical path in relationship to upcoming waypoints and mode transitions. In addition, the display shows both the MCP altitude window and any altitude restrictions. Vakil, Hansman, and Midkiff (1995) describe the details of the their design and an evaluation experiment that is currently underway. The system as been implemented on the Aeronautical Systems Laboratory Part Task simulator at MIT.

5.4.5.2 Integrated Mode Management Interface

Hutchins' (1992,1994) Integrated Mode Management Interface (IMMI) is a more ambitious proposal. The IMMI replaces the MCP and incorporates a Horizontal Situation Display (HSD) and a Vertical Situation Display (VSD). These displays contain much of the information in Mangold and Eldredge's Views 1 to 3. Both contain representations of the currently engaged, armed, and available lateral and vertical control modes with their associated targets. Hutchins does not annunciate the predicted next mode.

The pilot selects a mode by pressing an icon representing an available mode. A major goal of Hutchins' design is to make available to pilots information about the consequences of engaging a mode at or near their focus of attention which is the tip of the finger used to touch an icon representing the mode they intend to engage.

The vertical mode icons are arranged next to the speed and altitude tapes and the positions of each icon represent target values for speed and altitude. Control allocation (e.g., speed on elevators or thrust) is represented by the shape of an icon. A graphical representation of the vertical flight, the window altitude, altitude restrictions, and predicted flight path are displayed in relationship to upcoming waypoints. Information about the expected vertical profile in relationship to the vertical flightplan would enable pilots to extract much of the same information from the IMMI that is represented in our text annunciation of operational procedures, control modes, and targets.

5.4.6 Comparisons Between the Vertical Guidance Annunciation Schemes

The three examples used to motivate our annunciation scheme can also be used to compare the designs for vertical situation displays proposed by Hutchins, Vakil et al, and our proposal. The first example, unexpected level off, is dealt with effectively by all three designs. The second and third examples, automation surprises during descent, test the capabilities of the underlying avionics software. The proposed displays could certainly annunciate high on the descent path (late descent). However, our examples annunciate trajectory predictions that the aircraft will successfully recapture the path from above and distinguish between less and more aggressive speed targets to be used to recapture the path. Obviously, this information has to be available in the underlying avionics software in order for it to be represented on a vertical situation display.

In summary, the designs developed by Hutchins, Vakil and his colleagues, and our annunciation scheme all share common goals. They are to answer the questions Why?, What now? and What next?. Neither of these alternatives is inconsistent with the Cockpit System Model with its distinction between guidance and control. Hutchins' IMMI in particular is an intriguing alternative.

Our proposed scheme requires that pilots understand and have memorized the labels for all of the top level guidance operational procedures. One possibility is that an alternative version of Hutchins' IMMI could graphically represent all of the information contained in the descriptions of the operational procedures. In this case, all of the information about Why?, What now? and What next? would be made available to pilots without requiring them to explicitly understand the Cockpit System Model and to memorize the labels for the guidance operational procedures. Another possibility is that effective use of the information contained in such a graphical display might depend on knowledge of the Cockpit System Model.

5.5 Details of the Vertical Guidance Annunciation Scheme

Our proposed vertical guidance annunciation scheme is based directly on the content and organization of the vertical guidance operation procedures. Recall that the vertical guidance operational procedures were developed using task analysis and knowledge engineering techniques employing senior pilots and avionics designers as subject matter experts. The procedures are not arbitrary implementation of vertical guidance but are meaningful components of the task during all phases of the mission.

Operational Procedure	Scenarios	Behavior
Late Descent Airmass-referenced descent with automated speed selection and airbrake extension to return the aircarft to the Descent/Approach Path	- Aircraft is Long (above the Descent/Approach Path) and is descending - Aircraft is Long, level at the Clearance Altitude, and the Clearance Altitude is lowered	**Integrated Pitch/Thrust Control-mode** - Speed on Elevators/Idle-Thrust **Altitude Target** - Clearance Altitude Note: Descent Altitude Constraints are included in the Descent/Approach Path **Speed Target** - Unconstrained Descent: Econ (or Edit) Descent/Approach Path CAS/Mach Schedule + 20 knots - Speed Constrained Descent: Descent/Approach Path CAS/MAch Schedule - Altitude Constrained: V_{Max} **Vertical Speed Target** - None **Descent/Approach Path Target** - None

Figure 2 Details of the Late Descent Operational Procedure

The 10 procedures described in Section 3.4.1 and Appendix B are at the top of a hierarchy of over 350 vertical guidance operational procedures. The scenarios described in Sections 3.4.1.1 to 3.4.1.10 and in Appendix B invoke one of the top-level operational procedures. The special cases of each of these top-level procedures are defined by speed, altitude, and other targets. These targets are selected by operational procedures that distinguish between the various special cases of the top level operational procedure. Annunciating the name of the top-level operational procedure provides the crew with a general characterization of the avionics representation of the objectives, strategy, situation and information about what kinds of maneuvers to expect. Annunciation of lower-level procedures provides more detail about the avionics' representation of the situation and the expected behavior.

An illustration of this hierarchy is the difference between the two descent automation surprise examples described in Section 5.3. The part of the complete Table from Appendix B showing the details of the late descent operational procedure is presented in Figure 2. The different special cases of late descent are defined by scenarios that lead to the selection of different speed targets nominal late descent (Unconstrained Descent) and the expedite late descent (Altitude Constrained) to make a flightplan altitude constraint.

The crew gets a much more detailed description of the avionics' representation of the situation by annunciating both the top-level operation procedures and the names of the second-level operational procedures that determine speed, altitude, and other targets. Annunciating the fact that the avionics trying to make an altitude constraint rationalizes the choice of V_{Max} as a target speed.

