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Crew Aiding and Automation: A System Concept for Terminal Area Operations, and Guidelines for Automation Design

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ACRONYMS AND ABBREVIATIONS

ADI	Attitude Director Indicator
ARNES	The ARNES waypoint
ASRS	Aviation Safety Reporting System
ATC	Air Traffic Control
ATIS	Automatic Terminal Information Service
AVENAL VOR	The AVENAL VOR
BAYST	The BAYST waypoint
CBT	Computer Based Training
CIVET	The CIVET waypoint
CIVET TWO, CIVET2	The CIVET TWO Profile Descent into LAX
CTAS	Center/TRACON Automation System
DA	Descent Advisor
DAC	Douglas Aircraft Company
DERBB	The DERBB waypoint
DL	Data Link
DME	Distance Measuring Equipment
DOWNE	The DOWNE approach fix
Dx	Distance of x miles past a given waypoint
EC	Enhanced Cockpit
ETA	Estimated Time of Arrival
FAA	Federal Aviation Administration
FAST	Final Approach Spacing Tool
FCP	Flight (Mode) Control Panel
FGS	Flight Guidance System
FIM VOR, FIM	The FILLMORE VOR
FMCP	Flight Mode Control Panel
FMEAs	Failure Modes and Effects Analyses
FMS	Flight Management System
FUELR	The FUELR waypoint
GPS	Global Positioning System
GPWS	Ground Proximity Warning System

GS	Glide slope
HDF	The HOMELAND waypoint
HUNDA	The HUNDA approach fix
ILS	Instrument Landing System
IM	Inner Marker
INS/IRS	Inertial Navigation System/Inertial Reference System
JOGIT	The JOGIT waypoint
KAYOH	The KAYOH waypoint
KAYOH TWO	
STAR	The KAYOH TWO Standard Terminal Arrival Route into SNA
KTS	Knots
LA	Los Angeles
LAX	Los Angeles International Airport
LEMON	The LEMON approach marker
LIMMA	The LIMMA outer marker
LOC	Localizer
MCDET	Most Current Data Exchange Transmission
MCDU	Multifunction Control/Display Unit
MDA	McDonnell Douglas Aerospace
MDC	McDonnell Douglas Corporation
MM	Middle Marker
NASA	National Aeronautics and Space Administration
NAV	Navigation
ND	Navigation Display
NE	North East
NI	Navigation Implementation
nm	nautical mile
OM	Outer Marker
PD	Profile planning Display
PFD	Primary Flight Display
REYES	The REYES waypoint
ROGER	acknowledge receipt of last communication transmission
ROMEN	The ROMEN outer marker
SADDE	The SADDE waypoint

SADDE FOUR	
STAR	The SADDE FOUR Standard Terminal Arrival Route into LAX
SADDE4 Profile	
Descent	The (hypothetical) profile descent version of the SADDE FOUR Arrival
SLI VOR	The SEAL BEACH VOR
SMO VOR	The SANTA MONICA VOR
SNA	Orange County, California's John Wayne Airport
SNAKE	The SNAKE approach fix
STA	Scheduled Time of Arrival
SUZZI	The SUZZI waypoint
SYMON	The SYMON waypoint
SYS	An abbreviation for the TANDAM system
TANDAM	Terminal Area Navigation Decision Aiding Mediator
TCAS	Traffic alert and Collision Avoidance System
TMA	Traffic Management Advisor
TOD	Top Of Descent
TRACON	Terminal Radar Area Control
VOR	VHF Omnidirectional Range transmitter
VTU VOR	The VENTURA VOR
WILCO	Will Comply
4-D, 4D	Four Dimensional
24R	The 24 Right runway at LAX
25L	The 25 Left runway at LAX

Crew Aiding and Automation: A System Concept for Terminal Area Operations, and Guidelines for Automation Design

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Advanced Transport Aircraft Development

SUMMARY

This research and development program comprised two sets of technical efforts: The development of a set of guidelines for the design of automated systems, with particular emphasis on automation design that takes advantage of contextual information; and the concept-level design of a crew aiding system -- the Terminal Area Navigation Decision Aiding Mediator (TANDAM). This concept outlines a system capable of organizing navigation and communication information and assisting the crew in executing the operations required in descent and approach. This design concept exemplified the incorporation of the automation guidelines, and provided a design that was responsive to the requirements of the commercial transport mission. In service of this endeavor, problem definition activities were conducted that identified terminal area navigation and guidance as the focus for the ensuing conceptual design activity. The effort began with detailed requirements definition and operational familiarization exercises of direct relevance to the terminal area navigation problem. Both airborne and ground-based (ATC) elements of aircraft control were extensively researched. The products of these activities constituted the starting points for the design effort, in which the TANDAM system concept was specified, and the crew interface and associated systems were described. Additionally, three detailed descent and approach scenarios were devised in order to illustrate the principal functions of the TANDAM system concept in relation to the crew, the aircraft, and ATC. A proposed test plan for the evaluation of the TANDAM system was established. The guidelines were developed and refined based on reviews of relevant literature, and on experience gained in the design effort.

INTRODUCTION

BACKGROUND

The development of modern transport aircraft continues to introduce new, powerful technologies to the domain of the National Airspace System. Advances in data input, analysis, and transfer, coupled with developments in information display, control, and management have provided the air transport crew with the potential for unprecedented operational capabilities. Current automated systems for information management, (i.e., systems that organize, filter, and provide other systems and the crew with vital information) have made possible dramatic improvements in ride quality, fuel burn, navigation, systems monitoring and diagnosis, and communications. Automation has also played heavily in the recent incorporation of time-critical safety systems such as the Traffic alert and Collision Avoidance System (TCAS) and reactive windshear technologies. In the near future, these advances in airborne automation will be accompanied by major changes in equipment and procedures for ground-based air traffic management. Next generation Air Traffic Control (ATC) will rely heavily on automation for assistance in aircraft spacing, flow rates, collision avoidance, complex approaches, handoffs, and air-ground communications--all designed to increase capacity and efficiency while maintaining or even increasing levels of air travel safety.

These increased capabilities arrive at a time when they are sorely needed;

by some accounts, air transport passenger growth will more than double in the next two decades, and instrument controlled operations will be more than half again as frequent in terminal areas as they are at present (reviewed in ref. 1). However, according to researchers such as Wiener (ref. 2), the full benefits of these capabilities have yet to be realized. Sarter and Woods (ref. 3), for example, reported that pilots view certain Flight Management System functions as providing advanced capabilities at the price of increased crew workload, difficulty in anticipating all of the automation's actions, and the possible degradation in the crew's awareness of the aircraft's overall status and flight situation.

These concerns arising from operational experience with the current generation of automation have prompted NASA and industry to re-evaluate the implementations of these advanced capabilities. Billings (ref. 4), in his review of cockpit automation, states the issue succinctly:

It should be noted immediately that it is not clear whether this [issue regarding the capabilities of some current automation] is an inherent automation problem, or whether this is because we have not provided simple enough interfaces through which pilots interact with automation. (p. 17)

One often mentioned concern about current automation is that designers have not gone far enough in accommodating and capitalizing on human cognitive and perceptual abilities. For example, in a comparison of operations in more and less automated cockpits, Wiener and his colleagues (ref. 5) observed that ostensibly similar navigation tasks -- either performed manually (in one aircraft) or by means of automation (in

another) -- demonstrated differences in crew procedures that did not take full advantage of the crew's ability to effectively manage workload.

In an effort to galvanize the research and development community around such concerns, NASA has developed a major research thrust that expressly calls for the development of automated systems designed to fully capitalize on the capabilities of the human operator while still providing to that operator the rather substantial benefits realizable with automation. This philosophy of "human-centered" automation was identified as critical to the success of the next generation of automated systems in NASA's "Aviation Safety/Automation Program" (ref. 6). Wiener and Curry (ref. 7) and Billings (ref. 4) have articulated the major tenets of this philosophy in the form of design guidelines and recommendations.

Flight deck automation design can clearly profit from adherence to all aspects of human-centered design, but several general issues are of particular importance:

- Ensuring that the crew can readily understand, anticipate, and influence the actions of the automation;
- Ensuring that use of the automation does not detract from, but rather enhances the crew's continual situation awareness;
- Ensuring that the automation optimizes crew workload, and that it operates in an error-resistant and error-tolerant fashion, without contributing to such dangerous conditions as complacency or unnoticed failures;

- Ensuring that the automation interface facilitates crew involvement and awareness, and maintains crew prerogative by recognizing and supplementing the crew's understanding of mission objectives, current flight status, and probable future situational variables.

A human-centered approach to automation presupposes that the human operator possesses many of the critical skills and knowledge required for safe, efficient flight; this approach therefore endorses the employment of human capabilities as vital to successful design. Researchers and the pilot community both point to such human assets as the ability to learn from experience, to make quick, decisive judgements in uncertain, time-critical situations, and to cope with unanticipated, perplexing problems--even when these problems have, perhaps, never been encountered before, or when they may suggest no one "correct" solution. It is perhaps no surprise, therefore, that the most sophisticated efforts in developing artificial intelligence and other "smart" automated systems focus on these same problem-solving and decision-making abilities. Thus, it is essential that advanced automated systems assist the transport crew in these high-level tasks, if these systems are to be considered genuinely human-centered. But to be able to perform such functions, automated systems must be able to monitor and assess several classes of mission-relevant variables: The rapidly changing situation of the aircraft at any given point in its route, the more strategic elements of the mission plan (and modifications by ATC and other external conditions), the crew's cognitive and physical states, and their anticipated needs and preferences. In these important respects,

human-centered automation must be adaptive to the flight situation, and responsive to crew and mission demands.

PROBLEM

Information flow in the modern transport cockpit continues to increase in quantity and variety; the need to effectively manage and use this information is rapidly outstripping the limited processing capabilities of the human crew in many operational arenas (ref. 2; ref. 3). This explosion of information (and its consequent critical need for effective control) can be seen in virtually all flight-critical functions:

- Communication functions--these can range from Data Link functions to voice communications activities.
- Flight and navigation functions--this area encompasses several classes of activities: those currently covered by the Flight Guidance System and the Flight Management System; those related to aspects of flight control optimization; and those involved with such time-critical event systems as the Ground Proximity Warning System (GPWS), the Traffic alert and Collision Avoidance System (TCAS), and windshear alerts.
- Aircraft systems functions--these concern functions involved with electrical, hydraulic, fuel, and propulsion systems. Future applications include sophisticated component failure diagnostic capabilities associated with a broad range of onboard systems.

It is evident, then, that effective human interface systems, automation responsive to mission requirements, and other aspects of human-centered design will have to keep pace with the rapid development of flight deck automation if successful implementation is to result. And while pilots' opinions of current-day automation are clearly positive, their concerns with some aspects of current implementation readily highlight areas for improvement. For example, studies by Wiener (ref. 2) and Billings (ref. 4) have reported that crews characterize some instances of automation as:

- Sometimes confusing or opaque in their operation, and in the consequences of their actions;
- Workload-intensive during already high-workload periods and workload-alleviating during already low-workload periods;
- Insidious with respect to error creation and propagation, and inadequate with respect to error detection and rectification;
- Unresponsive or cumbersome with regard to on-line modifications necessitated by unplanned changes or unanticipated events; and
- Poorly integrated with related onboard and/or ground-based systems.

Researchers have characterized the crew's changing role in the modern, highly automated cockpit as moving from continuous hands-on control of the aircraft to managing its many sophisticated systems. While this is certainly true, the characterization does not sufficiently emphasize the important point that this new managerial role, if not executed prudently, carries with it the danger of removing the crew from their primary

responsibility--safely and efficiently transporting passengers and aircraft from Point A to Point B. In this important sense, the role of the crew has not changed and is not likely to change in the near future. The problem, then, is how to allow the crew to maintain involvement, prerogative, and awareness of mission functions while fully exploiting the capabilities of automated assistance to efficiently perform these essential duties.

RESEARCH OBJECTIVES

The principal goal of this research was to develop and demonstrate a concept for an automated system capable of fully exploiting situation-specific information in order to tailor and optimize its assistance to the aircrew. This use of situational cues (e.g., significant flight plan events, environmental conditions, aircraft state data, crew inputs, and ATC directives) to constrain and direct the automation's operation is herein referred to as employing "context-sensitive" automation. Based on analyses of accident and incident reports and other relevant operational data, descent- and approach-phase navigation and communication activities were identified as the functional domains to be incorporated in this conceptual design. At the onset, it was clear that this research was to embrace two related themes: A heavy reliance on human-centered design principles and guidelines, and the aforementioned incorporation of automation concepts capable of adapting to and utilizing operational, situational, and crew-initiated inputs. It was anticipated that the concept for the automated system would, where appropriate, incorporate or accommodate:

- Mission/functional requirements and safety considerations;
- Situational conditions that could vary due to mission phase, specific events (planned and unplanned), pilot preference, etc.;
- Mental models, and other cognitive, perceptual, and operational characteristics of crew members. Included also in this concern were relevant crew emotional and physiological states.

A supporting goal of this research was the delineation of improved integration and coordinated operation of the system concept with other airborne (e.g., Data Link) and ground-based systems. This goal was served by conducting research concerning the overall integration of the individual onboard systems at a crew system information management level. Among other duties, this overall mission/aircraft management function would be responsible for the timely coordination and high-level processing of all aircraft systems necessary for continual crew involvement and control.

The second major goal of this program was to develop design guidelines suitable for assisting designers in their creation of automation. Particular emphasis was placed on developing guidelines for automation designed to exploit aspects of specific situational information. Significant efforts were made to ensure that these guidelines incorporated relevant issues raised in other existing design guidelines documents.

APPROACH

OVERVIEW

This research and development program comprised two technical efforts: (1) The development of a set of guidelines for the design of automated systems, with particular focus placed on automation that takes advantage of contextual information; and (2) the conceptual design of an automated system capable of assisting the crew in terminal area navigation and communication operations. The design effort would both exemplify the incorporation of the guidelines, and hopefully offer a point design demonstrating the superior value of an automated system responsive to the mission-driven requirements of the commercial transport environment. These two sets of technical activities are schematicized in Figure 1. As is depicted in the figure, identifying candidates for automation and conducting preliminary problem definition activities yielded the (aforementioned) candidate issue for the resulting design effort. These activities and a literature review also provided inputs to the generation of the design guidelines. The design effort began with detailed requirements definition, and operational familiarization activities of direct relevance to the terminal area navigation and communication problem. The products of these activities constituted the starting points for the design effort proper, in which the system concept was specified, and the crew interface and associated systems were described. A test plan for the evaluation of the system concept was then established. Guidelines for conducting design efforts with technical objectives similar to the present endeavor were documented.

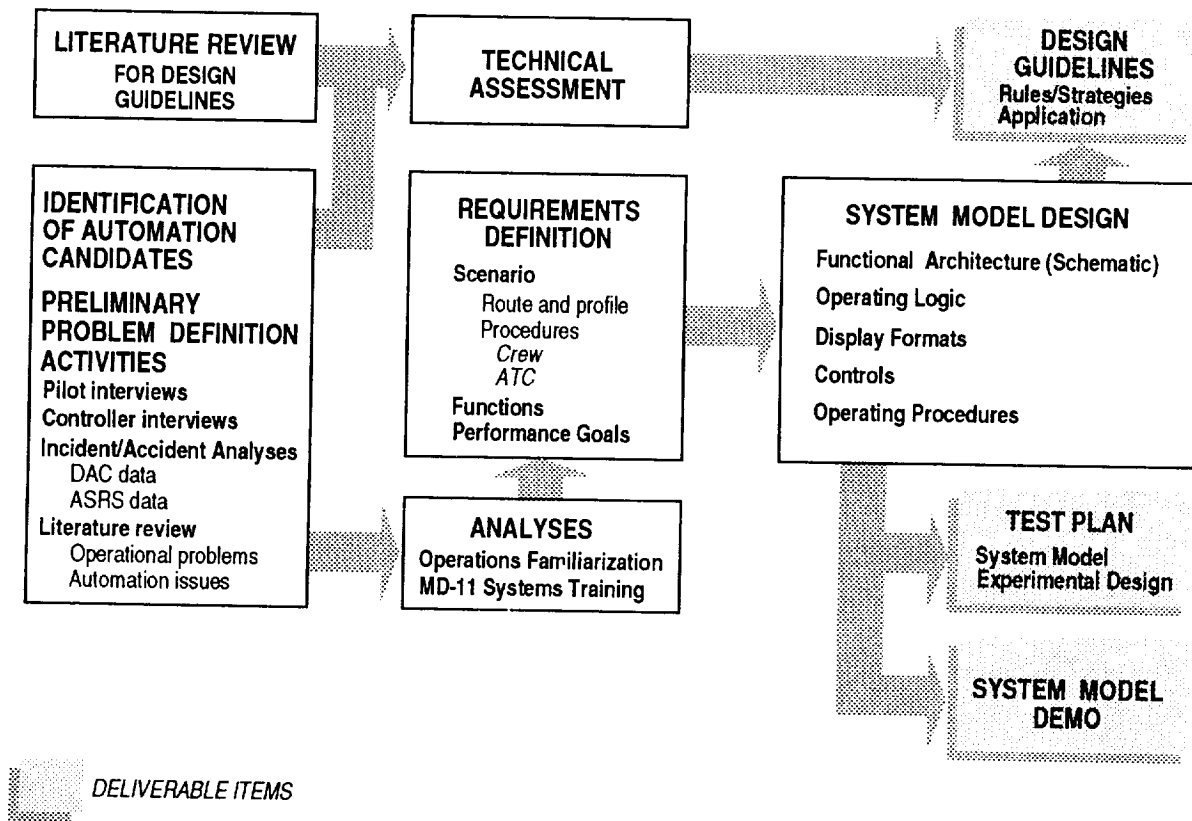


FIGURE 1. TECHNICAL APPROACH

DESCRIPTION OF PROJECT ACTIVITIES

Development of Design Guidelines

Development of the design guidelines began with a review of two sets of technical literature: A sizable and varied set of papers addressing issues in automation development, and a small number of papers offering design guidelines, general suggestions, and organizational schemes relevant to automation design. From these readings, and from our experiences on the present design effort, a framework for the current guidelines was established. Detailed design guidelines (gleaned from this literature review and developed in the course of the current design effort) were then generated in response to this organization. These guidelines were subsequently reviewed and refined by McDonnell Douglas Corporation (MDC) crew station design personnel.

Problem Definition for Design of an Automated System

The first component of the design effort was a problem definition activity involving the analysis of incident and accident data, and the review of literature germane to operational problems and to automation issues generally. Incident and accident data were obtained from three sources: A data base maintained by MDC, anecdotal accounts and pilot interview responses reported in research papers (e.g., ref. 4), and a contractor-solicited Aviation Safety Reporting System analysis of FMS operation problems occurring during descents and approaches (ref. 8). Analysis of these data yielded a

fairly clear representation of the problems with current automated systems (principally the FMS), and a rough indication of what aspects of the mission (in terms of crew workload and situation awareness, phase of flight, aircraft configuration, and external conditions) "invited" their characteristic occurrence. This analysis also provided indirect guidance for recognizing potential design shortcomings, and for suggesting ways of preventing their incorporation into future systems.

The literature review generally supported and amplified the aforementioned incident/accident findings, and also provided information as to the probable direction and scope of advanced automation technologies currently under development for inclusion in the National Airspace System. Airborne technologies mentioned included sophisticated data base systems, 4-D navigation capabilities, differential global positioning systems, and Data Link systems. Ground-based developments ranged from automated maintenance and diagnosis equipment to the Center/TRACON Automation System (CTAS) designed to control aircraft spacing in the terminal area. This information was invaluable since it helped define the sort of general automated environment that could reasonably be assumed to exist in the time frame when a system like the one under consideration might become operational. Moreover, a thorough understanding of these advanced technology concepts (in particular, CTAS) proved to be a strong driver in the determination of the present system concept's functional requirements, and an important constraint on the responsibilities this system would possess, share, or depend upon from other sources. Similarly, insights were gained regarding the possible

allocations of functions between the aircrew and the automation. In large part, these insights dictated the role of the automated system and the design philosophy adopted in this concept development effort.

This problem definition activity concluded with the identification of the general operational domain to be served by the automated system -- navigation, guidance, and supporting communications functions occurring in descents, approaches, and landings.

Operational Familiarization

Following this problem definition effort, a number of operational familiarization activities were pursued. Familiarization with relevant airborne systems and operations covered an extensive range of activities. The MD-11's Computer-Based Training (CBT) program offered operational information about all major guidance and control systems. CBT sessions on the MD-11's Autoflight system (Autopilot, Autothrottles, etc.), Flight Management System (FMS), and associated displays and controls provided detailed procedural knowledge regarding these systems and their functioning. Extensive reviews of the MD-11's various operational manuals complemented the CBT information. The MD-88's operational manual for its FMS was also studied in order to compare this earlier generation flight guidance and navigation automation with the MD-11's configuration.

Accompanying these efforts to become familiar with existing automated systems were reviews of a number of critical capabilities not yet in service (in their more fully capable versions). Airborne 4-D navigation (i.e., navigation including precise schedule constraints along the route) capabilities were reviewed for their obvious potential utility for advanced navigation management. Concepts for Data Link systems -- including interface issues such as display content and format, and air-ground interactive requirements -- were evaluated so as to ascertain the probable operational advantages and limitations they would present for the automated system under consideration in this research effort. Familiarization with airborne systems also included a review of the sophisticated capabilities and operations envisioned for next-generation commercial transports such as the Enhanced Cockpit (EC) concept for the MD-90 aircraft.

Substantial familiarization with the relevant ground-based systems was seen as essential to the ultimate viability of the automated system design concept under development in the present research effort. To this end, significant effort was expended studying the procedures of terminal area air traffic controllers and their associated reasoning and decision making. Familiarization activities included studying ATC-related research reports, monitoring ATC-aircraft clearance sequences, observing TRACON controllers, and conducting extensive interviews with a number of these controllers.

In addition to surveying current ATC procedures and functions, a concerted effort was made to become familiar with relevant aspects of ATC's next

generation of automation aids and computational capabilities. Chief among these (at least with respect to the current design effort) is NASA's Center/TRACON Automation System (CTAS) which will function to assist controllers in scheduling and metering aircraft as they enter the terminal control area. The means by which this control of aircraft order and spacing is accomplished -- complex clearances optimized to reduce overall delays -- had an important impact on the proposed operation (and capability) of the system concept developed in the present research effort.

Requirements Definition and Technical Assessment

Consideration of the automation issues identified in the previously discussed literature review, and familiarization with airborne and ground-based technologies in the National Airspace System, directed the present research effort to develop a concept for a crew aiding system -- the Terminal Area Navigation Decision Aiding Mediator (TANDAM) -- that would assist the crew in executing next-generation navigation, guidance and communication functions to be required in Descent and Approach operations. To this end, functional requirements for the TANDAM system were derived, and these, in turn, were translated into design requirements. Functional capabilities of the TANDAM system concept were supported by a thorough incorporation of human-centered design principles, and by considering the employment of flight-context triggered cuing mechanisms to enable the automation to be responsive to situational changes throughout the mission. The TANDAM system would conduct such navigation and guidance activities as presenting

ATC clearances to the crew, assisting in the evaluation and possible negotiation of these clearances, preparing probable alternate routes subsequent to clearances, readying the flight deck for anticipated changes (e.g., runway step-over maneuvers), and facilitating the down-linking of context-specific information (e.g., weather at altitude, estimated waypoint arrival times).

These capabilities were demonstrated in operationally representative Descent and Approach scenarios. In these scenarios, critical aspects of the TANDAM system's performance were shown in the temporally sequenced context of probable future operational procedures involving the crew and ATC (principally via CTAS), and utilizing an advanced, 4-D capable navigation and guidance system, and Data Link. The scenarios were designed to be relatively realistic in terms of hardware and software capabilities, operational requirements, situational influences, and crew and ATC workload. Three scenarios were generated: A descent and approach into Los Angeles International Airport (LAX) under CTAS governance and using Data Link, a descent and approach into John Wayne Airport (SNA) without the benefit of CTAS or Data Link, and an approach into LAX (with CTAS and Data Link) focusing on preparations for a possible change in runway assignments.

