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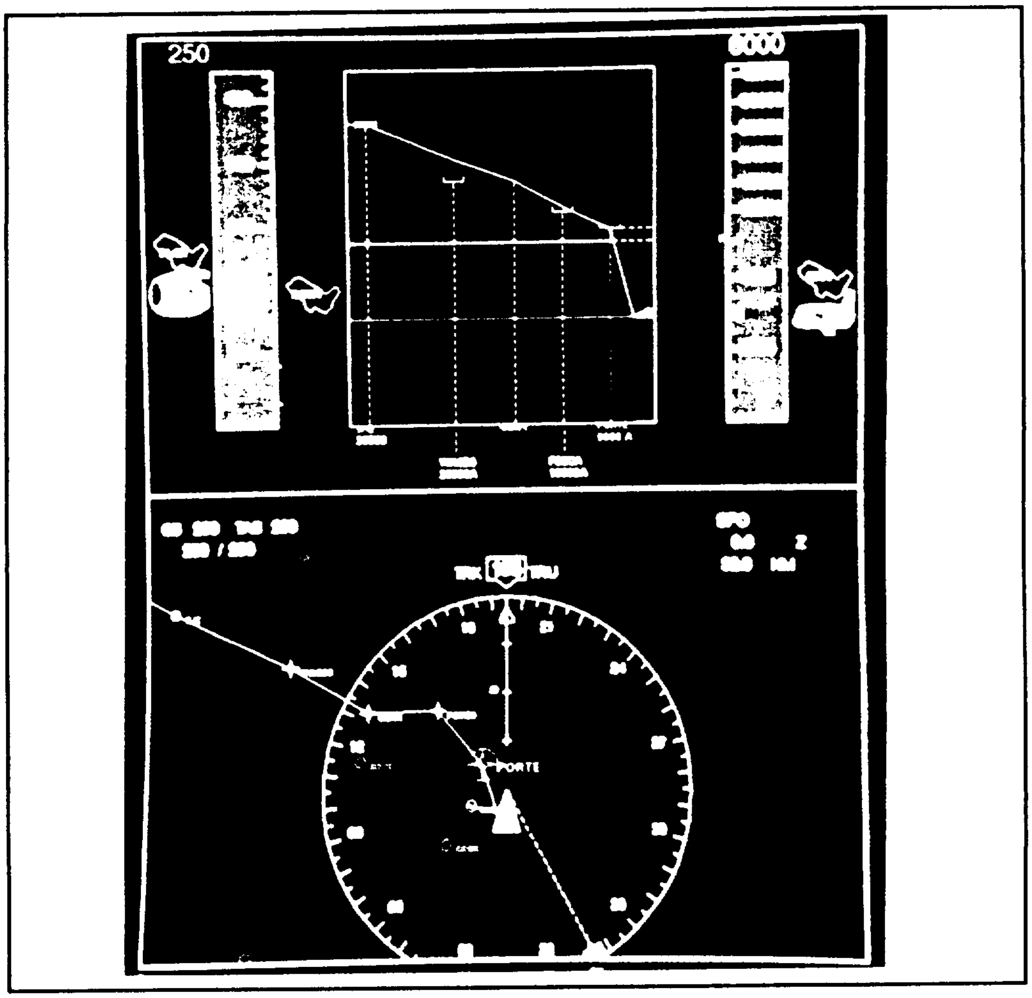
IMMI   Hutchins

THE INTEGRATED MODE MANAGEMENT INTERFACE



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The integrated mode management interface

1. Introduction

Mode management is the processes of understanding the character and consequences of autoflight modes, planning and selecting the engagement, disengagement and transitions between modes, and anticipating automatic mode transitions made by the autoflight system itself. The state of the art is represented by the latest designs produced by each of the major airframe manufacturers, the Boeing 747-400, the Boeing 777, the McDonnell Douglas MD-11, and the Airbus A320/A340 family of airplanes. In these airplanes autoflight modes are selected by manipulating switches on the control panel. The state of the autoflight system is displayed on the flight mode annunciators. The integrated mode management interface (IMMI) is a graphical interface to autoflight mode management systems for aircraft equipped with flight management computer systems (FMCS). The interface consists of a vertical mode manager and a lateral mode manager. Autoflight modes are depicted by icons on a graphical display. Mode selection is accomplished by touching (or mousing) the appropriate icon. The IMMI provides flight crews with an integrated interface to autoflight systems for aircraft equipped with flight management computer systems (FMCS).

The current version is modeled on the Boeing glass-cockpit airplanes (747-400, 757/767). It runs on the SGI Indigo workstation. A working prototype of this graphics-based crew interface to the autoflight mode management tasks of glass cockpit airplanes has been installed in the Advanced Concepts Flight Simulator of the CSSRF of NASA Ames Research Center.

This IMMI replaces the devices in FMCS equipped airplanes currently known as mode control panel (Boeing), flight guidance control panel (McDonnell Douglas), and flight control unit (Airbus). It also augments the functions of the flight mode annunciators. All glass cockpit airplanes are sufficiently similar that the IMMI could be tailored to the mode management system of any modern cockpit. The IMMI does not replace the functions of the FMCS control and display unit.

The purpose of the IMMI is to provide flight crews with a shared medium in which they can assess the state of the autoflight system, take control actions on it, reason about its behavior, and communicate with each other about its behavior. The design is intended to increase mode awareness and provide a better interface to autoflight mode management.

This report describes the IMMI, the methods that were used in designing and developing it, and the theory underlying the design and development processes.

2. Theoretical stance.

Every designed device instantiates a theory about the nature of the operator and the task(s) to be done with the device. The present generation of interfaces is based on a model of cognition in which the person takes in information, codes it symbolically, and operates on the internal symbolic representations. Such a model of cognition predicts that operators will be able to make use of external representations that are already symbolic codes. All current mode management interfaces represent autoflight modes as text strings. Many other instruments in the "glass-cockpit" do the same.

The need to provide operators with the right information at the right time, and to avoid overwhelming the operator with too much information is widely recognized. This need has led to many efforts to manage information displays in various clever ways. However, simply controlling what information is presented when is not enough. How information is represented is also important. In fact, it may be more important than efforts to reduce the "amount" of information presented.

The study of culturally-elaborated, naturally-occurring distributed cognitive systems leads us to consider how people accomplish cognitive work by establishing coordination with structure in the environment. This view puts more emphasis on the role of perception and action in cognition than on centralized symbolic processing (See Clark, in press). Recent work in embodied and situated cognition question the fundamental status of symbol processing as a model of internal cognitive processes. In the place of symbolic processing, we see processes in which internal structure is brought into coordination with environmental structure. The theory that is instantiated in the IMMI is the theory of distributed cognition. (Hutchins, 1995a).

A new understanding of the role of cognitive artifacts has emerged in the last decade. Rather than amplifiers of abilities, cognitive artifacts are seen as elements that participate in cognitive functional systems that transcend the boundaries of the individual. (Cole and Griffin, 1981; Hutchins, 1995a; Norman, 1993; Hutchins, in prep). In these functional systems, cognitive work is done via the propagation and transformation of representational state. Symbolic rules provide one way to transform representational state, but this is a relatively expensive sort of process for humans. To establish coordination between text representations of autoflight modes and conceptual representations of those modes takes considerable effort (Sherry and Polson, 1996).

The analysis of the use of speed bugs in a modern airline cockpit (Hutchins, 1995b) has lessons for the design of airspeed instruments and the IMMI as a whole. Traditional round-dial speed instruments give the pilot perceptually salient structure that corresponds to important conceptual states. This is lacking in the existing tapes (and in existing interfaces in general).

These material structures provide the operator with the perceptual raw materials for the construction of coherent conceptual understandings. Conceptually important conditions should be perceptually distinguishable from one another. This means more than simply using graphics instead of text.

Designing perceptual distinctions that mirror conceptual distinctions accomplishes several goals at once. First, it puts reasoning into the interaction with the external world where it can be accomplished by fast robust perceptual processes rather than by slow, vulnerable conceptual processes. . It makes visualizing the consequences of mode engagements easy to do. Second, it supports reasoning as an activity undertaken jointly by crew members sharing the activity

When we move the boundaries of the unit of analysis out to encompass functional systems that transcend the boundaries of the individual, we not only find processes at work that we might not have suspected, but we also find new places to locate designed activities. It suggests designing crew activities rather than designing just objects or artifacts.

A popular strategy in AI in general and in cockpit automation is to use automation to build intelligent agents or expert assistants to help human operators. This strategy recreates a number of already difficult problems with communication (and intent inferencing.) A different strategy is to use computing power to create worlds where operators get to be smart while using simple cognitive processes. An examination of existing highly culturally elaborated action environments shows how they work to make us smart. Section 3 below shows how we can use these ideas as design criteria.

In the next section, I will use this theory to interpret the significance of observed problems.

As a final note, it is important to focus on what goes right in current operations as well as on what goes wrong. The existing aviation system is very robust and error tolerant (Palmer, et.al, 1994). Many things really do go right in modern mode management. It is as important to understand these phenomena and to capitalize on the principles underlying them as it is to see why things go wrong.

3. Observed problems.

Mode management is a problem. The fact that flight crews are sometimes surprised by autoflight system behaviors is well documented in Wiener's (1989) study of the 757 flightdeck. When flight crews ask "What's it doing now?" and wonder how to make the plane do certain things, there is a problem. Problems with mode management are also easy to see in ASRS reports. Vakil, et.al. (1996) surveyed reports for the years 1990-1994 and found 184 reports in which crews reported automation surprises. Palmer, et al. (1994) in a study of altitude deviations reported to ASRS document several cases in which flight crew uncertainty about the behavior of glass cockpit automation led to altitude busts.

Symptoms of this problem show up in a variety of places in the aviation industry. For example, many Boeing customers who come to Boeing for training, ask that their crews *not* be taught the VNAV functions of the FMCS. These airlines instruct their crews to make all of their altitude changes in Flight Level Change (FLCH) mode. United Airlines does not teach VNAV operation in its training center[1]. In both cases, the reason given is that VNAV is too complex to teach. In both cases, it is expected that the competence required to use this aspect of the system will be acquired "on the line" as a consequence of learning (and teaching) in actual operations. Another major carrier (Southwest) has placed metal covers over the VNAV and LNAV mode select switches on their 737 mode control panels to prevent crews from using those modes.

Jean Pinet, president of Airbus Industrie subsidiary Aeroformation describing new A-320 training program called Aircrew Integrated Management (AIM), recently said,

"We took a prudent approach when we saw the proliferation of flight modes and configurations on the A320 and other modern aircraft....We did not want to teach all of the combinations; we kept a 'classic' approach where the training emphasis was on those configurations that seem the best adapted to each of the flight procedures." (Lenorvitz, 1992)

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1 I believe that the manufacturers have a special responsibility to provide the very best training possible. The operators look to the manufacturer as the source of training concepts as well as hardware. An America West training captain complained that Amercian West does not provide conceptual training in the use of the FMCS because none is available from Boeing.

The authors of the AIM program should probably be congratulated for their operations-centered approach to training. Still, the proliferation of modes is perceived as a problem, and the solution taken has often been to teach only a subset of the full system capabilities. Presumably this is because the entire system is thought to be too complex for the instructional designers to describe, too complex for the instructors to teach, too complex for the pilots to learn, or all of the above.

Autoflight logic is too complex to be easily understood, even, apparently, by the engineers who created it. The logic diagrams that describe the behavior of the system in all anticipated conditions typically span dozens of pages. Much of this complexity arises from rarely encountered conditions. Still, the actual behavior of the autoflight system in operational circumstances can be baffling (Wiener, 1989). In spite of this complexity, pilots should and do develop simplified models of what the autoflight system is doing.

The decisions to avoid teaching some parts of the autoflight system are symptoms of serious problems with the new generation of highly automated aircraft. Granted that vertical navigation involves the constant interaction of thrust, flight path and speed, there is no need for it to be this difficult. The engineers have created a system of great utility, but the interface to it is conceptually so difficult that operators have given up trying to train their crews to operate and trust instead to the pilots, as a community, to discover and transmit ways of using it in flight[2].

The difficulties that pilots have with mode management are understandable given the nature of the current system. This goes for all major airframe manufacturers. The differences between Boeing and Douglas mode controls is insignificant. Airbus has a different philosophy, but it may actually be more challenging to the pilot than the American systems because even more is hidden from the pilot in the Airbus airplanes.

3.1. Autoflight modes

An autoflight mode is a means of linking a performance target (speed, or path) to a control axis (pitch, roll, thrust). It has been said that the flight management computer system (FMCS) has replaced the autopilot in the current generation of flightdecks (Robert Dorsett, sci.aviation). This is a

2 Just what it is that pilots are inventing to deal with automated flight modes that are not taught in schools is a very interesting topic that deserves systematic study.

misconception. The autopilot remains as an alternative to the human pilot as a way of manipulating the control surfaces of the airplane. What has changed is the way of specifying and computing the targets that autopilot may be asked to achieve. The FMCS provides new classes of abstractly specified targets for the Autopilot flight director system (AFDS) which can then be achieved either by the pilot acting on the controls to track flight director cues or by the autopilot servos acting on the controls.

The introduction of automation is not often driven primarily by cognitive considerations, but it inevitably has powerful effects on cognition. Automation on the flightdeck is changing both the cognitive tasks that are faced by individual crew members and changing the cognitive properties of the flightdeck itself as a cognitive system.

Although cockpit automation has touched all aspects of flightdeck operations, it has probably had more impact on flight path management than on any other aspect. Through the years there has been a continual process of upgrading and adding new devices and new functions in support of aircraft flight path control. The innovations have come in waves as technologies have matured and made new sorts of operations possible. Unfortunately, the consequence of this process has been the accumulation of a set of poorly integrated devices and functions for flight path management.

3.2. Flightdeck Automation

Consider a brief history of flightdeck automation beginning with the Boeing 727.

The 727 flightdeck[3] is a "round-dial" or "steam-gauge" system. The instrumentation is based on electromechanical gauges. Flight path is controlled primarily through the flight controls: control column, rudder pedals, thrust levers, flap handle, trim switches, spoiler lever, landing gear handle, etc. There is a rudimentary autopilot which is capable of holding an already established altitude, maintaining a heading, tracking a VOR radial, and holding an attitude. There is an altitude alerting system, which provides warnings on approaching or deviating from a selected altitude, but it is not connected to the autopilot system and the airplane is not capable of capturing an altitude. Horizontal situation (heading and positional relation to a specified VOR radial or localizer course) are displayed on a Horizontal situation indicator. DME (distance measuring equipment) provides information about distance from station. Considerable cognitive processing is required to construct and maintain situation awareness in this sort of flightdeck. The representations that are provided by the instrumentation

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[3] I use the 727 as a representative of a class of airplanes. The 737 models prior to the -300, and the older DC-9 models prior to the MD-80 are comparable.

must be coordinated with other representations in the form of air navigation charts.

The DC-10[4] represents another step in flightdeck automation. It is still a "round-dial" flightdeck, but it contains several new features. The autopilot is much more capable. It can not only hold an altitude or track a VOR radial, it can capture a specified altitude and capture a radial or a localizer. The autopilot is capable of controlling pitch to produce a specified target vertical speed. There is also an autothrottle system which is capable of controlling engine thrust in two modes: a thrust reference mode in which a particular thrust parameter (e.g., N1) is tracked, and a speed mode in which thrust is varied to track an airspeed target. The control of the autopilot and the autothrottle are brought together on an autopilot panel mounted in the glareshield. The airspeed, altitude, heading and vertical speed targets to be provided to the autoflight systems are entered on this panel. Modes of operation are armed for engagement or selected by button presses and switch throws on this panel. The selected, armed or engaged modes of flight control are annunciated on a Flight Mode Annunciator panel. Some of the longer-range models of the DC-10 were also equipped (retro-fitted?) with RNAV (inertial navigation) systems that are capable of flying off-airway tracks to distant navigation fixes specified by latitude and longitude.

The MD-80 added to this a "performance box" which can be used to fly more fuel efficient climbs, cruises and descents. This Performance Management System (PMS) is a precursor of the current VNAV functions of the FMS. The computations of the performance system can be coupled to the Flight Director and to the autopilot if desired. Inputs to the performance system are made with a small limited keyboard (digits 0-9 plus characters N, E, S, W, and /) and PMS data entry and computed data are displayed in a 4 line 24 character per line display. The MD-80 also has coupled autopilot approach and autolanding capability to Category III minimums.

The Boeing 767/757[5] marked another jump in flightdeck automation. In this airplane, the performance box expanded to become the Flight Management Computer system. This coupled a comprehensive navigation data base with autotuning of navigation radios and automatic position updating. A two-dimensional color lateral navigation display replaced the HSI[6]. CRT displays driven by symbol generators provide great display

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4 Early versions of the Boeing 747 and the Mc Donnell Douglas DC-9 have comparable flightdeck designs.

5 The Boeing 737-300, and the McDonnel Douglas MD-88 have comparable flight deck designs

6 An HSI type display can still be presented by the symbol generators that drive the computer displays. There are operational reasons for prefering

plasticity. The inertial reference systems support navigation displays that show motion in either track up or heading up modes. They also permit computation and display of ground speed and true wind - items that were simply not possible to compute in earlier technologies.

The plasticity of navigation displays permits the superimposition of other kinds of information onto the depiction of the aircraft track. Nearby airports, navigation aids, and weather radar returns can all be superimposed on the depiction of lateral flight path. Information about the vertical aspect of flight path can be added in the form of data blocks attached to waypoint icons. LNAV provides facilities for flying complete complex lateral paths that consist of a succession of geographic waypoints. Off airway navigation, complete approach procedures, and autolandings are also supported. Complex vertical profiles can be specified and flown in VNAV modes. The 757/767 also introduced additional autothrottle modes. Altitude callouts were added as part of the newest GPWS systems.

All of these new facilities increased the capabilities of the aircraft autoflight systems, but also created new systems for the crew to monitor and supervise.

The present state of the art in flightdeck design is represented by the Airbus A-320, the McDonnell Douglas MD-11 and the Boeing 747-400. These airplanes have full EFIS[7]. Full EFIS means that the airspeed, altitude and vertical speed instruments are also CRT presentations. This permits soft bugs for altitude and airspeed as well as for heading, decision height and minimum descent altitudes. As an acknowledgment of the importance and difficulty of keeping track of autoflight modes, the Flight Mode Annunciators (FMA) have been improved, and consolidated.

There is no doubt that these innovations have transformed the activities of flight crews, changed the cognitive requirements of flight, and changed the properties of the flight deck as a cognitive system. It is easy to focus on the shortcomings of the automation, but any evaluation of this technology must take full account of the increased functionality and ease of operation provided by these systems. In some cases the automation makes possible things that could simply not be done without it; autoland in zero/zero conditions being perhaps the most striking example. In other cases, crew workload is dramatically reduced; flying a DME arc approach procedure is an example.

Modern flight decks present many alternatives for linking elements of descriptions of the aircraft flight path to autoflight systems. One pilot boasted to me that there are six ways to climb or descend the 737-300. The Operations

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this old-style display to the map display in some circumstances.

7 All except the standby instruments are now on glass. The Boeing 777 may have even the standby instruments on glass.

manual for the MD-88 lists four ways to climb, but on closer inspection one discovers that there are actually eleven different mode configurations involved in these climb methods.

These alternative methods provide the pilots with functional flexibility, but the space of possible linkages is large and complex. Mode changes occur at pilot command, but also automatically without pilot action under many conditions. Automatic control modes may revert to other modes as a consequence of pilot action, due to changing flight circumstances, and due to equipment or signal failure. It is not always apparent which mode combination will best accomplish the desired goals. Modes of operation carry with them other implications, so that what appears to be a good solution (and may be at the moment) could become an unsatisfactory solution as flight conditions change. For example, in the Boeing airplanes, the vertical speed mode provides no stall protection in climb. A rate of climb that is perfectly safe at low altitude may lead to a stall at high altitude.

Even if a pilot knows which mode to select, it is not always clear how to select the desired mode. Some modes will only arm under certain circumstances and may then only engage when other conditions are met. In most cases, the limiting conditions for mode arming and engagement are not represented anywhere in the flightdeck system (except in the mind of the pilots if they remember the criteria).

As serious as not being able to engage a desired mode is the inability to disengage an undesired mode. This is sometimes an even more subtle problem that mode engagement (Sarter & Woods, 1994) Some methods of engaging one mode may unintentionally lead to the disengagement of other modes (Palmer, et al, 1994).

Even though autoflight modes are annunciated, it is not clear at all times which modes are actually engaged or what the engaged modes imply about aircraft performance. These problems may be due to the following factors: 1) the annunciations are sometimes cryptic (see discussion of mode names below), 2) the annunciated modes combine with each other in complex ways; there are modes for thrust, armed captures, roll and pitch guidance, 3) Mode transitions can occur without pilot intervention and sometimes without apparent change in aircraft behavior, 4) the mode annunciations are not prominently displayed, 5) pilots often take the state of the MCP or FGCP as a mode indicator (which it is not), 6) some modes have very complex behaviors, what Vakil, et.al. (1996) call multi-input multi-output (MIMO) controllers.

The complexity of the autoflight systems requires the crew to reason in a complex space about not only the situation of the aircraft and its flight configuration, but also about the configuration of the automatic systems. This creates situations in which pilots are unsure what is being done by which "intelligent" agents. Pilots are very careful about making clear which pilot "has the airplane", and usually communicate efficiently about their

intentions. In interaction with sophisticated automation, however, it is sometimes not clear to the crew who (or what) has what part of the airplane and what the automated systems' intentions are. Glass cockpit crews occasionally ask aloud, "Why's it doing that?", "What's it doing, now?", "Is it supposed to do that?" (Wiener, 1989). When unexpected mode behavior occurs, there is little support in the modern cockpit for determining the cause or communicating about the state of the system.

Most (but, alas, not all) mode selections are made by taking action on the MCP. The language of execution is button presses and switch throws on the MCP. And on the MCP, there is feedback for the flight crew about the actions they have taken. Flow-bars in the switches on the MCP indicate that a selection has been made. For some, but not all, of the switches an illuminated light means that the mode can be disengaged by selecting the switch again. The proper evaluation of the consequences of mode selection actions taken on the MCP cannot be made on the MCP. Instead, evaluation takes place in a different language, the language of flight mode annunciation and in another place, on the FMA panel (Douglas) or on the PFD (Boeing).