6. Conclusions

The Cockpit System Model (Sherry, 1994) was used to carry out an analysis of the operational issues with annunciation in modern cockpits that have been documented in the literature. The Model decomposes the mission of flying a modern airliner from origin to destination into five asynchronous tasks: flightplanning, navigation, guidance, control, and stability augmentation. The behavior of the operationally embedded and reactive tasks (flightplanning, navigation, and guidance) are described by operational procedures which are complex situation-action rules. Control and stability augmentation are described by models based on deterministic, linear models with feedback terms described in classical control theory texts (e.g., McRuer, et al, 1973).

6.1 Current Annunciation Schemes

FMAs and MCPs in current glass cockpit aircraft use annunciation schemes that are generalizations of designs that were originally developed for an earlier generation of avionics systems that only automated control and stability augmentation tasks. Vakil, at al (1995b) found in interviews with pilots that they generalize the concepts of SISO control systems and modes to provide a model of and account for the behavior of modern avionics systems automating all five tasks. There are numerous operational consequences of extending annunciation schemes and conceptual models appropriate to avionics that automated control and stability augmentation tasks to modern avionics systems that automate all five tasks.

6.1.1 Construction of a Representation of the Current State of the Avionics

Pilots have to utilize effortful, cognitive processes to construct useful representations of the current state of the avionics, being able to answer Wiener's questions (Why ?, What Now?, What Next?). They have to scan other displays in addition to the FMA. They have to recall and compare previous readings with the current reading to recognize changes and to make correct inferences about the current state of the automation. All of this information on different displays has to be integrated in complex ways to make useful inferences about the immediate and near term behavior of the aircraft.

6.1.2 Not Distinguishing Between Guidance and Control

A cause of automation surprises and other operational issues with modern avionics is lack of annunciation and training on the guidance task. The guidance task is hidden in current annunciation schemes. Many of the problems attributed to the complexity of the mode structure (e.g., Hutchins, 1993; Sarter and Woods, 1995a) are in fact due to interactions between the guidance and control tasks. The meta button problem described by Hutchins (1992, 1994) and in Section 5.4.3 is another consequence of hiding the guidance task.

6.2 Annunciation Based on The Cockpit System Model

The following conclusions were drawn from the analysis of cockpit operation using the Cockpit System Model.

Annunciation in the cockpit should be explicitly based on the Model providing the flight crew information about the operation of each of the five tasks. This information enables the flight crew to monitor the avionics systems operation during fully automated operation, to evaluate the effect of engaging automated operation, and to perform tasks manually with the advice of the automated systems. This information should answer the three Wiener questions "Why?", "What's Now ?", and "What's Next ?"

6.2.1 Annunciating Patterns of Delegation and the Operation of the Five Tasks

Annunciation in the cockpit should provide the flight crew with the automation/manual configuration of each of the five tasks in the Cockpit System Model, patterns of delegation. This annunciation should be displayed in a single location.

Annunciation for flightplanning, guidance, and navigation should be based on operational procedures. The annunciation of the operational procedure label provides information about the objectives and strategies for the operation. The scenario label provides a summary of the current or predicted state of a task. For example, the guidance scenario labels summarize the guidance task's representation of the position of the aircraft relative to the path. The values or states of the outputs of each task provide information about the behavior of the avionics systems.

6.2.2 Distinguishing Between Guidance and Control

No where are the current lateral and vertical guidance operational procedures annunciated to the crew, although an experienced avionics developer can infer the currently active operational procedure from information displayed on the ND, FMA, and various pages of the CDU. FMAs provide partial information about the output of the guidance task and the selected control task modes and targets for those modes. Furthermore, no pilot training program instructs crews on the existence of guidance let alone its operation.

There are several reasons for distinguishing between guidance operational procedures and control modes. Guidance and control are very different tasks. Guidance is operationally embedded. Guidance decisions are based on a complete model of the mission (e.g., the 250 knot/FL100 speed limit). Control is not operationally embedded. The control task's behaviors are based on the current mode, its targets, and a model of the aircraft dynamics. The selection of modes and targets must be done by either the guidance task or the pilots taking into account all mission consideration.

Guidance and control actions have different implication for the behavior of the aircraft. The control mode and current targets determine the immediate behavior of the aircraft. Guidance task actions determine the behavior of the aircraft for the next several or tens of minutes. Pilots need both kinds of information.

Guidance and control tasks are described by different underlying formalisms and the resulting subsystems behave differently. Control is concisely described by classical control theory models (e.g., McRuer, et al., 1973). Guidance is a symbolic subsystem. Small changes in the situation can trigger a different scenario and cause very large changes in the behavior of the aircraft.

Guidance annunciation would enable crew to correctly anticipate the behavior of the aircraft during the next few minutes. In a previous sections, we summarized Mangold and Eldredge's (1995) proposal to provide pilots with a form of annunciation that is a guidance view of the current flight segment including the expected path, target values and limits, and feedback on whether the aircraft will actually achieve target values. They claimed that many ASRS incident reports were caused by the fact that pilots had no way to anticipating whether an aircraft would fail to achieve a target that was a constraint included in the current clearance, e.g., an altitude restriction.

6.3 Further Research

This paper makes numerous claims about the superiority of the Cockpit System Model has basis for annunciation of the avionics in modern glass cockpits. Unfortunately, there is no research that enables us to directly support such assertions. This section briefly outlines a research program that would provide direct evidence for our claims.

The first step is to perform more detailed analyses of existing data sets on automation surprises and operational issues. For example, Vakil's, et al (1995b) ASRS reports should be analyzed from the perspective of the Model. Similar analyses could be done for the incidents described by Corwin (1995) and Eldredge, et al's (1992) ASRS reports. The goal of these analyzes would be to obtain evidence for claims like that many automation surprise are caused by not annunciating the guidance task in current cockpits.

Another possible method for evaluating the Model would be to perform a training experiment using a current glass cockpit aircraft like the MD-11 or A320. A strong test would be to show that the conceptual model provided by the Cockpit Systems Model supports better understanding and more rapid acquisition of high levels of skill in using the avionics. However, we have reservations about this method for evaluating the Model. The Model may not be that useful in a cockpit that uses current forms of annunciation. It may be to difficult to infer the current and predicted operational procedures from such displays. Except for the vertical guidance task on the MD-11, no design of current avionics is based on operational procedures. Thus, using operation procedures as a conceptual model would only be an approximation. Such approximations may not be useful to pilots.