Conceptual Design of the TANDAM system

The functional organization, and detailed capabilities of the TANDAM system were articulated to define the system concept, and to better delineate the system's role as a navigation and guidance assistant. In support of this goal,

critical interface elements (e.g., the Flight Mode Control Panel, Navigation Display formats), procedures regarding 4-D clearance negotiations, and automation/crew interactions were described. Schematics of some significant operational capabilities were provided in order to suggest possible directions for the eventual structure of the TANDAM system's functional architecture. Lastly, the TANDAM system was portrayed in its functional relationship with other aircraft systems in order to demonstrate its anticipated integration and coordination with these systems.

Products

A number of significant design products were developed in the course of this research project, and are presented in this report. First, in consideration of certain critical assumptions and philosophy issues, the utility of automation design guidelines was addressed. These positions made explicit, guidelines for the design of automated systems were documented, and have been placed in an appendix to the main body of the report (due to their substantial length). The report also contains the detailed description of the TANDAM system concept, and the three descent and approach scenarios instantiating its operation and functional interaction with the aircraft, crew, and ATC. These capabilities, initially excerpted from the descent and approach scenarios, were elaborated upon to further explicate significant aspects of the system's potential operational utility. A test plan to evaluate a more complete and refined version of the TANDAM system is also provided. This plan describes the proposed scope and method of evaluation, as well as the test's general content.

The test was designed to evaluate several relevant factors: Operational utility; ease and accuracy of crew usage; depth and accuracy of system functioning; and potential for enhanced safety and economic advantage.

RESULTS

ISSUES REGARDING DESIGN PHILOSOPHY AND THE DEVELOPMENT OF GUIDELINES

The assumptions and philosophical positions adopted in the development of the automation guidelines are now discussed in some detail. This underlying philosophy was articulated so as to make explicit the design principles embodied in the guidelines, and to thereby explain the reasons for choices made in their construction. These assumptions address several areas of design: Software and hardware capabilities; automation control, operating logics, and computational techniques; and the role of the automation and the operator in the control of the mission function(s) being supported. In (at least) these important respects, the assumptions designers make can clearly have significant and often critical influence over the capabilities and appropriateness of the automated systems developed for future commercial flight decks. The guidelines themselves are presented in the appendix to this document.

Introductory Comments

Recommendations and guidelines for the effective design of automated systems share a number of important characteristics with other design guidelines. For example, since the human operator often interacts with the automated system, guidelines regarding the design of an interface are typically relevant. And, since the automated systems are specialized software and/or hardware systems residing

in the overall avionics system, guidelines for the design of such technologies are, of course, pertinent. What makes automation design unique, however, is the need to establish guidelines advising designers about translating operational and functional requirements into routines for gathering and interpreting data, applying rules, etc., and subsequently executing advisories and/or commands to the aircraft and crew. In this sense, design guidelines for automation must consider both the system's states and the crew's strategic awareness and understanding of those states.

Thus, the desire to provide specific, concrete guidelines is often, of necessity, replaced with the goal of developing guidelines that keep the designer responsive to the general intent of the design requirement. For example, how a particular system is programmed may be irrelevant from a design point of view; however, how it acts as a result of that programming (i.e., how it obtains information, processes it, makes interpretations, and informs its users) is of central concern to the designer.

It is essential to keep in mind that the designer of an automated system is (or at least should be) driven by one overriding concern: The satisfaction of mission and functional requirements. Moreover, the means by which this automated system satisfies these requirements must follow two interrelated tenets: The designed system must be able to effectively accomplish (or support) the execution of its identified technical tasks (e.g., ensuring that 4-D calculations to a fix are accurate and timely), and it must be able to accomplish these tasks in ways that involve, inform, and assist the crew without also resulting in undue levels of

workload, and while still ensuring an optimal level of situational awareness. Moreover, this second tenet, often referred to as human-centered design, demands that this inclusion of the human operator go well beyond mere accommodation of his or her presence. Human-centered design endeavors to develop technologies that take advantage of human cognitive and perceptual strengths and preferences, and that help compensate for human limitations. These guidelines for the design of automated systems must, therefore, direct the designer of advanced commercial flight decks to remain cognizant of human skills and their possible utility in satisfying the mission and functional requirements.

Assumptions and Design Philosophy

In any design effort, assumptions must be made regarding mission requirements, relative level of functional advancement over current flight deck capabilities, software and hardware capabilities, and extent of the system's impact on the integrity of other cockpit systems, and on the crew's procedures. These assumptions in large part govern the designer's thinking in the design process, and greatly constrain the design philosophy adopted -- the designer does well to make explicit the assumptions of the design goal and the consequent design philosophy being followed. Determination of these assumptions could come from any number of pragmatic, technical, or theoretical considerations. In human-centered design, assumptions must be the products of mission requirements, human information processing capabilities, and constraints emergent from other relevant systems, procedures, and the like.

In any effort to design an automated system for an advanced flight deck, several assumptions must be made if a coherent, principled design is to be developed. Chief among these are assumptions regarding the following general design parameters.

Software and hardware system capabilities. In the case of the present design effort, several current avionics technologies (e.g., the Flight Guidance System) will be assumed to exist in advanced forms. Some of the required technologies would possess substantially enhanced capabilities (e.g., the FMS will need to be able to rapidly load and customize alternate flight plans, approach plates, etc.), and certain of the technologies not yet in service (e.g., onboard 4-D navigation, CTAS) would be posited to be operational in the time frame envisioned for the automated system's incorporation into the commercial transport fleet.

The types of systems controls, operating logics, and associated computational schemes. In the case of the present effort, the design philosophy chosen was to be as conservative as possible (i.e., deterministic, rule-based) in the programming techniques that would be called for to support the automated system concept. In the case of this design effort, this decision was motivated by the kinds of operational capabilities revealed in the analysis of mission requirements and further articulated in the development of the scenarios (e.g., facilitating the negotiation of a 4-D descent clearance). In the problems identified for terminal area navigation operations, standard computational

techniques (that were fast and able to deal with large bodies of data) would probably be able to accomplish the large majority of mission functions called out in the scenarios. In the design of automated systems for more advanced flight deck applications, programming approaches such as neural network technologies or various non-deterministic (probabilistic) computational techniques might be required.

Determination of the extent of automaticity versus extent of human involvement. One decision crucial to the choice of design philosophy is determining the degree to which the automation will function autonomously, versus the degree to which dependence on human monitoring and intervention will be required. This issue of extent of automaticity is critical since the consequences of a poorly thought out philosophy in this regard can result, at one extreme, in ineffectual (minimal) automation and, at the other, in completely opaque and surprising (maximal) automated control. Unfortunately, this decision is too often made on the basis of any number of peripheral criteria -- technical feasibility, for example, or even simple expedience. From a human-centered design perspective, only the potential for reduced workload, the expectation of maintained or increased situational awareness, and the ability to capitalize on mission-enhancing options should be determinants of the applicability and extent of automaticity.

However, determining the appropriate extent of automated functioning is potentially complicated by other tenets of human-centered design. Consider, for

example, two of Charles Billings' (ref. 4) general principles for human-centered automation:

"To command effectively, the human operator must be involved. (p. 13)"

"To be involved, the human operator must be informed. (p. 13)"

Taking these principles at face value, one could reason that the more involved (and, by implication, informed) the human operator, the more in command that operator would be. But, since one of the typical motivations for deciding to automate is to unburden the operator from having to be cognizant of all aspects of a function, -- that is, purposefully rendering the operator less informed about every detail of the function's execution -- automating could easily be seen as lessening informativeness and involvement, and therefore being opposed to Billings' design principles.

The resolution to this apparent dilemma, of course, lies in what the human operator is informed about. Billings is certainly not recommending that an automated system should tell the operator about every detail of that system's processing. Rather, he is recommending that the automated system (and any context-sensitive mechanisms used to support it) be crafted such that precisely and only the relevant calculations, events, states, etc., be interpreted for, and reported to, the crew.

To re-couch the issue then, it is perhaps more accurate to say that the appropriate degree of automaticity is determined by the designer's success in first identifying

the essential operational information required by the operator (for situation awareness), and then effectively presenting that information to the operator in the course of the system's execution of the automated function. In this regard, then, the designer cannot be free to make the arbitrary decision to specify more or less automated functioning -- done correctly, such decisions can only result from an understanding of human information processing requirements, and the mission's purpose.

In summary, it is evident that the determination of automation requirements should be based on a thorough understanding of mission requirements, operational constraints, and human capabilities and limitations. This understanding is essential since it is on its basis that the designer must determine what functions and activities, in what contexts, should be accomplished or assisted by an automated system. This understanding must be both comprehensive (in terms of mission goals) and procedural (in terms of specific crew and system decisions and activities) so as to provide the designer with both strategic and tactical goals for the system design. The understanding of the mission objectives and operational context -- whether learned from flight phase, environmental factors, or pilot state -- provide the cuing mechanisms for enlisting the assistance of the automated system, and for determining what data must be evaluated and what decisions and actions must be considered.

PROBLEM IDENTIFICATION AND OPERATIONAL CONSIDERATIONS

Determination of the operational problem being addressed in the current design effort was based on an evaluation of automation use in current "glass cockpit" aircraft. This evaluation first considered summary statistic and anecdotal reports of incidents and accidents relevant to cockpit automation. Also reviewed were compilations of pilot-solicited comments regarding the operation and understanding of automated systems. Additionally, this evaluation studied experimental investigations demonstrating characteristic procedural errors, non-optimal uses of the airborne systems, and problems with mode awareness and consequences related to flight deck automation.

From this evaluation, evidence converged on a number of interrelated factors that have all contributed to the identification of the functional problems addressed in the present TANDAM system design concept. A summary of this evidence, and an explanation of its consequence for this research effort, are now provided.

Characterizing Problems with Cockpit Automation

As was indicated above, reports of incidents and accidents were evaluated for their relevance to the identification of possible problems with current automation. Two types of reports were available for analysis: Incidents and accidents obligatorily reported to the FAA (and subsequently recorded in aircraft safety data bases), and pilot accounts elicited in various interview settings.

The present study's analysis of incident and accident data was accomplished in two phases. First, an inspection of Douglas Aircraft Company's "Commercial Jet Transport Safety Statistics; 1991" (ref. 9) document was performed in order to establish general statistical trends regarding aircraft safety mishaps, etc. This review of aircraft safety data revealed a number of relevant statistical patterns. For example, of the approximately 1285 serious accidents (with aircraft damage sustained) observed between 1958 and 1991, 736 (57%) occurred during approach and landing, even though only about 15% of an average flight's time is spent in these phases. The flight phase containing the next most frequent accident occurrence, takeoff (typically comprising about 1% of total flight time) accounted for some 18% (237) of the total events, and exhibited over twice the accident frequency observed for any of the remaining flight phases. For the purposes of the current design effort, it is significant to note that aircraft safety data also showed that the majority of accidents that related to problems with control activities involved crew-induced mishaps. Moreover, of accidents clearly involving crew behaviors, the captain's actions have been at least partially responsible in 657 (80%) of the 817 recorded cases. Of these captain-involved accidents, less than adequate executive (i.e., command) actions (40%) and judgements (21%), and failure to follow proper procedures (11%) were cited in the clear majority of cases. Other reasons implicated in captain-involved accidents included less than adequate awareness (6%), failure to monitor instruments (5%), less than adequate preparations (4%), failure to take immediate action (3%), and failure to use proper safety procedures (3%).

After this general pass through reported safety data, a search of McDonnell Douglas Aerospace's aircraft safety data base was conducted using a small number of selection criteria: Events were selected that were reported between 1983 and 1992 inclusive, that had occurred in any phase of flight, and that had appeared to have involved (or at least implicated) some onboard automated system. This search yielded 64 events. Subsequent inspection of these events yielded 32 that were reliably classifiable in terms of phase of flight, and probable type of automated flight function involved and phase of flight. As can be seen in Figure 2, the overwhelming majority of these events occurred in the Approach and Landing phases and involved navigation and guidance functions. Of this group, the most frequent problems concerned various nonprecision approaches and non-optimal environmental conditions, and thus tended to involve the operation of autoflight systems, and navaid and tracking systems employed in final approach segments.

A selected compilation of aircraft events recounted by Billings (ref. 4), identifies several critical examples of automation-related problems. Classification of these events, in terms of phase of flight and type of function, is shown in Figure 2. In Billings' sample (not intended to be statistically representative), automation problems are noted in every phase of flight, and are most prevalent in Systems functions during Takeoff (as shown in Figure 2).

Accounts of automation difficulties elicited from pilots are available in a number of studies (e.g., ref.10). Some studies by Wiener and his colleagues (ref. 2; ref. 5) are among the best of these accounts and are therefore used in this evaluation.

In these investigations, line pilots described experiences in which they encountered difficulties or made mistakes in their operations of automated systems such as the FMS and the Autoflight System. These elicited comments, again sorted in terms of flight phase and type of function, are presented in Figure 2. This classification of reports indicates that pilots were most aware of navigation and guidance difficulties, followed by problems related to aircraft systems operations. And, as would be assumed, navigation and guidance problems were most prevalent subsequent to takeoff activities.

To summarize thus far, a few significant patterns clearly recur in the foregoing studies and analyses. Firstly, while problems with present-day automation are possible in every phase of flight, their prevalence in later phases, and, in particular, Descent, Approach, and Landing, constitutes a significant portion (if not the majority) of all automation-related accidents, incidents, and operational difficulties. Secondly, the largest segment of these automation problems directly impacts navigation and guidance functions, and therefore tends to involve use of the FMS, the Autoflight System, and navaid tracking systems. And, while these analyses of the available data are admittedly imprecise and incomplete, they do unambiguously indict significant aspects of current automation, and strongly demonstrate the need for improved capability in future navigation and guidance automation.

Some Analyses of FMS-Related Difficulties

This discussion of automation-related problems has now been narrowed to concentrate on difficulties with the management of navigation and guidance occurring during descents, approaches, and landings. To more precisely identify these FMS-involved difficulties, two (of the many available) representative studies are now considered.

A survey of line pilots

With an expressly exclusive focus on navigation functions, Sarter and Woods (ref. 3) surveyed 135 Boeing 737-300 pilots about their experiences operating that aircraft's FMS. In their analysis, these researchers identified several specific FMS-related "surprises" -- unforeseen or seemingly inexplicable behaviors of the FMS -- that were potentially problematic for effective planning and execution of navigation activities. These "surprises," along with the frequencies with which they were volunteered (pp. 15-19), are summarized here:

- Problems related to the use of the FMS's Vertical Navigation Modes were common:
 - Pilots reported difficulties in understanding the logic of calculations related to vertical maneuvers, and were therefore often unable to accurately predict how and when such maneuvers would be initiated, maintained (or modified), and concluded. (38 reports)

- Pilots reported difficulties in understanding the consequences (for the FMS plan) of interrupting an FMS-initiated vertical maneuver with a change executed on the Flight Mode Control Panel. (11 reports)
- Pilots reported a general lack of understanding for how the FMS's Vertical Navigation Speed Descent mode operates, including how targets, restrictions, and general maneuver calculation logics work. (8 reports)
- Pilots reported substantial difficulties disengaging the Approach mode when required. (6 reports)
- Problems involving data entry were frequently cited, including problems arising from inadequate feedback after erroneous entries. (54 reports)
- Pilots indicated problems understanding and predicting FMS-initiated (so called "uncommanded") changes between flight modes. The most common situation mentioned was the FMS's reversion from Vertical Speed mode to Level Change mode when airspeed deviated from a critical range. (28 reports)
- Not surprisingly, pilots volunteered that they lacked adequate understanding of infrequently used FMS features. (14 reports)

- Some pilots commented that pitch commands indicated with the PFD's flight director did not always appear appropriate to the maneuver being executed, and therefore lessened their confidence in the FMS logic. (11 reports)
- Some pilots reported being confused about what the currently active target values are, owing largely to a lack of understanding of how the Autoflight System and the FMS were coordinating in a given flight regime (i.e., were the FMCP or the FMS settings active). (10 reports)
- Several pilots expressed frustration with the relatively large -- and in their opinions, excessive -- number of ways to achieve various navigation and guidance functions. (10 reports)
- Several pilots expressed frustration and concern about having to repeatedly enter the same data into different FMS pages. These pilots would have preferred that such data entry was done only once, and was then automatically copied to other relevant pages. (9 reports)
- A few pilots admitted that they lacked a clear understanding of which subsystems of the FMS would remain operational in the event of failures of other components of the FMS. (3 reports)

Aviation Safety Reporting System findings

In an effort to obtain a sample that was more representative of all FMSs currently in service, a NASA Aviation Safety Reporting System search was solicited on FMS-related incidents. The documentation of this search, "Last Minute FMS Reprogramming Changes" (ref. 8), presented pilot reports of FMS-involved incidents occurring in Climb, Cruise, Descent, and Approach phases (since the previously reported statistical data indicated that these flight phases yielded the majority of potentially significant problems with FMS functioning). The search of 38051 reports filed since the beginning of 1986 yielded 76 incidents, of which 53 clearly implicated nominal operation of the FMS and/or the Flight Guidance System (FGS). Except for 2 incidents reported in Climb (1 FGS error, and 1 FMS error), all occurred in Descent (39 FMS-, and 5 FGS- involved) and Approach (6 FMS-, and 1 FGS-involved). Figure 3 presents a summary of the reports for Descent and Approach phases.

Of the FMS-involved incidents reported in Descent, the most numerous, 28, were caused by programming errors that lead to failures to attain assigned altitudes. In 21 of these incidents, the aircraft's altitude was above the ATC directive, and in the remaining 7, it was below the assigned altitude. As is evident in Figure 3, the high altitude violations were fairly evenly split between incidents due to late initiations of FMS programming (10), and those in which the root causes were not adequately specified (11), suggesting that the late initiation count may well be underestimated in these reports. The 5 FGS-related incidents observed in Descents involved errors or misinterpretations of guidance parameter settings and

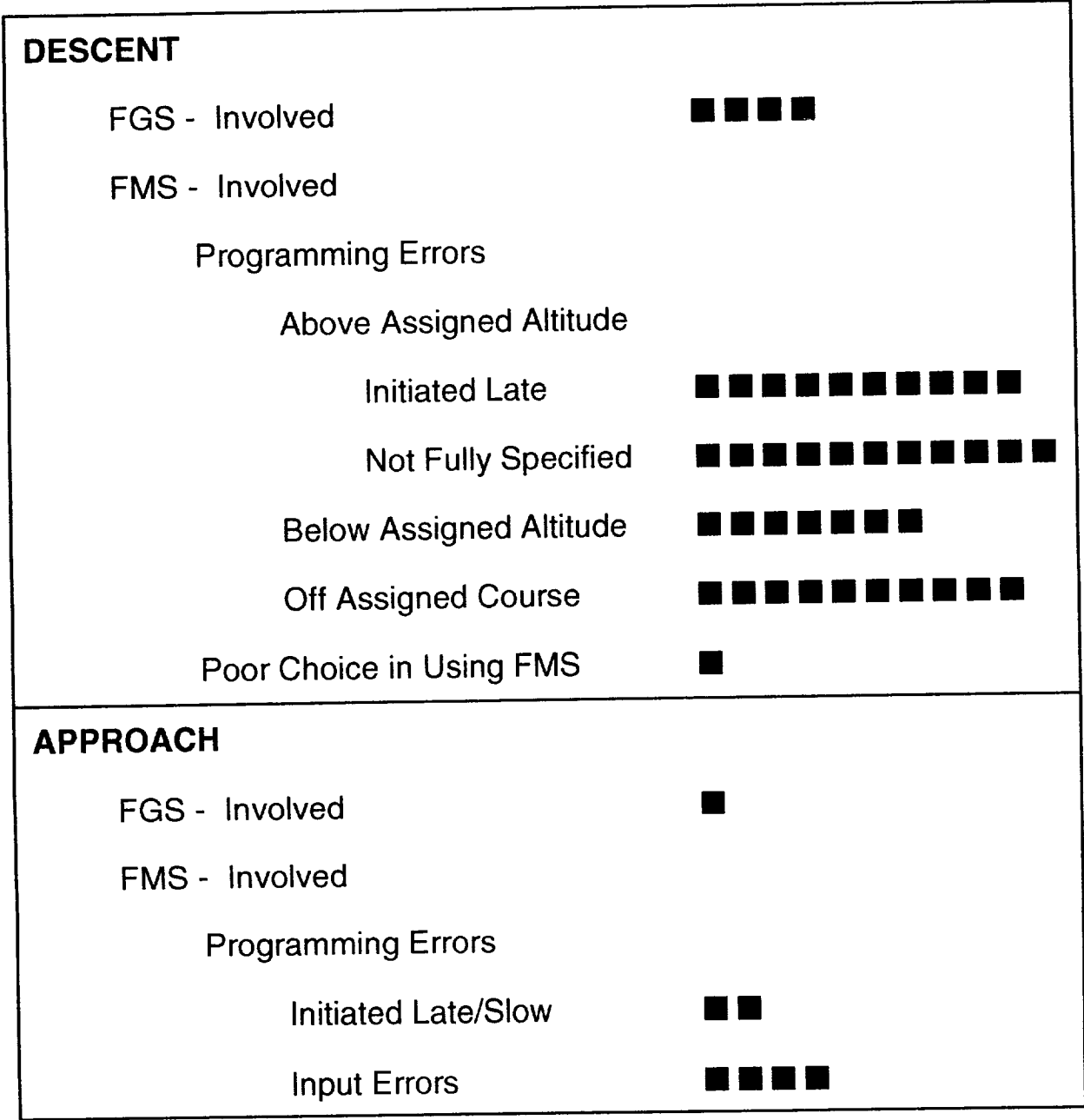


FIGURE 3. SUMMARY OF ASRS - REPORTED INCIDENTS INVOLVING FMS AND FGS OPERATION

selections. Two of these were reported to have resulted in altitude busts; one in which the executed altitude was above the ATC assignment, and one in which it was below.

Incidents reported for Approach were substantially fewer in frequency: 6 involved FMS usage, and 1 involved the FGS. All of the FMS-related events involved programming errors, with 2 resulting from slow or late initiation of the programming sequence, and 4 resulting from input errors. In the single FGS-related Approach incident, the aircraft failed to descend when required by ATC.

It is significant to report that confusions about the functional integration of the FMS and FGS were directly implicated in a small number of the aforementioned incidents (5), and appeared to be involved in several others as well. Pilots reported confusions about FMS or FGS control of flight modes and parameter settings, and about determining the "best" way to execute maneuvers required by ATC clearances. Similarly, 5 cases were reported in which pilots caused procedural errors, reportedly because focus on the FMS distracted them from adequately attending to immediate flight control and monitoring activities.

Operating in the Future National Airspace

The next generation of automation-assisted aircraft will operate in a National Airspace traffic control system that will itself be highly automated, and will provide greatly increased aircraft through-put and scheduling flexibility. Because of this, the determination of requirements for the automated system

under study in this research effort must be accomplished with due consideration given to this anticipated ATC environment. To this end, a brief description is now given of the ground-based ATC system that is assumed to be in place when the TANDAM system would be implemented in commercial transports. Specifically, air traffic control in the near future will be substantially aided by a highly integrated network of automated systems designed to help manage the control of arrival traffic. This network, the Center/TRACON Automation System (CTAS), will plan aircraft arrival schedules, and will determine optimal aircraft speeds, descents, and routes for the controller to use in managing precise sequencing and spacing functions (ref. 11; ref. 12). CTAS renders this assistance to the controller in the form of clearance advisories and graphically portrayed situational information. CTAS performs these functions by means of three interdependent modules: The Traffic Management Advisor (TMA), the Descent Advisor (DA), and the Final Approach Spacing Tool (FAST).

Landing times (optimized to accommodate incoming aircraft) are calculated by the TMA in order to develop a continually updated landing schedule that minimizes delays for the great majority of incoming traffic. The TMA also ensures that the scheduling scheme that is generated minimizes the possibility of traffic conflicts by optimizing inter-aircraft spacing.

The DA enables controllers to effectively command the maneuvers necessary to follow the TMA's schedule by providing air speed and vertical speed profiles, and descent and turn advisories, all adhering to 4-D navigational constraints. Aircraft spacing is maintained first by speed-related commands, and when

necessary, by route-change commands as well. Additionally, the DA identifies down-route traffic conflicts, thereby enabling CTAS to issue resolution advisories well beyond the range of individual aircraft TCAS units.