3.2.1 Failure of integration: the flightdeck tower of babel

The introduction of several waves of automation over the years has made the modern flightdeck a tower of babel. Flight path information is expressed in at least ten different identifiable languages: 1. Spoken ATC, 2. Written IFR shorthand, 3. Primary flight control positions, 4. MCP selections, 5. FMA indications, 6. Primary flight display indications, 7. FMCS/CDU character strings, 8. Navigation Displays, 9. Published navigation charts and plates, and 10. The behavior of the aircraft itself. Some pilots have observed that this list is too short, since the FMS/CDU, the navigation displays, and navigation charts may each contain a number of languages themselves. In a typical approach to landing, the crew will interpret, manipulate, and translate expressions in and among all of these languages (except perhaps 2).

In some cases, the multi-voicedness of the flightdeck is useful. The costs of computing some result in a representation that is not well suited to the computation may be greater than the costs of translating the problem into another representation and solving the problem there. For example, weather avoidance planning can be done on the basis of printed descriptions of the locations of weather fronts, but it is so much easier to do the planning on a chart that it may be worth plotting the locations of the fronts on a chart before attempting to formulate a plan for avoiding the weather.

The descriptions of flight path that are supplied to the autoflight systems always ultimately decompose to heading, altitude, airspeed, and implicitly, time. The bottom region of Figure 1 shows the basic control loops of the modern aircraft. These are unlikely to change much in the foreseeable future. The upper region shows, from the bottom up, the layering of

increasingly complex specifications of flight path that have been introduced over the years. This corresponds to the discussion above of the history of flightdeck automation. The right hand column of the upper section of figure 1 lists the media in which the constraints to be satisfied are represented at each level.

Given the state of the art in technology, there is no need to have this many representations. What we see now is a consequence of a particular history of innovation. A considerable reduction in complexity is possible through an integration of these languages into a smaller number of ways to represent and evaluate flight path information. There is probably no need to eliminate specific functions nor should the ability to revert to simpler descriptions when they are needed be sacrificed in the interest of simplification. The issue concerns the representational media in which the descriptions are composed and in which the adequacy of the descriptions is evaluated.

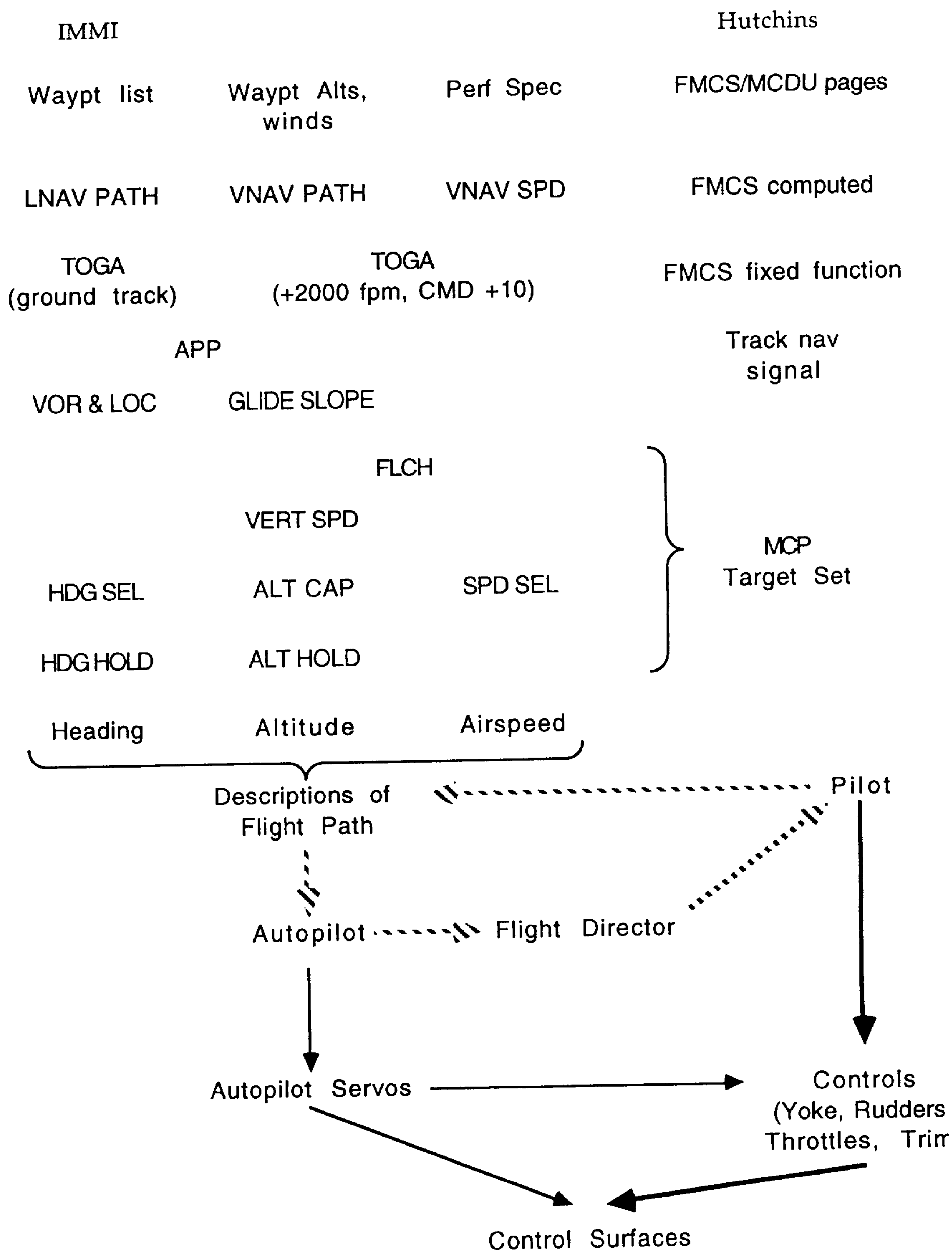
IMMI
Hutchins
Waypt list
Waypt Alts, winds
Perf Spec
FMCS/MCDU pages
LNAV PATH
VNAV PATH
VNAV SPD
FMCS computed
TOGA (ground track)
TOGA (+2000 fpm, CMD +10)
FMCS fixed function
APP
Track nav signal
VOR & LOC
GLIDE SLOPE
FLCH
VERT SPD
MCP Target Set
HDG SEL
ALT CAP
SPD SEL
HDG HOLD
ALT HOLD
Heading
Altitude
Airspeed
Descriptions of Flight Path
Pilot
Autopilot
Flight Director
Autopilot Servos
Controls (Yoke, Rudders Throttles, Trim
Control Surfaces

Figure 1. (Previous page) showing how descriptions of flight path are linked to the flight controls.

Descriptions of flight path can be linked to the flight controls either by way of the autopilot servos, or via the flight director and pilot inputs to the controls. The modes concerning lateral navigation of the airplane are called **roll modes** because they achieve their goals primarily through the control of the roll attitudes of the airplane. The modes concerning the vertical navigation of the airplane are called **pitch modes** because they achieve their goals primarily through control of the pitch attitudes of the airplane. The modes concerning the thrust of the engines are called **autothrottle modes** because they primarily act through the autothrottle system to control engine thrust.

In the 747-400, there are 7 roll modes, 9 pitch modes, and 5 autothrottle modes. Logically 315 mode combinations are possible! Fortunately only about 60 of these logical possibilities actually occur. That is still a large space of modes to think about. Is there any way to simplify the conception of the space of modes and the problems of mode management?

3.3. Operational incidents

The following selection of incidents (most observed from the jumpseat on actual revenue flights) will serve to illustrate a number of categories of operational problems with autoflight mode management. Many of these incidents represent instances of problems that have been identified in other contexts, training, simulator flights, and in other studies of aviation automation. Each incident will be analyzed as a small case study. A theoretical interpretation of the cognitive sources of the incident will be given. The theoretical interpretations of the problems lead to design goals for a system in which the observed problems can be expected to occur less frequently. Furthermore, the theoretical interpretations should support design goals that will not only fix the observed problem, but other potential problems as well. (e.g. what are called "metabutton" effects observed in some lateral navigation events argue for the elimination of metabutton effects in all contexts of the interface.)

In section 5, actual design decisions based on the design goals are described. One can then come back to the described incident and ask how the system with the new design would operate in the circumstances described in the incident.

These incidents and their theoretical interpretations were also used in the design of the flight scenarios used in the evaluation of the IMMI described in section 6 below.

It is widely acknowledged that vertical navigation presents more difficulties for flight crews than horizontal navigation. (Vakal, et.al., 1996).

Horizontal or lateral navigation is simpler than vertical navigation because it is governed by a single roll axis, roll, and because it is supported by the lateral navigation display (moving map). There are, however, still some observed mode management problems in the domain of lateral navigation. We will begin with a few of these.

3.3.1. Modify RTE, execute, and then...

Climbing out the airplane was given a vector to intercept a published SID routing. The airplane was then given a vector for traffic that was not a vector to intercept. Finally the aircraft was cleared to resume the departure. At that point, the captain set up the intercept by modifying the RTE-LEGS page of the CDU, but did not press the NAV button to arm the lateral navigation function. As a result, the aircraft flew, in heading select mode, through the departure route by about 2 miles. The captain noticed the deviation of the airplane symbol from the magenta track on the navigation display, ND, and brought the airplane around with heading select. He then selected NAV, which engaged. No mention of a deviation from course was made by ATC. The captain subsequently complained that the automatics had failed to capture the route.

This a classic case of Polson calls an "and then" problem (Polson: cognitive walkthroughs). The modification to the route is made on the MCDU, (and in Boeing airplanes, is executed there). If a mode that uses the modification is not already engaged, it is then necessary to arm that mode on the MCP. This additional action is difficult to remember because it is carried out in a different place from the route modification actions and because the execution of the modification has the feel of a completion to the route modification plan. **Design goal**: Route modification and mode selection should take place in the same location as a single course of action. The IMMI does not address the problem of route creation and modification. A second design goal is to make the distinctions among modes more perceptually salient and conceptually meaningful on the NAV display. This can easily be done.

3.3.2. Engage LNAV with active waypoint on wingtip

Just prior to top of descent, the aircraft was given a vector for traffic. When the captain attempted to re-engage NAV, the aircraft made an unexpected turn to the right. The captain engaged heading select and spun the heading bug to the left to reintercept the FMC route as displayed on the ND. After the airplane was again established on a heading to intercept the route, the captain selected

NAV and the plane made another unexpected turn. He went back to heading select. Finally, he was able to get NAV to engage and continue on course as he wanted it to.

The cause of this unexpected behavior by the autoflight system is that while being vectored the airplane had almost, but not quite, passed the active waypoint. With the active waypoint having a relative bearing of less than 90 degrees, it will not transition. The airplane was trying to fly to a waypoint that was nearly abeam of the plane, thus entering an unexpected steep turn.

This problem has been observed in actual and simulated flights in many glass cockpit airplanes. It is possible that some crew members consult neither the ND nor the ACT F-PLN or RTE-LEGS pages of the FMS before re-selecting NAV. For those who do consult the ND, the active waypoint is not saliently marked on the ND. Down-course waypoints are white, the active waypoint is magenta. That makes sense because the active route is displayed in magenta, and for the sake of consistency, all items depicted in magenta are elements of the active route. Unfortunately, there is a conflict here between consistency and discriminability. That is, the inactive waypoints are perceptually easier to find on the display than the active waypoints. This is because the white symbology contrasts with the magenta route line while the magenta symbology blends into it. The white symbology also has a better contrast with the display background. **Design goal**: Make the active waypoint perceptually more salient on the lateral navigation display.

The deeper problem here is that the NAV button on the GCP (or LNAV button on the MCP) is what Ev Palmer (Palmer, personal communication) has called a "meta-button." The structure of the button itself contains no information about the content of the mode that it selects. The meaning of the button is "fly the lateral route described in that active legs page beginning with the active waypoint." The route description is available on the RTE-LEGS page of the CDU (which might not be visible when mode selections is made, and on which the information is in text form), and in graphical form on the NAV display (but as noted above, the active waypoint is not salient), but this information is not represented in any way on the glareshield where the mode selection is made. The act of selecting the mode can proceed to conclusion without the pilot processing any representation of the content that will be evoked by the engaged mode. This is what makes unintended outcomes possible. **Design goal**: Require the operator to process the content of the mode in the act of selecting any mode. A simple way to do this is to have NAV mode selected by touching the active waypoint icon on the NAV display. This requires a bit more work than pressing the NAV button on the GCP because the pilot must first find the active waypoint in order to touch it. This search and touch activity make the spatial relation of the active waypoint to the airplane apparent to the pilot. This extra work is part of the work the pilot should always do before engaging the mode in any case. The wider design implication is that for all modes, the action taken to

select or engage the mode should somehow bring the operator into contact with easy to process representations of the specific consequences of engaging that mode.

3.3.3. Heading bug behind the airplane

This one was observed in a simulator flight rather than in revenue service.

The departure SID contains a turn of nearly 180° early in the procedure. The heading bug is lined up with the runway for takeoff. LNAV is engaged after liftoff and the procedure is flown as depicted. After turning more than 90°, ATC calls traffic and asks for a turn. The crew engages heading select, but now finds that the heading bug is behind the airplane and not visible on the nav display. The airplane continues its uncontrolled turn until the crew can spin the bug around in front of the airplane.

The root of the problem here is that the button press that engages Heading Select mode is a meta-button. Its meaning is roll to capture the heading indicated by the current position of the heading bug (wherever that may be). The current position of the heading bug is indicated as a number of degrees in the window above the heading select knob. This representation does provide some information, but it is not in a form that is easy to process. Suppose ATC said turn left 15° for traffic. One would have to read one's current heading, and then subtract 15° to get the desired heading. Now, suppose the desired heading is 320 and the heading window reads 130. which way should one spin the bug to get it to the desired heading? The act that engages the mode does not require the crew to process any aspect of the heading that will be selected. The crew may use the heading window to determine the current location of the heading bug, but this representation is not easy to process. Furthermore, the heading bug itself is only visible when it is ahead of the airplane symbol on the navigation display. When the heading bug is on a heading that is behind the airplane, the bug itself is hidden. Many instructors and line pilots emphasize the importance of establishing a habit of keeping the heading bug in front of the airplane in order to eliminate this problem.

Design goal: Like the problem with wingtip LNAV, the solution to the meta-button problem here is to require the crew to process the content of the mode that will be selected in the act of selecting the mode. In this case, that can be accomplished by having heading select mode be selected by touching the heading bug on the NAV display. This implies another design goal, having the heading bug always be visible on the NAV display. A further goal is to have the display itself change in some way to indicate that the heading bug is going behind the airplane.

We now turn to the more complex, and less well supported, task of vertical mode management.

3.3.4. Unexpected leveloff at crossing restriction

The Peble One departure out of San Diego includes an at-or-below altitude restriction early in the SID. This restriction protects airspace used by fighters operating out of Mirimar Naval Air Station. I have observed this departure from the jumpseat many times. Out of 5 departures I observed in 757s, three crews were surprised by an unexpected leveloff at this altitude restriction. Other researchers (Palmer, Degani) flying this leg in 757 have also observed this problem. The following two incidents are typical.

Peble incident 1: The Peble one departure was selected to go with the company route. The departure clearance was to 14 thousand. The crew briefed the departure and put 8000 in the altitude window "just to be safe." After TOGA, the climb was commenced in FLCH and LNAV. Out of 4,000, the aircraft was cleared unrestricted to 14,000. The crew put 14,000 in the window, and engaged VNAV. Approaching 8,000', the aircraft began to leveloff. The Captain said, "Oh, I know what it's doing" and selected FLCH. He then deleted the restriction from the RTE-LEGS page and reengaged VNAV.

Peble incident 2: The crew carefully briefed the departure, and talked about the restriction. They put the company route with the Peble 1 departure in the CDU. After takeoff the aircraft was cleared unrestricted to 9000'. The airplane leveled at 8000'. It took quite a while for the crew to figure out why it leveled off. The FO finally pushed FLCH to resume the climb. By the time they began to remove the restriction, the waypoint had transitioned.

In these two cases, the MCP window altitude seems to be the most salient representation of anticipated flight path. The restriction to pass a waypoint at or below 8000' is visible as text on the RTE LEGS page of the CDU, but is not obvious even if that page is displayed. In each case, the clearance to climb unrestricted should lead the crew to delete the restriction from the FMS.

In a third case involving this departure (reported by Palmer, personal communication b), the crew were required to meet the altitude restriction. They did so successfully, but while trying to confirm that they had done so, they failed to continue the climb after the waypoint as expected.

The problem here is that the relevant system state - the representations of the altitude restriction - are weak and possibly hidden. Sherry and Polson (1995) discuss this sort of unexpected level-off as an example of the weakness

of current mode annunciation systems. **Design goal**: provide a graphical representation of the future vertical trajectory of the airplane. Just as the lateral navigation display makes the lateral path visible, a vertical navigation display could represent the vertical path. It should be noted that there are many problems with constructing vertical situation displays.

3.3.5. Unexpected level-off at cruise altitude

The aircraft was climbing out to the west with VNAV, LNAV and right autopilot engaged. Out of FL240 the aircraft was cleared to FL350. The captain put 35000 in the MCP altitude window. The FMS had been programmed for an initial cruise at FL310. (It is not known why the clearance did not match the programmed cruise altitude). The airplane was handed off to a new sector at about FL300. As the Captain began to check in, the airplane began to capture FL310 so he said, "Callsign 281, leveling at FL310." The controller replied: "I thought you were cleared to FL350, Sir." The captain glanced at the altitude window (he must have immediately figured out what happened), and said: "Yes, I guess we were, but we'd like to stay here if the ride has been okay here."

In this case, it is not clear that the captain had well formed expectation concerning the behavior of the airplane, but he and the FO were surprised that the airplane had leveled off before reaching the altitude in the MCP window. The problem here is that there are multiple descriptions of flight path, these descriptions are not always consistent with one another, and which of the descriptions is actually controlling depends on situational factors. The mismatch between the representation of flight path programmed into the FMC and the representation on the MCP leaves the behavior of the airplane ambiguous. The MCP representation occupies a more central location in the cockpit, but in this case, the less accessible FMC representation is the controlling representation. Again, the difference between what is programmed into the FMS (not immediately accessible - but operative) and what is displayed on the MCP (immediately accessible -but not necessarily operative) led to an altitude awareness problem. These discoordinations are symptoms of the complexity of operation via the two different interfaces located in different parts of the cockpit.

Design goal: To have a single representation in which all descriptions of flight path are displayed in such a way that it is easy to determine which will be controlling in any situation.

3.3.6. *Failure to note FMA change*

Navigation error on the Border 3 departure. Just before reaching the turn at PGY 19 DME cleared direct PGY. FO programs FMS, Capt goes to heading select. I think he went for a 080° heading (the final inbound course to PGY if the whole SID was flown.) With the FMS programmed, should have gone back to LNAV. I think the FO did not know that the capt had selected heading select. So FO believed LNAV still selected. 080° heading brought us over North Island. Capt noticed then and reselected LNAV.

This should have been easy to see on the annunciators on the PFD, but I have heard many complaints by crew that they do not use the annunciations as much as they should. Autoflight instruction packages always stress: "When you make a change up here (MCP), you've gotta look down here (PFD annunciations) to make sure you really have what you think you have." The problem here is that the annunciations are cryptic and not salient. Also, lateral mode status is not indicated on the map display itself. **Design goal:** indicate lateral mode status on the map display, and do it is a way that makes the mode annunciation perceptually salient.

3.3.7. *Unanticipated automatic mode transitions*

VNAV PTH reverts to VNAV SPD mode without warning in overspeed descent. Sherry and Polson (1995) also discuss this automation behavior as a context for crew confusion. Vakil, et.al. (1995) describe three kinds of mode transitions: commanded mode transitions, immediate consequences of crew mode selections; uncommanded transitions, usually invoked by the automation as envelope protection; and automatic/conditional transitions, such as when an armed mode engages. **Design goal:** Indicate impending uncommanded, and automatic/conditional mode transitions.

3.3.8. *Knowing which modes can be engaged when.*

On the climb we were given a speed restriction to maintain 250 until further advised. It wasn't until we were out of FL250 that we got econ speed. I was looking at the captain's climb page and could see that econ speed was 309 KIAS or Mach .797. I wasn't exactly sure how to get back to econ speed since we had the speed intervention showing in the window 250. When the captain asked the FO to restore the econ speed, the FO reached up and pressed the VNAV button. VNAV was already engaged though, so this had no effect. (Note: part of the logic of the system is that modes are

normally only dis-engaged by the selection of another mode.) The captain pointed to the speed select knob, making a pressing motion. the FO pressed the knob. The window blanked and the command speed bug jumped up to the econ speed.

Technically, this is not a mode change. It is instead a change in the target for the engaged mode. Still, it presents a problem for the crew. There is nothing to tell the pilot that econ speed target will be restored when one pushes that knob, or even that the knob is pushable. This is a case of more hidden system state. **Design goal**: represent engaged, armed, and selectable modes and their performance targets (speed, path) explicitly.

This raises the more general issue of knowing which modes can be selected for engagement at any point in time.

3.3.9. Why SPD is not selectable when in FLCH, VNAV or TOGA.

At the end of a VNAV-PTH descent, the FO wanted to reduce speed. He reached up and pressed the SPD button on the MCP. Nothing happened. He pressed it again, and still nothing happened. He pressed it five times in all before giving up and selecting vertical speed (which automatically activated SPD mode).

In this example, it is clear that the FO did not know that the SPD mode is not available for selection when in FLCH, TOGA, or any VNAV mode. A pilot could memorize this fact, but there are many other facts just like it. Fortunately, there is a simple conceptual regularity in the system that implies this constraint. This regularity will be presented below in the discussion of the conceptual organization of autoflight functions. A better solution would be to base one's knowledge of this constraint on the underlying regularity. Unfortunately, the existing interface masks the underlying conceptual regularities that govern the behavior of the autoflight system. **Design goal**: Present for selection, only those modes that can be engaged or armed from the current operating mode. **Design goal**: Associate salient perceptual regularities in the display with the underlying conceptual regularities that govern the behavior of the autoflight system.