The ultimate test would be to design and evaluate an annunciation scheme based on the Cockpit System Model. The new annunciation scheme we used in our analysis of vertical guidance presented in Section 5 could be starting point for such a design. Another possibility would be to attempt to integrate the Cockpit System Model into the designs for annunciation being developed at MIT (Vakil, Hansman, Midkiff, 1995) or by Hutchins (1992, 1994). A third possibility would be to develop the avionics and associated annunciation scheme for the High Speed Civil Transport based on the Cockpit System Model (Sherry, Youssefi, and Hynes, 1995).

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8. Appendix A
Profile Operational Procedures Vertical Guidance Descent/Approach

Description of the Profile

The profile is a sequence of 23 situation-behavior pairs. This descent and approach is performed with fully automated Flightplanning, Guidance and Control operation. The pilot actions are described only in general terms. The actual mechanization of the pilot actions are aircraft dependent and are not described in this report.

Each pair is described by two elements. The label of each element is in bold face. The first is a situation, a specific event occurs in the process of flying the descent describe in the complete profile. An example is when aircraft sequences a point in space where it initiates an altitude capture maneuver to level off at an intermediate altitude specified in a clearance. The current cockpit annunciation of the situation is also provided. This description is also general and not aircraft type dependent.

The second is the behavior of the avionics which includes the label for a vertical guidance operational procedure and a description of its behavior. Again this description is a general, non-aircraft specific description. The underlined items identify what has changed from the previous situation-behavior pair. The pilot is required to have memorized the previous set of annunciations and then by noticing a change during continuous scanning, infer the operation of the automation. The current cockpit annunciation of the behavior is also described.

The proposed application of the operational procedures as annunciation is illustrated as well in the section titled Proposed Cockpit Annunciation. This proposed annunciation is presented to convey content only (not format) and answers the questions Why ?, What now? and What next ? The targets and control-modes are defined between angular brackets. The control-modes are defined the integrated pitch/thrust nomencalture. The pitch axis can control speed, vertical speed, altitude hold, or path. The thrust axis can control speed, be set to maximum thrust, or be set to idle thrust. The operational procedure invoked in the selection of these targets and control-modes follow the angular brackets.

The Summary

The following is a summary of the complete Profile. The number(s) after a sentences are the situation-behavior pair numbers.

The profile begins with the aircraft level flight at the Cruise Flightlevel before the Top-of-Descent point (1). The aircraft is cleared for descent an early descent (2). Before intercepting the Descent/Approach Path, the pilot increases the descent rate (3, 4). The aircraft intercepts the Descent/Approach Path and levels off at the Clearance Altitude. (5,6,7)

In anticipation of being held up at the Clearance Altitude, the pilot selects a slower speed (8). The aircraft is cleared to continue the descent (9). While attempting the capture the path from above, the aircraft is cleared to the next waypoint (10). The flight plan change shortens the distance to the destination, and causes a change of the relative position of the aircraft to the path. The aircraft now has less distance to achieve the AT altitude constraint at waypoint CCC. The aircraft captures the path from above at high speed and then decelerates to the Descent CAS (11).

The aircraft is vectored to Waypoint DDD. The flight plan change increases the distance to the destination, and causes the relative position of the aircraft to the path to change (12). The aircraft now has more distance to the destination and is now below the path and captures is from below (13).

The aircraft approaches FL 100 and decelerates to 250 knots (14, 15). The aircraft approaches the Clearance Altitude and noses up to capture the level altitude (16). The aircraft is cleared to continue the descent and noses down to initiate the descent. The 250 knot speed restriction requires extension of airbrakes to converge on the path (17).

The aircraft decelerates to satsify a 240 knot speed restriction (18). The aircraft recaptures the path (19). The aircraft performs a standard approach with the capture of the glideslope from below (20, 21, 22, 23).

1

Situation: The aircraft is level at the Cruise Flightlevel before the Top-of-Descent.

Current Cockpit Annunciation: *Aircraft Altitude and Altitude Target coincide on the PFD Altitude Tape. These altitudes are the same as the Cruise Flightlevel on the CDU Performance page. CDU Performance page is titled Econ Cruise.*

Behavior: Cruise Operational Procedure. Level at the Cruise Flightlevel at the Cruise Mach

Current Cockpit Annunciation:

ALTITUDE HOLD|SPEED
PFD Altitude Target on Tape and FMA - Cruise Flightlevel
PFD Speed Target on Tape and FMA - Econ Cruise Mach.

Proposed Cockpit Annunciation:

Why/What:- *Cruise Operational Procedure*

- *ALTITUDE HOLD|SPEED Level Flight*
- *<Mach Tgt> Econ Cruise Mach*
- *<Alt Tgt> Descend to Clear Alt*

Whats Next- *Path Descent Operational Procedure*

- *PATH|IDLE-THRUST Earth-ref Descent*
- *<Mach Tgt> Econ Descent Mach*
- *<Alt Tgt> Descent to Clear Alt*

2

Situation: The aircraft is cleared for descent. The pilot lowers the Clearance Altitude and initiates the descent.

Current Cockpit Annunciation: *Pilot action.*

Behavior: The aircraft initiates the descent in Early Descent Operational Procedure. The descent is performed at -750 fpm at the Cruise Mach. The elevators control the rate of descent. The throttles maintain speed.