FAST, operating in the later stages of aircraft approaches, performs scheduling optimization and 4-D maneuver calculations essentially similar to those used in the TMA and DA, except that they are customized for fine-tuned control during final approach. FAST is also capable of assisting controllers with pop-ups and aircraft re-entering the pattern after a missed approach.

With the assumption that clearances for descents and approaches will be largely governed by CTAS, an airborne navigation and guidance system appears to require substantial assistance from an onboard system designed to take advantage of situational variables and to work in accord with CTAS. This anticipated requirement is underscored by recent research by Williams and Green (ref. 13) in which effective compliance with CTAS-class 4-D clearances was demonstrated when a 4-D capable FMS and Data Link system were used. And Waller's Data Link simulation work exploring clearance receipt and execution (ref. 14) clearly suggested significant improvements in time to compliance when the Data Link system was capable of routing (accepted) clearance parameters to relevant navigation and guidance systems. The development of a concept (i.e., TANDAM) for such a system is therefore the objective of the present research effort. The description of this system concept -- along with a number of flight scenarios employed to depict its major functional roles -- is presented in the following sections of this report.

DESIGN CONCEPT FOR THE TANDAM SYSTEM

The system concept developed in this research effort was designed to provide context-sensitive decision aiding (and other assistance) for crew activities in Descent and Approach flight phases. More specifically, the TANDAM system was designed to assist in 4-D navigation and guidance functions, and in the clearance negotiations often integral to these functions. The TANDAM system's functional organization, and its varied capabilities are now described.

Description of the TANDAM System and Related Components

To effectively execute its functions, the TANDAM system will rely heavily on the capabilities of a number of airborne and ground-based systems. Figure 4 presents a schematic of these systems and their relationships with the TANDAM system and the aircraft. As can be seen in the figure, the TANDAM system interacts with airborne sensors, digital (and, to some extent, voice) communications systems, and an advanced flight management system. Crew interaction with the automation occurs on an advanced suite of controls and displays, specialized to accommodate the TANDAM system's functions. (The TANDAM system's operation is depicted in detail in three flight scenarios presented later in this report.)

Sensors and other onboard systems provide the FMS and the TANDAM system with continuously updated data on environmental conditions, aircraft performance, and configuration characteristics. They are also responsible for

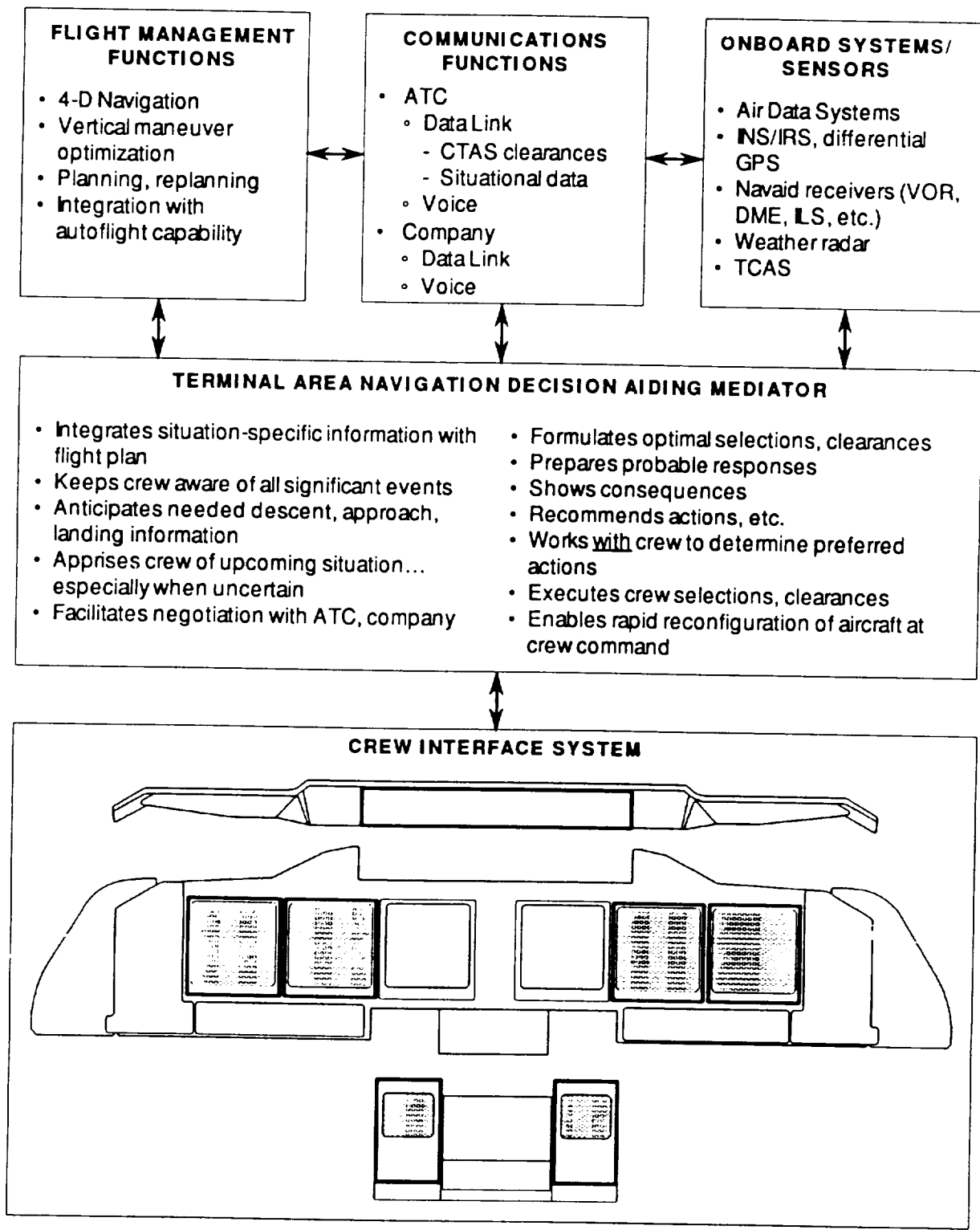


FIGURE 4. RELATIONSHIP OF THE TANDAM SYSTEM TO MAJOR AIRCRAFT FUNCTIONS AND THE CREW INTERFACE

providing aircraft position, altitude, and attitude information. As Figure 4 indicates, the onboard systems may include advanced versions of air data systems, INS/IRS and differential GPS, Navaid receivers (for VORs, DMEs, ILS, etc.), weather radar, and TCAS.

The communication systems, relying principally on an advanced Data Link system (e.g., satcom), send information to the FMS, and directly to the TANDAM system and the crew. These systems of course also downlink data to ATC and to the company. The most important (and typically the most demanding) information handled by these systems concerns complex 4-D clearances and their negotiations. Because of the interaction-intensive nature of these negotiations, no appreciable delays in transmission times will be tolerated (thus, for example, Mode S will not be adequate for these negotiations).

The FMS and its associated data base conduct all navigation and guidance calculations, including 4-D estimations. Within the 4-D navigation capability, the FMS contains a module specialized for the calculation of vertical maneuvers. This 4-D navigation capability is able to continually re-calculate 4-D waypoint ETAs, deviations from on-time positions, and compensatory control inputs for maintaining or regaining these on-time positions. With the assistance of the TANDAM system, the FMS is able to continually modify its flight plan in reaction to onboard system, ATC, and other situational inputs. Computational speed, data base access, and storage (buffering) of data and of alternate calculations (of maneuvers, speeds, or whole route segments) will far exceed current FMS capabilities in terms of both capacity and sophistication. The flight

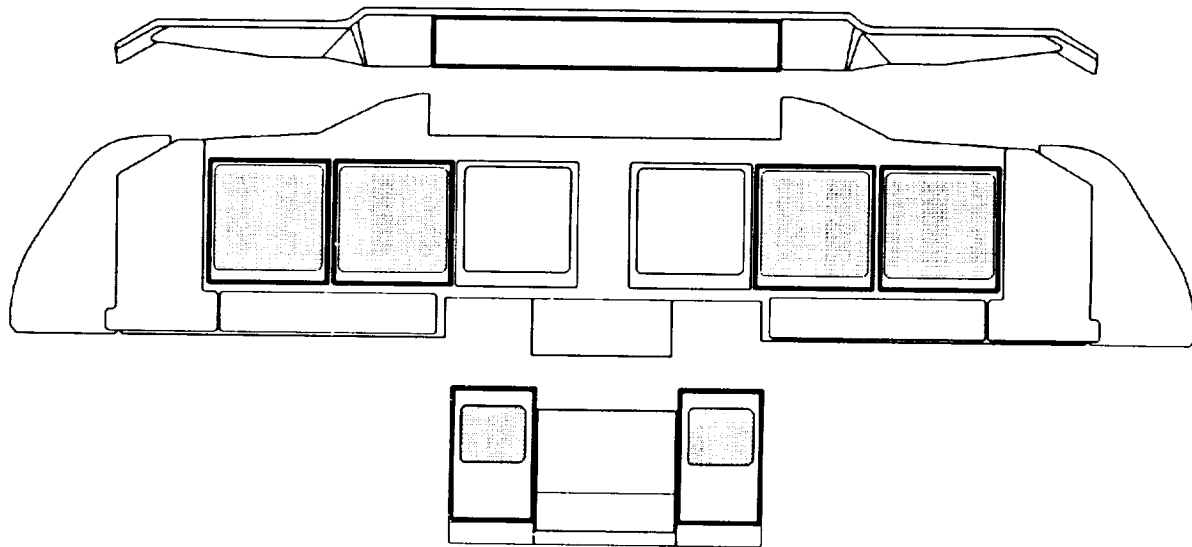
plan data base (including information on all relevant airways, departures, and approaches) will need to store detailed flight segment information such as altitude and other airspace restrictions, and uplinked information regarding current environmental and traffic conditions. Associated with significant mission events (e.g., obtaining ATIS information, or initiating a descent) will be data base elements that cue the TANDAM system to prepare various procedures designed to facilitate performance in these events (see the mission scenarios for examples). Also included in the data base will be tags for mission events typified as being high in workload and/or low in situation awareness. Again, these events will signal the TANDAM system to prepare assistance routines for use by the crew. In addition to facilitating clearance negotiations, these assistance procedures will include offering to take over selected crew tasks, apprising the crew about upcoming events, making recommendations or suggestions regarding these events (including recommending task rescheduling for workload management), informing the crew about significant consequences of current or proposed actions, and executing crew-selected commands.

The TANDAM system will interact directly with the crew by means of a functionally integrated system of annunciators, displays, and controls. In this regard, the initial design position, therefore, was to use a modern "glass" cockpit configuration (an MD-11-class crew station) as the baseline, adding capabilities as design requirements dictated. As is evident from the preceding discussion, several necessary advanced capabilities have indeed been identified and all, to differing degrees, have had consequences for the crew interface. Those that have

constituted significant deviations from the MD-11's controls and displays are presented in Figure 5 and will now be described.

The Flight Mode Control Panel (FMCP) will generally resemble existing advanced FMCPs in both appearance and function (see Figure 6). However, one significant addition to this panel will be an "Arrival Time" control that is designed to permit the input of fix arrival-time commands (in a manner analogous to heading and speed control arrangements). As such, the Arrival Time control will allow "time-at-fix" assignment, and will operate in pre-select and select modes. Time will be able to be set in either of two ways, in minutes and seconds from the present time, or in standard time coordinates. Additionally, the setting of a time will affect the planned flight path shown on the navigation display. The display will show the 4-D fix information, or will indicate that the time-at-fix could not be made. In the latter case, the display will indicate how late the aircraft would be, or where the aircraft would be at the proposed time setting. As with other FMCP entries, the consequent effects on speed and vertical rate will be displayed. A second element of the FMCP will be the incorporation of a pre-select feature for the vertical speed control. This feature was added to the FMCP to improve the crew's ability to prepare, inspect, and precisely execute 4-D maneuvers.

The last significant interface feature incorporated in the FMCP -- the highly integrated functional relationship between the FMCP and the FMS -- ensures that inputs to the FMCP will not inevitably cause problematic disengagements or discontinuities in the overall FMS governance of the flight plan. This advanced



**FIGURE 5. MAIN INSTRUMENT PANELS FOR BASELINE
COCKPIT, EMPHASIZING CONTROL AND DISPLAY
SYSTEMS INTERFACING WITH THE *TANDAM* SYSTEM**

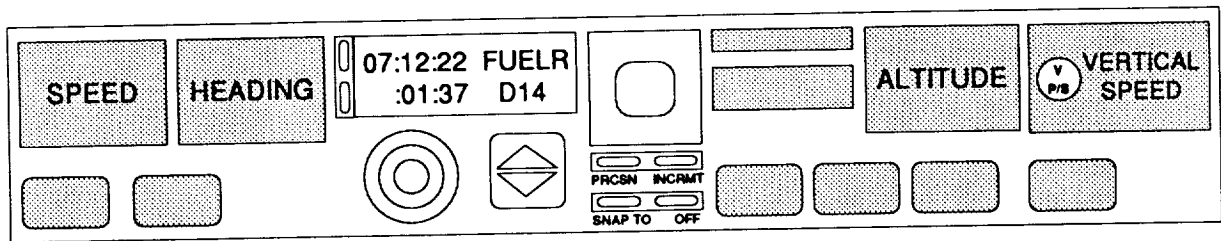


FIGURE 6. 4-D GUIDANCE-CAPABLE FLIGHT MODE CONTROL PANEL

FMCP-FMS concept will be able to logically edit and modify an existing flight plan by simply entering new inputs in the FMCP (as well as in the FMS of course). In addition, the FMS MCDU's scratch pad can be used during FMCP editing to enter waypoints, etc., that are not in the current flight plan (and thus not accessible via the FMCP's scroll key). And a cursor pad device located on the FMCP can be used (in either FMCP or FMS modes) to quickly designate or create waypoints, etc., on the NAV display, and in the flight plan. FMS routines will be able to re-optimize the flight plan for the newly added modifications, especially with regard to the rather precise tolerances required of the 4-D flight path management posited for the TANDAM system's cockpit.

The crew will be able to conduct flight path planning and editing on of the FMS using control features analogous to those outlined for the FMCP. The FMS will possess a real-time 4-D navigation capability that is fully editable, produces "hot" updates to all calculations, and can calculate running solutions (i.e., solutions that are automatically updated as input parameters change) to upcoming 4-D maneuvers. Moreover, all such calculations will be able to compensate for situation-specific variations (e.g., wind speed, direction shifts). And, information regarding such compensatory strategies will be readily accessible to the crew. Additionally, all course and time deviations resulting in scheduling violations (i.e., not able to be compensated for by the 4-D FMS) will be clearly indicated to the crew, along with any suggested replans, etc., to be considered. A vertical flight path optimization capability (also resident in the advanced FMS) will generate profile data that can be readied for display and accessed by the crew. Access will be either at crew discretion, or in response to suggestions based on

the TANDAM system's prediction of significant consequences of the upcoming vertical maneuver (e.g., underflying a crossing altitude).

Again because of the design philosophy followed, the working decision has been to have the FMS share its display/control head with the Data Link system, thereby obviating the need to identify another acceptable location for an MCDU on the flight deck. This co-location of FMS and Data Link was also adopted because of the interaction-intensive sequences that would necessarily obtain between the two systems during clearance negotiations. Also, using the common MCDU, uplinked clearances in formats quite similar to their eventual representations on FMS pages will be easily and accurately inspected by the crew. With the development of an effective message prioritization and annunciation scheme, this display/control co-location will constitute the core of an efficient and reliable functionally integrated system.

The FMS's MCDU, as shown in Figure 7, will generally resemble other advanced MCDU designs except for space allotted for the co-location of the dedicated Data Link controls. Additionally, specialized formats, modes, line-select settings, etc., will be required to support advanced functions such as 4-D clearance negotiations, and other FMS- and Data Link-related interactions with the TANDAM system. Similar accommodations will be required for non-clearance and other non-flight-critical communications, and for company business.

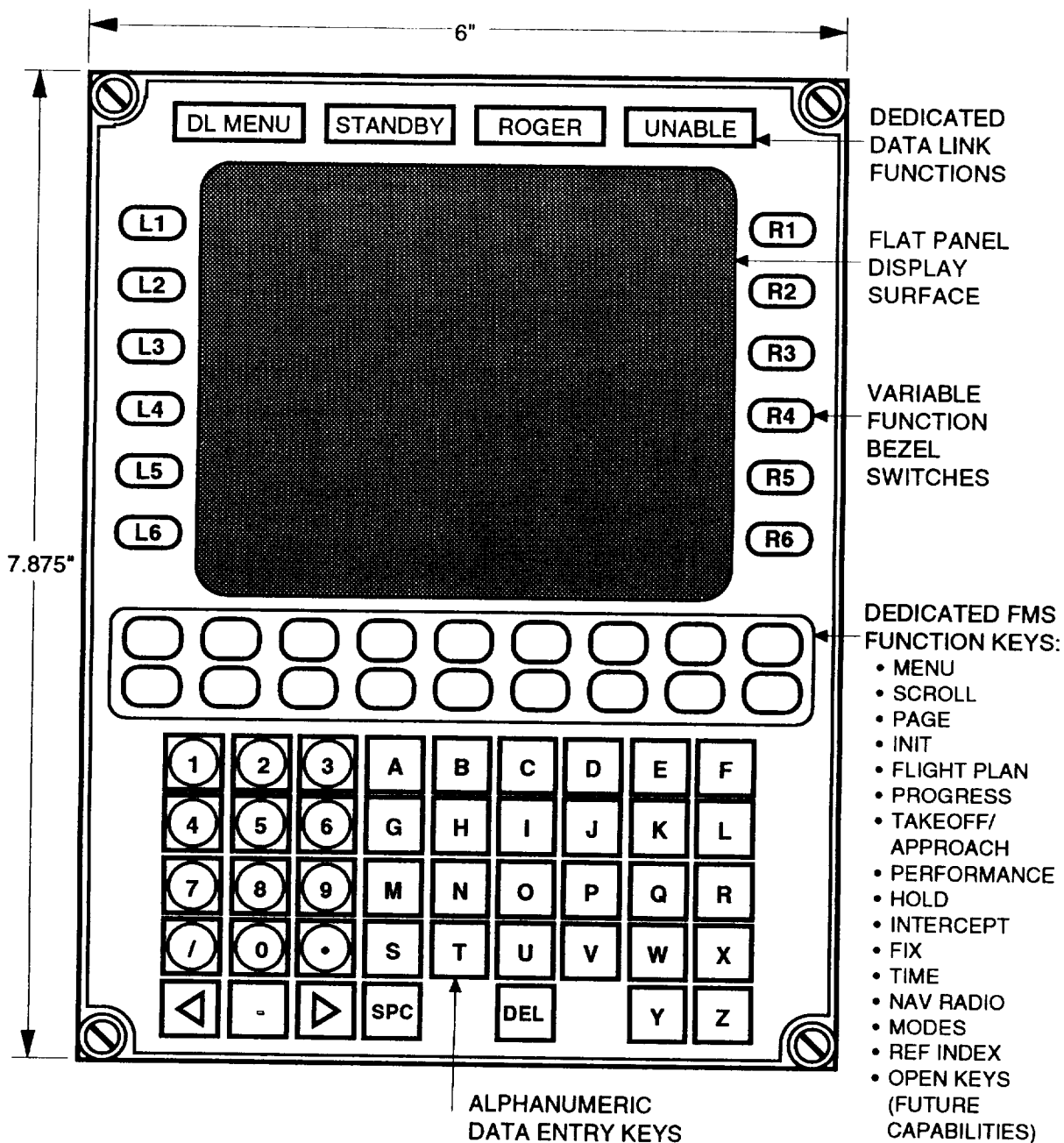


FIGURE 7. MULTIFUNCTION CONTROL/DISPLAY UNIT FOR THE FLIGHT MANAGEMENT AND DATA LINK SYSTEMS

4-D clearance and associated guidance information will be presented on the Primary Flight and Navigation displays (PFD and ND). In addition to standard tactical flight parameters and direction, the PFD (see Figure 8) will also display 4-D navigation mode selection, "bugs" associated with speed, heading, altitude, and vertical speed settings (determined by the pre-selected or currently operational 4-D maneuvers), and time-to-maneuver information when relevant. The ND will present its information on two general formats: A modified map mode that presents 4-D information, and various maneuver guidance and configuration change prompts (see Figure 9); and a vertical profile planning schematic (see Figure 10) used to assist the crew in their selection of guidance by showing vertical maneuver options, constraints, etc., and their associated fuel use and passenger comfort estimates

Capabilities of the TANDAM System

As conceptualized in this design effort, the TANDAM system will (in conjunction with other systems) perform sophisticated flight management functions, and will, in reaction to situational changes and general operational goals, customize its assistance to the crew, to other onboard systems, and to ATC.