3.3.10. Mode selection in wrong operational context: Killing the capture

Palmer (1994) reports a case from a simulated flight in which a pilot intending to soften a level-off maneuver caused a failure to capture the target altitude. In some automated airplanes, pilots find the level-off maneuver to be somewhat abrupt. One way to provide more passenger comfort is to select

V-SPD mode prior to the capture and to reduce the vertical rate at which the target altitude is approached. This normally works fine. If however, the selection of V-SPD is made after the altitude capture has begun, the selection of the new mode will "Kill the capture." In the case observed by Palmer, the new mode selection came less than a second late. Since modes are not annunciated in the same place where mode selections are made, there is a possibility that the operating context could change between the time the pilot decides on an action and when the pilot takes the action. **Design goal**: Put the means of evaluating the current state of the system, making changes to the system, and assessing the consequences of changes all in the same location.

As long as the parameters of flight path are specified through the CDU, the autoflight modes that link those parameters to the controls are selected via actions on the MCP, the consequences of mode selection actions are evaluated on the FMAs and the compliance of the airplane with the specified parameters is monitored on the PFD and ND, there will be problems like those observed in these flights. These flightdecks scatter flight path displays and controls all over the instrument panel.

3.4 Mode Naming

A lexicon for verbally representing the states and guiding one's own and the attention of the other pilot is needed. How are pilots going to talk about what they see and what they are doing on this interface? This raises the issues of mode naming. Currently, the mode naming and the representations of the modes are a single system. The mode names appear as text in the mode annunciation. Pilots refer to the modes by their text names or phonetic variants of them. Because of display space constraints, most text representations of mode names are contractions of longer words. Sometimes pilots use the longer words - expanding the contraction. e.g. LvlChg= Level change. Sometimes they coin a new phonetic token based on the contraction. e.g., FLCH = flitch. Even within the current system of mode naming it is possible to make improvements along the lines of the theory presented here. That is, conceptually similar modes could have conceptually similar names. Some of this is present in a partial compositional structure of names. For example, the vertical navigation modes in which performance targets are set by the FMCS all begin with the character string "VNAV". One can see why engineers would name modes this way. Grouping modes that are controlled by the FMCS reflects both the history of the introduction of modes and the nature of the data flow within the autoflight system. However, there are other ways to group modes. For pilots, the source of the target may not the most important feature of modes. From an operational perspective, VNAV-SPD may be more similar to FLCH (both are pitch to target speed modes) than it is to VNAV-PTH.

The general problem here is that the mode space is multi-dimensional, and text string annunciations tightly constrain the number of independent

features that can be meaningfully distinguished in the representation of modes. The hyphenated mode names convey only two dimensions. The graphical depictions of the IMMI permit simultaneous representation of a wider range of features - up to four dimensions simultaneously. However, regardless of the capabilities of graphic displays, the mode naming issue remains a factor in crew communications and reasoning about modes. Airbus naming conventions may have some advantages because they are more explicitly compositional. For example, the difference between what Boeing calls VNAV-SPD climb and FLCH climb is noted in the Airbus system as the difference between managed speed climb and selected speed climb.

3.5 Folk models:

The failure of the current interfaces to provide the crew with the raw materials necessary to construct coherent models of the conceptual organization of autoflight, and the failure of most manufacturer and airline training programs to teach the conceptual structure of autoflight leaves to pilots themselves the job of trying to come up with conceptual models to understand the behavior of the systems they use. Unfortunately, the regularities that are most important are often masked in the current designs.

Sometimes, these folk models are quite good. In some cases they are charmingly naive, and on other cases they are probably quite dangerous. Here is an example of a naive model. Most airlines specify a procedure for autopilot use in which the autopilot that is used to control the airplane should not also be used to drive the flight director of the pilot flying. In airplanes with three autopilots, the center autopilot is usually engaged. In two autopilot airplanes, the autopilot on the side opposite the pilot flying is used. One captain told me that you can't use same autopilot to drive the servos and to generate the f/d command bars. His folk theory to account for this fact was a resource limitation argument. He claimed that "the box can't drive both at once. That's why with 3 autopilots, we normally use center in command." A better reason is that if an autopilot fails active, you don't want it sending bad information to both the f/d command bars and to the servos. If these are on separate boxes, then if the one driving the command bars fails, the airplane will continue flying fine. If the one driving the servos fails, the pilot will be able to use the command bars to recover.

The MCP is not completely lacking in conceptual organization. While explaining to me how the MCP is laid out, one captain seemed to achieve the insight that N1 and SPD are thrust modes and that FLCH and VNAV are pitch modes. N1 and SPD are on the left of the speed select knob while FLCH and VNAV are to the right. Unfortunately, the conceptual organization of the MCP is at best local and inconsistent. Another pilot (B-737-300) told me that "this stuff up here (top row of buttons on MCP has to do with this (the MCP). This stuff down here (bottom row of buttons) has to do with this (FMS). "

This desire on the part of pilots to read conceptual meaning into the spatial layout and the behavior of the MCP and other mode management displays and controls suggests a final **design goal**: to build an interface in which the physical layout and behavior of the displays and controls maps easily onto the underlying conceptual regularities of the autoflight system.

4. A conceptual analysis of autoflight modes

If the analysis presented above is correct, then making the concepts that underlie autoflight operations more explicit in the behavior of the interface may improve operability and the rate and quality of learning. What are the underlying conceptual regularities and conceptual distinctions? Some of these come from the realm of flight in general (e.g. the distinction between pitching to a speed and pitching to a path) and some are specific to automated airplanes (e.g. is the performance target set by the crew or computed by the flight management computer system.)

4.1. Methods for discovering the conceptual basis.

Over the years cognitive anthropology has developed several methods for discovering conceptual structures. First and foremost among these methods is participant observation in which the researcher participates in the normal activities of the people and thereby learns to speak and act like the people do (Agar, 1980, 1986). Engaging in appropriate talk and action requires at least partial mastery of the conceptual structures that the natives use to organize their own behavior. Over the past 7 years, I have become a pilot. I now hold a commercial pilot's license with multi-engine and instrument ratings. This, of course, does not mean that I can claim to know the conceptual structures on the basis of introspection, but it has permitted me to engage real line pilots in meaningful discussions concerning the problems they face. I have conducted dozens of interviews with pilots, both in the cockpit and out. Analysis of discourse and interviews is a second major technique of cognitive anthropology (Hutchins, 1980, Holland and Quinn, 1984; D'Andrade, 1995).

To construct a knowledge of autoflight systems in state of the art aircraft, I have completed the ground schools for the Boeing 747-400 and the Airbus A-320. These ground schools do not qualify me to fly these airplanes, but they do permit me to observe pilots in flight in a different way. Before I took the training, I could see what pilots were doing. After the training, I could see not only what they were doing, but what they could have done but chose not to do. These courses enhanced my abilities as an observer. I have logged over 300 hours of jumpseat observations of line operations in domestic and international flights. These observations are the basis of the observed problems section of this paper. Participation in the training also gave me access to training materials, operational manuals, pilots, instructors, and, at Boeing, access to engineers who designed the systems.

A third method for discovering conceptual structure is called componential analysis (Goodenough, 1957; Romney & D'Andrade, 1961; Werner & Schoepfle, 1987). The goal of componential analysis is to isolate a set of underlying distinctions that can account for the system of meanings in a noun domain. In this case, the names of the autoflight modes constitute a

noun domain. A componential analysis of the mode names reveals the underlying conceptual distinctions that account for the differences in meaning among the mode names. A comparative componential analysis contrasting the underlying distinctions for the Boeing and Airbus mode naming conventions has been completed[8]. The major results of this analysis will be given below.

4.2. Autoflight modes

The following sections present the autoflight modes for the Boeing 747-400. This aircraft was the original target for the IMMI development.

4.2.1. Roll Modes

The roll modes for the 747-400 are given the following names: HDG SEL (heading select), HDG HOLD (heading hold), LNAV (lateral navigation), TOGA (takeoff and go-around), LOC (localizer) , ROLLOUT, and ATT (attitude). The conception of roll modes can be simplified considerably by noting that each mode is no more than a method for computing the directional target for the airplane. While there are seven roll modes, the modes fall into two major classes: modes in which the target is the **heading** of the airplane, and modes in which the target is the **ground track** of the airplane. The heading based roll modes are HDG SEL and HDG HOLD. HDG SEL turns to the airplane to a selected heading and keeps it on that heading. HDG HOLD rolls the airplane's wings level and holds the heading that was achieved when the wings came level.

Further distinctions among modes are made on the basis of the sources of track information. In LNAV mode, a ground track is computed by the flight management computer system, based on inputs to the MCDU. This ground track may be used to do the equivalent of VOR radial tracking, although it is the ground track defined by the radial, rather than the VOR signal that is being tracked. LOC and ROLLOUT modes track the localizer signal of an instrument landing system approach facility. TOGA uses the on-board inertial navigation system to determine the ground track of the airplane at the onset of TOGA guided flight and uses that ground track as the target.

Ground track can thus be defined by geographic coordinates (LNAV), by signals from ground based navigation aids (LOC and ROLLOUT), or by a momentary sensation of the inertial reference system (TOGA).

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8 The details of this method and its results will be reported in detail

elsewhere.

The one remaining roll mode, ATT (attitude) is an infrequently used reversion mode. It engages only when a flight director is turned on in flight after a period in which neither flight director and none of the autopilots have been engaged and the bank angle exceeds 5°. Its main function is to provide a flight director guidance mode that keeps doing what ever the airplane was doing before the flight director was turned on.

4.2.2. Pitch Modes

The pitch modes are: TO/GA (takeoff and go-around), ALT (altitude), V/S (vertical speed), VNAV PTH (path), VNAV SPD (speed), VNAV ALT (altitude), G/S (glide slope), FLARE, and FLCH SPD (flight level change, speed).

4.2.3. Autothrottle Modes

The autothrottle modes are: THR-REF, THR, HOLD, IDLE, and SPD.

These come in two flavors: speed modes and thrust modes.

4.3. Mode Interactions

Fortunately, the Roll modes are essentially independent of the Pitch and Autothrottle modes. The exceptions are that the toga and rollout roll modes only occur with certain pitch and autothrottle modes. Unfortunately, this independence is conceptually masked by the fact that the flight mode annunciator formats of both Boeing and Douglas aircraft display roll mode between the pitch and autothrottle mode displays. This is probably an attempt to maintain consistency with the layout of the primary flight displays in which the ADI and the HI (primary roll instruments) lie between the ASI (thrust instrument in level flight) and the Altimeter (a pitch instrument in level flight).

Treating roll modes independently and knowing that there are few interactions between roll modes and other modes simplifies the mode management problem considerably.

There are, however, significant interactions between pitch and autothrottle modes, and it is here that most of the conceptual problems seem to arise. Segregating the modes into classes and showing a simple set of relations among the classes may help to simplify the conceptual space.

The rule is that whenever the pitch mode is controlling to a speed target, the autothrottle mode will be controlling to a thrust target. Whenever the pitch mode is controlling to a path target, the autothrottle mode will be

controlling to a speed target[9]. Figure 3 shows the interactions between the pitch modes and autothrottle modes.

4.3.1. What every pilot knows

PITCH	AUTOTHROTTLE: THRUST	AUTOTHROTTLE: SPEED
PATH	NO	YES
SPEED	YES	NO

Figure 3. The general rule of interaction between pitch and autothrottle modes.

This should make sense to all instrument rated pilots, since it reflects the changes in the primacy of instruments in standard maneuvers. That is, in a normal climb, thrust is set, and speed is controlled by pitch. If the airspeed is too high, raise the nose; if the airspeed is low, lower the nose. When approaching cruise altitude, the nose is pushed down and the airplane accelerates to cruise speed. Pitch is now controlling flight path and thrust is controlling speed, which will increase if thrust is not reduced. A similar transition occurs at top of descent where thrust is typically brought to flight idle (or other descent value), and speed is controlled by pitch.

4.3.2. 747-400 vertical mode interactions

Note that speed should always by controlled by a pitch mode or an autothrottle mode.[10] This regularity considerably reduces the complexity of

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9 One exception exists. On an autoland, the pitch mode FLARE engages at about 50' AGL and the autothrottle mode IDLE engages at about 25' AGL. For that last 25' of descent, speed bleeds off and neither pitch nor thrust controls to a speed target.

the space of mode combinations. Figure 4 shows the space of possible combinations of pitch and autothrottle modes. In this table, the distinctions among modes are made on the basis of the mode type (pitch or autothrottle), the controlled parameter (speed or path for pitch modes, speed or thrust for autothrottle modes), and the source of the target (Mode Control Panel, Flight Management Computer, or Ground Signal).

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10 There is a hidden danger here. It is possible to fly a visual approach in the 747-400 with the autopilot, flight directors, and autothrottles off. If a go around is required, pushing the go-around buttons will provide go around thrust. The upward pitching moment caused by the below -wing mounting of the engines can feel like the TOGA pitch mode acting through the autopilot, even though the autopilot and pitch modes have not engaged. In this case, the autothrottle mode controls thrust, but only pilot action with the control column can control speed. It is possible for a distracted pilot in such a situation to inadvertently approach a stall condition.

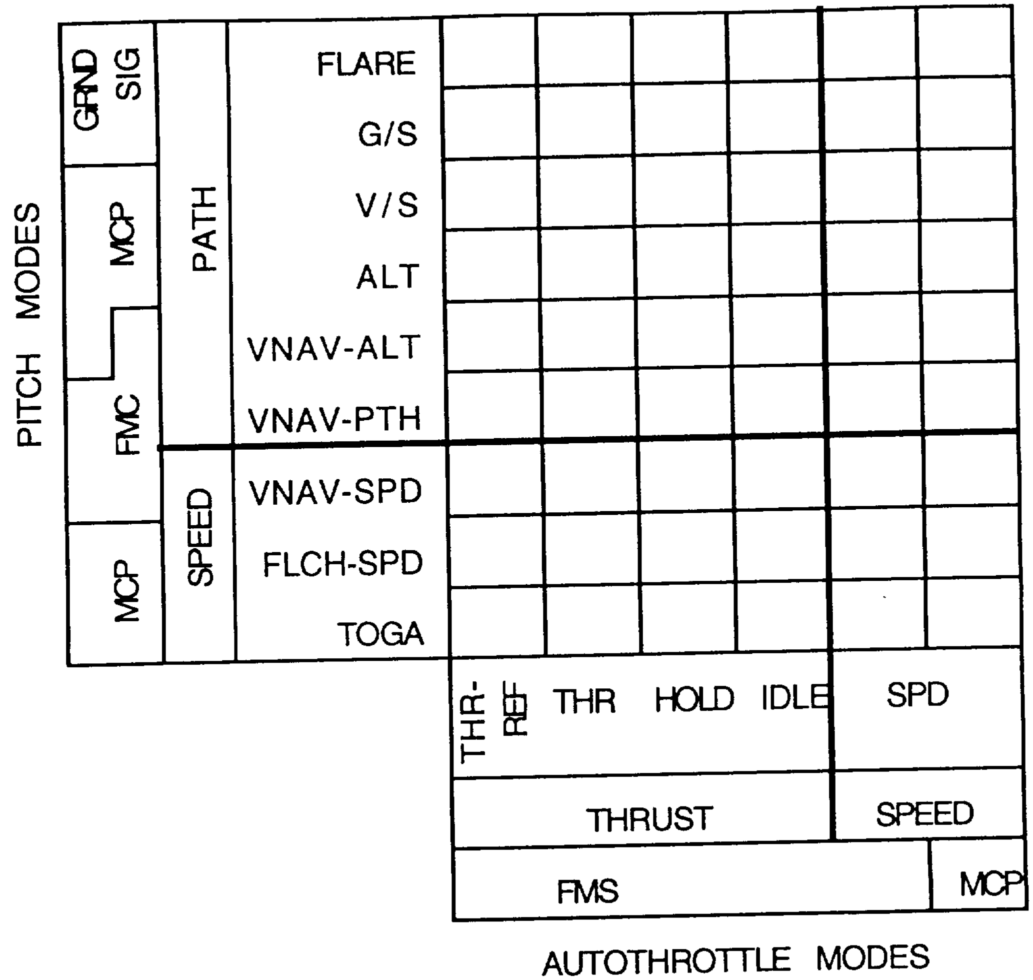
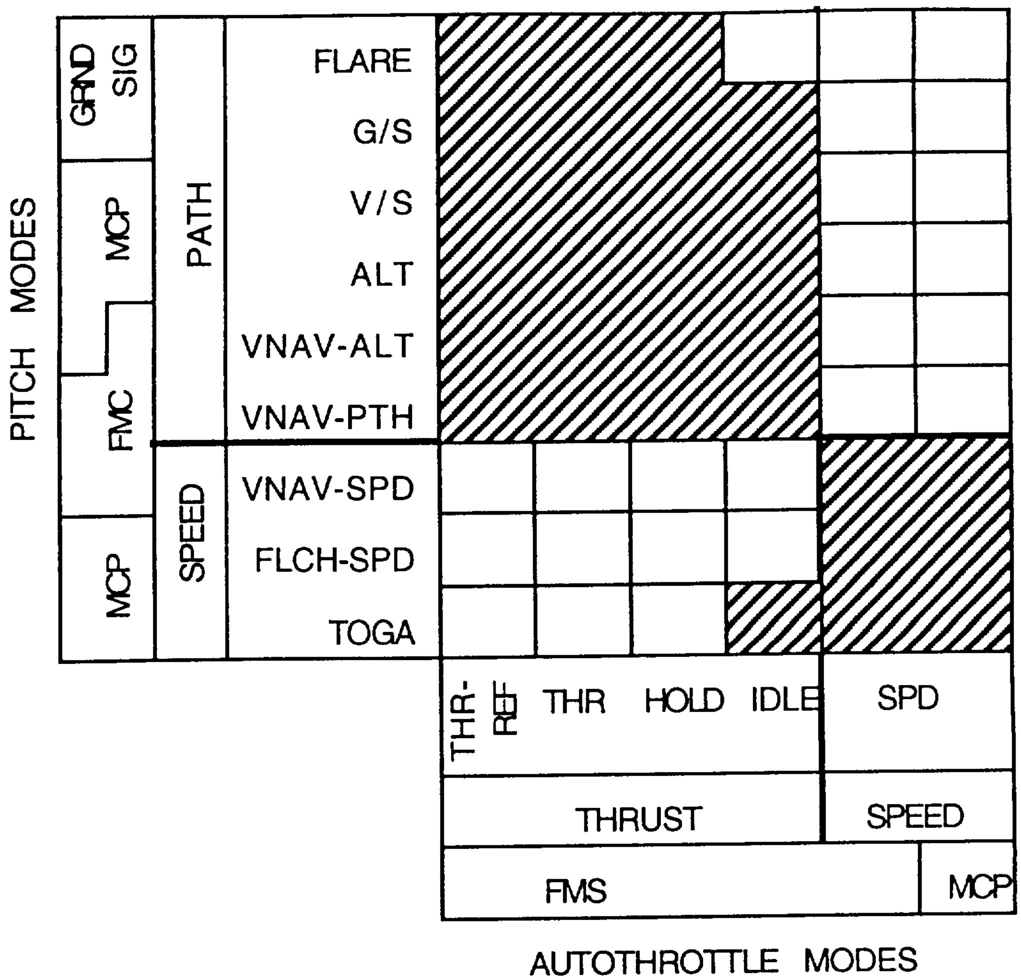


Figure 4. The logically possible mode combinations.

Figure 5 shows the space of actually occurring mode combinations. the cross-hatched area indicates combinations that do not occur.



In training a lot of emphasis is placed on monitoring and calling out mode transitions whether they are crew selected or automatic. The purpose of making mode transition callouts must be to bring the conceptual implications of the current mode to the attention of the pilots. These conceptual implications concern what is being controlled and how. This is precisely what the figures above attempt to capture. Unfortunately, these relationships do not appear explicitly anywhere in the training materials. One reason that crews in training have so much trouble learning to attend to and call out mode transitions is that such callouts are only perceived as useful to the extent they bring to mind operational implications. When crew members are unclear on the meanings of the modes, they have little motivation to note mode transitions.

What can be done about the seemingly arbitrary rules governing the availability of modes?

In the automatic flight section of the 747-400 airplane operations manual the description of the speed switch on the mode control panel states that the speed switch is "inactive if in FLCH, VNAV, or TOGA" (07.10.2A). A pilot in training may choose to memorize this bit of information. If he

does not, he is at risk (as reported in section 3.3.9 above) of pushing this button while on one of these modes and finding that it does not respond. "What's going on?", he might ask. "Why can't I get speed mode?"

The answer is difficult to see in the current system for two reasons, one having to do with the design of the mode control panel, the other having to do with the training. The answer to the question is that the speed switch engages an autothrottle speed mode. FLCH, TO/GA, and VNAV-SPD (pitch modes) are speed controlling modes. Speed is already being controlled by pitch in these modes, so it cannot also be controlled by the autothrottle. All the VNAV modes include an automatic speed control function, so SPD mode is not appropriate. But this is hard to see because 1) the layout of the MCP provides only implicit hints that the speed switch controls an autothrottle mode rather than a pitch mode (after all, either sort of mode could control speed) and 2) the training does not make it clear that autothrottle and pitch modes have a mutually exclusive relationships with respect to the control of speed. If these relationships had been made clear, it would be easy for a pilot reading the manual to know immediately why this switch will be inactive when the pitch mode is FLCH, VNAV, or TO/GA. The need to memorize the fact that SPD is inactive in these modes is eliminated. The behavior of the airplane autoflight system becomes meaningful rather than mysterious.

In the description of the IAS/MACH selector, the pilot is told that when the IAS/MACH selector is pushed, the "IAS/MACH window does not blank if SPD, FLCH, or TO/GA mode is active" (07.10.02B). Again, to avoid surprises in flight, the pilot could either memorize these facts, or understand the reasons behind them. But the underlying conceptions are masked by the organization of the presentation of information. In this case, no effort has been made to distinguish the autothrottle mode, SPD, from the pitch modes, FLCH and TO/GA. If this had been done, it would be easy to see from the diagrams above that these three modes share in common the properties that they are modes that control the speed parameter on the basis of a speed target that is set on the MCP. The existing instruction and design of the flight deck give absolutely no explicit representations of the dimensions on which these three modes are members of a single conceptual category. If these dimensions were to be represented to the pilots, it would be obvious why the IAS/MACH window does not blank when the selector knob is pushed while these modes are engaged. These are just the modes in which a speed target is already being set on the MCP. A simple conceptual regularity replaces the need to memorize what otherwise seem to be unrelated facts.