Current Cockpit Annunciation:

VERTICAL SPEED|SPEED
PFD Altitude Target on Tape and FMA - Clearance Altitude
PFD Speed Target on Tape and FMA - Econ Cruise Mach.
MCP Vertical Speed Window - Dashed (Vertical Speed Target is not annunciated)

Proposed Cockpit Annunciation:

Why/What:- *Early Descent Operational Procedure*

- *<VS|SPEED > Vertical Speed Descent*
- *<Mach Tgt> Econ Cruise Mach*
- *<Alt Tgt> Descend to Clear Alt*
- *<-750> Default Descent*

Whats Next: - *Path Descent Operational Procedure*

- *<PATH|IDLE THRUST > Earth-ref Descent*
- *<Mach Tgt> Econ Descent Mach*
- *<Alt Tgt> Descent to Clear Alt*

3

Situation: The pilot evaluates the predicted intercept of the Descent/Approach Path and decides to increase the rate of descent to -1000 fpm (by adjusting the VS Wheel on the MCP).

Current Cockpit Annunciation: *Pilot action.*

Behavior: The aircraft continues the descent in Early Descent Cruise Operational Procedure. The descent is performed at --1000 fpm at the Cruise Mach. The elevators control the rate of descent. The throttles maintain speed.

Current Cockpit Annunciation:

VERTICAL SPEED|SPEED
PFD Altitude Target on Tape and FMA - Clearance Altitude
PFD Speed Target on Tape and FMA - Econ Cruise Mach.
MCP Vertical Speed Window - -1000

Proposed Cockpit Annunciation:

Why/What *:-Early Descent Operational Procedure*

- *< VS|SPEED> Vertical Speed Descent*
- *<Mach Tgt> Econ Cruise Mach*
- *<Alt Tgt> Descend to Clear Alt*
- *<-1000> Default Descent*

Whats Next: *-Path Descent Operational Procedure*

- *<PATH|IDLE THRUST > Earth-ref Descent*
- *<Mach Tgt> Econ Descent Mach*
- *<Alt Tgt> Descent to Clear Alt*

4

Situation: The aircraft sequences the start of the Cruise Deceleration Segment of the Descent/Approach Path.

Current Cockpit Annunciation: None.

Behavior: Early Descent Cruise Operational Procedure. The speed target switches from the Cruise Mach to the Descent Mach. The aircraft continues the descent -1000 fpm. The elevators control the rate of descent. The throttles maintain speed.

Current Cockpit Annunciation:

VERTICAL SPEED|SPEED
PFD Altitude Target on Tape and FMA - Clearance Altitude
PFD Speed Target on Tape and FMA - Econ Descent Mach.
MCP Vertical Speed Window - -1000

Proposed Cockpit Annunciation:

Why/What: *-Early Descent Operational Procedure*

- *< VS|SPEED> Vertical Speed Descent*
- *<Mach Tgt> Econ Descent Mach*
- *<Alt Tgt> Descend to Clear Alt*
- *<-1000> Default Descent*

Whats Next: *-Path Descent Operational Procedure*

- *<PATH|IDLE THRUST > Earth-ref Descent*
- *<Mach Tgt> Econ Descent Mach*
- *<Alt Tgt> Descent to Clear Alt*

5

Situation: The aircraft sequences the Descent/Approach Path capture initiation.
Current Cockpit Annunciation*: None.*
Behavior: Path Descent Operational Procedure is invoked. The aircraft noses down to capture the path. The elevators control to the path. The throttles maintain speed at the Descent Mach.
Current Cockpit Annunciation
PATH|IDLE THRUST
PFD Altitude Target on Tape and FMA - Clearance Altitude
PFD Speed Target on Tape and FMA - Econ Descent Mach..

Proposed Cockpit Annunciation:
Why/What: *-Path Descent Operational Procedure*
- *< PATH|IDLE THRUST> Earth-ref Idle Descent*
- *<Mach Tgt> Econ Des Mach*
- *<Alt Tgt> Descend to Clear Alt*

Whats Next: *-Descent Int Level Operational Procedure*
- *<ALTITUDE HOLD|SPEED > Level- flight*
- *<Mach Tgt> Econ Descent CAS*
- *<Alt Tgt> Level at Clear Alt*

6

Situation: The aircraft sequences the Descent CAS/Mach crossover.
Current Cockpit Annunciation*: None.*
Behavior: Path Descent Operational Procedure. The speed target switches from the Descent Mach to the Descent CAS. The elevators control to the path. The throttles are set to idle thrust. The aircraft speed control is open-loop and is determined by the flight path angle of the path.
Current Cockpit Annunciation:
PATH|IDLE THRUST
PFD Altitude Target on Tape and FMA - Clearance Altitude
PFD Speed Target on Tape and FMA - Econ Descent CAS.

Proposed Cockpit Annunciation:
Why/What: *-Path Descent Operational Procedure*
- *< PATH|IDLE THRUST > Earth-ref Idle Descent*
- *<CAS Tgt> Econ Des CAS*
- *<Alt Tgt> Descend to Clear Alt*

Whats Next: *-Descent Int Level Operational Procedure*
- *<ALTITUDE HOLD|SPEED > Level flight*
- *<Mach Tgt> Econ Descent CAS*
- *<Alt Tgt> Level at Clear Alt*

7

Situation: The aircraft sequences the Clearance Altitude Capture Initiation Point.
***Current Cockpit Annunciation**: None.*
Behavior: Descent Intermediate Level Operational Procedure. The aircraft noses up to capture the level altitude. The speed target remains at the Descent CAS. The elevators control to the level altitude. The throttles advance to the thrust rating for the speed at level flight and then adjust themselves to maintain speed.
***Current Cockpit Annunciation**:*
ALTITUDE HOLD|SPEED
PFD Altitude Target on Tape and FMA - Clearance Altitude
PFD Speed Target on Tape and FMA - Econ Descent CAS.