The TANDAM system will act to coordinate data base updates, prepare for anticipated events in the flight plan, and manage air-ground communications. Additionally, it will help coordinate, negotiate, and comply with the directives of ATC (principally generated by CTAS) while still endeavoring to optimize the flight plan for the aircraft. And, while much of this work would of course

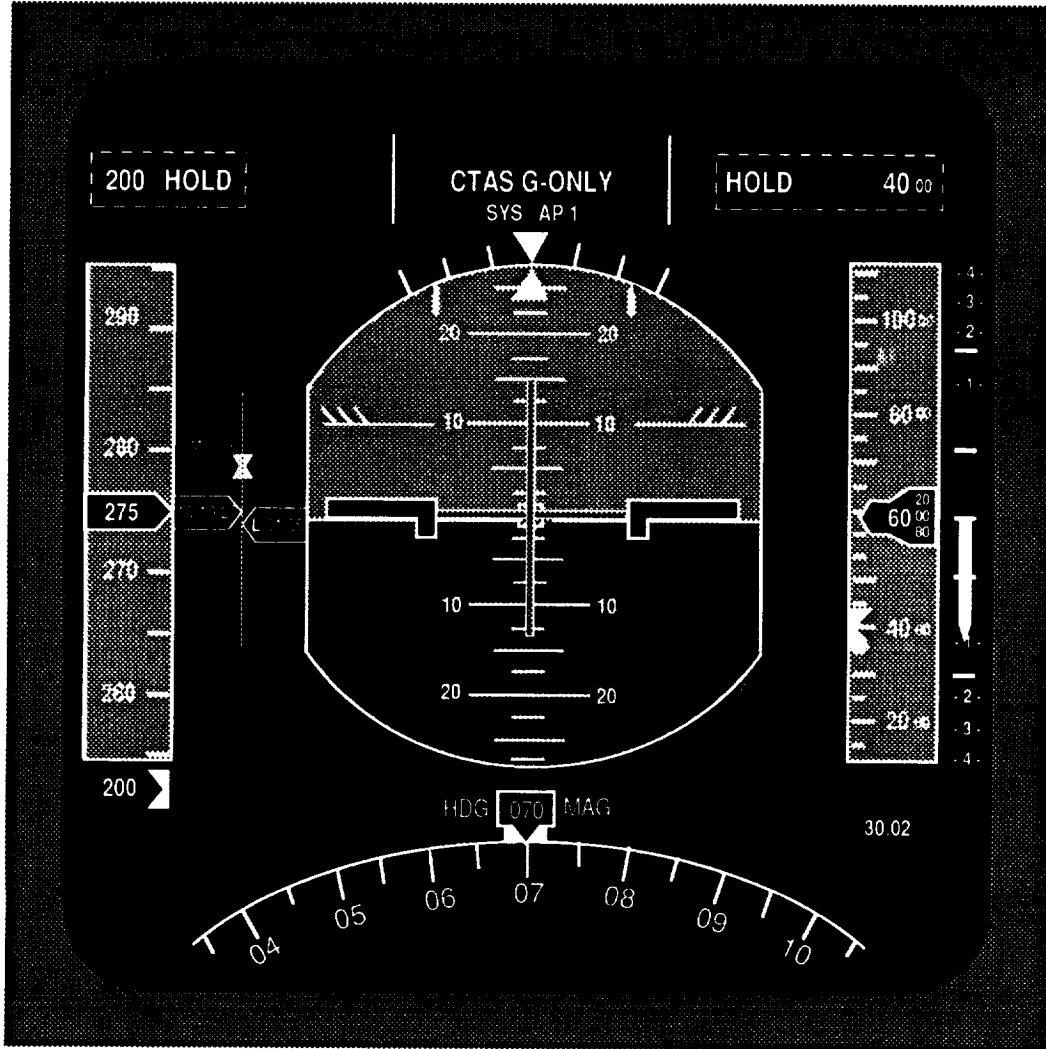


FIGURE 8. PRIMARY FLIGHT DISPLAY, SHOWING 4-D NAVIGATION INFORMATION

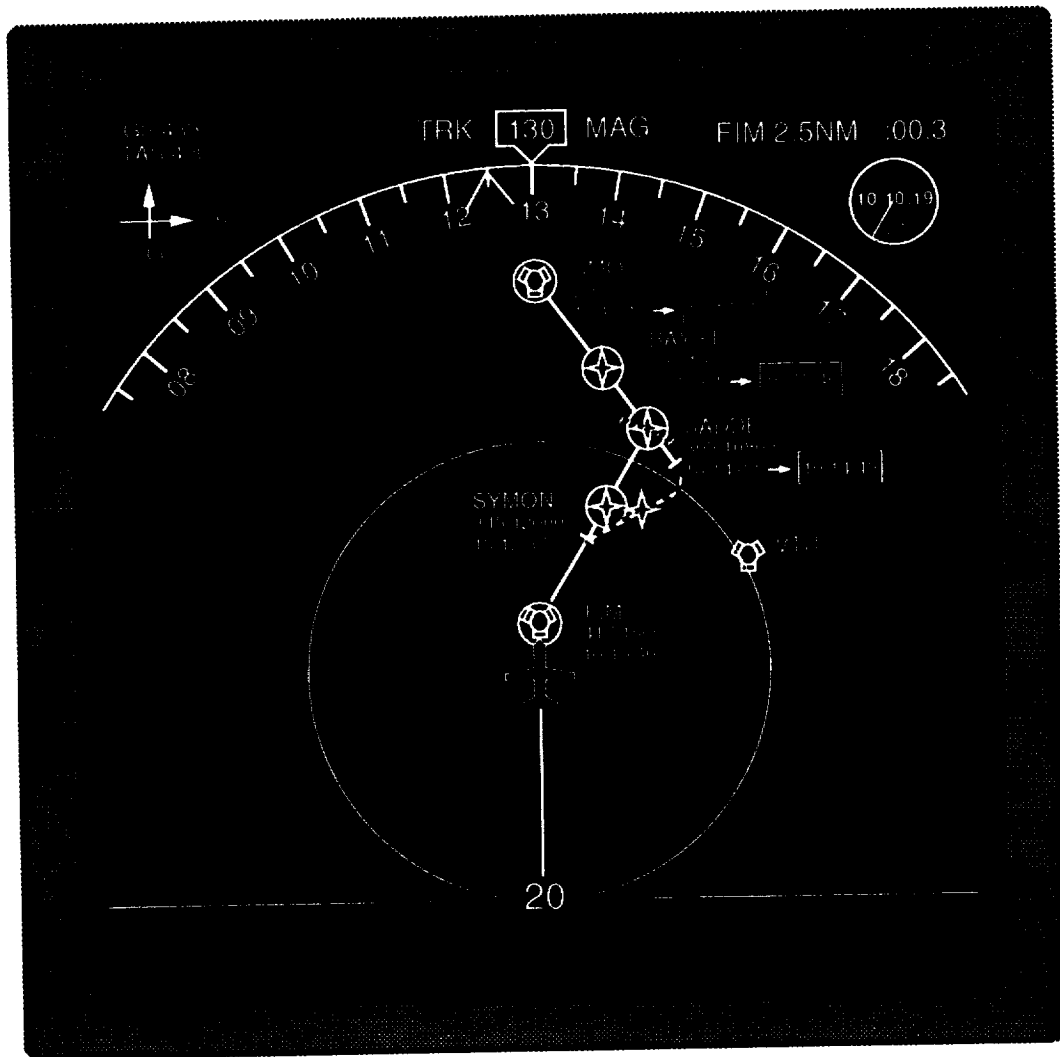


FIGURE 9. NAVIGATION DISPLAY, IN MAP MODE, SHOWING 4-D NAVIGATION INFORMATION

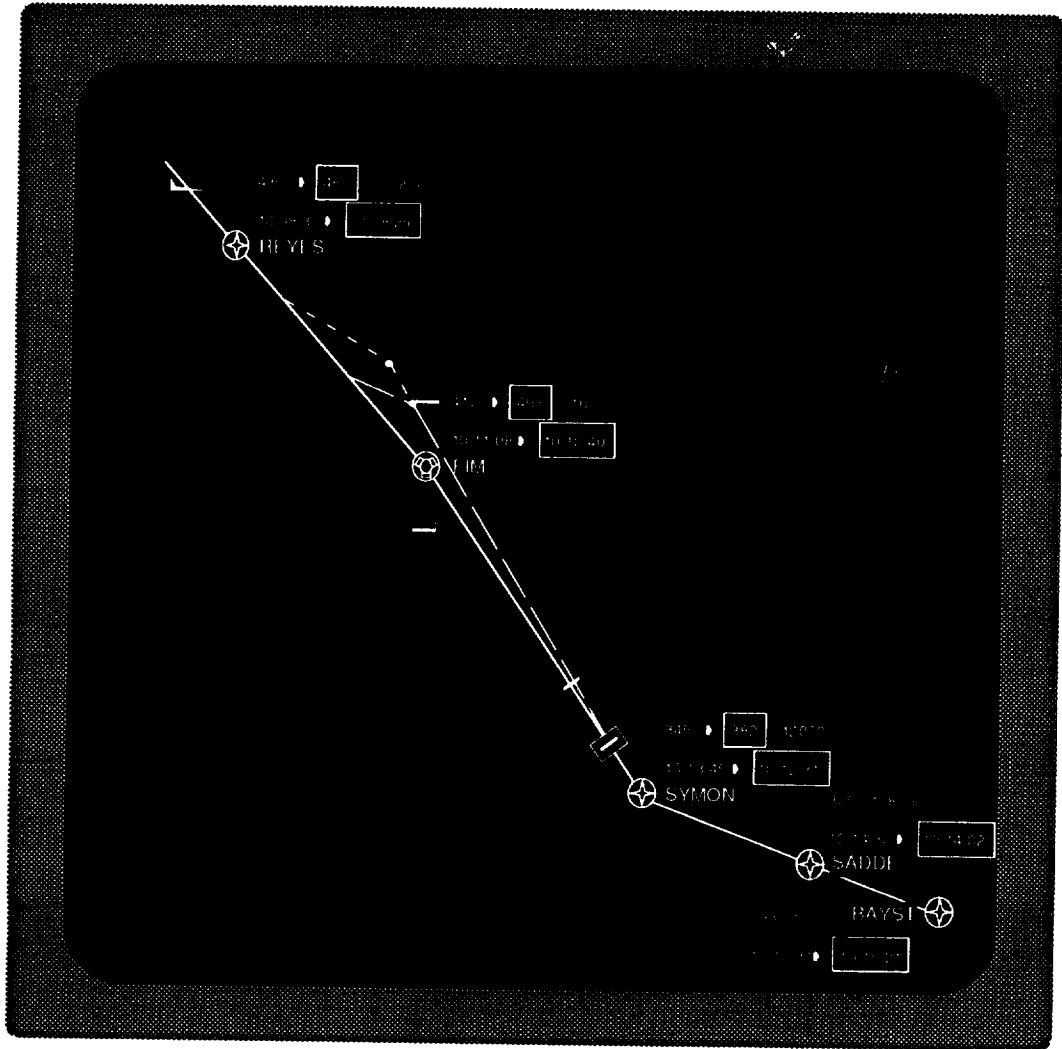


FIGURE 10. NAVIGATION DISPLAY, IN VERTICAL PROFILE MODE, SHOWING MANEUVER OPTIONS

involve automated functioning, the system will perform these activities in a largely advisory and assistance capacity, maximizing the expertise of the crew while unburdening them of time-consuming and distracting tasks.

To perform these functions, the TANDAM system must possess a number of processing and control capabilities. These capabilities comprise two operational domains: The utilization of various communications functions, and the management of tactical and strategic elements of navigation and guidance functions.

The TANDAM system's management of communications

The TANDAM system will govern two critical aspects of communications activities: The monitoring and use of on-going situational communications, and the management of communications with ATC that pertain to clearances. The TANDAM system's situation-specific management of each of these classes of communication activity will now be described.

Situational communications -- In service of the TANDAM system's objective of optimizing aircraft and crew performance, it conducts a number of communications management activities. For example, in the operational environment envisioned for this advanced concept, the TANDAM system provides the FMS with runway and approach assignments that it obtains from ATIS (or its advanced equivalent) typically just before initial descent. This acquisition of final flight path assignment is timely as well as useful because it

affords the FMS substantial time to complete its flight plan, including the determination of optimal terminal area navigation. It also allows the FMS to calculate precise waypoint ETAs, etc., in preparation for rapid, yet optimized, negotiations with CTAS. Lastly, automatic processing of ATIS information eliminates the potential for crew errors caused by late or erroneous accessing of ATIS information (a very common cause of "getting behind the aircraft"). The TANDAM system determines when to obtain the appropriate ATIS information by considering flight plan information regarding approximate time until landing, and data base knowledge regarding the schedule for periodic ATIS updates. After this initial employment of ATIS data, the TANDAM system periodically monitors ATIS for any changes that might affect the newly established runway and approach assignments, etc.

In a related communications management activity, the TANDAM system continually inspects data linked information for data that might significantly alter the current flight plan (e.g., winds, weather). In a more advanced version of this capability, the source of this uplinked information would be CTAS -- which would itself be sending a synthesis of data recently received from other nearby aircraft and other sources. Whatever the source of this data, the TANDAM system would have the job of assessing the implications of the new information. For example, if the TANDAM system receives information about severe clear air turbulence at a soon to be crossed altitude near, say, the SMO VOR -- and the system notes that this VOR is closely abeam the aircraft's future flight path -- it can inform the crew about the likely occurrence of turbulence down route.

Clearance communications -- The principal communications activities managed by the TANDAM system are those involved in the negotiation and acceptance of the complex clearances issued by CTAS. In these activities, the TANDAM system notes the reception of a CTAS clearance, and interrogates it for priority level and anticipated data processing requirements (e.g., changing a crossing altitude while maintaining the crossing ETA would involve new calculations by the 4-D component of the FMS). In the typical case, the TANDAM system then loads the clearance parameters into an FMS holding buffer ready for processing. Based on priority information and time available to comply, the TANDAM system determines whether to consider evaluating the clearance for optimality (in terms of aircraft performance); in short, the system decides whether it should propose a negotiation of the clearance. The system informs the crew of the clearance, the time until compliance is required, and whether it recommends negotiation of the clearance's parameters (while still abiding by its overall intent). In cases where the crew elects to evaluate the specifics of a clearance (for possible negotiation), the TANDAM system submits the buffered clearance data to the FMS and requests an estimate of an optimized compliance with the relevant waypoint(s), etc., and ETA(s). The system also reminds the crew to communicate compliance with the intent of the clearance, and their interest in negotiating the specific means of compliance. The resulting FMS solution (e.g., a delayed and steeper descent that still makes a particular waypoint on time and saves X pounds of fuel) is made available to the crew for approval, and is readied for downlink in the negotiation process. Upon reception of CTAS approval, the modified clearance is WILCOed by the crew. The system (with crew consent) directs the FMS to edit the flight plan and execute the

modified clearance. As the compliance point is reached (e.g., at top of descent), the TANDAM system ensures that actual clearance data (e.g., exact time and location of descent initiation) is downlinked to CTAS.

The TANDAM system's management of navigation and guidance

Several significant navigation and guidance functions are assisted or managed by the TANDAM system. These functions support a number of related activities: clearance negotiation and compliance; anticipation and reaction to situational changes connected to aircraft performance and environmental factors; and crew-initiated modifications to flight path management. These activities range in purview of control from relatively tactical to clearly strategic, and they therefore involve both FMS and FMCP-oriented governance of flight control and guidance. Moreover, the form of accommodation the TANDAM system will afford these navigation activities is greatly constrained by phase of flight and type of function.

Navigation management and clearance negotiation -- As was mentioned briefly in describing the TANDAM system's support of communications functions, the system ensures that a newly cleared flight profile appropriately modifies the FMS's existing flight plan, including all requisite changes in flight parameters relevant to 4-D compliance. To support the FMS, the TANDAM system first evaluates data on current environmental conditions (obtained from sensors and from uplinked reports) and aircraft performance, and then integrates this information with clearance directives. This precise, updated information is used to edit the existing flight plan, modifying the flight path and schedule as

necessary. In cases where CTAS clearances involve modifications of the vertical flight regime, a computational module of the FMS that is specialized for determining optimal vertical maneuvers (in terms of the aircraft's current performance characteristics) generates a range of solutions that comply with the clearance. The TANDAM system then directs the FMS to estimate passenger comfort (based on speed, vertical rate, anticipated turbulence, etc.) and fuel savings for this range of solutions. The TANDAM system readies the solution set and accompanying passenger comfort and fuel savings estimates for presentation to the crew, along with recommendations when appropriate.

The TANDAM system's "cognizance" of flight phase substantially influences its support of the clearance negotiation function. For example, the previously described procedure (in the discussion of communications functions) for the TANDAM system's management of negotiating a clearance was representative of clearances issued while an aircraft is at altitude, transitioning from Cruise to Descent phases of flight. In contrast, clearance negotiation procedures conducted in the terminal area would be automatically modified to be more conservative in several important respects. Operation at low altitudes and slow speeds, greatly delimited maneuvering options, and increased proximity of traffic necessarily constrain the TANDAM system's role in clearance negotiation. In the terminal area, then, the TANDAM system would consider negotiation only when such negotiations could clearly serve efforts to lower workload, improve or maintain situation awareness, increase safety margins, or better satisfy scheduling preferences. Thus, criteria for the negotiation of terminal area clearances will not (as in initial Descent) emphasize fuel savings, or perhaps even passenger

comfort. Instead, negotiations with ATC will be largely limited to supporting such activities as: Providing ATC with accurate ETAs, etc., to negotiating final clearances as early in the approach as possible; informing ATC of the aircraft's readiness for reaching the outer marker at any of a range of ATC-determined arrival times; and providing ATC with aircraft readiness status for potential ATC-instigated changes to alternate runways, etc., or even for crew-initiated negotiations for such runway changes when safe and advantageous.

As an example of this process, Figure 11 depicts a small segment of the TANDAM system's functioning at a very general level. Specifically, two interrelated functions are schematicized. For one function, the flow diagram shows the situational triggers (in one of the cases, the aircraft's proximity to a significant waypoint, BAYST, and its requisite altitude of approximately 10,000 feet) that cause the TANDAM system's criteria for recommending clearance negotiations to be modified. In this example, the clearance is optimized for terminal area (as opposed to Descent phase) navigation. Secondly, the diagram sketches out the broad factors addressed by the TANDAM system whenever it must consider recommending a negotiation of a clearance's specific parameters.

In both functions, the TANDAM system interacts with three context-relevant data sources: The Flight Plan Data Base, containing all significant navigational and regulatory information germane to the flight route; the Data Link system through which CTAS-generated clearances and environmental reports will be received; and the aircraft's sensors and onboard systems that provide positional

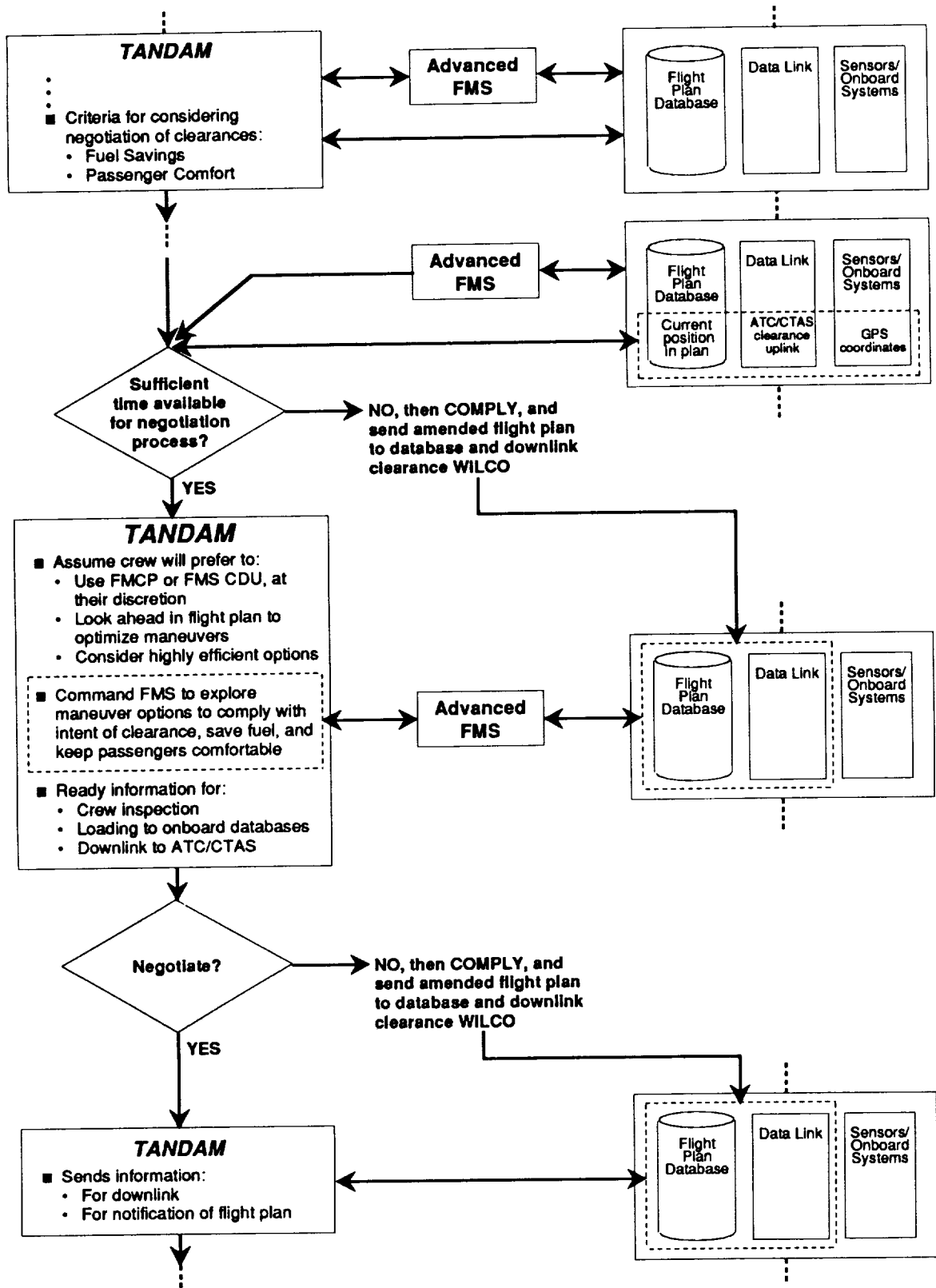


FIGURE 11. PARTIAL SCHEMATIC OF A SUGGESTED FUNCTIONAL ARCHITECTURE FOR THE TANDAM SYSTEM

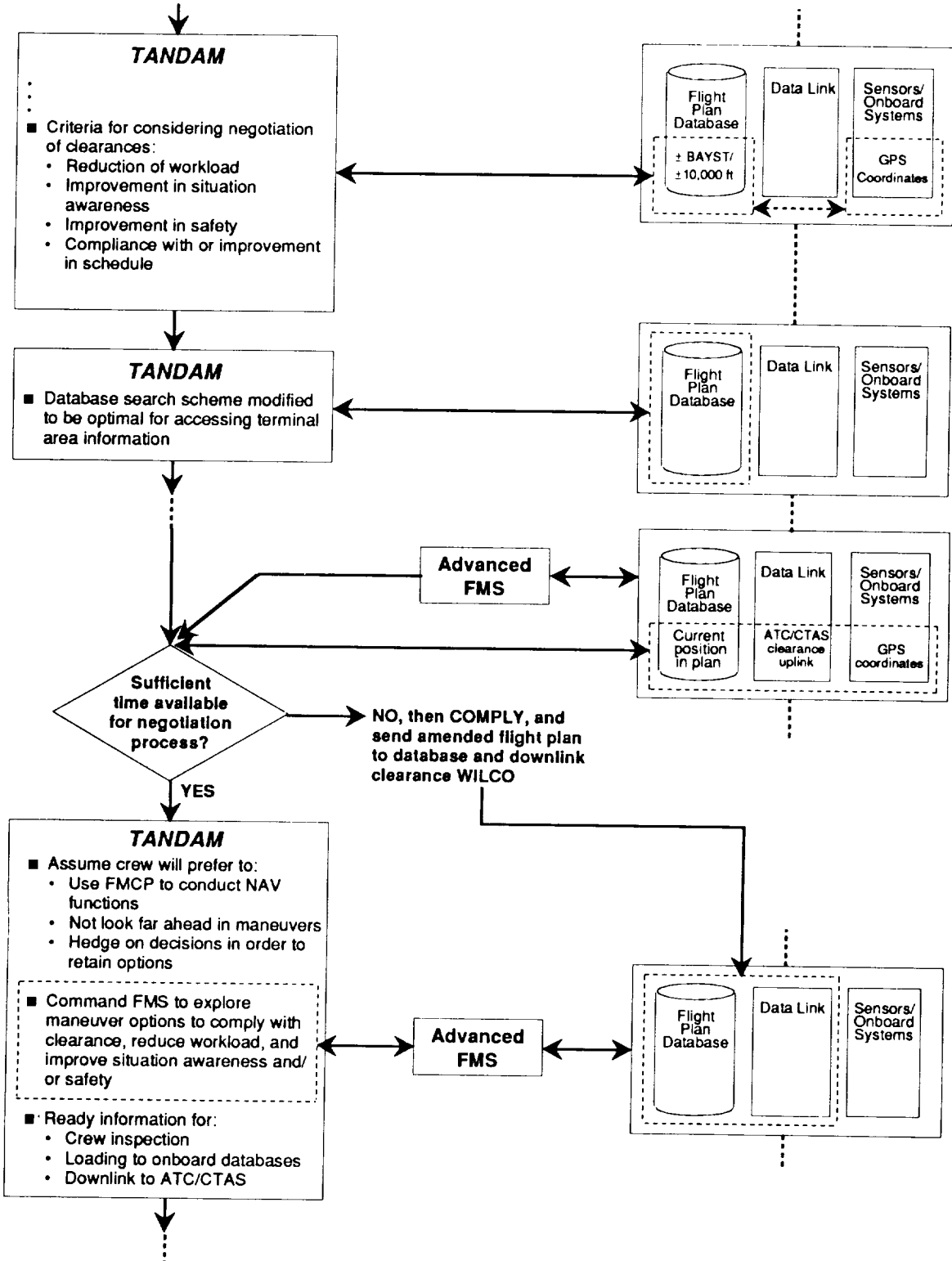


FIGURE 11. - Concluded.

information, performance data, and system status reports. Also evident in this depiction is the TANDAM system's critical reliance on the 4-D capable FMS.

(The reader is cautioned to understand that this schematic is not meant to be comprehensive or exhaustive, and does not presuppose a given programming or computational approach. Rather, its purpose is simply to give a "flavor" for the general logic involved with the notion of context-sensitive automation.)

Navigation management and position on flight plan -- The TANDAM system performs a number of functions designed to keep track of and modify the aircraft's progress in the flight plan, to prepare for upcoming activities, and to inform or remind the crew about the options available to them at various points along the planned route. For example, in 4-D navigation, the TANDAM system monitors progress on the flight path (i.e., performs trajectory tracking), automatically performing minor adjustments that keep the aircraft on route and on schedule. When a particular adjustment would exceed a context-sensitive tolerance, or when such an adjustment might have a significant effect on anticipated workload, etc., the TANDAM system will inform the crew and offer options appropriate to the situation.

More generally, the TANDAM system monitors position and time on the flight path, and compares this information with a flight path data base which stores all expected significant aircraft events. The TANDAM system determines whether actual events occur within the expected (data base) parameters, and notes any deviations from the predicted events, reporting them to the crew when necessary.