Similar problems exist in the relationship between the autothrottle mode engaged with the speed switch and the speed modes engaged by "speed intervention" when the IAS/MACH selector is pushed. The former is exclusively an autothrottle mode. The latter is a "hidden" pitch mode. I say hidden because when speed intervention is selected on a descent, all the outward indications are that pitch is controlling path. However, "During descent, when speed intervention is used, the guidance mode essentially

changes to speed on elevator...." FCTM, p. 3-7. Path is no longer controlled by the pitch of the airplane. Deviations from path must be controlled with speed brakes or throttle.

4.4. The conceptual distinctions for vertical navigation.

The componential analysis reveals that the following dimensions and dimension values are required to make all the distinctions made in vertical modes for either of the mode naming schemes:

Pitch target type:	speed, path, vertical speed, attitude
Thrust target type:	idle, limit, speed
Target source:	MCP/FCU window, FMC, Nav aid, Autopilot
Respect FMC constraints:	Yes, No
Profile shape:	Airbus: Level, Up, Down.
	Boeing: Constant altitude, Changing Altitude

Table 4.1. Conceptual distinctions needed to distinguish all modes in Boeing and Airbus mode naming schemes.

Additional distinctions are needed to actually operate the system. These include:

Autopilot engagement status:	engaged, not engaged
Mode status	engaged, armed, selectable
Target priority	When there are two targets of the same type, which one will affect the flight path? e.g. when window alt and FMC alt targets disagree

Table 4.2. Additional conceptual distinctions.

5. The current design

An overview of the IMMI is shown in figure 6. The display consists of two main areas: a vertical mode manager at the top, and a lateral mode manager at the bottom.

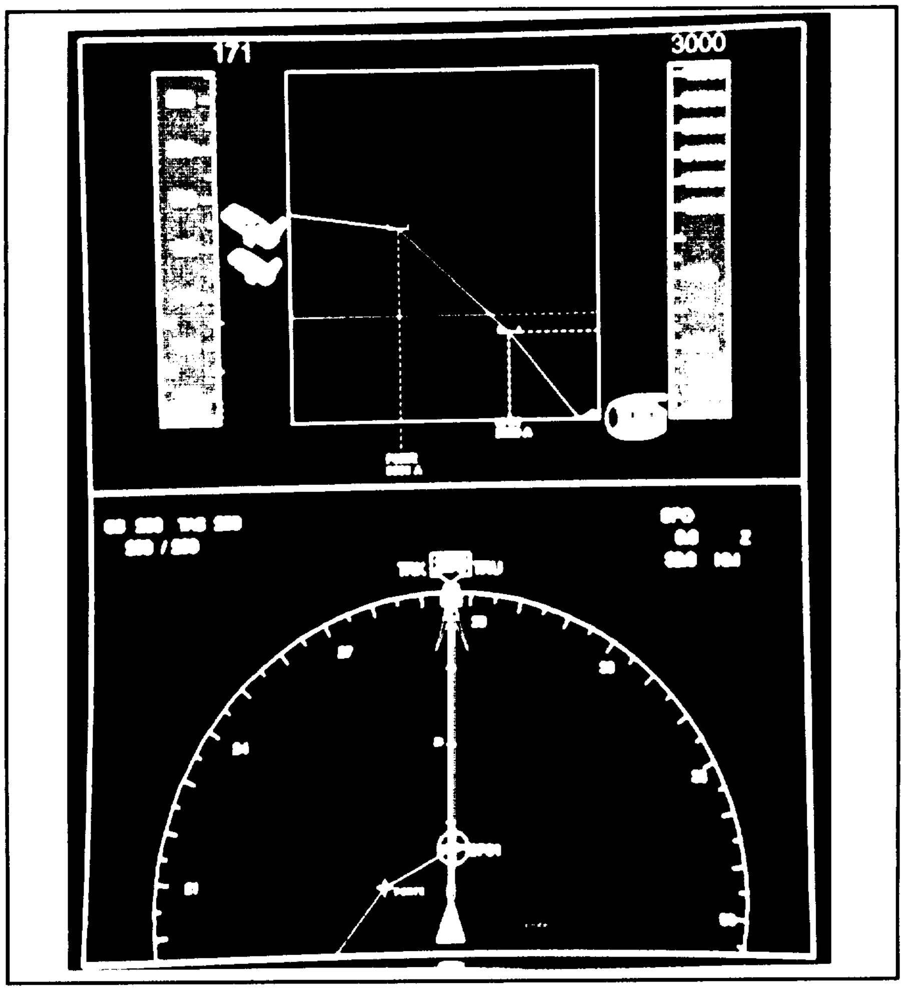


Figure 6. Overview of the IMMI display. Ready for takeoff. TOGA pitch and roll engaged, LNAV and VNAV armed.

The lateral mode manager looks and behaves much like the current generation of lateral navigation displays. However, in accordance with the design goal to put the means of evaluating the current state of the system, making changes to the system, and assessing the consequences of changes all in the same location, the lateral mode manager has been enhanced to combine the earlier functions of route, data, and weather display with the new functions of mode annunciation and selection. The lateral mode manager hardware consists of a lateral situation indicator display and a heading select knob. Icons on the lateral mode manager show aircraft roll

guidance for heading and lateral path. Icon display state, color, and size indicate mode availability, and mode status (engaged, armed, selectable).

Targets values are set by manipulating the hardware select knobs. The mappings of functions from the mode control panel of a Boeing 747-400 to the IMMI are shown in appendix 1. The appropriate mode icons appear according to the situation of the airplane and the settings of the select knobs. Modes are selected by touching the icons that represent the desired mode. A complete description of the controls and indicators on the IMMI display is given in appendix 2.

The vertical mode manager is an all new display which combines altitude and speed tapes with a vertical situation display that depicts the vertical path of the airplane. Mode engagement status is depicted by the positioning, shape and color of graphical icons. Modes are armed and selected for engagement by touching the icon depicting a selectable mode. The vertical mode manager hardware consists of a vertical navigation display, a speed select knob, an altitude select knob, and a vertical speed select wheel. The vertical navigation display contains an airspeed tape, a vertical profile display, an altitude tape, four columns for the display of mode icons. Icons on the vertical mode manager show relationships of aircraft pitch and thrust to airspeed/mach and vertical flight path. Target source (FMCS or crew input) and target value are indicated by the location of the icon with respect to airspeed/mach and altitude tapes.

Autoflight systems' state display and mode selection actions are co-located. In both mode managers, autoflight modes are depicted by icons on a conceptually meaningful graphical display rather than by strings of characters. Target values are set by manipulating hardware knobs.

Although the IMMI includes an airspeed and altitude tapes, it is not intended as a primary flight instrument. Part of the mode management task is setting targets (speed and path) with respect to other targets, the current operating envelope limits, and the current operating parameters. These tapes are provided to make this possible.

5.1. The lateral mode manager

There were three related design goals relating to the lateral mode management.

1. Make the distinctions among modes more perceptually salient and conceptually meaningful on the NAV display.
2. Make the active waypoint perceptually more salient on the lateral navigation display.
3. For all modes, the action taken to select or engage the mode should somehow bring the operator into contact with easy to process representations of the specific consequences of engaging that mode.

Figure 6 shows the IMMI display with the aircraft ready for takeoff. The active waypoint icon is the white circle in front of the airplane labeled SFO01. It has been increased in size to make it perceptually more salient. It also always is shown in a color that contrasts with the magenta color of the FMC computed track line. The active waypoint icon is now a mode annunciator and mode selector. The color of the waypoint icon indicates the engagement status of the mode. In this case, the white color indicates that LNAV mode is armed for engagement. When the conditions for engagement are met (50' of radar altitude) the mode will automatically engage, and the icon will turn green. Figure 7 shows LNAV engaged with Porte the active waypoint. When LNAV is selectable, but neither armed or engaged, the icon appears blue (Figure 12, a&b). In order to engage or arm the mode, the pilot must find the active waypoint icon and touch it. This makes the spatial relationships between the airplane, it's current course, and the location of the active waypoint apparent to the pilot before the mode is engaged. This solves the "meta-button" problem observed in some engagements of LNAV mode in the current generation of aircraft.

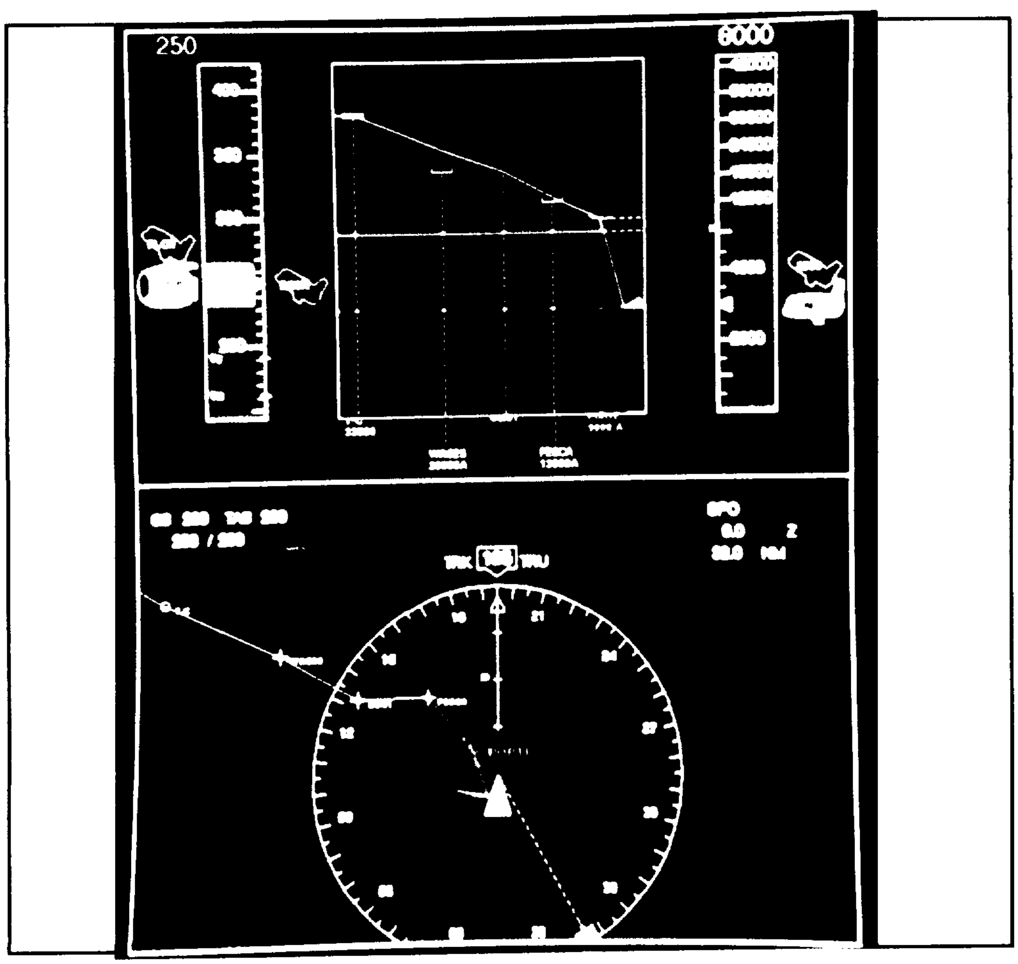


Figure 7. LNAV engaged, heading bug behind airplane and compass rose wrapped to keep heading bug visible.

A similar solution has been adopted for the heading select mode. The heading select mode is selected by touching the heading bug on the NAV display. Just as was the case for LNAV selection, this makes the spatial relationship between the airplane's current heading and the selected heading apparent to the pilot before mode engagement. For this to work in all conditions, the heading bug must always be visible on the NAV display. As the heading bug moves away from the nose of the airplane, the compass rose on the lateral navigation display expands to always include a wide enough arc to include the heading bug. Figure 7 shows the display with the heading bug nearly behind the airplane. This expansion and contraction of the compass rose satisfies another goal of having the display itself change to indicate that the heading bug is going behind the airplane. This additional bit of structure in the display's behavior provides the crew with an additional cue about the location of the heading bug.

5.2. The vertical mode manager

Our most general design goal was to build an interface in which the physical layout and behavior of the displays and controls maps easily onto the underlying conceptual regularities of the autoflight system. The table below shows the correspondence of conceptual distinctions underlying the operation of the vertical component of the autoflight system to perceptual distinctions in the interface.

Conceptual distinction	**Perceptual distinction**
Target source: FMS/MCP	Icon location: Between tapes/Outboard of tapes
Target type: Speed/Path	Icon location: Adjacent speed tape/ Adjacent altitude tape
Control axis: Pitch/Thrust	Icon shape: Airplane /Engine
Mode status: Engaged/Armed/Selectable/Envelope limit	Icon color and fill: Green(solid)/White(solid)/Blue (outline)/Amber(solid)
Path source: FMS/MCP	Path line color: Magenta/Green

Table 5.1. Correspondence of conceptual distinctions to perceptual distinctions for vertical mode management.

The vertical path display satisfies the design goals to provide a graphical representation of the future vertical trajectory of the airplane and to have a single representation in which all descriptions of flight path are displayed in such a way that it is easy to determine which will be controlling in any situation. Figure 8 (Climbing to an engaged altitude below cruise altitude. The solid green airplane icon on the inboard side of the speed tape shows that the airplane is climbing in a mode that uses pitch to attain an FMC specified economy speed target (VNAV-SPD). The solid green engine icon on

the inboard side of the altitude tape shows that the path of the airplane is controlled by a FMC specified level of engine thrust. The blue outline airplane icon outside the speed tape shows that a mode in which the airplane will pitch to an MCP specified speed (FLCH) is available for engagement. The blue outline airplane icon outside the altitude tape shows that a mode that will pitch to an MCP specified path (V-SPD) is also available for engagement. The green horizontal line at FL230 shows that unless a higher altitude is selected before reaching this altitude, the airplane will level off at this altitude even though the magenta FMC computed climb path continues up to the cruise altitude of FL330.

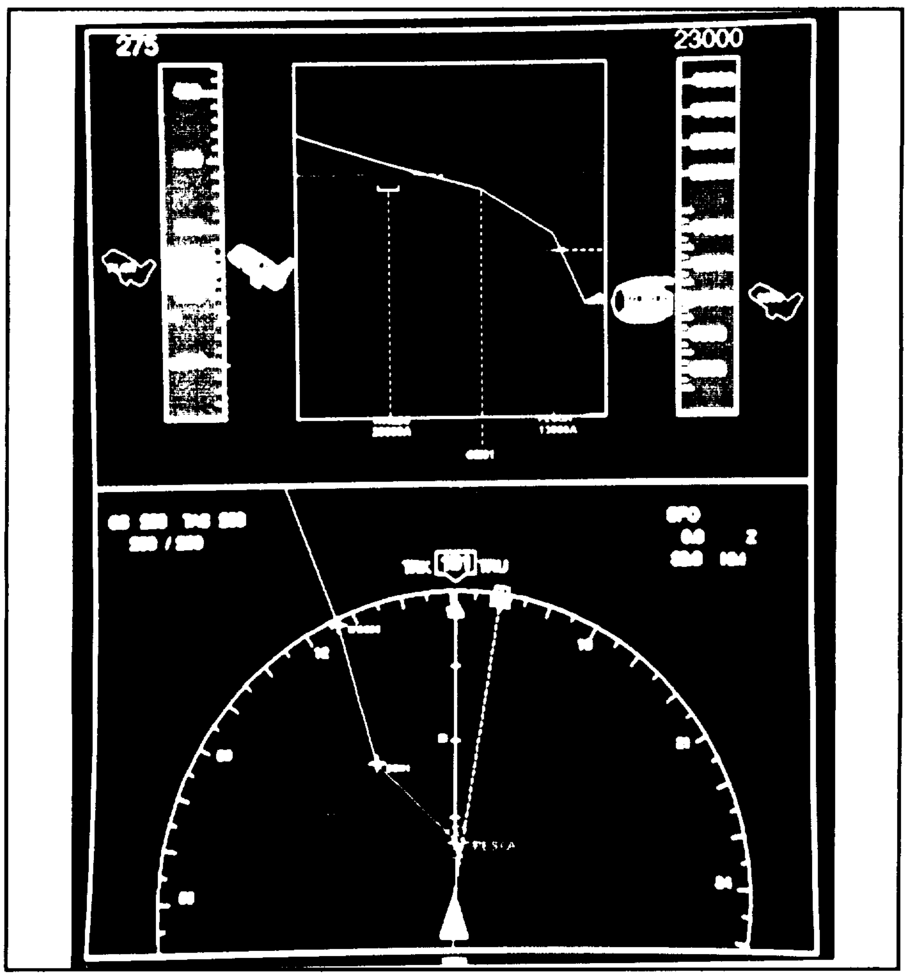


Figure 8. Climbing to an engaged altitude target by pitching to FMC specified Econ speed target.

The extent of the vertical path that is shown depends on the scale selected on the lateral navigation manager. The vertical path display shows the same path component as is shown on the lateral navigation manager. The enroute waypoints are shown along the bottom of the vertical path display. The "goal-posts" show altitude restrictions specified for the waypoints. This makes it easy to see if the airplane will meet or violate

altitude restrictions. If the autoflight system predicts that an altitude restriction will not be met, the goalpost will turn amber.

All and only those modes that can be engaged or armed from the current operating mode are presented for selection. The display of icons is context sensitive so that icons for modes that are not selectable from the present context are not displayed. Thus, when the airplane levels off at an intermediate altitude in a climb, no pitch modes are selectable until a new altitude has been selected. Figure 9 shows the leveloff condition before the selection of a new target altitude. Figure 7 shows the leveloff after the selection of a new altitude target, and figure 8 shows the situation after a climb method has been selected. On the systems currently in use, all mode select switches are continuously present (as hardware) even though they may not be selectable. In the IMMI it is easy to see that no vertical modes other than the currently engaged modes are available for selection.

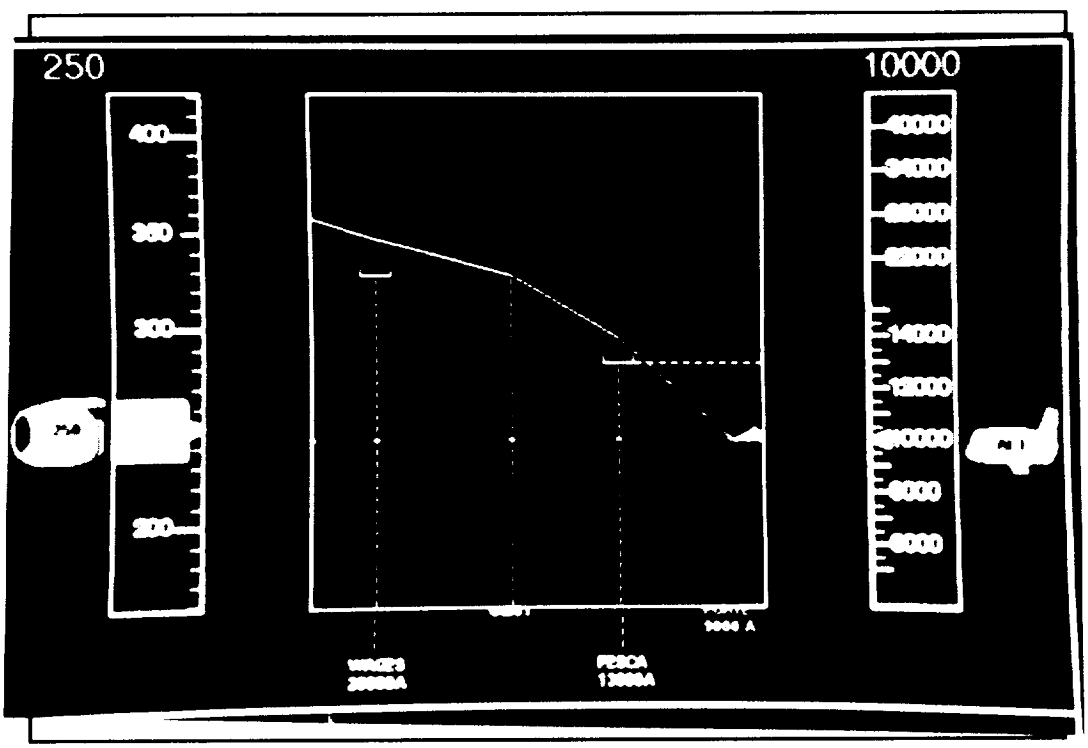


Figure 9. Level at 10,000′. No other vertical mode icons will appear until a new altitude target has been set.

Engaged, armed, and selectable modes and their performance targets (speed, path) are represented explicitly in the color and placement of the icons. When speed intervention has been selected in any VNAV mode, an icon indicating return to the FMC computed speed target appears as selectable. This solves the problem of knowing how to restore the econ-speed target for VNAV from the speed intervention condition.

Impending uncommanded mode changes are indicated by the engaged icon turning from solid green to solid amber color before the mode transition. The most frequently encountered such uncommanded change in normal operations is the transition from VNAV-PTH descent to VNAV-SPD when maintaining the path would lead to an overspeed. Figure 10 shows the VNAV-PTH icon turning amber as the speed approaches Vmax.

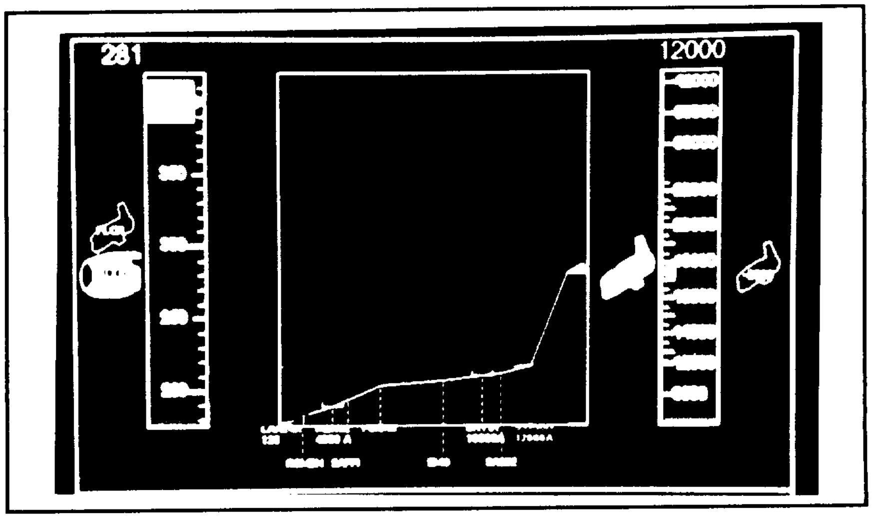


Figure 10. Impending uncommanded mode change for envelope protection. The VNAV-PTH icon turns amber to indicate impending change.