Proposed Cockpit Annunciation:
Why/What: *-Descent Int Level Operational Procedure*
- *< ALTITUDE HOLD|SPEED> Level Flight*
- *<CAS Tgt> Econ Des CAS*
- *<Alt Tgt> Level at Clear Alt*

Whats Next: *-Late Descent Operational Procedure*
- *<SPEED|IDLE THRUST > Airmass-ref Descent*
- *<CAS Tgt> Econ Descent CAS + 20 knots*
- *<Alt Tgt> Descent to Clear Alt*

8

Situation: In anticipation of being held up at the Clearance Altitude, the pilot selects the Decel speed.
***Current Cockpit Annunciation**: Pilot action.*

Behavior: Descent Intermediate Level Operational Procedure. The aircraft decelerates to Decel speed target (V_{MIN}.) at the Clearance Altitude. The elevators control to the level altitude. The throttles control speed.
***Current Cockpit Annunciation**:*
SPEED|ALTITUDE HOLD.
PFD Altitude Target on Tape and FMA - Clearance Altitude
PFD Speed Target on Tape and FMA - Minimum Speed.

Proposed Cockpit Annunciation:
Why/What: *-Descent Int Level Operational Procedure*
- *<ALTITUDE HOLD|SPEED> Level Flight*
- *<CAS Tgt> Decel*
- *<Alt Tgt> Level at Clear Alt*

Whats Next: *-Late Descent Operational Procedure*
- *<SPEED|IDLE THRUST > Airmass-ref Descent*
- *<CAS Tgt> Econ Descent CAS + 20 knots*
- *<Alt Tgt> Descent to Clear Alt*

9

Situation: The aircraft is cleared for descent. The pilot lowers the Clearance Altitude.
Current Cockpit Annunciation: *Pilot action.*

Behavior: Late Descent Operational Procedure. The aircraft noses down to initiate the descent. The speed target changes to the Descent CAS + 20 knots. This speed target ensures convergence to the path without airbrakes. The elevators control to the speed. The throttles retard and remain at an idle thrust setting.
Current Cockpit Annunciation:
SPEED|IDLE THRUST
PFD Altitude Target on Tape and FMA - Clearance Altitude
PFD Speed Target on Tape and FMA - Descent CAS + 20 knots.

Proposed Cockpit Annunciation:
Why/What: *-Late Descent Operational Procedure*
- *< SPEED|IDLE THRUST> Airmass-ref Descent*
- *<CAS Tgt> Econ CAS + 20 knots*
- *<Alt Tgt> Level at Clear Alt*

Whats Next: *- Path Descent Operational Procedure*
- *<PATH|IDLE THRUST > Earth-ref Descent*
- *<CAS Tgt> Econ Descent CAS*
- *<Alt Tgt> Descent to Clear Alt*

10

Situation: The aircraft is cleared to the next waypoint. The pilot performs a Direct To the waypoint. The flightplan change shortens the distance to the destination, and causes a change of the relative position of the aircraft to the path. The aircraft now has less distance to achieve the AT altitude constraint at waypoint CCC.
Current Cockpit Annunciation: *Pilot action.*
Behavior: Late Descent Operational Procedure. The speed target is increased to V_{MAX} to increase the rate of descent. The aircraft noses down to capture the speed target The elevators control speed. The throttles are set at an Idle thrust rating.
Current Cockpit Annunciation:
SPEED| IDLE THRUST
PFD Altitude Target on Tape and FMA - Clearance Altitude
PFD Speed Target on Tape and FMA - Maximum Speed.

Proposed Cockpit Annunciation:
Why/What: *- Late Descent Operational Procedure*
- *< SPEED|IDLE THRUST > Airmass-ref Descent*
- *<CAS Tgt> Max Speed to Expedite Descent*
- *<Alt Tgt> Level at Clear Alt*

Whats Next: *- Path Descent Operational Procedure*
- *<PATH|IDLE THRUST > Earth-ref Descent*
- *<CAS Tgt> Econ Descent CAS*
- *<Alt Tgt> Descent to Clear Alt*

11

Situation: The aircraft sequences the Descent/Approach Path Capture Initiation Point.

Current Cockpit Annunciation: *None.*

Behavior: Path Descent Operational Procedure. The aircraft noses up to capture the path. The aircraft decelerates to the speed target which is now the Descent CAS. The elevators control to path. The throttles are set to an idle thrust rating. Speed control is open loop.

Current Cockpit Annunciation:

PATH IDLE|THRUST.

PFD Altitude Target on Tape and FMA - Clearance Altitude

PFD Speed Target on Tape and FMA - Econ Descent CAS.

Proposed Cockpit Annunciation:

Why/What: *- Path Descent Operational Procedure*

- *< PATH|IDLE THRUST> Earth-ref Descent*
- *<CAS Tgt> Econ Descent CAS*
- *<Alt Tgt> Level at Clear Alt*

Whats Next: *- Descent Int Level Operational Procedure*

- *<ALTITIDE HOLD|SPEED > Level flight*
- *<CAS Tgt> Econ Descent CAS*
- *<Alt Tgt> Descent to Clear Alt*

12

Situation: The aircraft is vectored to Waypoint DDD. The flightplan change increases the distance to the destination, and causes the relative position of the aircraft to the path to change. The aircraft now has more distance to the destination and is now below the path.

Current Cockpit Annunciation: *Pilot action.*

Behavior: Early Descent Operational Procedure. The aircraft noses up to capture the default -750 fpm rate of descent. The throttles continue to control to the Descent CAS.

Current Cockpit Annunciation:

VERTICAL SPEED|SPEED

PFD Altitude Target on Tape and FMA - Clearance Altitude

PFD Speed Target on Tape and FMA - Econ Descent CAS.

MCP Vertical Speed Window - Dashed (Vertical Speed Target is not annunciated)

Proposed Cockpit Annunciation:

Why/What: *- Early Descent Operational Procedure*

- *<VS|SPEED> Airmass-ref Descentat Fixed RoD*
- *<CAS Tgt> Econ CAS*
- *<Alt Tgt> Level at Clear Alt*

Whats Next: *- Path Descent Operational Procedure*

- *<ALTITIDE HOLD|SPEED > Level flight*
- *<CAS Tgt> Econ Descent CAS*
- *<Alt Tgt> Descent to Clear Alt*

13

Situation: The aircraft sequences the Descent/Approach Path capture initiation.
Current Cockpit Annunciation: *None.*
Behavior: Path Descent Operational Procedure is invoked. The aircraft noses down to capture the path. The elevators control to the path. The throttles maintain speed at the Descent Mach.
Current Cockpit Annunciation:
PATH|IDLE THRUST.
PFD Altitude Target on Tape and FMA - Clearance Altitude
PFD Speed Target on Tape and FMA - Econ Descent CAS.