Additionally, the TANDAM system uses this monitoring function to help it anticipate and prepare for upcoming events. Thus, for example, when the system notes that the aircraft is about to enter an ATC sector handoff area, it automatically looks up and loads the new ATC frequency into a pre-select buffer for crew instigation. Similarly, in those terminal areas where ATC is known to provide the approach assignment relatively late (thus potentially increasing workload levels at inopportune times), the TANDAM system can look up possible approaches (given the already cleared descent and arrival route, approach restrictions due to winds, visibility, noise abatement, etc.) and rank order them in terms of probability of assignment. And, in cases where the most probable approach is appreciably more likely than its competitors, that approach can be loaded into an FMS pre-select buffer.

At altitude, the TANDAM system's monitoring of progress on the flight plan allows the system and the FMS to maintain running estimates of position and time 'windows' for maneuver execution such as deceleration schedules, points for speed break deployment, etc. In the terminal area, monitoring flight path progress also enables the system (via the FMS) to generate running solutions for points by which slats, flaps, and landing gear must be deployed, and for times associated with minimum altitudes and speeds to be achieved, etc.

As was mentioned previously, the TANDAM system also monitors the aircraft's terminal area flight path progress when the system is calculating running solutions for possible runway changes late in the final approach. In such cases, the TANDAM system considers the aircraft's position on its flight path, the

current environmental and traffic conditions, and relevant airspace regulations in order to precisely determine several important context-sensitive parameters, among these being:

- The point on the current approach by which the FMS must have the alternate runway's step-over maneuvers calculated, (in preparation for the earliest probable runway change clearance);
- The point on the current approach at which a step-over maneuver to the alternate runway would also involve significant speed and/or altitude changes; and,
- The points along the current (and alternate) approach by which checklists would have to be accomplished, ILS capture, centerlines, etc., would have to be established, and missed approach sequences would have to be loaded into pre-select.

The TANDAM system's integration with other systems

As was discussed earlier, the TANDAM system will rely on several advanced systems to perform its advisory and assistance functions. This reliance on supporting technologies will also depend on highly integrated software/hardware systems capable of accurately and rapidly sharing data sets and processing routines, and maintaining functional redundancy and safeguarding schemes. And, while the large majority of these supporting capabilities currently exist in limited

forms, it is clear that substantially advanced versions of these systems would have to be in place in order to enable the TANDAM system to fully function.

The TANDAM system's integration with the Flight Management System

As has been mentioned, the TANDAM system requires substantial coordination with an advanced FMS. In addition to current capabilities, this FMS will (in order to parallel and complement CTAS capabilities) also have to be capable of highly accurate and flexible 4-D navigation, demanding rapid and continual recalculation of the aircraft's current and future flight path, and its ETAs. These calculations of time and position information -- coupled with situation-specific data from onboard systems and sensors, from the flight plan data base (e.g., crossing restrictions), and from communications uplinks -- will be used by the FMS to continuously recalculate precise trajectory and speed solutions necessary for 4-D maneuvers and aircraft performance optimization. In particular, the FMS will have to be capable of generating and managing vertical profile sequences that optimize the aircraft's vertical maneuvers, since CTAS is currently slated to provide only nominal vertical flight paths in such clearances. The TANDAM system and the FMS will ensure that these 4-D maneuver solutions are constrained to preserve acceptable passenger comfort and crew workload. This 4-D maneuver management function (and, in particular, management of the vertical regime) will be accomplished by means of two critical capabilities: The FMS's highly integrated coordination with ATC's CTAS (which will supply 4-D clearance criteria, including route changes), and the employment of an FMS-

resident algorithmic system (similar to that employed in ATC's ground-based system) specialized for constructing aircraft-optimized 4-D vertical maneuvers still compliant with ATC directives. These capabilities will also enable the FMS and the TANDAM system to assist the crew in responding to unforeseen events (e.g., pop-up aircraft) by being ready to provide online recalculations, data base preparations, etc., for facilitating time-critical decision-making.

The TANDAM system's integration with communications systems

In addition to processing sensor, navaid, and performance data, the TANDAM system communicates with ATC and company sources. In this regard, the TANDAM system relies heavily on an advanced Data Link system capable of communicating complex CTAS 4-D clearances, rapid ATC/crew negotiations, and non-flight-critical and company business. Additionally, the Data Link capability will support a background-level continuous 'conduit' responsible for sending and receiving aircraft, environmental, ATC, and company data (referred to in the flight scenarios presented later as the Most Current Data Exchange Transmission (MCDET) system). Information downlinked by MCDET will include:

- Weather
- Turbulence levels
- Wind direction and speed
- Temperature
- Barometric pressure
- Estimated visibility

- Aircraft position, altitude, speed, and vertical speed
- Course and flight plan data, including waypoint ETAs
- Engine and performance data
- Weight, and fuel remaining
- Requests for non-time-critical company, and ATC data
- Certain clearance negotiation data

Uplinked information would include:

- Predicted weather, turbulence, wind, etc., down-route
- Non-time-critical company information, and ATC queries
- Certain clearance negotiation data

This data is used by the TANDAM system and the FMS to update the onboard flight plan data base, and to provide ATC with the most useful situational information available. ATC, in turn, will use these continual reports from individual aircraft to update its data bases, and, consequentially improve its ability to predict aircraft spacing margins, potential conflicts, arrival times, and general environmental conditions.

The TANDAM system's integration with the user interface

The functional integration of the TANDAM system with an advanced crew interface is fundamental to the automation's utility. This crew interface -- a functionally integrated system of annunciators, displays, and controls that helps

preserve crew awareness of, and prerogative over, the TANDAM system's actions and intentions -- is integrated with the TANDAM system in several respects. The TANDAM system will interact with the crew to assist in making decisions, alleviating or re-aggregating workload, and enhancing situation awareness. This assistance is possible as a result of the TANDAM system's continual "awareness" of situation-specific mission events. In this assistance role, the TANDAM system tailors the organization of information and recommendations to be readied for presentation to the crew, such that only relevant, vital information is proffered first; additional background, secondary considerations, etc., are provided only upon request (or after crew acceptance of the automation's suggestions). To ensure against over-reliance on this automated assistance, the TANDAM system is integrated with the crew interface system such that it continually has available for the crew information regarding the status of currently operating automated routines. Moreover, this information also clearly reflects the automation's processing so as to give the crew an understanding of the system's "mental" model and "intent." Where applicable, the TANDAM system is ready to report the potential consequences of its operation. When these consequences significantly exceed nominal expectations, the TANDAM system alerts the crew without waiting for their inquiries.

OPERATION OF THE TANDAM SYSTEM IN REPRESENTATIVE DESCENT AND APPROACH SCENARIOS

As mentioned previously, three representative Descent and Approach scenarios were created in order to demonstrate how the TANDAM system would function in accord with the onboard systems, the crew, and ATC. These scenarios, all based on modified versions of published arrivals and approaches, used Los Angeles' International (LAX) and Orange County's John Wayne (SNA) airports. These airports were used because MDC research personnel were already familiar with ATC procedures in the surrounding Los Angeles-area terminal airspaces (having previously interviewed and observed controllers at both facilities). The existing arrival/approach sequences are heavily flown, and all are known to demand fairly substantial workloads, even in ideal conditions. ATC-directed deviations from the published flight paths are common, some occurring in virtually every approach into these highly trafficked airports. Even runway changes (at LAX) occur with a relatively high frequency, and thus must, to varying degrees, be anticipated in any approach. And, while the number of ATC interventions contrived for these arrival/approach sequences are probably unrealistically high (in order to demonstrate significant capabilities of the TANDAM system), their type and placement are quite representative of clearances anticipated under CTAS governance.

The scenarios, presented in three multi-page tables (Tables I, II, III), are each arranged in an abridged function timeline format, moving from one significant mission event to the next. For each time- and/or fix-marked event, relevant

ATC/aircraft communications, the TANDAM system's functioning, and crew involvement are described as appropriate. When significant aspects of TANDAM's activities warrant special focus, selected Navigation Display formats are presented.

The SADDE FOUR Arrival into LAX

The first scenario, described in Table I, is based on the SADDE FOUR Arrival STAR into LAX. In keeping with likely ATC planning for CTAS-governed airspace, the arrival has been modified to be a profile descent. The modified SADDE FOUR is shown in Figure 12. In this scenario, it is assumed that CTAS is fully operational and is directing all navigation, sequencing, and spacing guidance for the aircraft on its descent and approach. The aircraft is equipped with an advanced Data Link system, as well as with the TANDAM system and an FMS capable of 4-D navigation.

A number of clearances are demonstrated in this scenario. At altitude, three major 4-D clearances are issued by CTAS: Two expedited descents designed to make the aircraft attain fixes at times substantially earlier than planned; and one route stretch clearance designed to make the aircraft late, relative to the revised plan. In these three cases, the scenario in Table I shows how the TANDAM system might assist the crew in evaluating, negotiating, and complying with the ATC directives -- and still optimizing the flight plan for aircraft performance and passenger comfort.

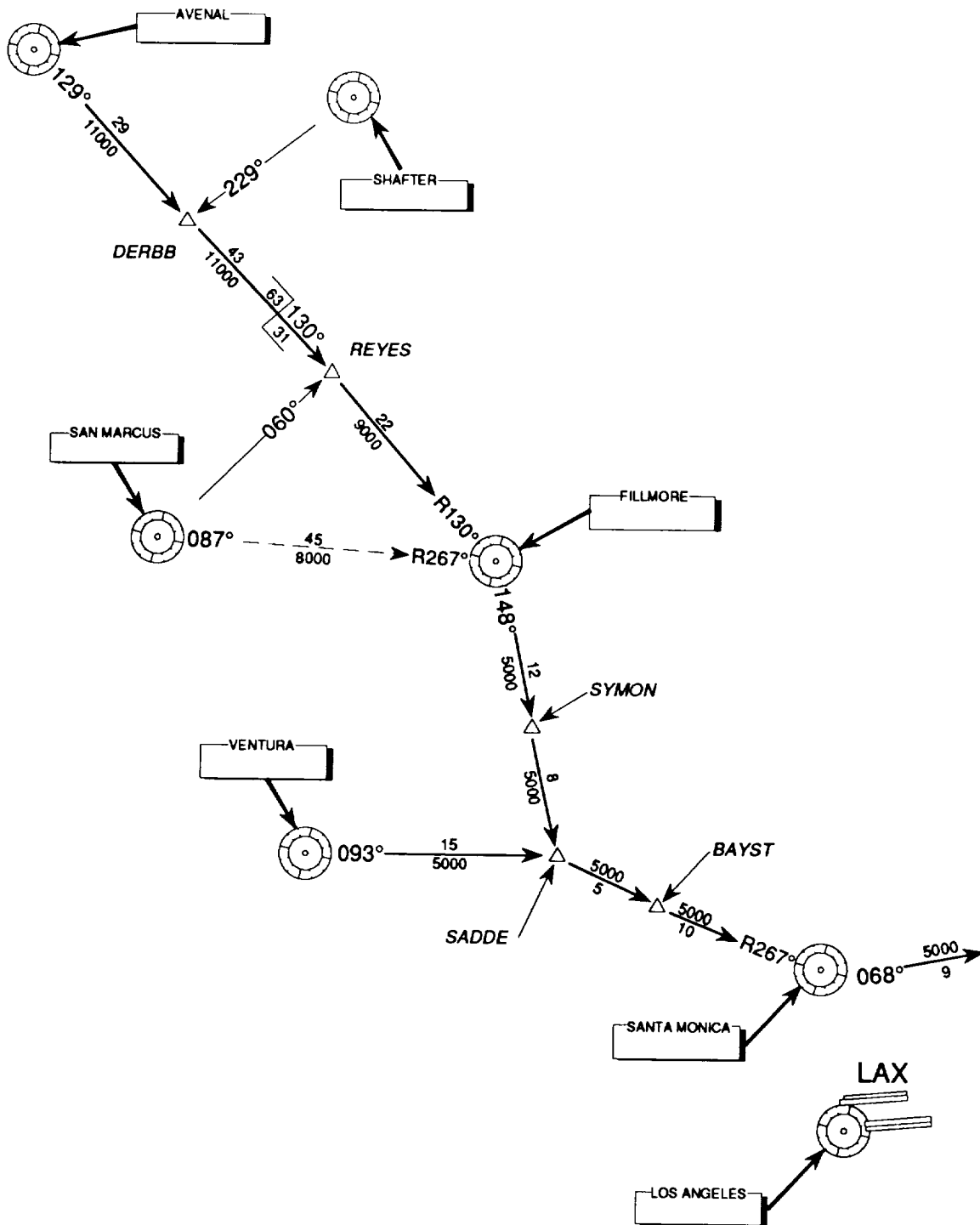


FIGURE 12. SCHEMATIC FOR THE SADDE FOUR ARRIVAL INTO LAX

In the LAX terminal area, the scenario depicts the aircraft on its cleared approach. However, due to various unforeseeable events, the aircraft's approach is repeatedly interrupted and changed by ATC. In each of these cases, the scenario describes the TANDAM system's efforts to keep the crew aware of the latest situation and the aircraft configuration, and poised to respond appropriately to the eventual final clearance.

TABLE I. THE SADDE FOUR ARRIVAL INTO LAX

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
		<p><ATIS obtained via DL between 9:51:00 and 10:00:00. Relevant data (runway information, winds, weather, etc.) loaded into SYS; crew informed as to data and loading.></p> <p><MCDET information continually updates SYS, crew about current and anticipated conditions on route.></p>	<p>SYS uses relevant ATIS information to help build preliminary versions of the primary and secondary flight plans to 24R and 25L, respectively.</p> <p>SYS consults terminal area data base and selects possible approaches. If several, ranks them probabilistically given track record for this flight, adjusted to recent updates, etc. Informs crew of these preparatory activities, and is ready to present these selections to the crew, if requested.</p> <p>SYS anticipates ATC communication frequency change, given position on flight plan, etc.; preselects new frequency, informs crew, awaits ATC instruction and crew selection.</p>	

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
		ATC directs communication frequency handoff to LA Center via DL, and ports (with crew awareness) to SYS.		Crew acknowledges handoff, and selects new frequency, contacts LA Center.
		LA Center requests identification squawk.		Crew commands SYS to commence identification squawk.
			SYS squawks identification to LA Center.	
			SYS logs that DL message and crew compliance occur within expected positional parameters.	
		LA Center acknowledges identification squawk.		
10:00:00	AVENAL 489/31000			Crew notes AVENAL VOR crossing; verifies flight data and time match flight plan.

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
10:01:45	AVENAL/D15 489/31000	<p>ATC/CTAS clears aircraft for 4D SADDE4 Profile Descent; uplinks time, speed, etc. data for clearance.</p> <p>ATC indicates that crew is to expect possible modifications to this arrival clearance (from CTAS).</p> <p><CTAS clearance's initial descent requires aircraft to make FIM VOR, between 19000 and 15000 feet (standard restriction), at an STA of 10:11:53. (CTAS assumes SADDE4's TOD between DERBB and REYES.)></p>	<p>SYS loads SADDE4 Profile Descent from preselected buffer and begins 4D calculations with on-board Descent Advisor (DA essentially similar to DA used by CTAS), using airborne data and current aircraft performance characteristics.</p> <p>SYS readies display of SADDE4 for crew inspection.</p> <p>SYS determines relevant center-of-display fix and range setting, 40nm, as probable initially desired selections for crew inspection of SADDE4 relative to present position.</p> <p>SYS evaluates feasibility of making 4D SADDE4, and readies its ETAs (in relation to the CTAS STAs) for downlink.</p> <p>SYS readies display of 4D information on ND Map page. SYS estimates will show that all 4D waypoints are within timed position tolerances.</p>	<p>Crew acknowledges clearance (with the belief that time constraints can be met. Actual on-board verification of satisfying expected 4D constraints not yet completed by SYS).</p> <p>Crew calls up Map mode of ND with SADDE4 now loaded. (SYS-modified from original flight plan).</p> <p>Crew inspects Map page and decides to zoom in on flight plan near SADDE fix.</p>

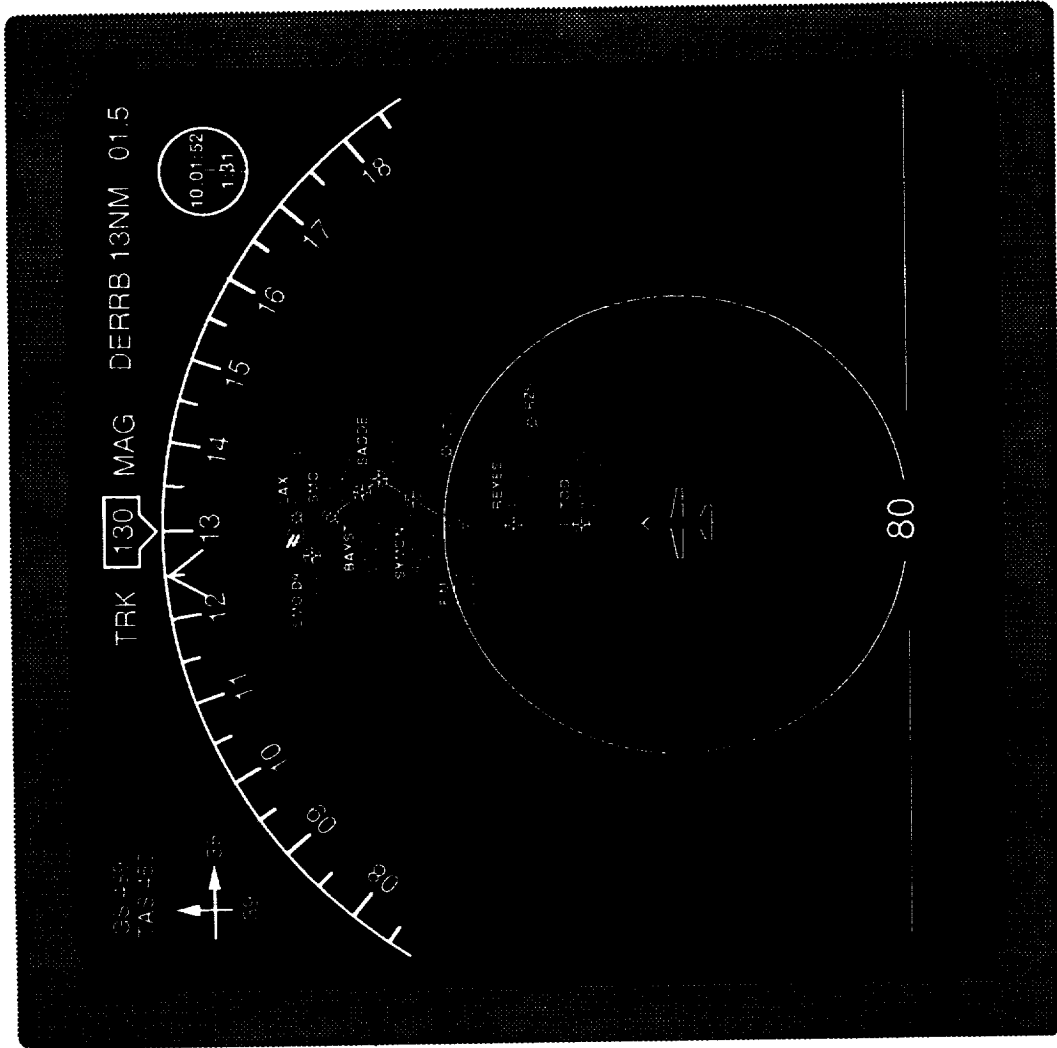


FIGURE 13. NAVIGATION DISPLAY, IN MAP MODE, SHOWING THE SADDE FOUR PROFILE DESCENT

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
10:03:31	DERBB 489/31000	Aircraft downlinks ETAs for 4D compliance; also MCDET for CTAS update. <CTAS reschedules aircraft's STA so new STA and aircraft's ETA differ by 45 seconds.> CTAS issues a time modification clearance to be at FIM crossing by current FIM ETA minus 45 seconds and continue on SADDE4 profile with new STAs (all minus 45 seconds from current.) Compliance method at crew discretion with approval of ATC.	SYS loads new CTAS clearance, notes compliance time constraints, and begins calculations for compliance options to be presented to crew. Given current and anticipated (from MCDET data trends) wind data, weather, turbulence levels, etc., SYS determines maximum vertical speed rate and KTS (using a predetermined passenger discomfort limit) to make FIM at new (minus 45 second) ETA, taking into account altitude restrictions, and descent rates and speeds for following legs. SYS then back-calculates lesser vertical speed/greater KTS combinations that will all make the 4D FIM clearance. Cost indices and estimated passenger comfort levels are also provided.	Crew inspects 4D information and approves downlink. Crew changes ND to map and prepares for initial descent.
				Crew observes SYS has at least a maximum (acceptable) performance solution to comply with clearance (and crew members mentally note that SYS jibes with their own informal appraisal).

TIME

EVENT

COMMUNICATIONS

TANDAM SYSTEM

CREW INVOLVEMENT

Crew WILCOs clearance; tells CTAS exact flight path, etc., will be downlinked momentarily.

SYS readies compliance options for presentation on vertical Profile planning Display (PD). Information to be displayed includes:

- Window of TOD points
- Maximum and minimum flight profiles (with associated vertical speeds, KTS, and cost and passenger acceptability indices).
- Relation of options to subsequent legs.
- Altitude restriction at FIM displayed.

Crew selects vertical PD, inspects SYS-generated options for clearance compliance.

TOD window also displayed on ND. 4D arc is on FIM. Time and altitude information displayed on PD and ND.

Crew selects descent profile by choosing TOD point that places speed brake deployment bug at FIM. Crew notes that this descent profile achieves good fuel savings and passenger comfort, and maintains FIM as a crossing altitude fix, yet allows for easy compliance with upcoming deceleration schedule.

SYS readies selected descent for downlink; updates ETA, profile, based on actual TOD.

Crew authorizes downlink of descent profile data.