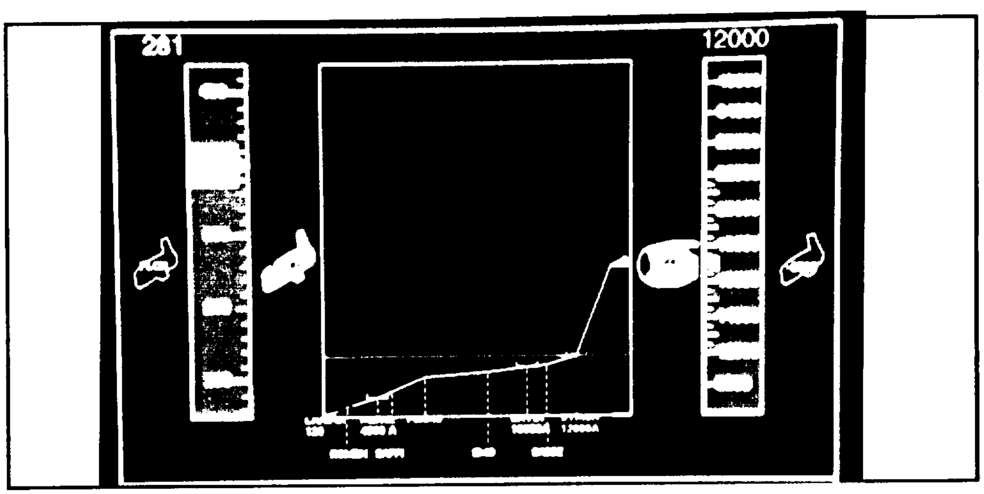
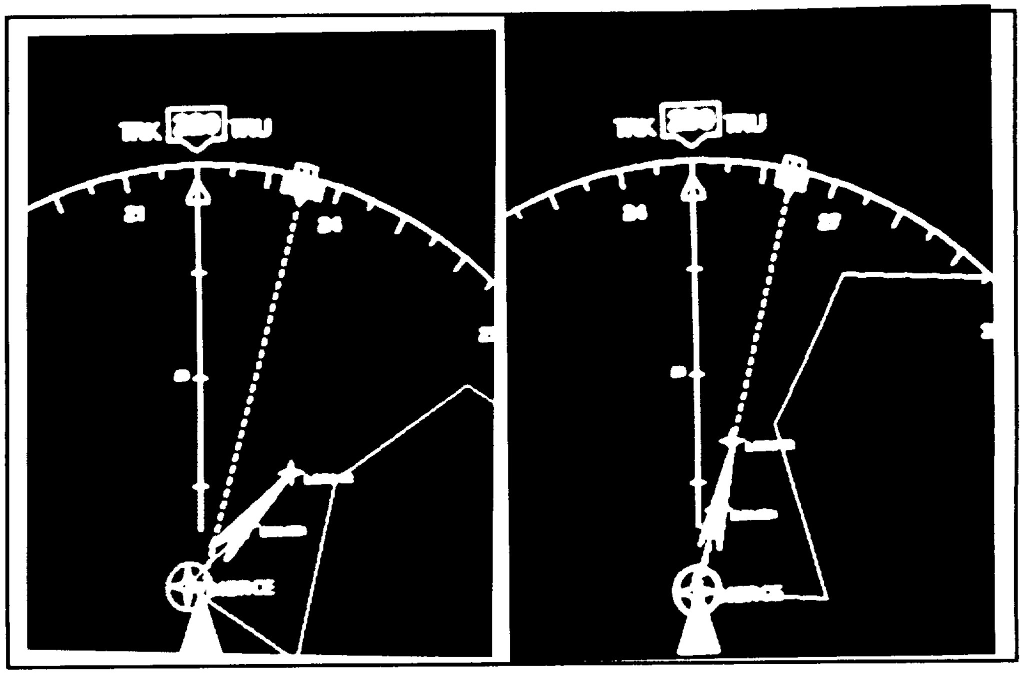


Figure 11. After the uncommanded transition to VNAV-SPD descent. Notice that the pitch icon has moved from the altitude tape (path) to the speed tape.

Figure 11 shows the state after the uncommanded change has taken place. Automatic/conditional mode transitions are not explicitly represented, but it is always easy to see which mode is coming next. On the vertical path display, the automatic transition from any climb mode to altitude keeping mode is shown by the position of the green line. The transition from

localizer armed to engaged on the lateral mode manager (figure 12a and b), and the transition from glideslope armed to engaged on the vertical are also easy to anticipate.

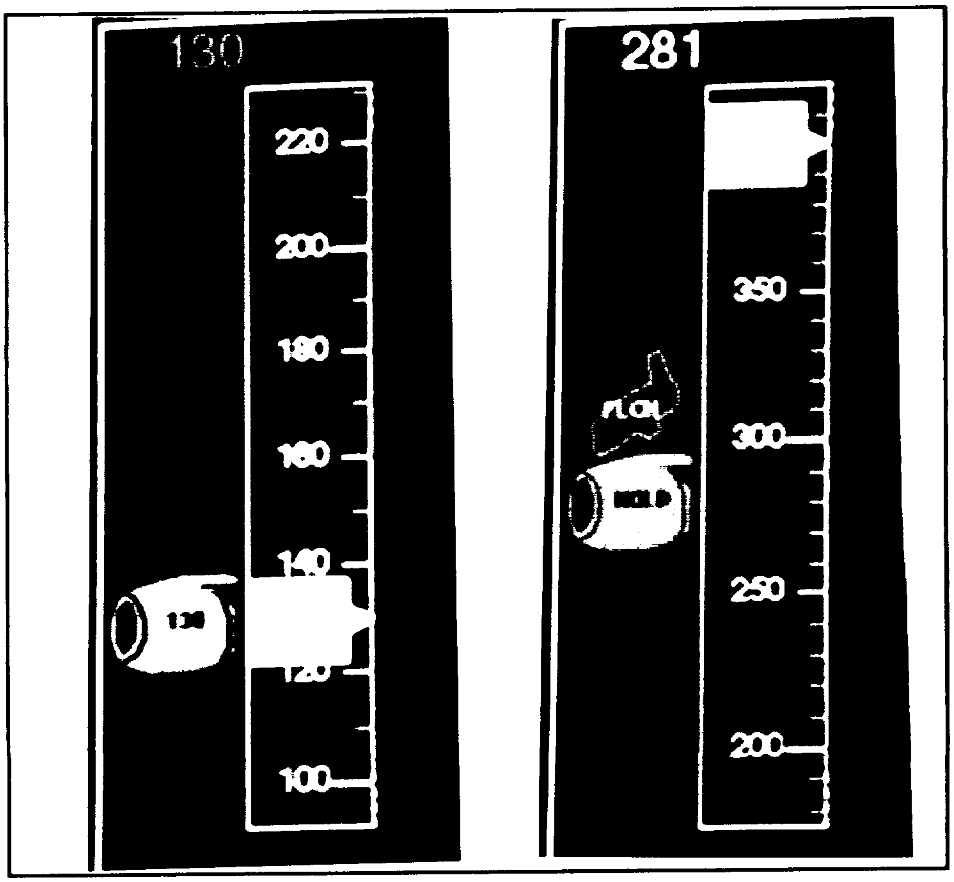


Figures 12a &b. The localizer is armed (12a) by touching the localizer icon. The localizer engages automatically upon localizer capture (12b) and the icon turns green.

5.3. The airspeed tape

The design goal of associating salient perceptual regularities in the display with the underlying conceptual regularities extends to the design of individual components of the displays. The airspeed tape presents an especially good example. The traditional round-dial airspeed indicator has some nice cognitive properties (Hutchins, 1995b). The mapping of the abstract quantity speed onto a fixed extent of space permits pilots to use fast, robust perceptual processes to do conceptual tasks. Speed bugs partition the space of speeds into meaningful regions. One of the most important properties of the airspeed indicator is that its gross physical appearance changes with speed. This is not true of the current generation of "glass" airspeed instruments. On these, the gross physical appearance of the display is the same at all speeds. Pilots often complain that they must read the number in the box in order to determine their speed. Some have advocated

giving up on airspeed tapes[11]. The problem does not lie in the technology, but in the way it is used. It is possible to build a "glass" tape that has the cognitive properties found in the round-dial instruments. The speed tape in the IMMI is an example. The airspeed tape on the IMMI always displays the entire current operating speed envelope for the airplane. Stall speed is at the bottom of the tape and Vmo or Mmo is at the top. This speed range is sensitive to airplane configuration and atmospheric conditions. Contrast this to the current practice in the 747-400, the A-320, and the MD-11 of showing a constant 120 knot window around present airspeed.



Figures 13a &b. The airspeed tape showing a slow speed during approach (13a), and a fast speed in descent (13b).

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11 Lovesey, 1992. claims that "tape displays have been introduced into cockpits at regular intervals (for example: 1925, 1938, 1960s, 1970s). Each time they are introduced, they are soon found to be inferior to round dials and are rejected. "

While the present airspeed always appears in the center of the tape in the current generation tapes, on the IMMI airspeed tape, the present airspeed box moves to the position on the tape corresponding to the present speed. This means that when the airplane is operating in the slow end of its current operating envelope, for example, the airspeed box will be at the bottom of the tape. This movement of the box is a perceptually salient cue for airspeed. It permits pilots to judge the speed of the aircraft in functional terms of fast and slow even with the instrument in peripheral vision. Figure 13a and b show the airspeed tape indicating a low speed on approach and a near overspeed condition in descent, respectively. Notice that the range of the airspeed scale depends on the airplane configuration and the atmospheric conditions.

5.4. Conceptual validation:

To ensure that the IMMI could represent all autoflight related actions and display changes we conducted a careful analysis of a simulated flight. We identified 102 autoflight related representations and actions in the simulated flight from PHX-LAX. For each event, we mapped out the corresponding IMMI action or display state.

5.5 New problems introduced by the design.

A small number of new problems are introduced by the IMMI design. These became most apparent when the IMMI was installed in the Advanced Concepts Flight Simulator of the CVSRF at NASA Ames. All proposed new instruments face the problem of cockpit real estate. Where can the device be placed in the already crowded cockpit. The design of the ACFS includes 5 display screens arrayed in a row across the instrument panel. The IMMI was installed on the center screen. The hardware knobs used to set target values were installed around the perimeter of the center display screen.

A potentially more serious problem arises from the requirement to have a touch-screen interface. While it is possible to use touch screens in aircraft, the designs are limited by two factors. First, the technology of touch screens is such that there appears to be just enough resolution in the current generation of technology to allow the discrimination of adjacent icons in the display. It is expected that this limitation will be relaxed as the technology matures. A second limitation concerns the pointing accuracy of an operator, especially when the airplane may be bouncing in turbulence. The touch accuracy at arm's length in bumpy conditions is not good, and there is some concern that a touch interface would become unreliable in turbulence. It is not known how serious this problem might actually be. By placing other fingers on the display frame, it is possible to improve touch accuracy considerably, even in bumpy conditions.

6. Evaluation

The plan for the evaluation of the IMMI has three parts. First, a comparative cognitive walkthrough for the 747-400 and the IMMI was performed. Appendix 3 shows sample pages from the analysis. This analysis led to the production of a set of predictions about the effects of replacing the current interface with an IMMI. Second, the IMMI was installed in the Advanced Concepts Flight Simulator of the CVSRF at NASA Ames research center. This required a large software engineering effort because the variables used by the simulators in the CVSRF are poorly documented and because the IMMI needed to interface with proprietary code supplied to CVSRF by airframe manufacturers. Third, a simulated flight scenario was designed to test the effects of the IMMI compared with the 747-400. Preliminary testing of the IMMI in the designed scenario was commenced in the summer of 1995. A comparative study was planned using 747-400 line pilots flying the scenario in both simulators at the CVSRF. The simulators were taken off-line in the fall of 1995, and unfortunately, the grant ended before the simulators became available again.

6.1. IMMI predictions

It is possible to make some predictions regarding the elimination or reduction of operational errors and the reduction of training time. Here are five different kinds of predictions about the IMMI.

1. Some errors that have been observed with the current system will be entirely eliminated because they are made impossible by the new design. For example, it is not possible with the IMMI to attempt to select a mode that is not available from the current state of the system. The suppression of icons depicting modes that cannot be selected in the current context should simplify the decision rules pilots employ in operating the autoflight system and should eliminate the now common instances of failed attempts to engage modes that are not available. This may be operationally important, but it is not interesting from a theoretical point of view because the prediction does not make much use of the theory. Perhaps a more interesting case is that one cannot choose heading select mode without being aware of the current location of the heading bug. This leads to the prediction that the error of entering heading select mode while the heading bug is behind the airplane (producing an undesired turn) will be eliminated.

Note the role of observations of current practices as a baseline against which we characterize the performance on the new interface.

2. Other classes of error are also expected to occur less frequently. The unexpected leveloff (e.g. in the Peble 1 departure described in section 3 above) and other vertical awareness problems should be remedied by the presence of the vertical path display. Conflicts between performance targets set by crew

and FMCS are explicitly depicted in the graphics of the vertical profile display. This should reduce the frequency of errors due to the autoflight system tracking a target that the crew is not attending to. This is a bit more interesting from the theoretical perspective than the suppression of unselectable modes, but not very much. In this case the presence of representations of the right kind makes the construction of a situation model easier for the pilot. The consequence of the actions are easy to see as long as one can interpret the graphical notation.

3. The frequency of unexpected steep turns to the active waypoint when rejoining a LNAV route should decrease. This is because the IMMI requires the pilot to know the position of the active waypoint relative to the airplane before engaging LNAV mode. Putting meaningful content in the action that engages the mode should help fix this problem.

This is the embodiment of a general principle. In the current system the internal structure of the actions that select modes have only arbitrary relations to the consequences of mode selection. In the IMMI, the content of the consequences is built into the selection action. For example, touch the active waypoint to engage LNAV or touch the heading bug to engage heading select.

4. The situation with vertical modes is more complex and more interesting. With the vertical modes the IMMI employs a theoretical principle that the underlying conceptual regularities in the behavior of the system should be reflected in the behavior of the interface itself. This goes back to the Hutchins, Hollan, and Norman (1986) work on direct manipulation interfaces. The basic notion is that the user must create a bridge from the structure of a representation to its meaning. We can make it easy for the user to construct this bridge by providing structure in the representation that can be seen as similar to the conceptual structure of the thing the representation refers to.

In the IMMI, the conceptually meaningful representation of modes mirrors the underlying regularities of the autoflight system. This should reduce the apparent complexity of the autoflight system, thereby promoting safer, more efficient use of the autoflight system. It should also reduce the amount of training required to prepare pilots to fly the airplane, and improve the quality of actual flight experience as a context for learning. This representation also permits flight crews to link perceptual routines for parsing the display to the underlying conceptual regularities.

This problem exists at all levels of organization of the system. Thus the static shapes of the icons should suggest the things they are intended to represent. But also, the behaviors of the icons should suggest the behaviors of the things they represent. The IMMI uses space and color to encode conceptual features of autoflight that are masked in the current interface. For example, icons depicting FMC targets are inside the tapes - adjacent to the FMC computed path. Icons depicting pilot specified targets are outside the

tapes. The icons are of only two types: pitch and thrust (distinguished by meaningful shapes) and they are associated with only two kinds of targets (speed and vertical path). The association of performance target with a control axis is indicated by the spatial adjacency of the icon(control axis) with one tape or another (performance target).

The prediction from this is that it will be easier for pilots to 1) see and understand what the system is doing. 2) operate the system, 3) learn to use the system.

5, Another class of predictions concerns the distribution of places where pilots must attend. MCP, FMA, MCDU, PFD in order to do the job. Co-location of mode state depiction and mode selection apparatus provides for the composition, execution and evaluation of mode management actions all in the same place. This should reduce the frequency of mode selection errors due to crew failure to note flight mode annunciator changes. See (Palmer, 1994) for a case in which an altitude capture was killed by a mode selection in a recently changed mode configuration.

All of these predictions have the character of noticing a problem in the current interface, characterizing the situations in terms of a cognitive theory (is it a memory problem, a reasoning problem, an activation error, etc.) and then exploring design alternatives that, when characterized in terns of the theory, do not generate the earlier observed errors.

6.2. Flight test scenario

A simulated flight from SFO to LAX was designed to test the IMMI. The simulated flight includes operational contexts which have been observed in line operations to lead to various classes of mode management problems. The ATC script for the scenario is shown in Appendix 4. A description of the flight, the interventions, and the expected consequences in terms of mode management are given in Appendix 5.

7. Conclusions

The Integrated Mode Management Interface is a graphical user interface to the autoflight mode management functions of state-of-the-art airline cockpits. It is based on the design principle that the perceptual distinctions available in the appearance and behavior of the interface itself should mirror the conceptual distinctions made in the structure and function of the underlying autoflight system.

More work could surely be done on the design of the icons and the graphics. It may well be that pilots would prefer a different sort of icon set to represent the distinction between pitch and thrust modes, for example. The current design also seems visually busy. A cleaner, simpler design with a lower spatial frequency would probably be an improvement. It may even be the case that a different conceptual model would better capture the underlying distinctions that pilots need to make to reason about and control the autoflight system. Captain Jim Irving has suggested that the display should also represent the energy situation of the airplane[12]. This would be especially important in an airplane like the High Speed Civil Transport.

Whatever the refinements that are made, I am confident that the principle of building an interface that provides a perceptual basis for conceptual process is correct. The IMMI is an attempt to explore the uses of that principle in the domain of autoflight mode management.

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12 Jim Irving, personal communication, August 1994 and May, 1995.

Aircraft (through the help of William Corwin) allowed me to attend MD-80 ground school. I am grateful to American West Airlines (especially, Beth Lyall) for the full A-320 ground school.

8. References

Agar, M. (1980) *The professional stranger.* New York: Academic Press.

Agar, M. (1986) *Speaking of ethnography.* Beverly Hills: Sage Publications.

Clark, A. (in press) *Being There: putting brain, body, and world together again.* Cambridge, MA: MIT Press.

D'Andrade, R. (1995). *The development of cognitive anthropology.* New York: Cambridge University Press.

Goodenough, W. 1956. Componential analysis and the study of meaning. *Language,* 32: 195-216.

Holland, D. and Quinn, N. (1987). *Cultural models in language and thought.* New York: Cambridge University Press.

Hutchins, E. (1980). *Culture and Inference.* Cambridge, MA: Harvard U. Press.

Hutchins, E. (1995a) *Cognition in the Wild.* Cambridge, MA: MIT Press.

Hutchins, E. (1995b). How a cockpit remembers its speeds. *Cognitive Science, 19*:3, 265-288.

Hutchins, E. (in prep) Cognitive Artifacts. in R. Wilson and F. Keil (Eds.) *The MIT Encyclopedia of Cognitive Science.* Cambridge, MA: MIT Press.

Hutchins, E., Hollan, J. D., & Norman, D. A. (1985). Direct manipulation interfaces. *Human-Computer Interaction,* 1, 311-338.

Lenorovitz, Jeffrey. (1992). "Airbus stresses cockpit management, coordination in transition training" Aviation Week and Space Technology, Vol 136, No. 6. Feb. 10, 1992. pp. 29-30

Lovesey, E. (1992). Displays vacillate with fashion. Flight International, 12-18 August, 1992.

Norman, D. (1993) *Things that make us Smart.* New York: Addison Wesley.

Palmer, E. A., E. L. Hutchins, R. A. Ritter, I. van Cleemput, (1993, October) Altitude deviations: breakdowns of an error tolerant system. NASA Technical Memorandum 108788. National Aeronautics and Space Administration, Ames Research Center, Moffett Field, CA.

Palmer, (1994) et al "OOPs it didn't arm." Paper presented at ASA contractors meeting. NASA Ames, August, 1994.

Polson, P. Cognitive Walkthroughs.

Romney and Dandrade, 1964. Cognitive aspects of English kin terms. *American Anthropologist.* 68:3:2 146-170.

Sarter & Woods (1994) Pilot interaction with cockpit automation An experimental study of pilots' mental awareness of the flight management system (FMS). *The International Journal of Aviation Psychology*. 4(1), 1-28.