Proposed Cockpit Annunciation:
Why/What: - *Path Descent Operational Procedure*
- *<PATH|IDLE THRUST> Earth-ref Descent*
- *<CAS Tgt> Econ Descent CAS*
- *<Alt Tgt> Level at Clear Alt*

Whats Next: - *Descent Int Level Operational Procedure*
- *<ALTITIDE HOLD|SPEED > Level flight*
- *<250> Descent Speed Limit*
- *<Alt Tgt> Descent to Clear Alt*

14

Situation: The aircraft sequences the start of the 250 knot deceleration segment on the Descent/Approach Path.
Current Cockpit Annunciation: *None.*
Behavior: Path Descent Operational Procedure. The aircraft noses up to maintain the path that is designed to decelerate the aircraft at 0.05g flight path acceleration. The elevators control to the path. The throttles, controlling to the speed target, retard to the idle stop.
Current Cockpit Annunciation:
PATH|IDLE THRUST.
PFD Altitude Target on Tape and FMA - Clearance Altitude
PFD Speed Target on Tape and FMA - 250 knots.

Proposed Cockpit Annunciation:
Why/What: - *Path Descent Operational Procedure*
- *<PATH|SPEED> Earth-ref Descent*
- *<CAS Tgt> Econ Descent CAS*
- *<Alt Tgt> Level at Clear Alt*

Whats Next: - *Descent Int Level Operational Procedure*
- *<ALTITIDE HOLD|SPEED > Level flight*
- *<CAS Tgt> Econ Descent CAS*
- *<Alt Tgt> Descent to Clear Alt*

15

Situation: The aircraft descends through FL100.
***Current Cockpit Annunciation**: PFD Altitude Tape.*
Behavior: Path Descent Operational Procedure. The aircraft speed is at 250 knots. The throttles advance to hold the speed. The elevators control to the path.
Current Cockpit Annunciation
PATH|IDLE THRUST.
PFD Altitude Target on Tape and FMA - Clearance Altitude
PFD Speed Target on Tape and FMA - 250 knots.

Proposed Cockpit Annunciation:
Why/What: *- Path Descent Operational Procedure*
- *<PATH|IDLE THRUST> Earth-ref Descent*
- *<CAS Tgt> Econ Descent CAS*
- *<Alt Tgt> Level at Clear Alt*

Whats Next: *- Descent Int Level Operational Procedure*
- *<ALTITIDE HOLD|SPEED > Level flight*
- *<CAS Tgt> Approach Decel*
- *<Alt Tgt> Descent to Clear Alt*

16

Situation: The aircraft sequences the Clearance Altitude Capture Initiation Point.
***Current Cockpit Annunciation**: None.*
Behavior: Descent Intermediate Level Operational Procedure. The aircraft noses up to capture the level altitude. The speed target remains at 250 knots. The elevators control to the level altitude. The throttles advance to the thrust rating for the speed at level flight and then adjust themselves to maintain speed.
Current Cockpit Annunciation:
ALTITUDE HOLD|SPEED.
PFD Altitude Target on Tape and FMA - Clearance Altitude
PFD Speed Target on Tape and FMA - 250 knots.

Proposed Cockpit Annunciation:
Why/What: *- Descent Int Level Operational Procedure*
- *<ALTITUDE HOLD|SPEED> Level Flight*
- *<250t> Descent Speed Limit*
- *<Alt Tgt> Level at Clear Alt*

Whats Next: *- Late Descent Operational Procedure*
- *<SPEED|IDLE THRUST > Airmass-ref Descent*
- *<250> Descent Speed Limit*
- *<Alt Tgt> Descent to Clear Alt*

17

Situation: The aircraft is cleared for descent. The pilot lowers the Clearance Altitude.
***Current Cockpit Annunciation**: Pilot action.*
Behavior: Late Descent Operational Procedure. The aircraft noses down to initiate the descent. The speed target changes to the 250 knots. This speed target requires extension of airbrakes to converge on the path. The elevators control to the speed. The throttles retard and remain at an idle thrust setting.
***Current Cockpit Annunciation**:*

SPEED|IDLE THRUST.
PFD Altitude Target on Tape and FMA - Clearance Altitude
PFD Speed Target on Tape and FMA - 250 knots.

Proposed Cockpit Annunciation:

Why/What: *- Late Descent Operational Procedure*
- *< SPEED|IDLE THRUST> Airmass-ref Descent*
- *<250> Descent Speed Limit*
- *<Alt Tgt> Level at Clear Alt*

Whats Next: *- Path Descent Operational Procedure*
- *<PATH|SPEED > Earth-ref Descent*
- *<240> Descent Speed Constraint*
- *<Alt Tgt> Descent to Clear Alt*

18

Situation: The aircraft sequences the start of the 240 knot speed constraint deceleration segment on the Descent/Approach Path. This segment is computed to decelerate the aircraft from 250 knots to 240 knots at 0.05g flight path deceleration.
***Current Cockpit Annunciation**: None.*
Behavior: Late Descent Operational Procedure. The aircraft noses up to decelerate to the new speed target of 240 knots. The elevators control to the speed. The throttles retard and remain at an idle thrust setting.
Current Cockpit Annunciation

SPEED|IDLE THRUST
PFD Altitude Target on Tape and FMA - Clearance Altitude
PFD Speed Target on Tape and FMA - 240 knots.