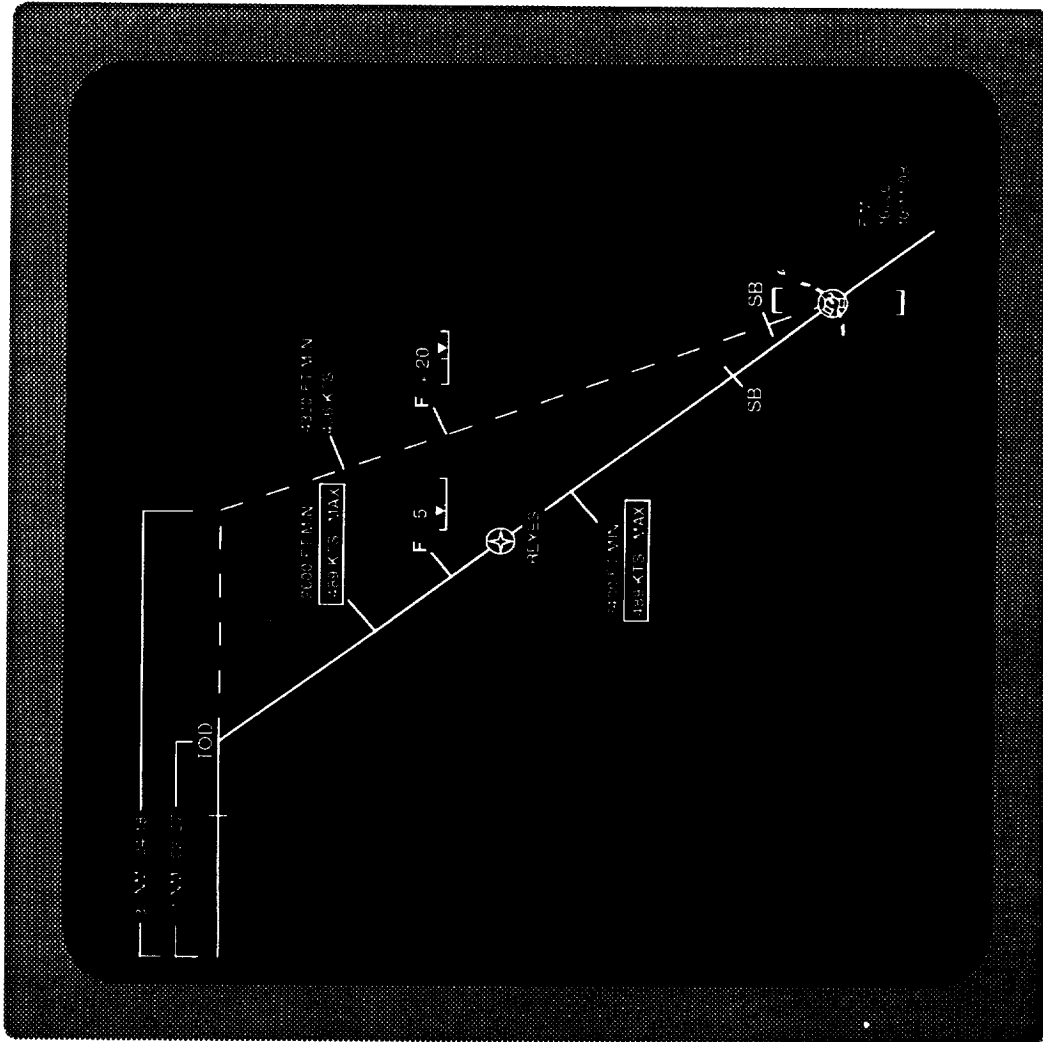


FIGURE 14. NAVIGATION DISPLAY, IN VERTICAL PROFILE MODE, SHOWING MANEUVER OPTIONS FROM TOD TO FIM

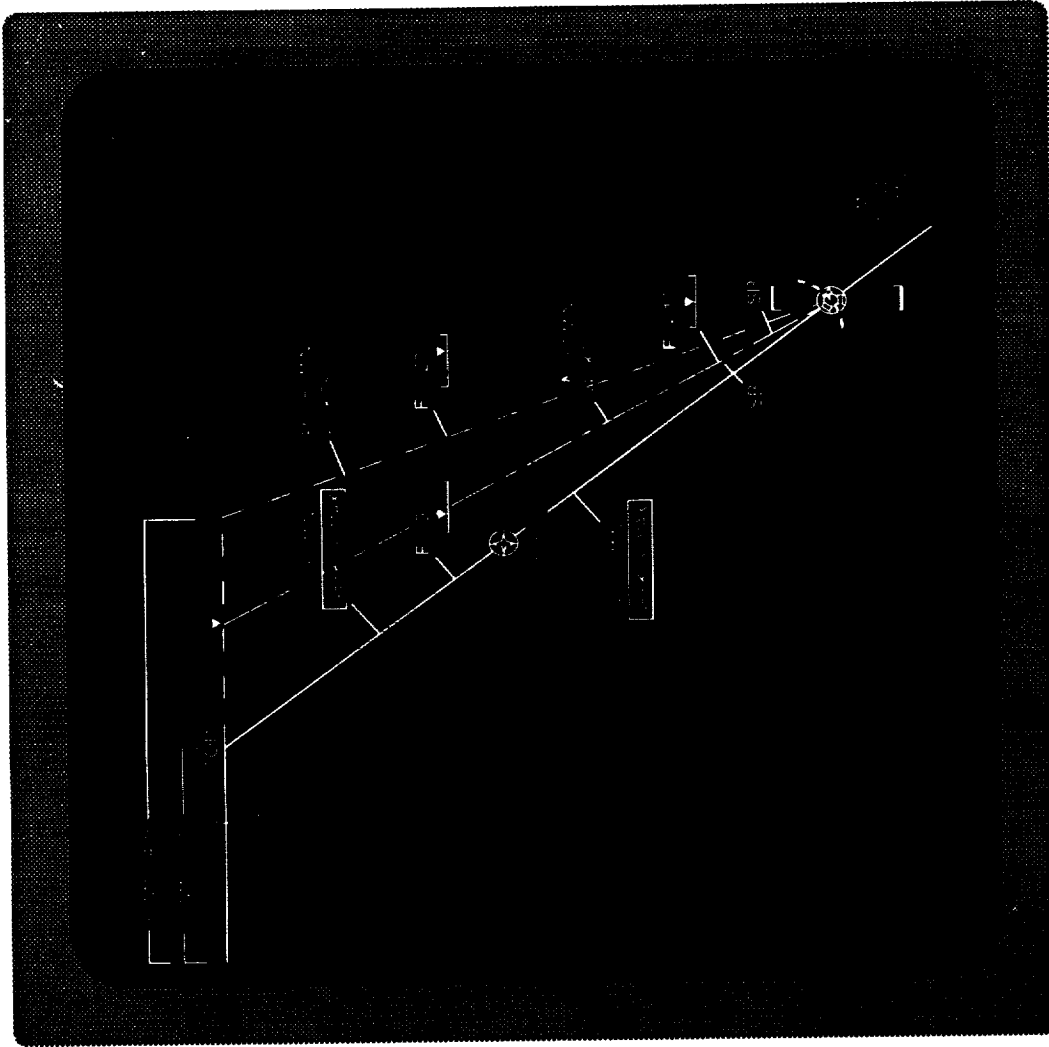


FIGURE 15. NAVIGATION DISPLAY, IN VERTICAL PROFILE MODE, SHOWING CREW SELECTION OF DESCENT PROFILE FROM TOD TO FIM

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
10:07:08	REVISED TOD 489/31000	Selected descent profile (and associated data) is downlinked to CTAS.	SYS readies display of new flight plan; prompts crew. SYS reminds crew of upcoming descent maneuver; descent is initiated.	Crew selects map mode on ND.
10:07:37	REVISED TOD/D4 482/29400	MCDET includes actual descent data in downlink to CTAS. CTAS amends descent: "Cross SYMON at 310KTS (begin deceleration 8 nm past FIM) and decelerate to (already planned) 250KTS by SADDE with the <u>intent</u> to cross BAYST at current STA minus 30 seconds. Then resume existing flight plan (with time adjustment of 30 seconds)." <(Clearance given well ahead of execute point/time.)>	SYS loads and evaluates CTAS solution for 4D fix at BAYST; determines fuel burn non-optimal and passenger comfort in question due to DL reported turbulence between 18000 and 20000 feet in vicinity of FIM.	Crew observes upcoming descent; monitors relevant controls and displays.
			SYS attempts to find a descent that minimizes time in turbulence zone, makes the FIM altitude restriction, and complies with CTAS's 4D clearance.	Crew WILCOs <u>intent</u> of BAYST 4D clearance. Informs CTAS that SYS is evaluating CTAS <u>method</u> of compliance for possible negotiation.

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
			<p>SYS readies for display alternate solutions that comply with the intent of the 4D clearance, and satisfy SYS concerns. (SYS-proposed solutions include lead time estimates sufficient for comfortable crew workload.) Since options involve changes to the vertical flight path, SYS prompts crew to examine vertical PD.</p>	<p>Crew calls up vertical PD, zooms in to crew-determined relevant segment, and evaluates SYS-generated solutions to clearance.</p>
			<p>Sys displays CTAS solution along with SYS-generated alternates.</p>	
			<p>SYS indicates advantages and disadvantages of alternates:</p> <ul style="list-style-type: none"> • Amount of fuel savings • Passenger comfort • Turbulence minimization. 	
				<p>Crew chooses one of the alternate solutions and elects to negotiate with ATC for SYS version of clearance. Crew commands SYS to initiate negotiation.</p>
			<p>SYS readies solution for downlink (for negotiation).</p>	

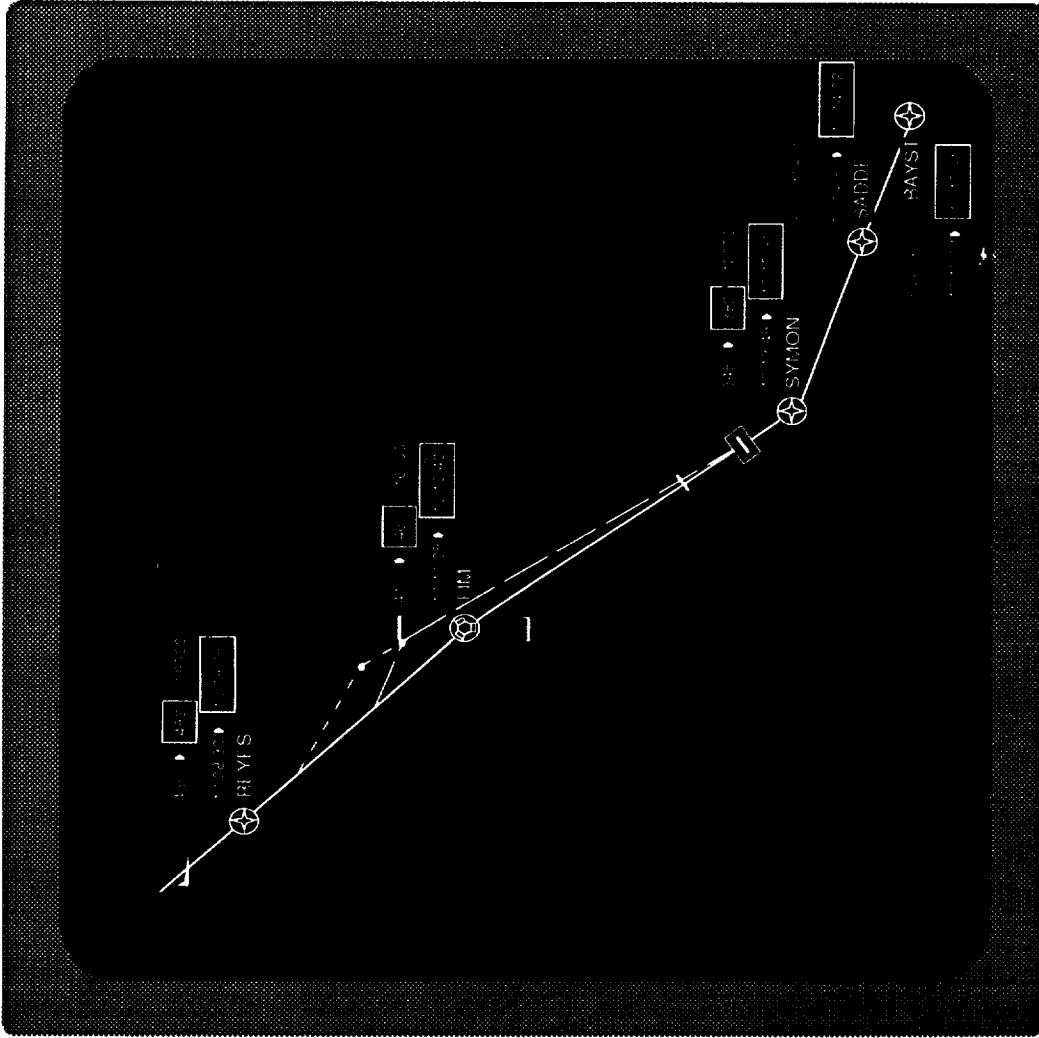


FIGURE 16. NAVIGATION DISPLAY, IN VERTICAL PROFILE MODE, SHOWING MANEUVER OPTIONS FROM REYES, THROUGH FIM ALTITUDE RESTRICTION, TO SYMON

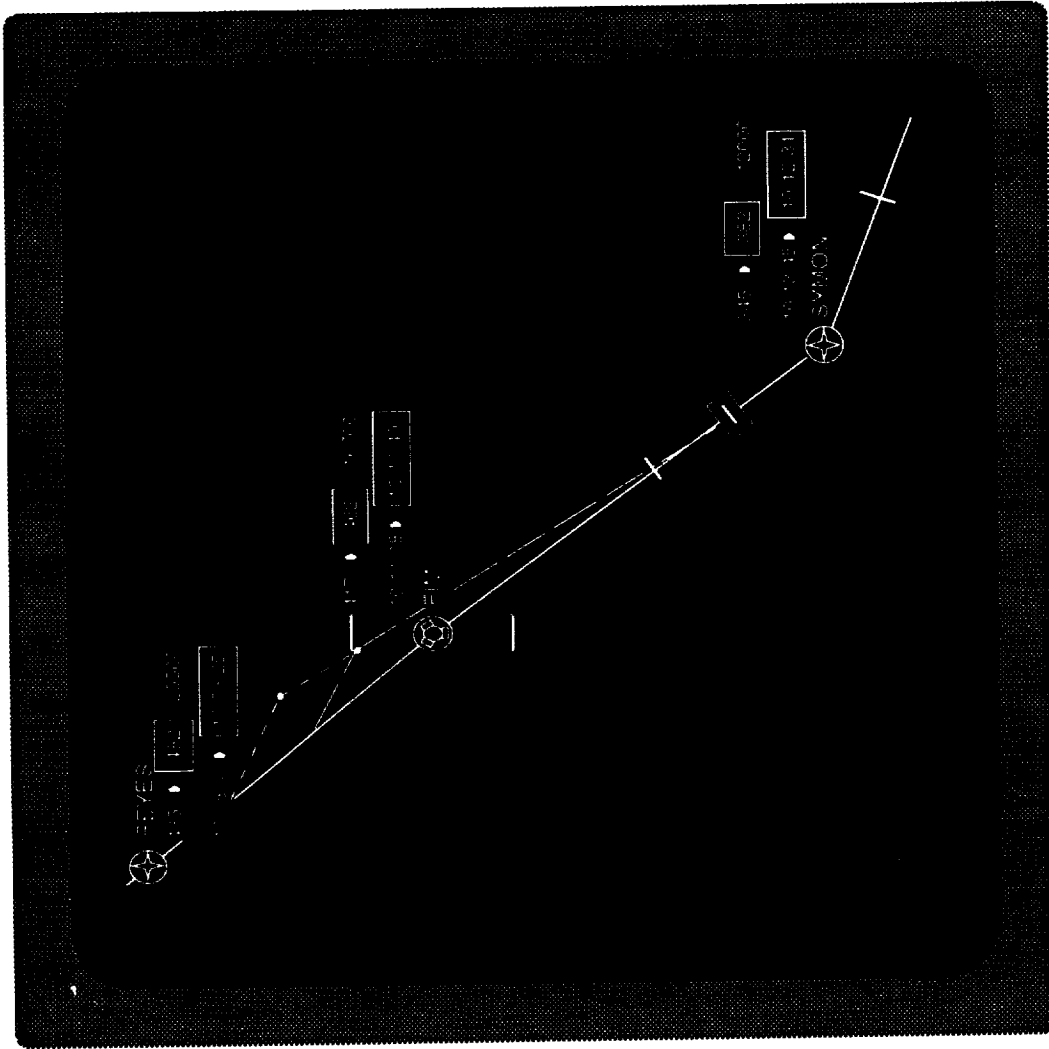


FIGURE 17. NAVIGATION DISPLAY, VERTICAL PROFILE MODE ZOOM IN, SHOWING MANEUVER OPTIONS FROM REYES, THROUGH FIM ALTITUDE RESTRICTION, TO SYMON

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
		Crew negotiates with ATC/CTAS (specifics DLed down).		
		ATC/CTAS approves SYS version of 4D clearance.	SYS initiates clearance.	Crew commands SYS version of clearance to be executed.
			SYS reminds crew of reported turbulence; informs them about possible anti-icing requirement.	
10:08:25	REYES 464/25500	Actual 4D crossing data is automatically downlinked to CTAS (via MCDET).	SYS displays actual and planned altitudes, times, for REYES waypoint.	Crew observes that actual crossing altitude and time at REYES match SYS-planned altitude and time.
10:10:06	REYES/D18 439/19700	<ATC handoff from CENTER to LA TRACON. Procedure similar to previous handoff.> Immediately following TRACON handoff, CTAS amends current clearance: <ul style="list-style-type: none"> • 2.4 nm before SYMON, turn heading 183 degrees and intercept the 093 degree radial out of VTU VOR; • Turn to 093 degrees and rejoin original flight plan at SADDE at current STA plus 43 seconds. 	<SYS functions similar to previous handoff.>	<Crew procedure similar to previous handoff.>

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
		<p><Because of speed changes and area restrictions, speed adjustments would not be sufficient to add required 43 seconds to ETA. Therefore, CTAS adopts a route stretching strategy to control the aircraft's STA.></p>	<p>SYS loads CTAS clearance parameters and cross-checks calculations for ETA plus 43 seconds at SADDE.</p>	<p>Crew acknowledges receipt of 4D clearance to SADDE; calls up ND showing current and CTAS-amended routes to SADDE. Crew, with SYS assistance, estimates that clearance is accomplishable and accepts <u>intent</u> of clearance.</p>
		<p><CTAS provides its estimates for deceleration schedules to make the 4D SADDE crossing.></p>	<p>SYS determines:</p> <ul style="list-style-type: none"> • Insufficient time to clearance initiation point for negotiation, given upcoming workload and situational awareness levels anticipated for navigation management activities. • Estimated fuel savings with alternate vertical regimes appear negligible. 	
		<p>Acknowledgement of clearance and acceptance of intent are downlinked to CTAS.</p>		

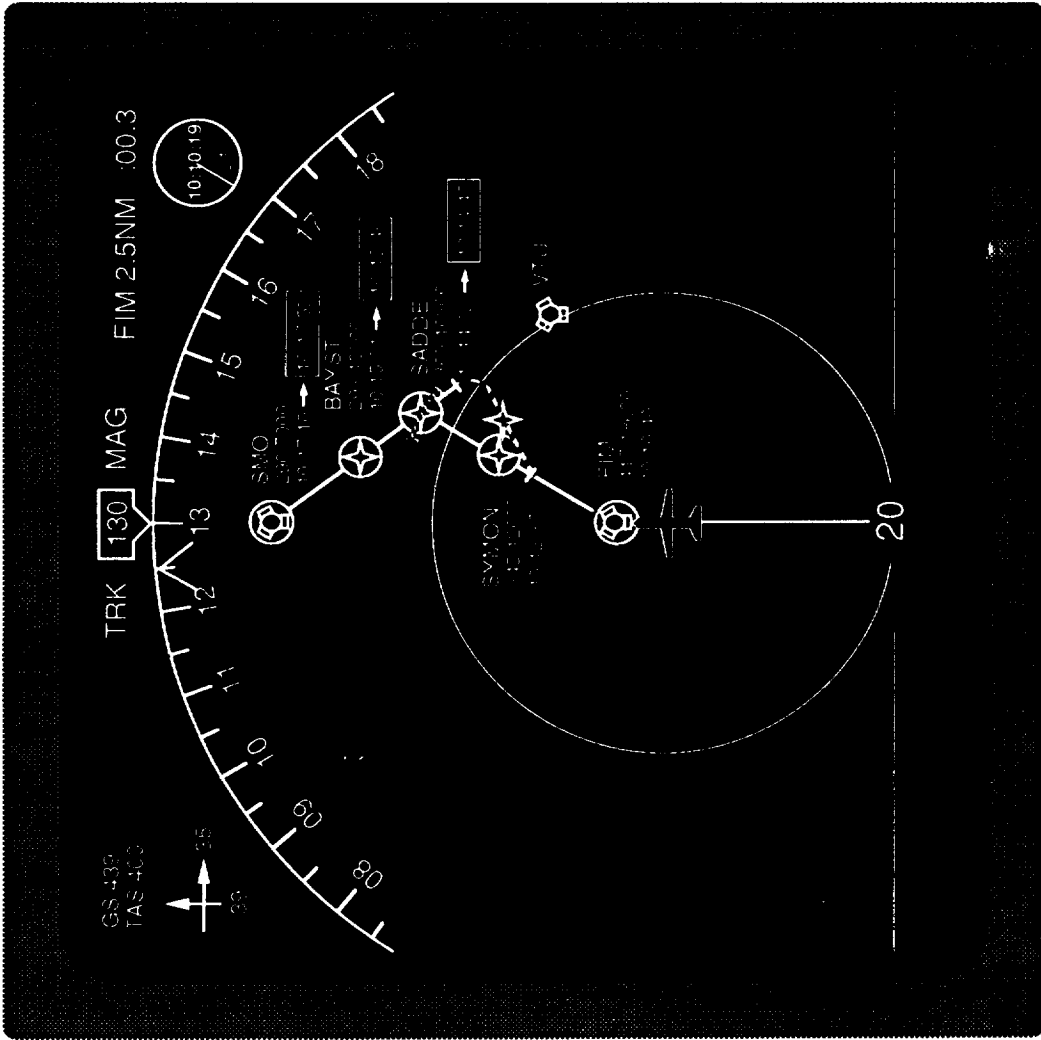


FIGURE 18. NAVIGATION DISPLAY, IN MAP MODE, SHOWING CTAS-AMENDED ROUTE FROM FIM TO SADDE

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
10:10:40	FIM 417/18600	DL downlinks flight data regarding course change (etc.) to CTAS.	SYS initiates previously planned course change over FIM: turns to a heading of 148 degrees.	Crew momentarily shifts attention from clearance interpretation to observe SYS- executed course change. Crossing altitude observed to be 18600 feet.
10:11:02	FIM/D2.5 407/17170		SYS recommends straight acceptance of CTAS clearance.	Crew accepts SYS recommendation, decides to ROGER clearance, and inform ATC that SYS-generated speeds and ETAs will follow.
		Clearance compliance datalinked down to CTAS. CTAS told to expect specifics momentarily.	SYS calculates new route's times, speeds and deceleration schedule (compares these to CTAS's estimates), determines new deceleration points for achieving 280 KTS, and for achieving 250 KTS by SADDE.	
				SYS displays proposed routes, profile, speed goal points, and ETAs; readies downlink.

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
			<p>SYS displays:</p> <ul style="list-style-type: none"> • First deceleration initiated 7.5nm after FIM (unchanged from last clearance). • First deceleration completed (i.e., at 280 KTS) at point 3.7nm down 183 degrees heading. • Deceleration to 250 KTS initiated 4nm before SADDE (coming out of turn on to 093 degree heading inbound to SADDE). • 250 KTS achieved <u>at</u> SADDE. • Waypoint ETAs. <p><SYS will show aircraft position relative to on-time position.></p> <p><Route-stretching solution commanded by CTAS provides SYS and crew with a significant level of speed adjustment control to keep aircraft on time. If clearance had been issued in an airspace free of altitude and speed restrictions, SYS would also have been able to use vertical speed changes to accomplish 4D compliance.></p>	<p>Crew inspects vertical plan display and ND for clearance parameters and approves downlink and execution.</p> <p><Crew decides to transition to a SYS guidance-only mode after BAYST (below 10,000 feet.) and execute flight commands via FCP. All SYS advisory capabilities will remain active.></p>
		<p>SYS-generated specifics of CTAS 4D clearance to SADDE are downlinked.</p>		

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
10:11:54	FIM/D7.6 385/14500 (Initiate deceleration to 280 KTS)		SYS initiates deceleration schedule to make and hold 280 KTS at a fix approximately 2nm west of (i.e., ABEAM) SYMON at 10:12:47.	Crew decides to monitor SYS implementation of course, altitude, and speed changes to make 4D waypoints; crew puts SYS into "Navigation Implementation" (NI) mode. Crew selects NI on ND.
10:12:15	FIM/D9.6 363/13340 (Initiate turn to 183 degrees)	Position, time, and maneuver downlinked to CTAS.	SYS displays 4D waypoints, significant points, and associated speed, altitude, and ETA data (format / symbology and procedures closely resemble manual/FCP control of same maneuvers).	Crew observes ND and PD display of 4D/deceleration, descent sequence.
10:12:31	On heading of 183 degrees 354/12700	Position, time, and maneuver completion/heading downlinked to CTAS.	SYS executes turn toward a heading of 183 degrees.	Crew monitors SYS-executed turn, deceleration, altitude, and time.
10:12:49 Late:02	ABEAM SYMON 345/12000 (280 KTS airspeed)	Position, time, etc., downlinked to CTAS.	SYS completes turn; verifies position, heading. SYS indicates 2 seconds late in reaching ABEAM SYMON waypoint at 280 KTS. SYS recalculates and adjusts deceleration schedule to SADDE to compensate for 2 second error.	Crew observes time error of late by 2 seconds; crew notes that error is within tolerance limits and can be made up down route by SYS.