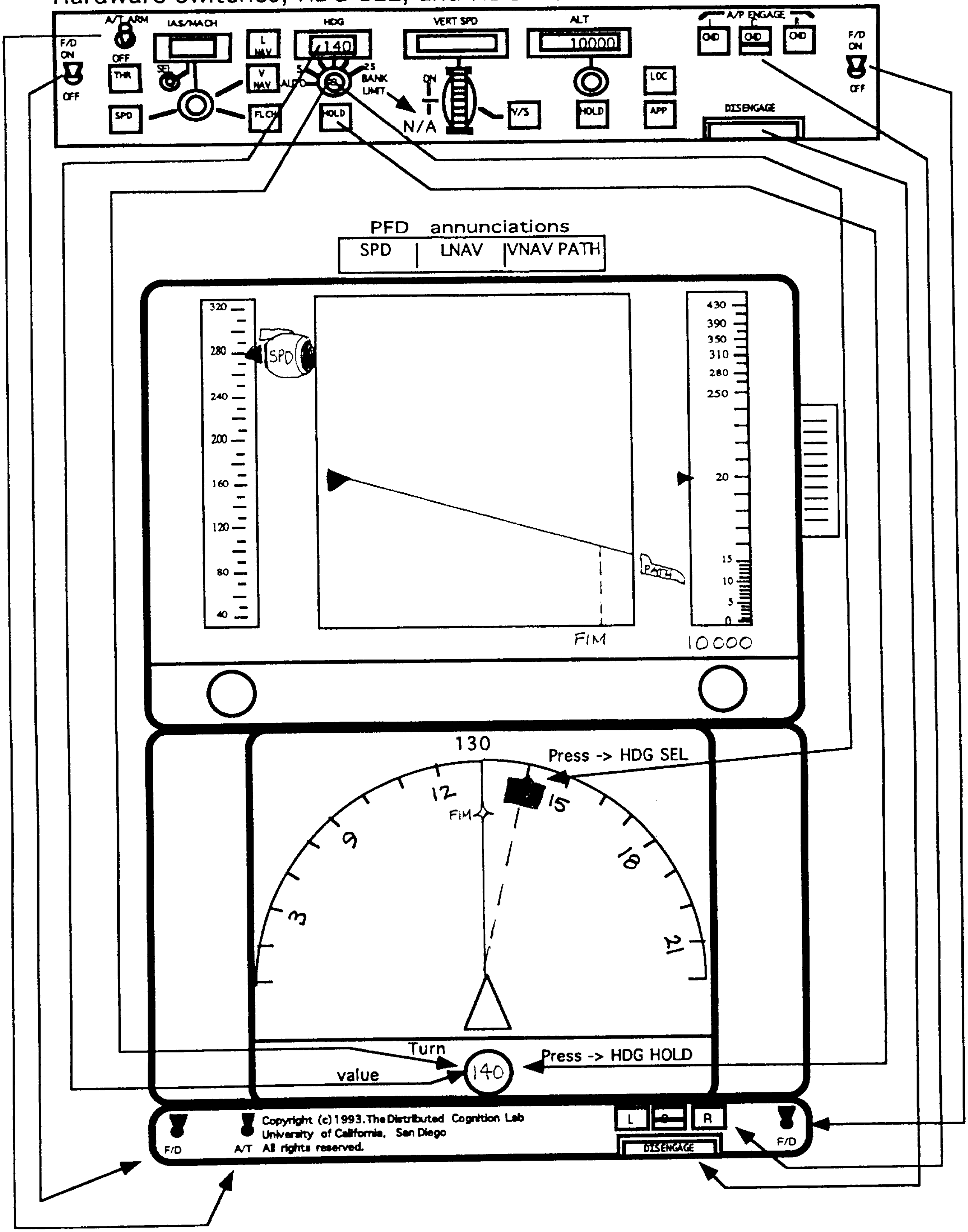
Vakil, S. S., Midkiff, A.H., and Hansman, R.J. (1996) Development and evaluation of an electronic vertical situation display. MIT Aeronautical systems Lab report ASL-96-2. (June, 1996).

Weiner, Earl. (1989). Human factors of advanced technology ("glass cockpit") transport aircraft (NASA Contractor Report No 177528). NASA Ames Research Center.

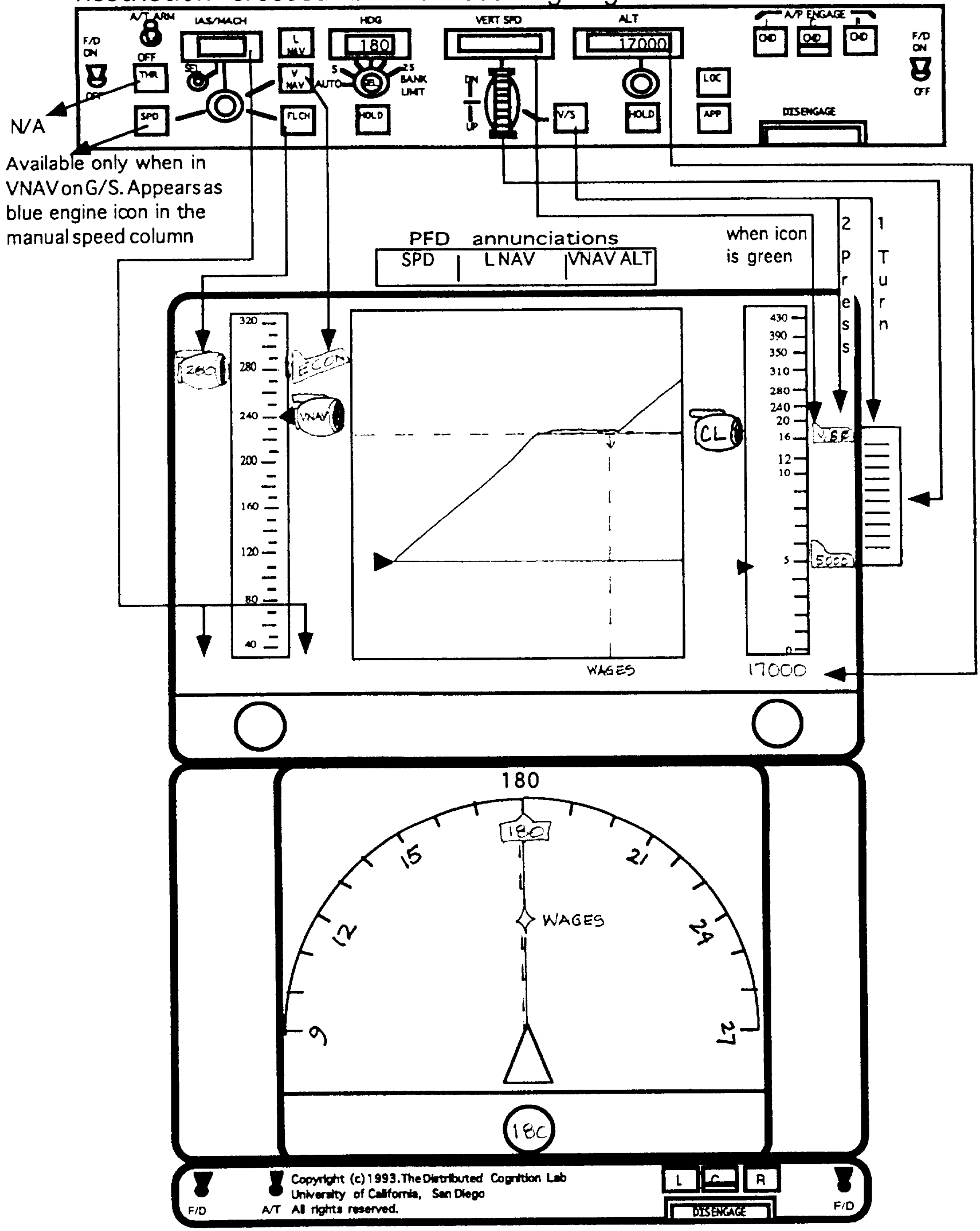
Werner, O Schoepfle, M, (1987) *Systematic Fieldwork*. Beverly Hills: Sage Publications.

Appendix 1

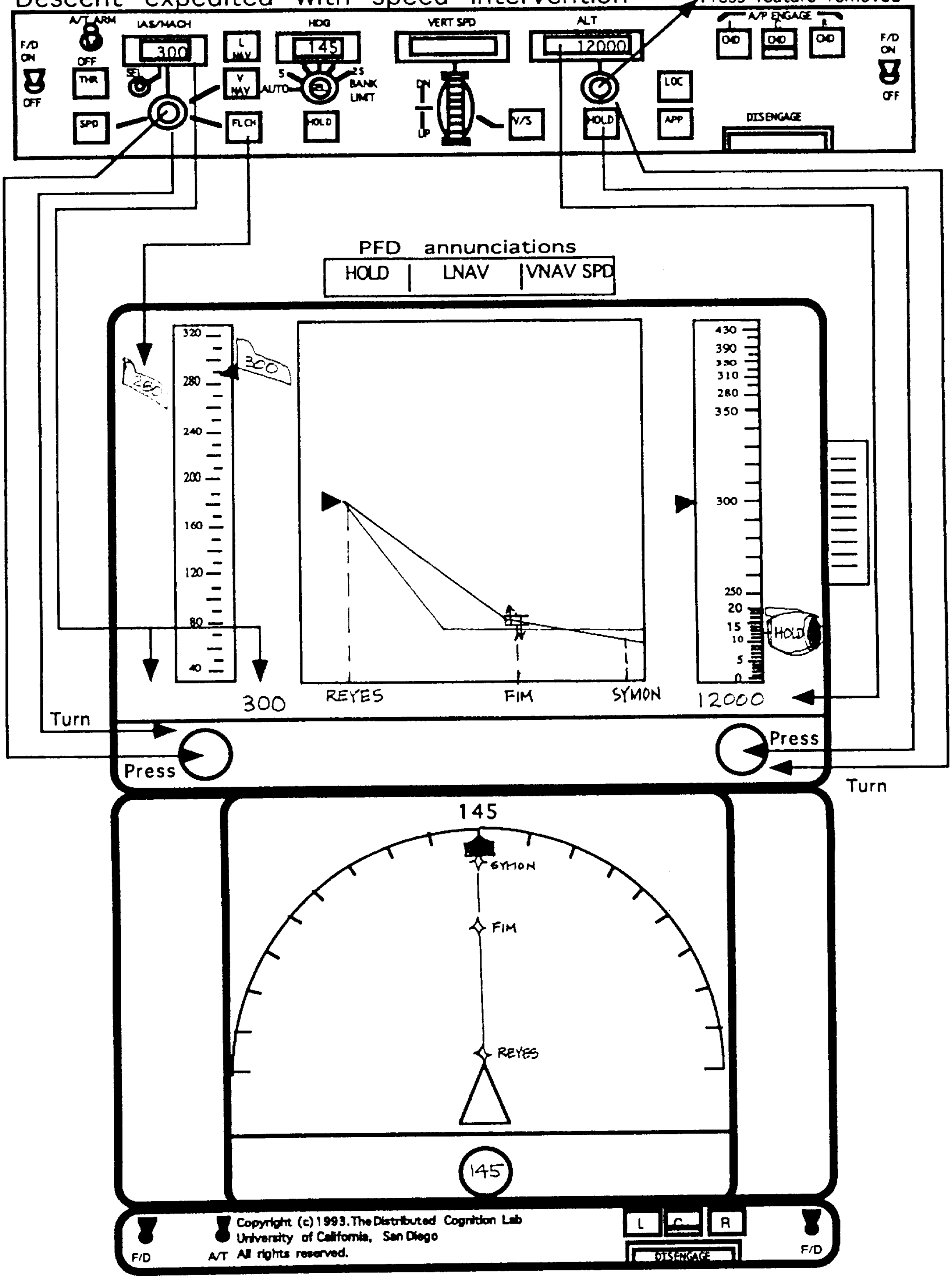
Hardware switches, HDG SEL, and HDG HOLD



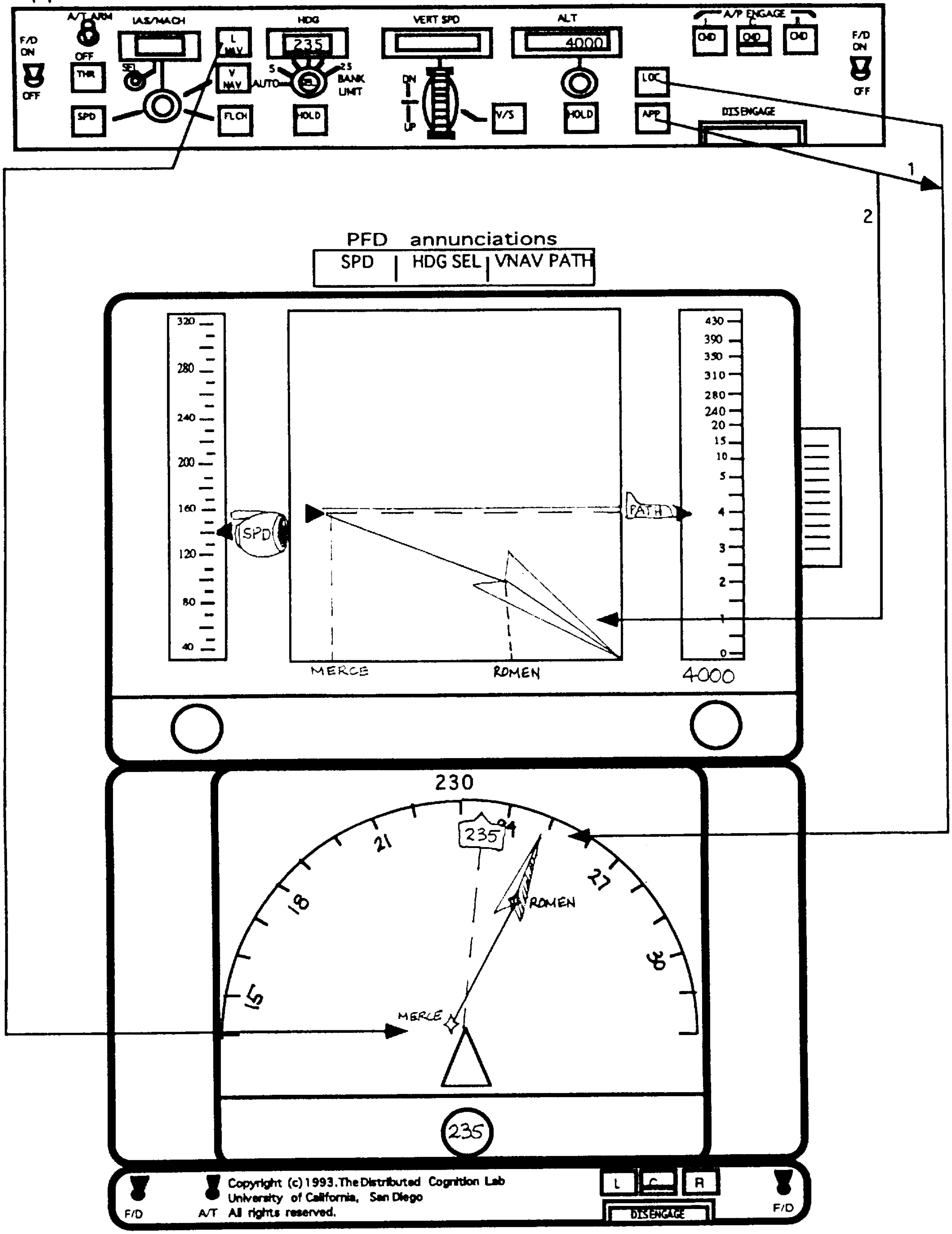
Restriction crossed before receiving higher clearance from ATC



Descent expedited with speed intervention



Approach and LNAV



Appendix 2

Top Panel - Vertical display

a. Speed Tape.

Displays the appropriate range of speeds for the flight's current operation envelope. (As determined by weight and altitude.)

b. Vertical profile display.

Displays the vertical component of the FMC entered route. Also displays manual adjustments and overrides.

c. Altitude Tape.

Always displays the complete range of altitudes for the direction of cruise. Includes a sliding virtual window that covers half of the tape in order to provide greater resolution for the 10000 feet surrounding the current altitude. See w for a more complete description.

d. Icon Column for manual speed changes.

All icons for manually adjusted speeds will appear in this column.

e. Icon Column for FMC speed changes.

All icons for either FMC controlled speeds, or FMC speed editing, will appear in this column.

f. Icon Column for FMC altitude changes.

All icons for FMC controlled altitudes will appear in this column. In general, all thrust-to target altitudes will be here, since the FMC controls thrust. (But there are exceptions, such as altitude capture or VNAV-PATH.) Pitch-to targets which are FMC entered altitude restrictions will also be here, even if a different window altitude target exists. Once the altitude target in the altitude window is captured however it will appear in the outside column, g. (see below).

g. Icon Column for manual altitude changes.

All icons for manually commanded altitudes will appear in this column, when captured. Since most altitude targets in the altitude window, although manually selected, are achieved via the FMC, their icons appear on the inside of the tape. At capture however their manual selection is recognized. Vertical speed icons will always go in this column, since they are completely manually determined. Thrust-to icons for A/T HOLD in either TO roll or descent will also go here, since

they indicate that if the pilot manually adjust the throttles the throttles will remain in place at the manual adjustment.

h. Pitch to target icon.

Engaged icons should be LARGER than armed or selectable icons.

Color: white Condition: armed.

This means that the icon is controlled by some other action, usually via the FMC. When the appropriate conditions are met the icon will automatically engage.

Color: blue Condition: selectable

This means that the icon represents an option that can be chosen. Touching the icon will engage that option if the conditions for engagement are met (which will usually be the case). Otherwise the icon will go to armed. (EX. localizer, G/S icons which appear on the lateral and vertical displays respectively.)

Color: green Condition: engaged

This means that this represents what is currently providing command guidance.

Shown are a selectable pitch-to-manual speed in the far left column, a selectable FMC computed pitch-to-ECON speed in the next column and an engaged pitch-to-path for the captured altitude in the far right column.

i. Thrust to target icon.

Engaged icons should be LARGER than armed or selectable icons. Note definitions of the conditions are the same as in h. above.

Color: white Condition: armed.

Color: blue Condition: selectable

Color: green Condition: engaged

Shown are an engaged thrust-to-speed, selected by speed intervention in the inside left column and an armed thrust-to-path/altitude in the inside right column.

j. Manual speed window.

Color: blue Condition: selectable

This shows the current speed of the aircraft and is associated with the pitch-to-speed icon in the manual column. The selectability is actually of the associated icon.

Color: green Condition: engaged.

Once the appropriate manual icon is selected that icon and this window changes to green to show that this is the engaged option.

k. FMC edited speed window.

Color: magenta.

The value in this window is always magenta so that it is clear that this is a target that edits the speed in the FMC. The airplane will follow the magenta path on the vertical profile display at the specified speed if possible.

l. Altitude window

Always displays the manually set altitude target, usually the last ATC cleared altitude.

Color: green. Condition: engaged.

This means that this is the current altitude target being flown to. It is also represented on the vertical display by a green line, n.

Color: blue Condition: selectable

Moving the knob changes the value in the altitude window and moves a line on the vertical display which represents the new altitude target. This line, m., and the number in the window, are both blue. This corresponds to a selectable pitch icon representing choices of how to meet that altitude target. When the desired icon is selected then the icon, the new altitude target in the altitude window, and it's associated line all turn green.

m. New altitude target.

Color: blue Condition: selectable

Color: green. Condition: engaged.

When a new altitude target is selected, if the previous altitude is captured, then a dashed blue line appears on the vertical display. As the altitude knob is adjusted, changing the number in the altitude window, this line moves to the appropriate spot on the display. The new altitude is engaged by touching the appropriate icon corresponding to the desired method of reaching the target altitude. Engaging the icon will change the line to green for engaged. The line for a previously captured altitude will disappear.

n. Captured altitude or engaged altitude target.

Color: green Condition: engaged.

See m.

o. Current FMC route - vertical component.

Color: magenta.

Shows the vertical portion of the active route entered in the FMC that the auto pilot will fly if A/P engaged and VNAV is the active mode. In this case the start of the path in front of the nose of the aircraft indicates the top-of-descent.

p. Alternate path

Color: blue. Condition: selectable

Color: green Condition: engaged.

Shows the vertical portion of the manual choice for ascent or descent to a different altitude when at a captured altitude, IF that path will be different from the FMC computed path. In this case the diagram assumes that the descent path associated with the manual pitch-to-speed icon is different than the FMC computed path. Note that paths associated with manual speed targets circumvent the FMC path and therefore any FMC known altitude restrictions.

If the manual pitch-to-speed icon is selected and engaged then this path will change to green. The FMC computed path will remain in magenta on the display.

Note: behavior of lines representing paths and altitudes

Magenta paths are always FMC controlled and solid lines.

Captured altitudes are represented by solid green lines. Engaged altitude targets that have not been reached are represented by dashed green lines. If this altitude target will cause the aircraft to level off then the portion of the line that continues from the path will be solid. Eg. on the diagram if line m became the engaged altitude target then the portion of m near the letter p would change to a solid line.

Alternate paths, other than FMC computed paths are solid lines shown in blue when selectable and green when engaged.

q. Crossing restriction.

Color: magenta. Condition: engaged.

Color: amber. Condition: warning.

Direction of arrow indicates "cross at or above" versus "cross at or below". If no arrow then it is a "cross at" restriction. Indicated in magenta to show a part of the FMC route. If one changes to amber it is a warning that the current performance of the aircraft may not meet that restriction. The first restriction that may affect the FMC path will have a horizontal dashed magenta line lining up with the altitude tape. For example, the FMC path shown here will easily make both restrictions at CZI, but the restriction to cross ROCKY @ 10000 will force the aircraft to level out, so there is a dashed magenta line.

r. active waypoint.

Color: green Condition: engaged.

Color: white Condition: armed.

Color: blue Condition: selectable.

Corresponds to the active waypoint on the lateral display. Green and engaged refers to the engagement of LNAV. If LNAV is not engaged because HDG-SEL is engaged, then the active waypoint is blue. If LNAV is not engaged because LNAV is armed before TO, but not engaged then the active waypoint is white.

Note: Waypoint identifiers are shown below the line delimiting the vertical display. Waypoint identifiers are assumed to be either 3-letter VOR identifiers, 5-letter intersection names, lat-long designators or fix/radial distances (eg. BLH275/075 where BLH is the VOR, 275 is the radial and 075 is the DME distance).

s. inactive waypoint(s)

Color: magenta. .

Corresponds to the inactive waypoint(s) showing on the lateral display. Regardless of whether LNAV is or is not engaged the inactive waypoints will always show in magenta.

Note: route mismatches on approach

Color: amber. Condition: warning.

If during approach a route in the FMC does not match the displayed glide slope (G/S) for the runway then the waypoint identifiers will appear in amber as a warning that the displayed waypoints and their restrictions are not for the G/S displayed.

t. Speed knob.

To manually adjust speed.

If the aircraft has captured an altitude and a new altitude target is selected, then the current speed will appear in the manual speed window and an associated pitch-to-speed icon will appear in the far left icon column. In this case moving the knob will adjust the speed, as well as moving the appropriate icon in the manual column.

If the aircraft has captured an altitude, but no new altitude target is selected, then **touching** the speed knob will cause the current speed to appear in blue in the manual speed window. An associated pitch-to-speed icon will appear in the far left icon column. Moving will then change the speed that appears in that window, as well as moving the appropriate icon in the manual column.

Pushing the knob is required for speed intervention. This will cause the current speed to appear in magenta in the FMC speed editing window. An associated pitch-to-speed icon will appear in the FMC speed icon column. Moving will then change the speed that appears in that window, as well as moving the appropriate icon in the FMC column.

u. Altitude knob.