Proposed Cockpit Annunciation:

Why/What: *- Late Descent Operational Procedure*
- *<SPEED|IDLE THRUST> Airmass-ref Descent*
- *<250> Descent Speed Limit*
- *<Alt Tgt> Level at Clear Alt*

Whats Next: *- Path Descent Operational Procedure*
- *<PATH|SPEED > Earth-ref Descent*
- *<240> Descent Speed Constraint at DDD*
- *<Alt Tgt> Descent to Clear Alt*

19

Situation: The aircraft sequences the Descent/Approach Path capture initiation.

Current Cockpit Annunciation*: None.*

Behavior: Path Descent Operational Procedure is invoked. The aircraft noses up to capture the path. The elevators control to the path. The throttles maintain speed at 240 knots.

Current Cockpit Annunciation*:*

PATH|SPEED.
PFD Altitude Target on Tape and FMA - Clearance Altitude
PFD Speed Target on Tape and FMA - Econ Descent CAS.

Proposed Cockpit Annunciation:

Why/What: *- Path Descent Operational Procedure*
- *<PATH|IDLE THRUST> Earth-ref Descent*
- *<240> Descent Speed Constraint*
- *<Alt Tgt> Level at Clear Alt*

Whats Next: *- Descent Int Level Operational Procedure*
- *<ALTITIDE HOLD|SPEED> Level flight*
- *<CAS Tgt> Approach Decel*
- *<Alt Tgt> Descent to Clear Alt*

20

Situation: The aircraft sequences the Start of Approach (or Bottom of Descent) point on the Descent/Approach Path.

Current Cockpit Annunciation*: None.*

Behavior: Path Descent Operational Procedure. The aircraft noses up to capture the deceleration segment. The elevators control to the path. The throttles retard to the idle stop then advance to hold speed.

Current Cockpit Annunciation*:*

PATH|SPEED.
PFD Altitude Target on Tape and FMA - Clearance Altitude
PFD Speed Target on Tape and FMA - Approach Speed limited to Minimum Speed (Clean Configuration).

Proposed Cockpit Annunciation:

Why/What: *- Path Descent Operational Procedure*
- *<PATH|SPEED> Earth-ref Descent*
- *<Min Spd> Clean Minimum Speed*
- *<Alt Tgt> Level at Clear Alt*

Whats Next: *- Descent Int Level Operational Procedure*
- *<ALTITUDE HOLD|SPEED > Level flight*
- *<Slat Min Spd> Slat Minimum*
- *<Alt Tgt> Descent to Clear Alt*

21

Situation: When the aircraft speed approaches the minimum speed (within 5 knots), the pilot extends slats.

***Current Cockpit Annunciation**: PFD Speed Tape.*

Behavior: Path Descent Operational Procedure. The aircraft noses up to capture the level glideslope intercept path. The elevators control to the path. The throttles are active but are at the idle stop during the deceleration.

***Current Cockpit Annunciation**:*

PATH|SPEED.

PFD Altitude Target on Tape and FMA - Clearance Altitude

PFD Speed Target on Tape and FMA - Approach Speed limited to Minimum Speed (Dirty Configuration).

Proposed Cockpit Annunciation:

Why/What:
- *Path Descent Operational Procedure*
- *<PATH|SPEED> Earth-ref Descent*
- *<Slat Min Speed> Approach Decel*
- *<Alt Tgt> Level at Clear Alt*

Whats Next:
- *Descent Int Level Operational Procedure*
- *<ALTITUDE HOLD|SPEED > Level-flight*
- *<Slat/Flap Min Spdt> Approach Decel*
- *<Alt Tgt> Go Around*

22

Situation: When the aircraft speed approaches the minimum speed (within 5 knots), the pilot extends flaps.

***Current Cockpit Annunciation**: PFD Speed Tape.*

Behavior: Path Descent Operational Procedure. The aircraft maintains the level glideslope intercept path. The elevators control to the path. The throttles are active but are at the idle stop during the deceleration.

***Current Cockpit Annunciation**:*

PATH|SPEED

PFD Altitude Target on Tape and FMA - Clearance Altitude

PFD Speed Target on Tape and FMA - Approach Speed limited to Minimum Speed (Dirty Configuration).

Proposed Cockpit Annunciation:

Why/What:
- *Path Descent Operational Procedure*
- *<PATH|SPEED> Earth-ref Descent*
- *<Flap/Slat Min Speed> Approach Decel*
- *<Alt Tgt> Level at Clear Alt*

Whats Next:
- *Descent Int Level Operational Procedure*
- *<ALTITUDE HOLD|SPEED > Level-flight*
- *<Gear Extend Spd> Approach Decel*
- *<Alt Tgt> Go Around*

23

Situation: When the aircraft speed approaches the minimum speed (within 5 knots), the pilot extends approach flaps.

***Current Cockpit Annunciation**: PFD Speed Tape.*

Behavior: Path Descent Operational Procedure. The aircraft noses over to capture the glideslope. The elevators control to the path. The throttles advance to maintain the Approach speed.

***Current Cockpit Annunciation**:*

PATH|SPEED.

PFD Altitude Target on Tape and FMA - Clearance Altitude

PFD Speed Target on Tape and FMA - Approach Speed limited to Minimum Speed (Dirty Configuration).