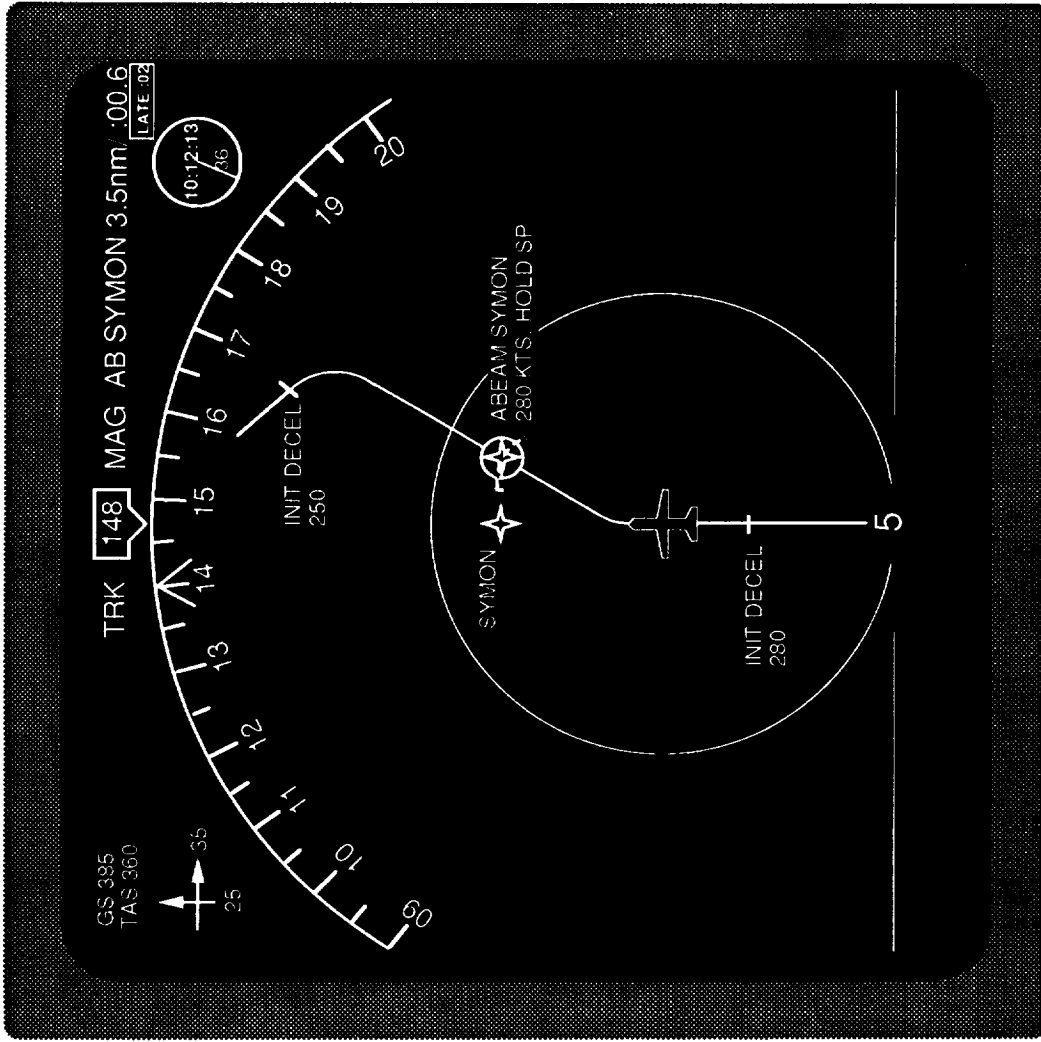


FIGURE 19. NAVIGATION DISPLAY, IN MAP MODE, SHOWING TANDAM-GOVERNED NAVIGATION IMPLEMENTATION APPROACHING ABEAM SYMON

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
10:13:10	Initiate turn to 093 degrees 338/11830 (VTU VOR radial toward SADDE)	Position, time, and maneuver downlinked to CTAS.	SYS executes turn to intercept a heading of 093 degrees off the VTU VOR toward SADDE.	Crew monitors SYS-executed turn, continued deceleration, altitude, and time.
10:13:48	4nm before SADDE 325/11330 (Initiate deceleration to 250 KTS)		SYS initiates deceleration schedule to be at 250 KTS at SADDE (corrected to make up for 2 seconds late at ABEAM SYMON).	Crew observes start of deceleration from 280 KTS as aircraft is rolling out of turn and intercepting the new route to SADDE.
10:13:53	3.6nm before SADDE 323/11200 (On heading of 093 degrees out of VTU VOR)	Position, time, and maneuver completion/heading downlinked to CTAS.	SYS completes turn; verifies position, heading/course to SADDE.	Crew observes 4D arc appear on SADDE; notes ETA reflects corrected time error from ABEAM SYMON.
10:14:45	SADDE 305/10800 (250 KTS air-speed)		Crossing SADDE, SYS changes heading to 081 degrees (via tuning and tracking SMO VOR radial 261 degrees). Because of altitude restriction at BAYST, SYS verifies change in descent rate and altitude on plan.	Crew observes SMO VOR autotune and heading change.
		Position, time, heading change, etc., downlinked to CTAS.		Crew monitors PD to ensure altitude crossing restriction will be met at BAYST.

TIME EVENT COMMUNICATIONS TANDAM SYSTEM CREW INVOLVEMENT

- CTAS/FAST uplinks final clearance:
- After SADDE along SADDE4 profile to LAX 24R.
 - SMO RO70/D9 plus 4nm, turn south heading 150 degrees. Decelerate to and hold 200 KTS, descend to and hold at 400 feet.
 - At crew discretion (but within LOC capture angle), turn from base, heading 220 degrees to intercept ILS for 24R.
 - Intercept ILS (heading 249 degrees) at least 2 nm before ROMEN OM.
 - Cross ROMEN at 2200 feet, 160 KTS, at 10:23:31.
 - Contact tower.

SYS loads clearance, determines time to compliance is adequate for negotiation, and evaluates optimality of CTAS/FAST version. SYS also cross-checks feasibility of making CTAS/FAST STA at ROMEN.

Crew acknowledges receipt of 4D clearance to ROMEN/24R. Crew estimates clearance accomplishable and accepts intent of clearance.

SYS determines clearance parameters approximately optimal and feasible within 4D requirements; advises straight acceptance.

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
10:15:46	BAYST 293/10000 (250 KTS air- speed)	Crew is downlinking acceptance of intent of clearance, and then amends the downlink (having received SYS's recommendation) to accept without negotiation. CTAS is informed to expect SYS-generated specifics (for descents, speeds, decelerations, and times).	SYS calculates specific waypoint ETAs, and corresponding speeds, decelerations, and altitudes to make 4D clearance at ROMEN. Current best estimates for slat, flap, and gear deployment points also generated.	Crew directs SYS to operate in "Guidance-Only" mode. All advisory and caution/warning capabilities remain active.
		Position, time, heading, altitude, etc., downlinked to CTAS.	SYS transitions to Guidance-Only mode; annunciates mode shift.	
		SYS-generated specifics of final clearance (given engine performance, weight, winds, etc.) are downlinked to CTAS.	SYS loads (into a preselect mode) a flight plan for 25L (as preparation for possible runway change) and continually re-calculates specifics of this alternate approach.	
			SYS loads ILS and missed approach parameters for both runways; sets data for 24R to operative, and 25L to alternate.	

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
			SYS readies display of cleared approach to 24R, and informs crew of solution to 25L alternate.	Crew inspects 24R approach on ND. Crew has SYS also display 25L alternate for crew evaluation. Crew removes 25L approach from ND (for declutter) and decides to inform ATC of its running solution to 25L as an alternate.
			SYS readies a downlink 'path' to send continuously updated 25L solutions, in case rapid downlinking of 25L alternate is required in the future.	
		Crew downlinks message informing CTAS of ongoing readiness for 25L approach as an alternate.		
10:17:55	SMO 290/7000	MCDET continues downlink/uplink flow of information.	SYS--using weather, wind data and traffic information from MCDET, and current engine performance, aircraft position, and aircraft weight--continuously updates clearance parameters for 24R ILS landing (and 25L), including: <ul style="list-style-type: none"> • Fixes, turns • Altitudes • Descent rates • Speeds • Times • Configuration changes 	Crew elects to display ETAs for ROMEN (OM) and 24R.

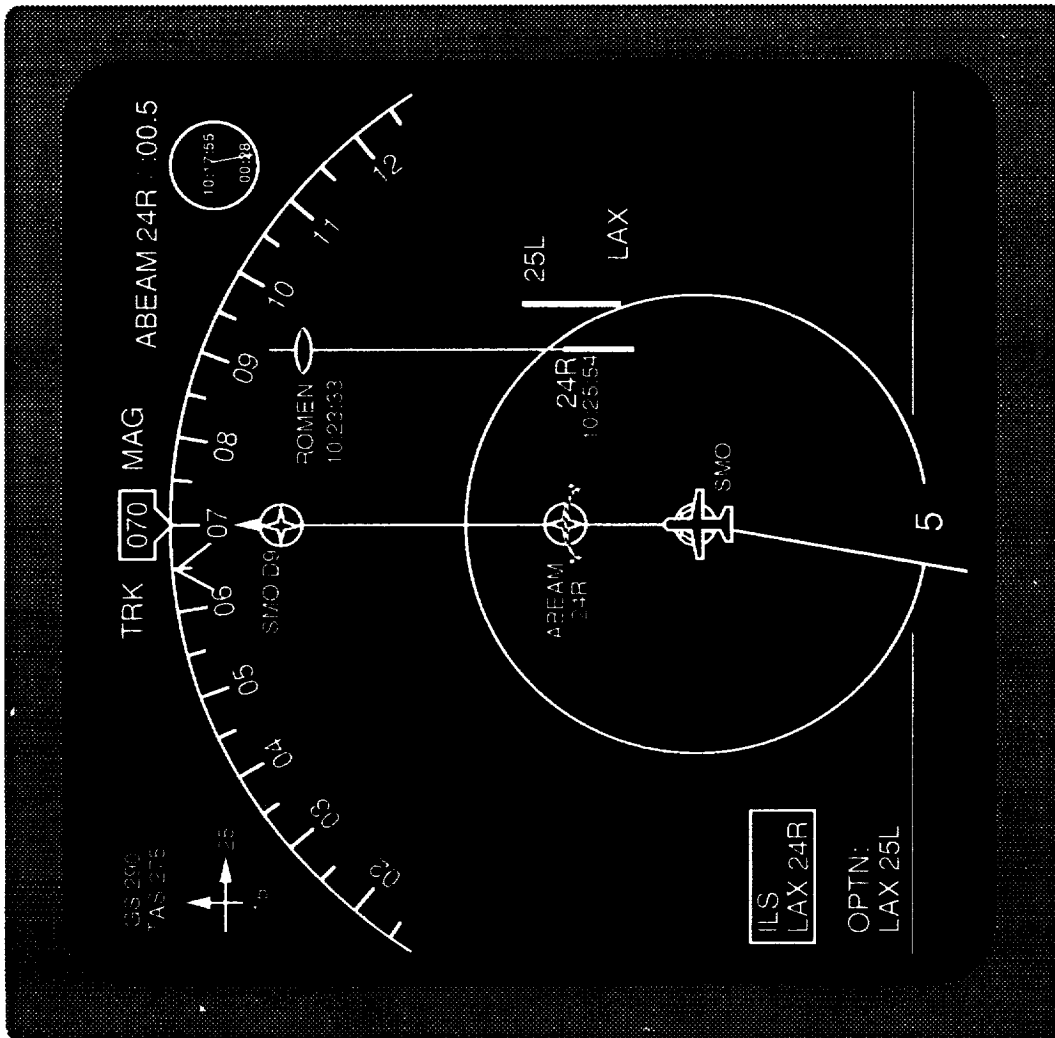


FIGURE 20. NAVIGATION DISPLAY, IN MAP MODE, SHOWING APPROACH TO LAX RUNWAY 24R FROM SMO

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
			SYS prepares information for presentation on ND; readies declutter options for crew selection.	
10:18:23	ABEAM 24R 290/6500		Current ETAs to OM (10:23:33), 24R (10:25:54) displayed.	Crew monitors progress on flight path; directs aircraft control by following SYS-generated guidance parameters.
10:18:50	ABEAM +2nm (SMO/D4) 278/6100		On ND, SYS displays cleared approach to 24R. Currently calculated configuration-change limits also shown: <ul style="list-style-type: none"> • Slats extension • Flaps, 28 degrees • Gear down • Flaps, 50 degrees 	Crew elects to also display speed and altitude for initial turn. (Crew continues to execute 4D maneuvers following SYS guidance.)
			SYS shows pre-selected bank angle limit.	Crew selects suggested bank angle limit.
			SYS shows safe zone ("window of opportunity") for intercepting final course.	

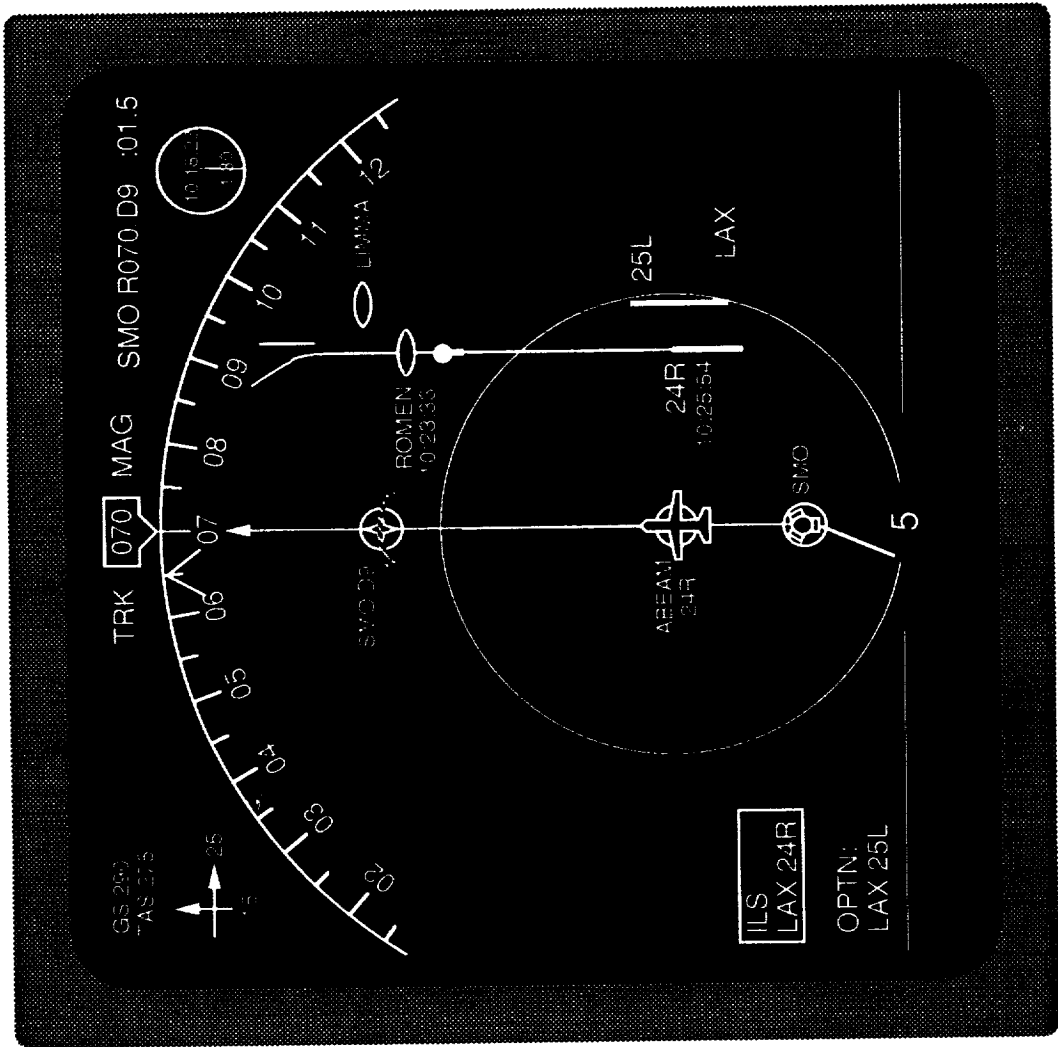


FIGURE 21. NAVIGATION DISPLAY, IN MAP MODE, SHOWING ETAS TO ROMEN OM AND TO LAX RUNWAY 24R

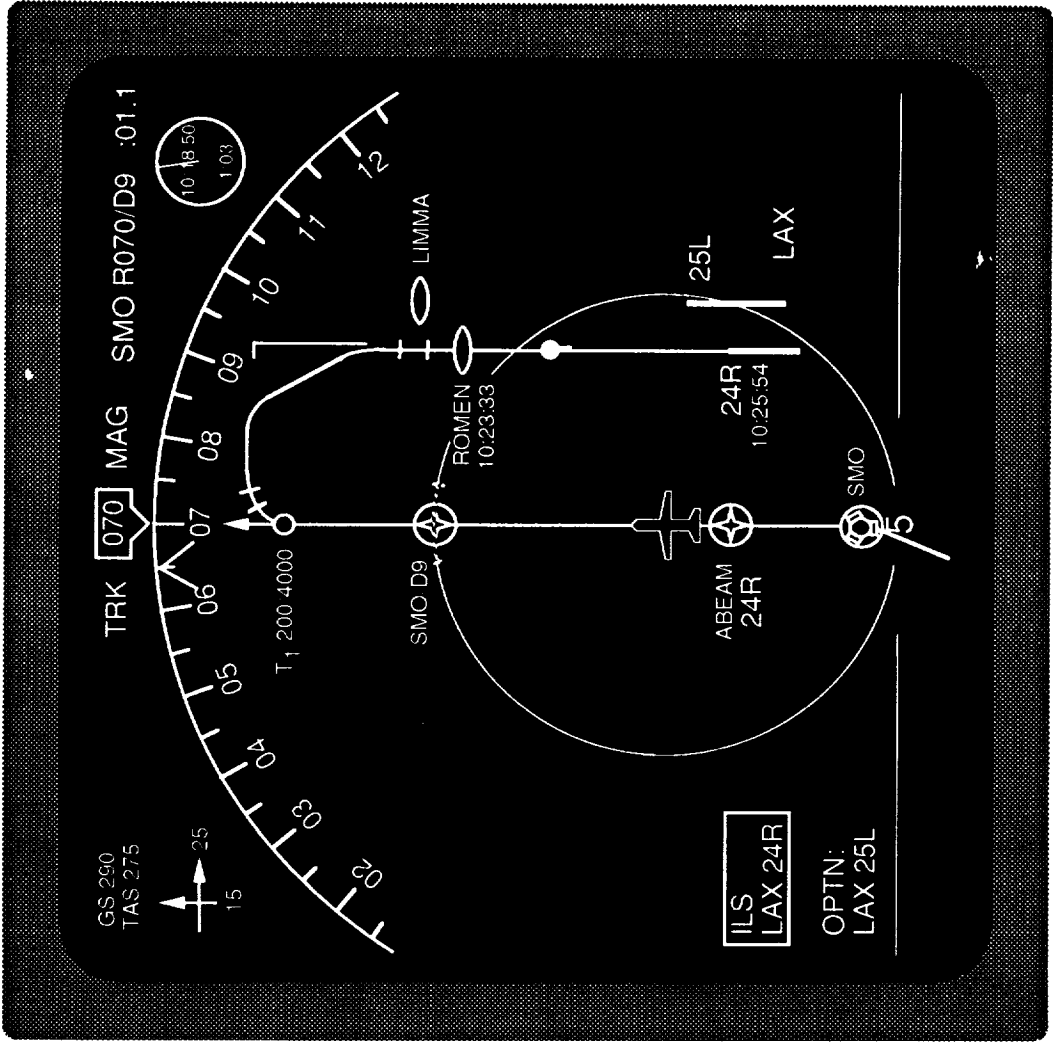


FIGURE 22. NAVIGATION DISPLAY, IN MAP MODE, SHOWING POINTS BY WHICH SLATS, FLAPS, AND LANDING GEAR ARE TO BE DEPLOYED

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
10:18:57	ABEAM +2.5nm (SMO/D4.5) 275/6000	CTAS/FAST cancels clearance route to 24R due to ground traffic. Aircraft is instructed to continue downwind and expect a new clearance soon -- possibly even original clearance reinstated.	SYS begins to modify flight plan, ND, to reflect clearance suspension. To be prepared for possible reinstatement of original clearance, SYS continues rate of deceleration to achieve 200 KTS, in preparation for slat deployment and turns. SYS plans for possible crew-commanded altitude hold at 4000 feet.	
			SYS informs crew of upcoming altitude and speed hold recommendation.	
			SYS continues to re-calculate approach paths and ETAs to 24R and 25L in preparation for upcoming clearance (not displayed).	Crew approves holds and has SYS execute necessary control modifications.
10:19:53	SMO D9 250/5000	CTAS/FAST issues new final clearance: <ul style="list-style-type: none"> • Turn to base (200 KTS) at SMO/D15; STA:10:21:36; • Cleared to the ILS for 24R; STA ROMEN:10:27:24. MCDET uplinks traffic constraints, current wind, visibility, etc.	SYS begins to modify flight plan to reflect new clearance. Configuration change waypoints calculated for new flight path, and readied for display. New ETAs calculated and readied for downlink. SYS presents crew with new data.	Crew WILCOs clearance.
				Crew evaluates SYS data and approves downlink to ATC.