The altitude knob is used to manually adjust the altitude target. The current altitude target always appears until a new altitude target is entered. This knob changes the value in the window, as well as moves the appropriate icon in the FMC or manual column, and the altitude target line on the vertical profile display.

v. Vertical speed wheel

Touching this wheel causes a pitch-to-path icon to appear in the manual altitude icon column at the current rate of vertical change. Note: here, at level flight the appropriate icon would show 0 for no rate of vertical change.

Moving the wheel will change the rate of descent or ascent. The icon will appear next to the altitude target and the value of vertical rate will alter inside the icon as the wheel is moved.

w. Altitude resolution window

The nearest 10000 feet to the aircraft are displayed at a higher resolution than the rest of the altitudes. This virtual window moves with the

aircraft. In the scenarios the window is shifted when the aircraft is in the middle of the range. Ideally in implementation the window shifts continuously.

During approach the resolution shifts from a tick mark every 1000 feet to a tick mark every 500 feet.

x. Aircraft

Color: white. Position on the vertical display indicates the aircraft altitude.

y. Glide Slope

NOT SHOWN-

Glide slope(G/S) symbol as shown on approach plates. When the runway is entered in the FMC the G/S symbol will appear on the appropriate place on the route in blue to show that it is selectable.

When touched, the blue icon changes to white to show that the G/S is armed for capture. When the G/S signal is captured the icon automatically changes to green to show engaged. When engaged this signal controls the vertical guidance of the aircraft, so horizontal lines associated with altitude targets disappear from the display. Note: at G/S capture the altitude window can be reset to show the missed approach altitude.

<u>Bottom Panel - Lateral display</u>

a. Heading bug knob.

Moving the knob moves the position of the heading bug in the direction of movement.

b. Aircraft indicator.

Color: white. Indicates the aircraft position and direction of flight.

c. FMC route.

Color: white Condition: armed.

Color: magenta. Condition: engaged.

Shows the active route entered in the FMC that the auto pilot will fly if A/P is engaged and LNAV is the engaged roll mode. Waypoints other than the active one are in the same color as the route. The extent of the laterally displayed route corresponds to the extent of the vertically displayed route.

d. Active waypoint.

Color: white Condition: armed.

Color: green. Condition: engaged.

Color: blue Condition: selectable

Shows the immediate target waypoint for the FMC. Distinctions between armed, selectable, and engaged correspond to that described for the vertical display.

e. Heading bug line.

Color: white, green

Dashed line that extends from the nose of the aircraft indicator to the current position of the heading bug.

If the heading bug is selected then this line will change to green.

f. Heading bug .

Color: blue Condition: selectable

Color: green. Condition: engaged.

When green the heading bug indicates in HDG-SEL mode. Changing the bug position will result in changes in aircraft position.

When blue the heading bug shows that HDG-SEL is available and selectable. In this mode moving the heading bug does not alter the aircraft's course.

g. Current heading/track indicator.

Color: white.

Always indicates the current heading or ground track being flown. Which one is determined by the display mode the lateral display is in.

h. Compass rose

Color: white

Note: this rose is not an accurate 180 degrees. Rose can be displayed in any of the legitimate display modes for the lateral display.

i. Ground track indicator.

NOT SHOWN-

Straight green line with arrow at the end where meets the compass rose.

Color: green Appears only during takeoff to indicate the ground track aircraft is flying for roll guidance during TOGA mode.

j. Localizer

NOT SHOWN-

Localizer symbol as shown on approach plates. When the runway is entered in the FMC the localizer symbol will appear on the appropriate place on the route in blue to show that it is selectable.

When touched, the blue icon changes to white to show that the localizer is armed for capture. When the localizer signal is captured the icon automatically changes to green to show engaged. When engaged this signal control the lateral guidance of the aircraft so if the aircraft was previously in heading select it is not any longer. Note: at localizer capture the heading bug automatically resets to the localizer inbound course.

HARDWARE

Duplicates the necessary hardware switches.

a. Flight Director toggle switch

Up is the on position, down is the off position. These switches must be manually flipped on in order to provide FMC generated flight director information to the primary flight displays.

b. Auto Throttle toggle switch

Up is the on position, down is the off position. When manually flipped this turns the auto-throttles (A/T) on and off. A/T can also be disconnected from buttons on the throttles themselves. When disconnected the toggle-switch should reset to the off position.

c. Auto Pilot Push buttons.

Pushing these buttons engages the auto pilot (A/P). Each button represents one of three available A/Ps. Usually the aircraft is flown with the Center (C) A/P engaged. Engaging the A/P means that the FMC computed commands are being directed to control surfaces to fly the aircraft, depending on the engaged modes. When an autopilot is engaged the button will change to green.

Appendix 3

IMMI System

Mode: HDG Select **Goal:** Turn aircraft to a target heading and maintain target heading

Representation: Target heading bug on the lateral display

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Available	HDG target bug is blue on lateral display	Decide to engage HDG SEL	Pilot	NONE
		Keep target heading bug in front of the plane on the lateral display	Pilot	
	Numbers in heading bug change to target	Set target heading Touch label (These actions may occur in either order)	Pilot Pilot	
Engaged	HDG target bug on lateral display turns green		AFDS	
	Numbers in heading bug change to selection	Set another target heading	Pilot	

Notes:

1. HDG SEL is always available
2. Location of icon is meaningful. Action of selecting HDG-SEL mode brings pilot into contact with the lateral display.

Outcome: AFDS provides guidence to follow target heading

IMMI System

Mode: LNAV **Goal:** Follow programmed route along lateral (N-S-E-W) headings

Representation: Waypoint and label on lateral display

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not available	No route visible on lateral display	Route from CDU Route programmed Set NM for LNAV display	CDU Pilot Pilot	•Route entered
Available	Route visible and label and active waypoint appear on display in blue	Decision to arm LNAV Touch label or waypoint on display to arm LNAV	Pilot Pilot	
Armed (while armed maybe in TOGA, HDG SEL or HDG hold)	Label and active waypoint turn white	Wait for engagement	FMC	•ALT minimum 50' AGL •Airplane w/in 2.5 nm of programmed route •Airplane on intercept course for active leg
	Still white, constraints are not met	If not engaging, begin diagnosis	Pilot	
Engaged	Label and active waypoint turn green FMA - green LNAV	LNAV engages	FMC	
Previous mode is disengaged				

Outcome: AFDS provides guidence for airplane to follow programmed route.

IMMI System

Mode: Localizer **Goal:** Find and track the localizer

Representation: Localizer icon on lateral display (at right scale?)

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available	Localizer icon is not on the lateral display	Arrival runway programmed into CDU	Pilot	Entered in CDU
		Localizer frequency dialed in?	Pilot	In 757 have to tune on the glare shield nav radio. Tuning not required on -400
		(* Additional Constraint) Lateral display set to a readable scale	Pilot	Display scale that shows airport
Available	Localizer icon appears on lateral display and it's blue	Decide to engage mode	Pilot	
		Touch either Loc icon to arm Loc-only or G/S icon to arm combined approach mode	Pilot	
Armed	Localizer icon turns white		AFDS	
		Aircraft within reception range of localizer signal	Pilot/AFDS	Aircraft close enough to receive signal
		Fly intercept course	Pilot/AFDS	120 degrees of localizer course, within 40 miles
		Be within capture range	Pilot/AFDS	Appropriate distance from runway

Disarm	Localizer icon turns blue	Touch white icon	Pilot	Disarms mode
	*Unreliable signal, icon turns amber and hides all other state colors-trouble	No actions, but pilot could arm/disarm inadvertantly by touching amber icon.	AFDS	Weak signal reception
Engaged	Localizer icon turns green	Localizer mode engaged	AFDS	Strong localizer signal
	Previous mode disengages		AFDS	

Outcome: AFDS provides guidence to steer to localizer heading and to then maintain that heading

IMMI System

Mode: TOGA/Roll **Goal:** Maintain ground track in flight

Representation: Arrow on lateral display

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available		3 ways to arm:		
	1. None	1. Turn on F/D while on the ground.	Pilot	
	2. None	2. Flaps out of up position in flight.	Pilot/AFDS	
	3. None	3. Capture glide slope in flight.	Pilot/AFDS	
Armed	White arrow projected from runway centerline on lateral display. (In old system TOGA just appears in green on FMA for arm method 1).	Press TOGA switch		
Engaged	Arrow from runway centerline turns green. (In old system there's no representation).	(From the ground, 1)	AFDS	TOGA armed
	Arrow from ground track in front of airplane turns green on the lateral display.	(From flight, 2&3)	AFDS	TOGA armed
Disengage	Arrow leaves lateral display	Select any other roll mode	Pilot	

Outcome: AFDS provides guidance to airplane to follow ground track in flight.

IMMI System

Mode: HDG Hold **Goal:** Maintain heading aircraft is on after wings are rolled level

Representation: (a) Button on Heading selector, and (b) two handed HDG Hold icon holding airplane symbol

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Available	Knowledge pilot has in the head, just know.	Primary method--Press HDG Select knob	Pilot	NONE
		Secondary method--With (a) bank angle less then or equal to 5 degrees and (b) FDs and A/P are off, Turning on the F/D or A/P engages HDG Hold.	Pilot	
Engaged	Green two handed icon		AFDS	

Notes:

1. HDG Hold is always available in flight
2. Need a heading hold icon on lateral display (IMMI needs a HDG hold bug on compass rose in front of the airplane on the lateral display)(Icon should stay in front of the airplane on the lateral display. When wings roll level the icon gets a HDG number).

Outcome: AFDS provide guidance to roll airplane wings level, then flys that heading when wings are level.

IMMI System

Mode: Attitude **Goal:** Maintain airplane's current roll attitude

Representation: Attitude Icon

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available	None	F/D and A/P off and bank angle is greater than 5 degrees of bank.	Pilot	None
Available	None	Turn on F/D or A/P	Pilot	None
Engaged	None (In old system ATT in FMAs turns green) IMMI should do the same. Attitude icon on Lateral Display ATT Green in FMA		AFDS	Bank Angle exceeds 5 degrees

Outcome: AFDS provides guidence for airplane to maintain current attitude

IMMI System

Mode: Rollout **Goal:** Maintain airplane on runway centerline till touchdown

Representation: Rollout icon appears on lateral display (heavy white line in front of airplane)

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available	none			Airplane is within 5 feet RA
Armed	No IMMI representation yet. Possibly draw a white arrow out of runway on the lateral display	Airplane descent below 1500' AGL?	Pilot/AFDS	Localizer mode engaged
Engaged	No IMMI representation yet. Possibly turn the white arrow from the runway green.	Airplane descent to 5 feet RA	AFDS	Assume runway HDG

Outcome: AFDS provides guidence so airplane lands on centerline. Passengers clap. Crew welcomes passengers to beautiful San Diego.

747-400 System

Mode: HDG Select **Goal:** Turn aircraft to a target heading and maintain target heading

Representation: Target heading bug on the lateral display (LNAV, TOC, LOC) (??? mike 1/6/94)

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Always Available	None	Decide to engage HDG SEL		NONE
	Numbers in MCP window ~~change to~~ target heading	Push heading select switch	Pilot	
Engaged	FMA - Green HDG-SEL is illuminated		AFDS	
		Set another target heading	Pilot	

Notes:
1. HDG SEL is always available
2. In any mode, at LOC capture HDG bug will go to inbound course for runway.

Outcome: AFDS provides guidence to follow target heading

747-400 System

Mode: LNAV **Goal:** Follow programmed route along lateral (N-S-E-W) headings

Representation: Flight mode annunciator - LNAV

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not available	No route visible on lateral display	Route from CDU Route programmed	CDU Pilot	•Route entered
Available	Route appears on lateral display	Decision to arm LNAV Push LNAV switch	Pilot Pilot	
Armed (while armed maybe in TOGA, HDG SEL or HDG hold)	Flowbar illuminates LNAV white on FMA	Wait for engagement	FMC	•ALT minimum 50' AGL •Airplane w/in 2.5 nm of programmed route •Airplane on intercept course for active leg
		If not engaging, begin diagnosis	Pilot	
Engaged	FMA - green LNAV	LNAV engages	FMC	

Previous mode is disengaged

Outcome: AFDS provides guidence for airplane to follow programmed route.

747-400 System

Mode: Localizer **Goal:** Find and track the localizer

Representation: Loc button flowbar or approach button flowbar

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available	none	Arrival runway programmed into CDU	Pilot	Entered in CDU
	Looking at Nav rad page to see if it's tuned in, tuning of VOR recievers shown in ND bottom corners	Localizer frequency dialed in?	Pilot	In 757 have to tune on the glare shield nav radio. Tuning not required on -400
	Nothing tells pilot that Loc freq is tuned			
Available	none	Decide to engage mode	Pilot	
		Touch either Loc button to arm Loc-only or Approach button to arm combined approach mode	Pilot	
Armed	FMA says LOC in white		AFDS	
	Flowbar for either loc button or loc and approach buttons innuminates white		AFDS	
		Aircraft within reception range of localizer signal	Pilot/AFDS	Aircraft close enough to receive signal
		Fly intercept course	Pilot/AFDS	120 degrees of localizer course, within 40 miles
		Be within capture range	Pilot/AFDS	Appropriate distance from runway

Disarm	Button flowbars go blank, White LOC disapears from FMA	Touch Loc button	Pilot	Disarms Loc or App mode
	*Unreliable signal, error flag appears at bottom center of ND	No actions	AFDS	Weak signal reception
Engaged	FMA - Green LOC	Localizer mode engaged	AFDS	Strong localizer signal
	Previous mode disengages		AFDS	

Outcome: AFDS provides guidence to steer to localizer heading and then to maintain that heading

747-400 System

Mode: TOGA/Roll **Goal:** Maintain ground track in flight

Representation: FMA Display

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available	1. None	3 ways to arm: 1. Turn on F/D while on the ground.	Pilot	
	2. None	2. Flaps out of up position in flight.	Pilot/AFDS	
	3. None	3. Capture glide slope in flight.	Pilot/AFDS	
Armed	FMA - green TOGA (only for arm method 1)	Press TOGA switch		
	None (for arm methods 2 and 3)			
Engaged	FMA - green TOGA		AFDS	TOGA armed
			AFDS	TOGA armed
Disengage	FMA - green TOGA disappears	Engage any other roll mode	Pilot/AFDS	

Outcome: AFDS provides guidance to airplane to follow ground track in flight.

747-400 System

Mode: HDG Hold **Goal:** Maintain heading airplane is on after wings are rolled level

Representation: Heading hold button and flowbar

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Always Available	Hold button under HDG select knob says hold Pilot needs to know mode is always available	Press hold button	Pilot	NONE
Engaged	Flowbar illuminates on HDG-Hold button. □□□FMA - Green HDG HOLD	Select a different roll mode	AFDS	

Notes:
1. HDG Hold is always available in flight

Outcome: AFDS provides guidance to roll airplane wings level, then flys that heading when wings are level.

747-400 System

Mode: Attitude **Goal:** Maintain airplane's current roll attitude

Representation: None

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available	None	F/D and A/P off and bank angle exceeds 5 degrees	Pilot	None
Available	None	Turn on F/D or AP	Pilot	Bank Angle exceeds 5 degrees
Engaged	ATT Green in FMA		AFDS	Bank Angle exceeds 5 degrees

Outcome: AFDS provides guidence for airplane to maintain current attitude

747-400 System

Mode: Rollout **Goal:** Maintain airplane on runway centerline till touchdown (Autoland)

Representation: FMA shows ROLLOUT

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available	none			Airplane is within 5 feet RA
Armed	White "ROLLOUT appears on FMA below green "LOCALIZER"	Airplane descent below 1500' AGL?	Pilot/AFDS	Localizer mode engaged
Engaged	FMA - green "ROLLOUT"	Airplane descent to 5 feet RA	AFDS	Assume runway HDG

Outcome: AFDS provides guidence so airplane lands on centerline. Passengers clap. Crew welcomes passengers to beautiful San Diego.

747-400 System

Mode: VNAV Path **Goal**: Follow FMC vertical route (pitching to FMC speed)

Representation: VNAV flow bar (any VNAV armed or engaged), white or green FMA "VNAV SPD"

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available	none	Make next waypoint restriction be: (a) above and within capture distance of current altitude or (b) below current altitude and "pathable"	Pilot	
			FMC	route programmed in FMC
Available	none	Push VNAV button	Pilot	
Armed	white FMA "VNAV ~~PTH~~" (none if automatic mode transition)	wait for engagement	FMC	
		If not engaging begin diagnosis	Pilot	
Engaged	green FMA "VNAV PTH" VNAV flowbar	Select a different vertical mode Change speed with speed intervention Change altitude	Pilot	

Outcome: FMC provides guidence to follow VNAV route with pitch to path

747-400 System

Mode: VNAV SPD

flies to an FMC alt target

Goal: ~~Follow FMC vertical route~~ (pitches to a speed)

Representation: VNAV flow bar (any VNAV armed or engaged), white or green FMA "VNAV SPD"

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available	none	Make next waypoint restriction be: Both: (a) above current altitude and (b) not within capture distance Or ~~both~~: (a) below current altitude and (b) not able to maintain path while staying within speed envelope.	Pilot	
			FMC	route programmed in FMC
Available	none	Push VNAV button	Pilot	
Armed	white FMA "VNAV" ~~SPD"~~ (none if automatic mode transition)	wait for engagement	FMC	
		If not engaging begin diagnosis	Pilot	
Engaged	green FMA "VNAV SPD" VNAV flowbar	Select a different vertical mode Change speed with speed intervention Change altitude	Pilot	

Outcome: FMC provides guidence to get near next FMC restriction altitude or FMC path (not really MJM) and then calls VNAV Path mode

747-400 System

Mode: VNAV ALT **Goal**: pitch to captured altitude with A/T to FMC speed

Representation: VNAV flow bar (any VNAV armed or engaged), white "VNAV" or green FMA "VNAV ALT"

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available	none	(a) be within capture distance of window altititude, and (b) have next restriction altitude be on oposite side of window altitude from airplane	Pilot	
			FMC	route programmed in FMC
Available	none	Push VNAV button	Pilot	
Armed	white FMA "VNAV ~~ALT~~" (none if automatic mode transition)	wait for engagement	FMC	
		If not engaging begin diagnosis	Pilot	
Engaged	green FMA "VNAV ALT" VNAV flowbar	Select a different vertical mode Change speed with speed intervention Change altitude window (does not affect airplane behavior until another mode is engaged)	Pilot	

Outcome: FMC provides guidence to follow window altitude with pitch to path and A/T to FMC speed

747-400 System

Mode: FLCH **Goal:** Reach and maintain window altitude (pitches to manual speed)

Representation: FLCH flowbar (engaged), green FMA "FLCH"

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available	none	make altitude window <> captured altitude	Pilot	window alt <> captured alt
Available	none	push FLCH button	Pilot	(if window alt is very close to current alt then FLCH engages for only a second then mode automaticaly changes to ALT)
Engaged	FLCH flowbar Green FMA "FLCH" Speed window opens as feedback	Select a different vertical mode Change speed Change altitude (before capture)	Pilot	

Outcome: AFDS provides guiedence to get near window altitude and then it calls ALT mode

Ignores FMC altitude restrictions.

IMMF
~~747-4~~00 System

Mode: TO/GA - Pitch **Goal:** Get the Airplane away from the ground

Representation: Up angled arrow on the VPD ???

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available		3 ways to arm:		
	1. None	1. Turn on F/D while on the ground	Pilot	
	2. None	2. Flaps out of up position in flight	Pilot/ AFDS	
	3. None	3. Capture glide slope in flight	Pilot/ AFDS	
Available	FMA - green TOGA Arrow (only for arm method 1) None (for arm methods 2 and 3)	Press TOGA switch	Pilot	
Engaged	~~Green TOGA arrow on VPD~~ FMA - green TOGA	Engage any other pitch mode	AFDS	TOGA armed

Outcome: AFDS provides guidence to get airplane away from the ground

printed 4/14/94

747-400 System

Mode: Vertical Speed **Goal:** Achieve and maintain vertical speed in MCP window

Representation: V/S flow bar (engaged), green FMA "V/S" V/S window is open ~~that~~ that shows V/S target.

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Always Available	none (must be in head) numbers in MCP window always show target V/S (what if mode not engaged? MJM)	Push V/S button	Pilot	none
Engaged	green FMA "V/S" V/S flowbar + open window	Select a different vertical mode Change airspeed Change vertical speed Change altitude (before capture)	Pilot	

Note: 1. Always available

Outcome: AFDS provides guiedence to maintain vertical speed
If vertical speed window is set to 0 then mode maintains current altitude.