Proposed Cockpit Annunciation:

Why/What: - *Path Descent Operational Procedure*

- *<PATH|SPEED> Earth-ref Descent*
- *<Slat Min Speed> Approach Decel*
- *<Alt Tgt> Level at Clear Alt*

Whats Next: - *Descent Int Level Operational Procedure*

- *<ALTITUDE HOLD|SPEED > Level-flight*
- *<Approach Spd> Approach Decel*
- *<Alt Tgt> Go Around*

9. Appendix B

Operational Procedure	Scenarios	Behavior
Takeoff Airmass-referenced ascent from Runway Threshold to Acceleration Altitude	- Aircraft below the Acceleration Altitude	**Integrated Pitch/Thrust Control-mode** - Speed/Takeoff-Thrust
		Altitude Target - Clearance Altitude - Climb Altitude Constraint - Criuse Flightlevel
		Speed Target - V_1 - V_2 - V_2+10
		Vertical Speed Target - None
		Descent/Approach Path Target - None
Climb Airmass-referenced ascent from Acceleration Altitude to the Cruise Flightlevel	- Aircraft ascending to Clearance Altitude, Climb Contraint Altitude, or Cruise Flightlevel - Aircraft level at Clearance Altitude and Clearance Altitude is raised - Aircraft sequences waypoint with Climb Altitude Constraint	**Integrated Pitch/Thrust Control-mode** - Speed/Climb-Thrust
		Altitude Target - Clearance Altitude - Climb Altitude Constraint - Criuse Flightlevel
		Speed Target - Hold to Manual Termination CAS - Max Angle Climb CAS - Econ Climb CAS/Mach Schedule - Edit Climb CAS/Mach Schedule
		Vertical Speed Target - None
		Descent/Approach Path Target - None

Operational Procedure	Scenarios	Behavior
Climb Intermediate Level Level flight at Clearance Altitudeor Climb Altitude Constraint	- Aircraft captures Clearance Altitude or Climb Altitude Contraint	**Integrated Pitch/Thrust Control-mode** - Altitude-Hold/Speed **Altitude Target** - Clearance Altitude - Climb Altitude Constraint **Speed Target** - Econ Climb CAS/Mach Schedule - Edit Climb CAS/Amch Schedule - Hold to Manual Termination CAS - Max Angle Climb CAS **Vertical Speed Target** - None **Descent/Approach Path Target** - None
Cruise Long-range level flight at the Cruise Flightlevel	- Aircraft captures the Cruise Flightlevel	**Integrated Pitch/Thrust Control-mode** - Altitude-Hold/Speed **Altitude Target** - Cruise Flightlevel **Speed Target** - Econ Cruise Mach - Edit Cruise Mach - Hold to Manual Termination CAS - Max Endurance CAS **Vertical Speed Target** - None **Descent/Approach Path Target** - None
Path Descent Earth-refrenced descent on the Descent/Approach Path	- Aircraft sequences the Top-of-Descent (T/D) and captures the Descent/Approach Path Note: The Clearance Altitude has been lowered	**Integrated Pitch/Thrust Control-mode** - Descent/Approach Path FPA/Speed - Descent/Approach Path FPA/Idle-Thrust **Altitude Target** - Clearance Altitude Note: Descent Altitude Constraints are included in the Descent/Approach Path **Speed Target** - Econ Descent CAS/Mach Schedule - Edit Descent CAS/Mach Schedule **Vertical Speed Target** - None **Descent/Approach Path Target** - Earth-referenced Flight Path Angle from the Descent/Approach Path

Operational Procedure	Scenarios	Behavior
Descent Intermediate Level Level flight at Clearance Altitudeor Descent Altitude Constraint	- Aircraft captures the Clearance Altitude - Aircraft captures the Descent Altitude Constraint	**Integrated Pitch/Thrust Control-mode** - Level flight - Altitude Hold/Speed **Altitude Target** - Clearance Altitude Note: Descent Altitude Constraints are included in the Descent/Approach Path **Speed Target** - Econ Descent CAS/Mach Schedule - Edit Descent CAS/Mach Schedule - Max Descent CAS - Hold to Manual Termination CAS **Vertical Speed Target** - None **Descent/Approach Path Target** - Earth-referenced Flight Path Angle from the Descent/Approach Path
Late Descent Airmass-referenced descent with automated speed selection and airbrake extension to return the aircarft to the Descent/Approach Path	- Aircraft is Long (above the Descent/Approach Path) and is descending - Aircraft is Long, level at the Clearance Altitude, and the Clearance Altitude is lowered	**Integrated Pitch/Thrust Control-mode** - Airmass-ref Descent - Speed/Idle Thrust **Altitude Target** - Clearance Altitude Note: Descent Altitude Constraints are included in the Descent/Approach Path **Speed Target** - Unconstrained Descent: Econ (or Edit) Descent/Approach Path CAS/Mach Schedule + 20 knots - Speed Constrained Descent: Descent/Approach Path CAS/MAch Schedule - Altitude Constrained: V_{Max} **Vertical Speed Target** - None **Descent/Approach Path Target** - None

Operational Procedure	Scenarios	Behavior
Early Descent Airmass-referenced descent to reacquire the Descent/Approach Path	- Aircraft is Short (below the Descent/Approach Path) and is descending - Aircraft is Short, level at the Clearance Altitude, and the Clearance Altitude is lowered	**Integrated Pitch/Thrust Control-mode** - Vertical Speed Descent: Vertical Speed/Speed - Level Change Descent: Speed/Idle-Thrust **Altitude Target** - Clearance Altitude - Descent Altitude Constraint Note: Descent Altitude Constraints are included in the Descent/Approach Path **Speed Target** - Descent/Approach Path CAS/Mach Schedule **Vertical Speed Target** - Pilot selected Vertical Speed (on MCP) - Default to -1000fpm - 1/2 Flight Path Angle of Descent/Approach Path **Descent/Approach Path Target** - None
Airmass Descent Airmass-referenced descent without altitude, speed, time restrictions	- Aircraft is descending to Clearance Altitude - Aircraft is level at the Clearance Altitude, and the Clearance Altitude is lowered	**Integrated Pitch/Thrust Control-mode** - Vertical Speed Descent: Vertical Speed/Speed - Level Change Descent: Speed/Idle-Thrust **Altitude Target** - Clearance Altitude **Speed Target** - Econ Descent CAS/Mach Schedule - Edit Descent CAS/Mach Schedule - Max Descent CAS - Hold to Manual Termination CAS **Vertical Speed Target** - Pilot selected Vertical Speed (on MCP) - Default to -1000fpm - 1/2 Flight Path Angle of Descent/Approach Path **Descent/Approach Path Target** - None