747-400 System

Mode: Alt **Goal:** Maintain aircraft at window altitude

Representation: FMA - ALT

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available	none	Approach window altitude while in FLCH or V/S	Pilot	
Available	none	None		Automatic mode transition from FLCH or V/S into ALT
Engaged	FMA - Green ALT	select a different vertical mode Change airspeed Change altitude (will not affect airplane untill another mode is engaged)	Pilot	

Outcome: AFDS provides guidence fro airplane to follow window altitude

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747-400 System

Mode: ALT (HOLD) **Goal:** Maintain airplane at altitude switch is pressed at

Representation: Flow bar on ALT Hold switch, FMA - ALT

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Always Available	Hold button under Alt select knob says "hold" Pilot needs to know mode is always available (because other switches are alwasy present that are not always available)	press hold button	Pilot	
Engaged	Flowbar illuminates on Alt-hold switch. FMA - Green ALT	Select a different vertical mode change the speed change the altitude window (will not affect airplane perfrmance untill another mode is engaged)	Pilot	

Notes:

1. Alt Hold is always available in flight.

Outcome: AFDS provides guidence to maintain altitude switch was pushed at (mode engages immediatly)

IMMI System

Mode: VNAV Path **Goal:** Follow FMC vertical route (pitching to FMC speed)

Representation: Pitch icon in FMC altitude column, white or green FMA "VNAV SPD"

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available	no blue pitch icon in FMC altitude column	Make next waypoint restriction be: (a) above and within capture distance of current altitude or (b) below current altitude and "pathable"	Pilot	
			FMC	route programmed in FMC
Available	blue pitch icon in FMC altitude column	touch blue pitch icon in FMC altitude column	Pilot	
Armed	white pitch icon in FMC altitude column (none if automatic mode transition)	wait for engagement	FMC	
		If not engaging begin diagnosis	Pilot	
Engaged	green pitch icon in FMC altitude column green FMA "VNAV PTH"	Select a different vertical mode Change speed with speed intervention Change altitude	Pilot	

Outcome: FMC provides guidence to follow VNAV route with pitch to path

IMMI System

Mode: VNAV SPD　　**Goal:** Follow FMC vertical route (pitches to a speed)

Representation: Pitch icon in FMC speed column, white or green FMA "VNAV SPD"

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available	no blue pitch icon in FMC speed column	Make next waypoint restriction be: Both: (a) above current altitude and (b) not within capture distance Or both:(a) below current altitude and (b) not able to maintain path	Pilot	
			FMC	route programmed in FMC
Available	blue pitch icon in FMC speed column	touch blue pitch icon in FMC speed column	Pilot	
Armed	white pitch icon in FMC speed column (none if automatic mode transition)	wait for engagement	FMC	
		If not engaging begin diagnosis	Pilot	
Engaged	green pitch icon in FMC speed column green FMA "VNAV SPD"	Select a different vertical mode Change speed with speed intervention Change altitude	Pilot	

Outcome: FMC provides guidence to get near next FMC restriction altitude or FMC path (not really MJM) and then calls VNAV Path mode

IMMI System

Mode: VNAV ALT **Goal:** pitch to captured altitude with A/T to FMC speed

Representation: Pitch icon in manual altitude column with engine icon in FMC speed column, white or green FMA "VNAV ALT"

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available	no blue engine icon in the FMC speed column	(a) be within capture distance of window altitude, and (b) have next restriction altitude be on oposite side of window altitude from airplane	Pilot	
			FMC	route programmed in FMC
Available	blue engine icon in the FMC speed column	~~Push~~ Touch blue engine icon in the FMC speed column	Pilot	
Armed	white engine icon in the FMC speed column ?? white FMA "VNAV ~~ALT"~~ (none if automatic mode transition)	wait for engagement If not engaging begin diagnosis	FMC Pilot	
Engaged	Green pitch icon in manual altitude column with green engine icon in FMC speed column green FMA "VNAV ALT"	Select a different vertical mode Change speed with speed intervention Change altitude window (does not affect airplane behavior until another mode is engaged)	Pilot	

[illegible] can follow window alt with pitch

IMMI System

Mode: FLCH **Goal:** Reach and maintain window altitude (pitches to manual speed)

Representation: pitch icon in manual speed column, green FMA "FLCH"

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available	no pitch icon in manual speed column	make altitude window <> captured altitude	Pilot	window alt <> captured alt
Available	blue pitch icon in manual speed column	touch blue pitch icon in manual speed column	Pilot	(if window alt is very close to current alt then FLCH engages for only a second then mode automaticaly changes to ALT)
Engaged	green pitch icon in manual speed column Green FMA "FLCH" Speed window above manual speed column opens as feedback	Select a different vertical mode Change speed Change altitude (before capture)	Pilot	

Outcome: AFDS provides guiedence to get near window altitude and then it calls ALT mode
Ignores FMC altitude restrictions.

747-400 System

Mode: TO/GA - Pitch **Goal:** Get the Airplane away from the ground

Representation: FMA display

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available		3 ways to arm:		
	1. None	1. Turn on F/D while on the ground	Pilot	
	2. None	2. Flaps out of up position in flight	Pilot/ AFDS	
	3. None	3. Capture glide slope in flight	Pilot/ AFDS	
Available	FMA - green TOGA (only for arm method 1)	Press TOGA switch	Pilot	
	None (for arm methods 2 and 3)			
Engaged	FMA - green TOGA	Engage any other pitch mode	AFDS	TOGA armed

Outcome: AFDS provides guidence to get airplane away from the ground

IMMI System

Mode: Vertical Speed **Goal:** Achieve and maintain vertical speed in MCP window

Representation: Pitch icon with arrow attached, green FMA "V/S"

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Always Available	none (must be in head) numbers in ~~MCP~~ icon ~~window~~ always show target V/S ~~(what if mode not engaged? -MJM)~~	1) touch V/S wheel, then 2) touch blue V/S icon (that appeared when wheel was touched)	Pilot	none
Engaged	green pitch icon with arrow attached in manual altitude column green FMA "V/S"	Select a different vertical mode Change airspeed Change vertical speed Change altitude (before capture)	Pilot	

Note: 1. Always available (by a two step process)

Outcome: AFDS provides guiedence to maintain vertical speed
If vertical speed window is set to 0 then mode maintains current altitude.

IMMI System

Mode: Alt **Goal:** Maintain aircraft at window altitude

Representation: Pitch icon in manual altitude column with engine icon in manual speed column

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available	none	Approach window altitude while in FLCH or V/S Select blue man-spd-engine from VNAV - ALT	Pilot	
Available	none	None		Automatic mode transition from FLCH or V/S into ALT
Engaged	Green pitch icon in manual altitude column with green engine icon in manual speed column FMA - Green ALT	select a different vertical mode Change airspeed Change altitude (will not affect airplane untill another mode is engaged)	Pilot	

Outcome: AFDS provides guidence for airplane to follow window altitude

IMMI System

Mode: ALT (HOLD) **Goal:** Maintain airplane at altitude switch is pressed at

Representation: Button in center of altitude knob, Green VPD line at the altitude button is pressed at, FMA - ALT

Mode State	Interpretation of System State	Available Actions	Source	AFDS Constraints
Not Available	center of altitude knob is not blue	get out of combined LOC and G/S mode	Pilot	
Available	Button in center of altitude knob is blue	press blue button in center of altitude knob	Pilot	
Engaged	Button in center of altitude knob is green FMA - Green ALT Man Pitch - PitG icon - Green c? ALT .	Select a different vertical mode change the speed change the altitude window (will not affect airplane perfrmance untill another mode is engaged)	Pilot	

Outcome: AFDS provides guidence to maintain altitude switch was pushed at (mode engages immediatly)

Appendix 4

May 22,1995
Rev

IMMI - SFO to LAX

ATC Script

This is a flight starting at the holding short position of runway01R at the San Francisco International Airport. The crew will enter the flightdeck with engines running. All checklists through the Before Take-off Checklist will have been completed. The only preflight tasks to beperformed by the crew will be set up of the MCP and loading the FMC. Afterobtaining ATC clearance, they will takeoff and proceed to the Los AngelesInternational Airport via a normal routing. There will be no malfunctions along the way.

IP 1 SFO RWY 01R
N 37.605
W 122.381666
HDG 130
Altitude 11ft.

InitialConditions:
GW - 190,000 lbs.(ACFS) 620,000 lbs (747)
Fuel - 30,000 lbs. (ACFS) 100,000 lbs (747)
Altimeter - 29.92
Wind - 0/0

Weather:

SFO - Clear, 50 nm vis

Enroute - Clear, 50 nm vis., TURB - Level 4, FL280 thru FL360
Level 1 at FL370

LAX - ~~Clear, 50 nm vis~~. CIG1500 OCST 5 FZ TOPS REPTD 3500

Airborn IP

This is a flight starting at approximately 50 nm prior to top of descent forthe SADDE 5 arrival for Los Angeles International Airport . The onlypreflight tasks to be performed by the crew will be set up of the MCP andloading the FMC. After obtaining ATC clearance, they will proceed to the Los Angeles International Airport viaa normal routing. There will be no malfunctions along the way.

IP2 APPROX 50 nm prior T/D
N 35.750
W 120.016666
HDG 130
Altitude FL330
Speed/Mach 0.82

InitialConditions:
GW - 190,000 lbs.
Fuel - 30,000 lbs.
Altimeter - 29.92
Wind - CALM

ATC PHRASEOLOGY

(After crew calls for clearance)

SFO CLR: NASA~~2001~~ *8001* IS CLEARED TO THE LAX AIRPORT VIA THE PORTE 9 DEPARTURE, AVE TRANSITION, FLIGHTPLAN ROUTE. MAINTAIN ~~FL230~~ *6000*, EXPECT FL330 10 MINUTES AFTERDEPARTURE. DEPARTURE FREQUENCY WILL BE 135.1, SQUAWK 3724.DO NOT EXCEED 250 KNOTS UNTIL ADVISED.

(After the crew calls for takeoff)

SFO TWR: NASA8001, AMEND YOUR CLEARANCE, CROSS PORTE ABOVE 9000 AND BELOW 11000 FEET. TAXI INTO POSITION AND HOLD, RWY 1R.

(Give the crew time to enter the alt and take position)

SFO TWR: NASA8001, WIND Calm, CLEARED FOR TAKEOFF

(When the cab leaves 500)

SFO TWR: NASA8001, CONTACT BAY DEPARTURE

(After crew calls)

BAY DEP: NASA8001 BAY DEPARTURE, RADAR CONTACT. MAINTAIN 6,000

(When cab's heading is 200)

BAY DEP: NASA8001, TURN ~~RIGHT TO 230~~ *LEFT TO 180* FOR SPACING

(After 30 seconds)

BAY DEP: NASA8001, TURN ~~LEFT~~ *RIGHT* TO xxx, INTERCEPT AND RESUME THE PORTE 9 DEPARTURE

(As cab approaches ~~6,000~~ *3,500*)

BAY DEP: NASA8001, ~~CROSS PORTE AT OR BELOW 11,000,~~ CLIMB *UNRESTRICTED* AND MAINTAIN 15,000

(As cab approaches 10,000)

BAY DEP: NASA8001, CONTACT OAK CENTER ON 125.45

(After crew calls)

OAK 12L: NASA8001 OAK CENTER, ROGER

(As cab approaches 15,000)

OAK 12L: NASA8001, CLIMB AND MAINTAIN FL240, RESUME NORMAL SPEED

(As cab approaches 20,000)

OAK 12L: NASA8001, CONTACT OAK CENTER ON 133.7

(After crew calls)

OAK 15H: NASA8001 ~~FLxxx~~ ROGER

~~(As cab approaches 21,000)~~

~~OAK 15H: NASA8001~~, CLIMB AND MAINTAIN FL290, EXPEDITE THROUGH ~~FL240~~ *FL250*

(At 25,000)

OAK 15H: NASA8001, CLIMB AND MAINTAIN FL370 -**TURBULENCE**

(At OAK/LAX border)

OAK 15H: NASA8001, CONTACT LAX CENTER ON 124.15

(After crew calls)

LAX 26H: NASA8001 LAX CENTER FL370 ROGER

(At .84)

Note for the researchers: the ACFS is unable to attain aspeed in excess of Mach .85

LAX 26H: NASA8001, CLEARED FOR THE SADDE 5 ARRIVAL. DESCEND AT PILOT'S DISCRETION, CROSS SIMON AT AND MAINTAIN 12,000~~. BEGIN YOURDESCENT AT THE FIM 64 DME, AT 280 KNOTS,~~ LAX ALTIMETER29.92

-OR-

(Between .82 and .84)

LAX 26H: NASA8001, CLEARED FOR THE SADDE 5 ARRIVAL. CROSS SIMON AT AND MAINTAIN 12,000. BEGIN YOURDESCENT AT THE FIM 58 DME, AT 280 KNOTS, LAX ALTIMETER29.92

-OR-
(Below .82)

LAX 26H: NASA8001, CLEARED FOR THE SADDE 5 ARRIVAL. CROSS SIMON AT AND MAINTAIN 12,000. BEGIN YOURDESCENT AT THE FIM 50 DME, AT 280 KNOTS, LAX ALTIMETER30.01

(When cab approaches 24,000)

LAX26H: NASA8001, CONTACT LAX CENTER ON 132.6

(After crew calls)

LAX14L: NASA8001 FLxxx, ROGER

(When cab passes 13,000)

LAX14L: NASA8001 CONTACT SOCAL APPROACH ON 124.5

(After crew calls)

SOCAL APP: NASA8001 SOCAL APPROACH ROGER, CROSS SADDE AT 250 KNOTS AND BAYST AT 10,000

(When cab passes SADDE)

Note for the researcher: If the crew loads and ***executes*** *the ILS 24R, they will be unable to changeto an ILS 25L*

SOCAL APP: NASA8001, DEPART SMO HEADING 070 FOR VECTORS TO THE FINAL APPROACH COURSE. ~~BEADVISED~~ EXPECT ILS 24~~L~~ *R* APPROACH. IF 25L BECOMES AVAILABLE, I WILL CHANGE YOUR RUNWAY.

(When cab passes BAYST)

SOCAL APP: NASA8001, REDUCE SPEED TO 200

(When cab passes SMO)

SOCAL APP: NASA8001, DESCEND AND MAINTAIN 5,000

(When cab passes 6,000)

SOCAL APP: NASA8001 REDUCE SPEED TO 180

(When cab ~~approaches FANGY~~ *is 1 mi east of SAPP)*

SOCAL APP: NASA8001, TURN RIGHT HEADING 160, FOR VECTORS TO THE FINAL APPROACH ILS ~~25L~~ *24R*. DESCEND AND MAINTAIN 4,000

(As cab passes 4,500)

SOCAL APP: NASA8001 REDUCE SPEED TO 170

(When cab approaches final)

SOCAL APP: NASA8001, xx MILES FROM ~~LIMMA~~ *ROMEN*, TURN RIGHT HEADING 220, MAINTAIN ~~3,000~~ *4000* UNTIL ESTABLISHED ON THE LOCALIZER, CLEARED FOR ~~ILS25L~~ *ILS24R* APPROACH

(When LOC and G/S have engaged)

SOCAL APP: NASA8001, xxx MILES FROM LIMMA, TURN LEFT HEADING 220 VECTOR FOR THE ILS25L LOCALIZER, MAINTAIN 3000 UNTIL ESTABLISHED, CLEARED FOR THE ILS25L APPROACH.

(When cab is on final)

SOCAL APP: NASA8001, MAINTAIN 170 KNOTS TO LIMMA, CONTACT LAX TOWER ON 120.95

After crew calls)

LAX TWR: NASA8001 LAX TOWER, WIND CALM, CLEARED TO LAND 25L

(When cab approaches taxi speed)

LAX TWR: NASA8001 JUST STOP ON THE RUNWAY

Appendix 5

```
======================
SCENARIO
=====================


==========
SFO-LAX
==========


SFO..PORTE9.AVE.FIM.FIM6..LAX
FL 330                  (note this FL is lower than the final ATC
                         clearance. We are looking for a problem here. )
```

Departure Clearance

CLDR:
"NASA eight hundred is cleared to the Los Angeles International Airport as filed, on departure fly heading 281 to the Porte 9 departure cross Porte above niner thousand and at or below one one thousand, climb and maintain six thousand, expect higher one zero minutes after departure, do not exceed two hundred fifty knots until advised, departure frequency will be one twenty one point three, squawk 3654."

or , if Departure Clearance by ACARS:

```
**DPTR CLRNC**
FLT 800  SFO - LAX
NASA800 KSFO
/B757/ P1815  RQ330                    /747-4/ for the -400
XPDR 3654
MAINT 6000 CROSS PORTE
ABOVE 9000 AND BELOW
11000 EXP REQ ALT 10 MIN
AFT T/O
GND CTL FREQ 121.8
/DPTR CTL SEE SID
DO NOT EXCEED 250 KTS
UNTIL ADVISED
EXPECT RWY 28L DEPT
KSFO.PORTE9.AVE.FIM.
FIM6..LAX
```

A/C Call for push back clearance

Ground:
"NASA eight hundred, clear to push"

A/C Call for taxi clearance

Ground:
"NASA eight hundred, taxi to runway 28L via the inner and Foxtrot."
[Note: 747-400s are restricted from using taxiway E to or from taxiway B]

```
=======================
Normal takeoff clearance.
=======================
```

After Takeoff and prior to 1000':
"NASA 800 contact departure"

```
=======================
```

NASA 800 checks in with departure "......"

"NASA 800 Bay departure radar contact"

Radio chatter from other pilots in area ......

We expect the crews to be flying in LNAV and VNAV with A/P engaged before reaching the first turn point.
====================== The SID calls for a 101 degree left turn.
Upon rolling out on the 180 degree heading
"NASA eight hundred, turn left 10 degrees for traffic."

30 seconds later
"NASA eight hundred, resume the Porte 9 departure."

What we expect to see:

MCP: Possible engagement of heading select with the heading bug behind the airplane.

IMMI: pilot has to find the heading bug in order to engage the mode. Can't make this mistake on our interface.

Rationale: It's been observed in training and from the jumpseat. It will be important to keep the crew busy looking for traffic while the airplane is making the turn in LNAV.

================(set up an unexpected VNAV level-off)
Out of 5000'
"NASA 800 climb unrestricted to one five thousand."

What we expect to see:

MCP: We have now set up the analog of the Peble1 departure from SAN. They will put 15000 in the window, but an at-or-below altitude restriction remains at PESCA. May see an unexpected level off. It will be essential to have the performance characteristics worked out so that the airplane will reach 10000 prior to Porte. Since Porte normally required at-or-above 9000, this should be assured in a light 747-400.

IMMI: The vertical path display should make the level-off apparent.

======================== (hand off to Center)
Out of 11000'
"NASA 800 contact Oakland Center on 125.45"

======================== (clearance higher)
Let them level at FL150
When level at FL150
"NASA 800 climb and maintain FL290"

========================= (set up wingtip LNAV)
after crossing Porte

"NASA 800 turn left 20 degrees for traffic" (to 115)

This has the effect of cutting the Pesca waypoint corner of the route

======================= (wingtip LNAV)
When almost abeam of Pesca

"NASA 800, traffic no factor, resume the Porte 9 departure, thanks for

your help."

What we expect to see:

MCP: Possible engagement of LNAV with active waypoint abeam. This produces a steep right turn toward Pesca when pilots expect a shallow left turn to line up with Wages waypoint in front of them.

IMMI: Pilots have to find the active waypoint to engage the mode. It should be obvious that it's off the end of the wing. So, they go to CDU and make the next wpt active, then engage it.

Rationale: MCP LNAV is a "meta-button." It has no content. IMMI's engagement operation requires the pilot to interact with the spatial meaning of the operation.

======================== (hand off to Center 2) .
Out of FL210
"NASA 800 contact Oakland Center on XXXXXX" (<- need freq)

A/C "Oakland Center NASA 800, out of 220 for 290."

======================= (Center 2 pick up and expedite climb)
"NASA 800 roger, expedite your climb through FL240."

Features: Speed intervention is not shown as available on either interface. The (someday) blue speed select button on the IMMI gives a clue that something is available there. Two problems here. 1) Getting a mode or sub-mode that will control speed. 2) What is the 'best rate of climb' speed right now?

What we expect to see:

MCP: "how do I find that? 250 ought to be about right." The right way to do it is to go to the VNAV page in the CDU. Field 6R of the VNAV page shows Vx. And from school you remember that you can get a good approximation of Vy by adding 25 Knots to Vx.

IMMI: If they can get into speed intervention, setting the icon next to the Vy bug should be easy.

==================== (resume normal speed, final alt clearance)
out of FL250
"NASA 800
----
resume normal speed, (if pilots forgot to resume on own)
-------- (or)
climb and maintain FL370
thanks for your help."

=================== (possible unexpected level off at cruise)
Final clearance is higher than initial clearance entered into CDU as cruise altitude. This is a hidden state in the MCP system.

What we expect to see:

MCP:
Expect that the pilots may not edit the cruise page in the CDU to reflect the final ATC clearance and will be surprised when the airplane levels prior to the altitude in the MCP window.

IMMI:
Expect that the pilots will notice the magenta line levels prior to the window altitude line and they will edit the CDU to change cruise altitude to reflect the final ATC clearance.

==============================(Descent Clearance:)

"NASA 800 cleared for the Runway 24/25 Profile descent"

============================== (Over Speed lose path)
During descent a tail wind forces the airplane to use higher and higher speeds to stay on the path. As the airspeed approaches the top of the operating envelope, the FMC abandons pitching to the path with VNAV PATH and instead pitches to a speed with VNAV SPD.

What we expect to see:

MCP:
(a) scratch pad message "drag required", (b) overspeed warning boxes on PFD airspeed tape move toward the current airspeed marker, (c) FMA's change from VNAV PTH to VNAV SPD. The pilots may not notice these changes and the mode transition.

IMMI:
(a) VPD predicted path will diverge from the FMC path at the 4D point of the expected mode transition, (b) the IMMI current airspeed window will climb up on the speed tape toward the overspeed warning area, (c) the pitch to path icon will turn amber, (d) the pitch and engine icons will swap sides of the IMMI when VNAV PTH changes to VNAV SPD, (e) all the changes above for the MCP will also occur. We expect the pilots will notice these changes before the mode transition occurs.

==============================
More clearances need to be written here for standard descent.

Los Angeles Airport information Sierra, 1650 zulu. ...

Somewhere in here
"Expect runway 24R."

==============================

East of Santa Monica:
"NASA 800 descend and maintain 5000'"

Over down-town:
"NASA 800 turn right heading 160 descend and maintain 4000"

Expect to see: use of V/S to make a smoother decent from 5000 to 4000. The IMMI will have the opportunity to show its awkward V/S interface which may be harder to use than the -400.

Turn inbound
"NASA 800 turn right heading 220 vector to the runway 24R localizer, cleared for the runway 24R approach."

==============================
The vectors, altitudes, and approach clearance must be given in such a way that LOC and G/S can engage well outside the outer marker. The altitude of the glideslope at Merce is 4783 MSL. Joining the localizer at 4000 will lead to G/S intercept about 6 miles outside of Romen. Once the aircraft is locked in on 24R,
ATC calls for a runway change. (This works in the Boeing Datalink study scenario, consult that for details).

"NASA 800, 24R glideslope signal is fluctuating, turn left to heading 220 vector for the Runway 25L localizer, cleared to land, runway 25L."

Expect to see:

BOTH:

Difficulties in disengaging from the LAND configuration

MCP:
No indication that TOGA is the only mode available.

IMMI:
Information available perceptually that no modes - except TOGA - are available (no blue on the screen). This should help crews remember that they have to disengage everything to get another pitch or roll mode.

====================
On 1 mile final, another aircraft moves onto the runway.
"NASA 800 go around fly the published missed approach.

A/C acknowledge

"NASA 800 contact departure on 124.3"

A/C "Departure, NASA 800, missed approach off 25L"

"NASA 800 climb and maintain 3000 proceed to the INISH intersection as published hold west on the SEAL BEACH 251 degree radial, left hand turns."

Release from hold and normal landing on 25L