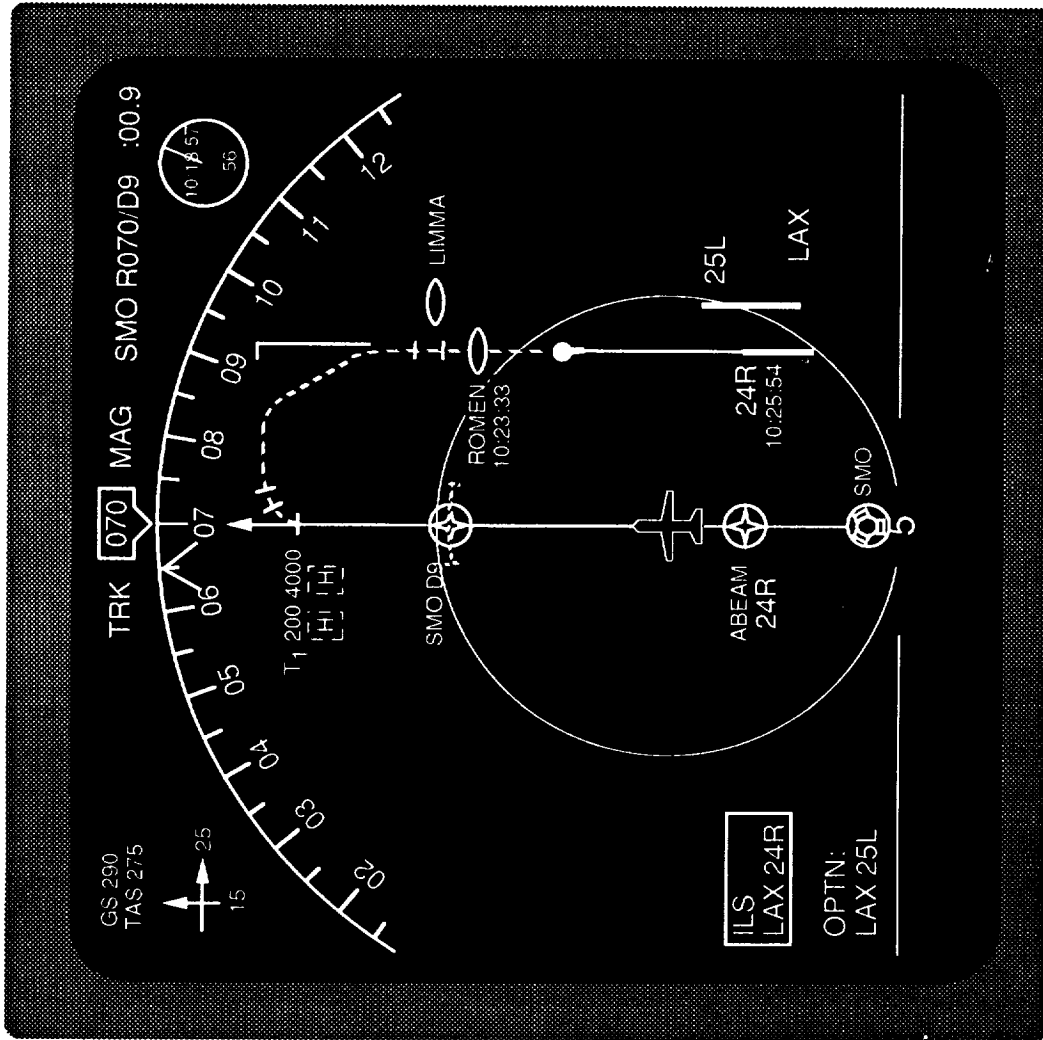


FIGURE 23. NAVIGATION DISPLAY, IN MAP MODE, SHOWING SUSPENDED CLEARANCE TO LAX RUNWAY 24R, AND POSSIBLE ALTITUDE AND SPEED HOLDS

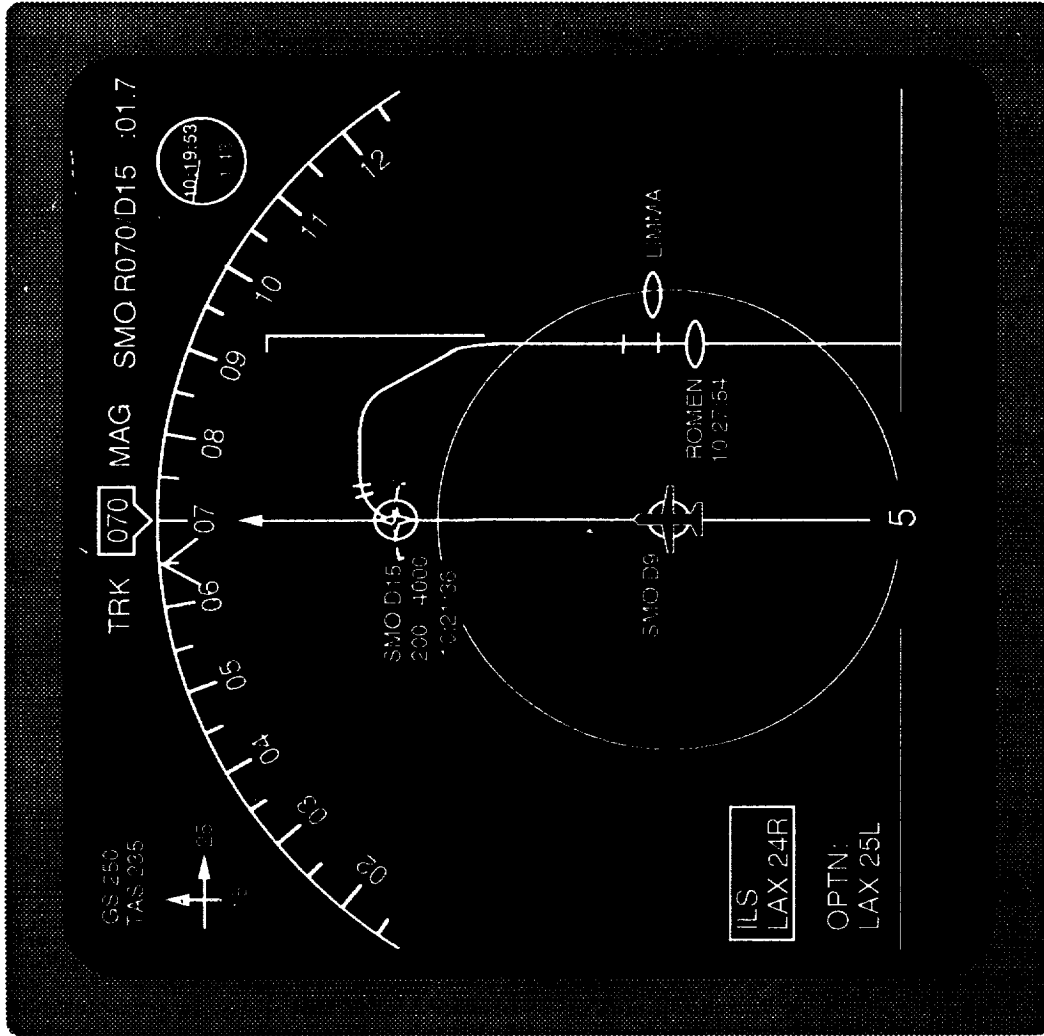


FIGURE 24. NAVIGATION DISPLAY, IN MAP MODE, SHOWING NEW CLEARANCE TO LAX RUNWAY 24R, INVOLVING TURN TO BASE AT SMO/D15

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
10:21:24	SMO/D14 200H/4000H	Crew downlinks flight path, altitudes, speeds, ETAs. Crew informs (reminds) ATC of upcoming compliance with clearance to 24R: "In ~15 seconds, initiating turn to base leg of 150 degrees, and will intercept ILS to 24R. ETA ROMEN, 10:27:26."	SYS informs crew of time to initiate turn 1, verifies speed and altitude within 4D tolerance; prepares to send actual turn initiation time to Data Link for transmission to CTAS. SYS readies updated guidance for maneuvers, etc., relevant to turn 2.	Crew monitors for visual traffic; looks ahead into path of upcoming turn. Crew tries to verify position by acquiring visual landmarks. Crew verifies altitude, speed; prepares to execute turn 1; continues to manually control heading and configuration changes; verifies that SYS is monitoring and maintaining 4D tolerances on altitude and speed holds set in FCP.
10:21:30	SMO/D14.5 200H/4000H	ATC voice break in, emergency cancellation of clearance; maintain heading 070 degrees, speed 200 KTS, altitude 4000 feet.		Crew informs SYS of clearance cancellation. Crew verifies maintenance of heading, altitude, speed. Crew informs SYS of change in clearance(i.e., maintenance of heading, speed, and altitude).
			SYS cancels clearance to 24R, verifies with crew that SYS is still in guidance-only mode, except for altitude and speed holds (which are SYS-governed via previous FCP settings).	
			SYS notes (and displays) resulting flight path discontinuity.	Crew directs SYS to calculate possible revised base/final maneuvers, waypoints, etc., for both runways.

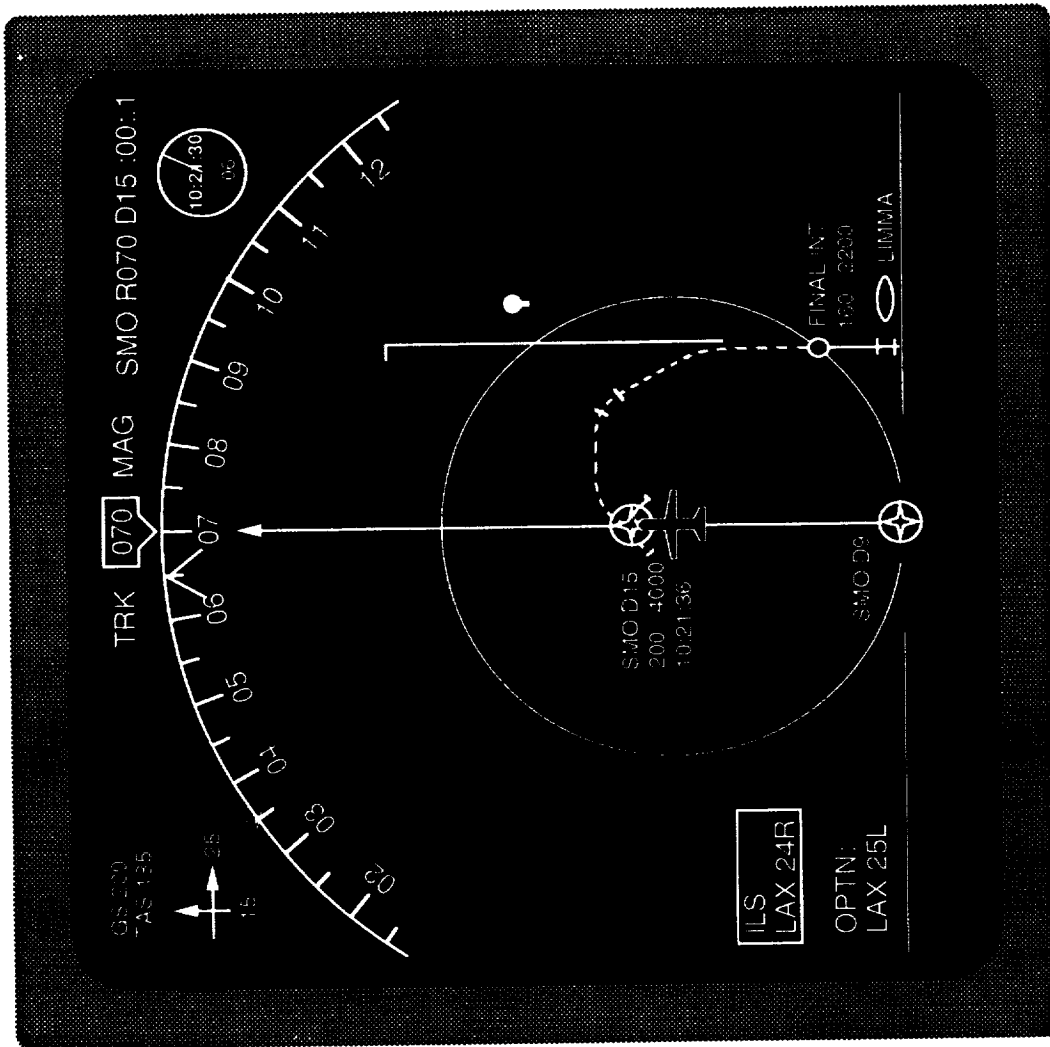


FIGURE 25. NAVIGATION DISPLAY, IN MAP MODE, SHOWING EMERGENCY CANCELLATION OF CLEARANCE TO LAX RUNWAY 24R, JUST PRIOR TO TURN TO BASE AT SMO/D15

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
			SYS recommends that it resume control of altitude and speed change schedule when next 4D clearance accepted, in order to free up crew to control course changes, maintain vigilance, and execute configuration changes.	
			Using MCDET and airborne data, SYS begins identifying and calculating next possible base/final approaches.	Crew acknowledges SYS recommendation, but makes no change at present; keeps SYS in guidance-only mode and aircraft in altitude and speed holds.
10:22:53	SMO/D19 200H/4000H		SYS displays soonest possible clearances.	Crew directs SYS to display soonest possible clearances to 24R and 25L.
			SYS compares ETAs for possible approaches; also includes estimates of taxi times.	
			SYS tells crew soonest 24R clearance will be 2:06 later to the dock than the soonest 25L clearance would be.	

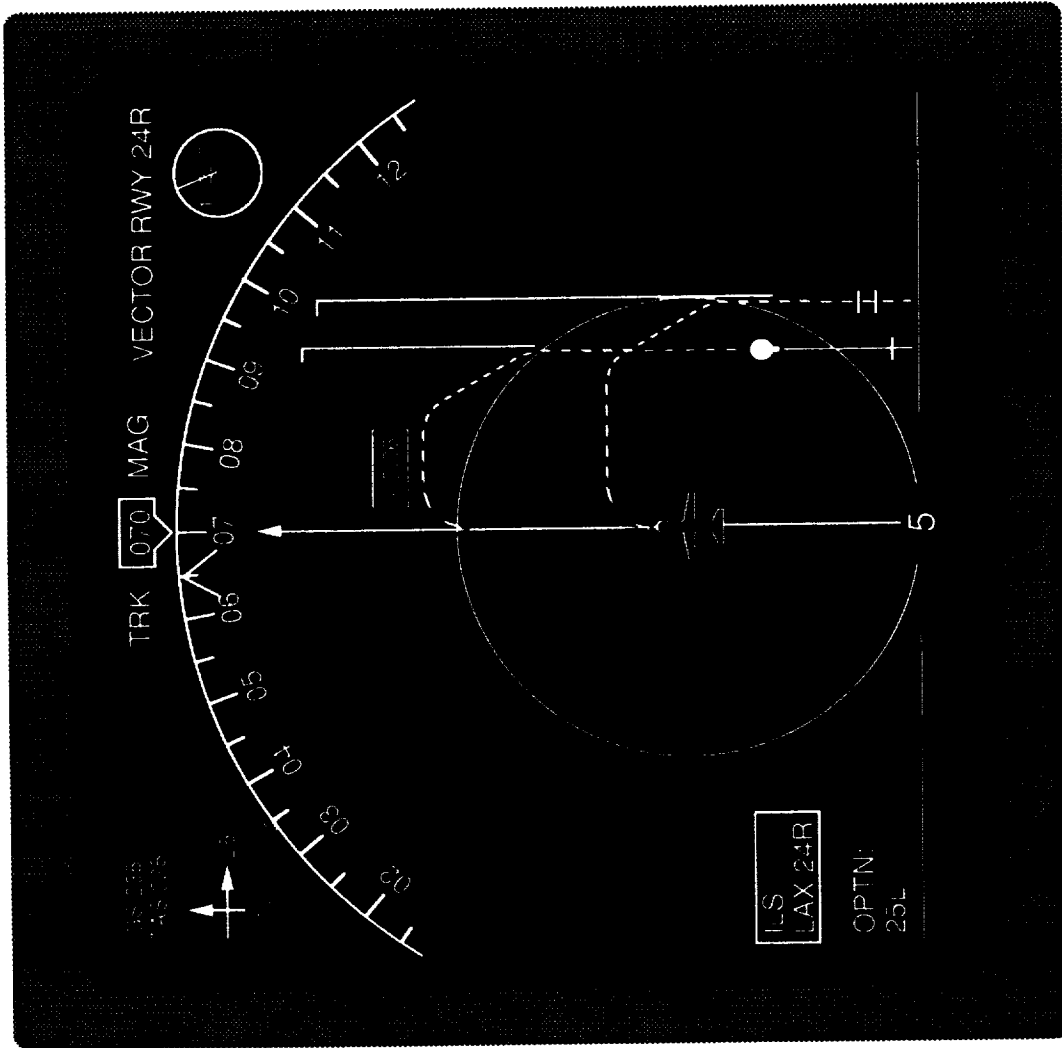


FIGURE 26. NAVIGATION DISPLAY, IN MAP MODE, SHOWING SOONEST POSSIBLE CLEARANCES TO LAX RUNWAYS 24R AND 25L

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
		Crew requests SYS-calculated clearance to 25L.		Crew evaluates SYS estimates, decides to request an immediate clearance for 25L.
		ATC/CTAS (having evaluated request) grants clearance to 25L.		
			SYS receives clearance.	Crew commands SYS to comply with clearance.
			SYS begins turn 1, re-calculates points for configuration changes and speed schedule. SYS displays relevant information.	
			SYS engages new flight plan to 25L.	
		SYS downlinks relevant runway and data to company, ATC (CTAS and Tower). Other aircraft data also sent to company.	SYS tunes new ILS frequency (and verifies readings), and initiates centerline/touchdown calculations; readies Go Around requirements for 25L.	

The KAYOH TWO Arrival into SNA

In the second scenario (presented in Table II), the aircraft follows the KAYOH TWO Arrival STAR into SNA, and transitions to an approach that takes it above and across the final approach course (see Figure 27). The aircraft is instructed to continue on its current heading, awaiting vectors to be turned downwind and then to base, in order to intercept the SNA localizer. In contrast to the first scenario, the TRACON for SNA (Coast TRACON) is not assisted by CTAS, and does not have an operational Data Link ground system. To add to ATC's difficulties, it is responsible for a large and varied population of aircraft types and capabilities, owing in large part to SNA's proximity to other major civilian and military airports. The aircraft is again equipped with the TANDAM system and the 4-D navigation-capable FMS.

This scenario depicts the assistance of the TANDAM system in an ATC environment not appreciably different from present-day capabilities. The TANDAM system helps the crew comply with last-minute clearances, and cancellations of these directives. Additionally, the scenario shows how the crew, TANDAM system, and FMS together might assist ATC in determining a useful 4-D clearance for the aircraft's final approach.

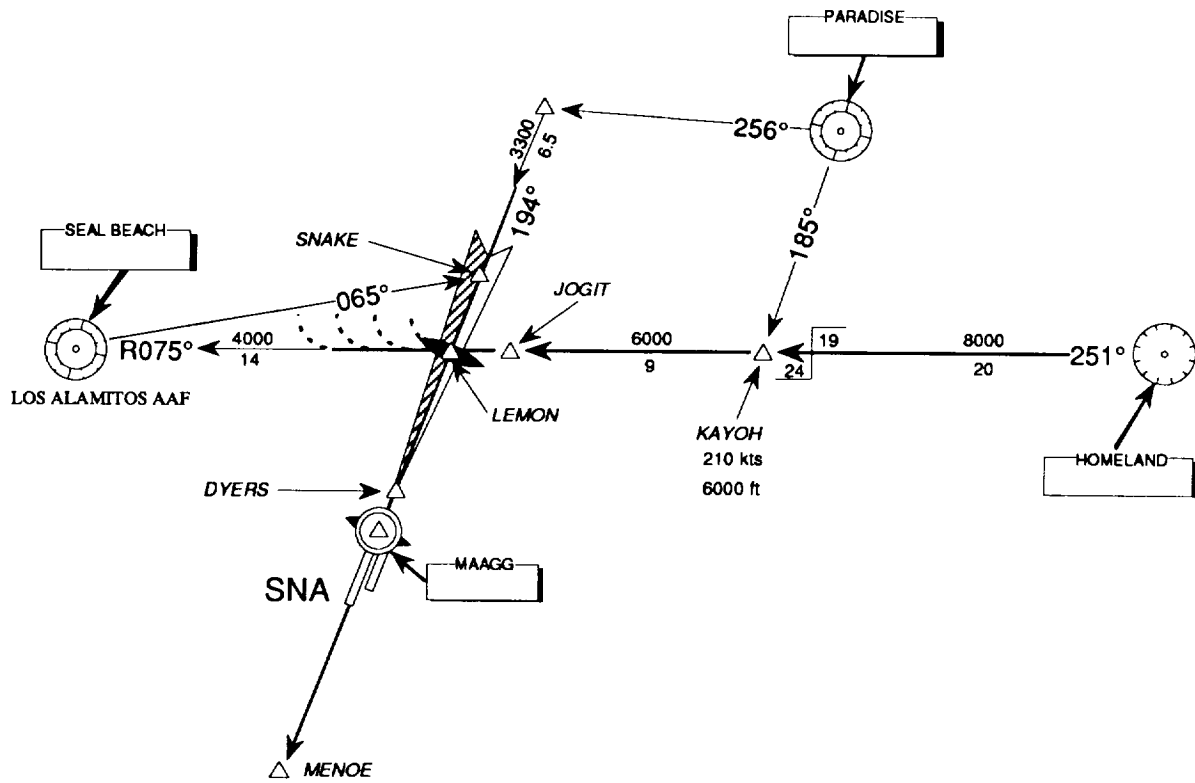


FIGURE 27. SCHEMATIC FOR THE KAYOH TWO ARRIVAL INTO SNA

TABLE II. THE KAYOH TWO ARRIVAL INTO SNA

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
14:56:20	HDF/D12 (8nm prior to KAYOH)		Noting distance to KAYOH, SYS queries crew for preferred bank angle limit setting.	
14:56:45	HDF/D14 305/8900		SYS reminds crew of possible upcoming approach pattern; shows crew latest slow-down (to 200 KTS) point to make approach; also indicates time to latest slow-down point.	Crew selects bank angle limit.
	HDF/D16 (4nm prior to KAYOH)	In order to prepare for possible speed reduction, crew asks ATC if they are to expect a turn to the right (~300 degrees) to accomplish an approach from east of LEMON.		Crew, also cognizant of possibility of upcoming approach, evaluates specific SYS information presented on ND; decides to query ATC regarding possible approach.
	HDF/D17 (3nm prior to KAYOH)	ATC tells crew that approach will commence at some point after crossing the final approach course (i.e., after passing ABEAM LEMON). ATC advises crew to expect vectors after ABEAM LEMON.		

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
	HDF/D17.5 (2.5 nm prior to KAYOH)	Crew acknowledges ATC and indicates it will maintain 210 KTS after KAYOH and is awaiting final clearance vectors and speeds; indicates to ATC that it is ready to supply reliable ETAs for all maneuvers, clearances.		Crew directs SYS to determine latest slow-down point (to 200 KTS) for clearances after crossing the final approach course.
			SYS calculates slow-down point for soonest clearance after crossing final approach course; sets up to perform running calculations of revised solutions, should the eventual clearance be later than this earliest point.	
14:58:00	KAYOH 265/8000	ATC, knowing aircraft is 4D-capable, informs crew to expect "non-optimal" speed reductions -- instead of 200 KTS may be as slow as 180 KTS -- due to slower, less able traffic; directs aircraft to be at 200 KTS by ABEAM LEMON on current heading; reminds crew of altitude restriction of at or above 4000 feet.		Crew notes crossing KAYOH fix; verifies speed and altitude restriction compliance.

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
		Crew ROGERS ATC cautions and clearance; using SYS-generated estimates displayed on ND, informs ATC of ETA to ABEAM LEMON, assuming latest safe slow-down to 200 KTS.		Crew chooses SYS-calculated deceleration sequence to 200 KTS to be achieved at ABEAM LEMON and commands SYS to execute maneuver.
			SYS initiates set up for deceleration maneuver; informs crew that deceleration from 210 KTS will begin 1 nm past JOGIT; reminds crew of presence of altitude restrictions along route.	
14:58:27	KAYOH/D1.6 265/7650			Crew calls up vertical PD to inspect descent path to ABEAM LEMON (and beyond), and to verify compliance with published altitude restrictions: 6000 feet between KAYOH and JOGIT, and 4000 feet thereafter.
				Crew decides to move back currently planned point of achieving 4000 feet to a (crew-determined) fix 1 nm prior to ABEAM LEMON (i.e., 1 nm after JOGIT).

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
14:58:44	KAYOH/ D2.6		SYS incorporates crew changes to vertical flight path and automatically calculates new descent rates and speeds to maintain compliance with ETA at ABEAM LEMON.	
14:59:01	KAYOH/D3.5			<p>Crew notes SYS-generated changes to descent rates and speeds; verifies ETA unchanged.</p> <p>Crew directs SYS to construct deceleration solution from current point of 200 KTS to soonest point at (and maintaining) 180 KTS; directs SYS to keep this solution in a pre-select mode, and to re-calculate as necessary after aircraft has achieved 200 KTS.</p>
			SYS calculates deceleration sequence, and necessary slat and flap reconfiguration points in slow-down maneuver; SYS displays current solution in pre-select symbology.	

CREW INVOLVEMENT

TANDAM SYSTEM

COMMUNICATIONS

EVENT

TIME

14:59:09 KAYOH/D4

Triggered by position in approach sequence, SYS consults approach data base and observes that all legal approaches crossing ABEAM LEMON involve downwind turns to the NE and base legs that intercept the ILS within 30 degrees of final course, out from SNAKE. SYS displays nominal course from SNAKE out to estimated point of completion for closest base-to-final turn from NE of SNAKE. SYS also displays (in a pre-select mode) point of earliest permitted turn to downwind after ABEAM LEMON; queries crew as to whether it should begin calculating running solutions for final approaches to SNAKE after ABEAM LEMON.

Crew chooses to have SYS perform solutions to SNAKE. However, due to uncertainty regarding ATC's actual upcoming clearances, crew elects not to have solutions in immediate pre-select mode; instead, solutions are to be stored in a secondary buffer available to load into pre-select at crew command.

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
14:59:26	KAYOH/D5			Crew elects to have SYS display modified race track solutions with progressively lengthening base legs; crew directs SYS's "shortest to" solutions to not be displayed unless requested.
15:00:00	KAYOH/D7	Crew tells ATC it will begin deceleration to 200 KTS at JOGIT, and will be at and hold 4000 feet, 1 nm after JOGIT. Crew indicates it will arrive ABEAM LEMON at and holding 200 KTS. Crew reminds ATC of ETA to ABEAM LEMON.	SYS initiates calculation of soonest clearance to SNAKE after ABEAM LEMON.	
15:00:54	JOGIT 215/4000	ATC acknowledges crew information, thanks them for ETA. ATC commands expedited deceleration to 180 KTS prior to crossing over final approach course. Aircraft is to maintain heading of 255 degrees and altitude of 4000 feet.		

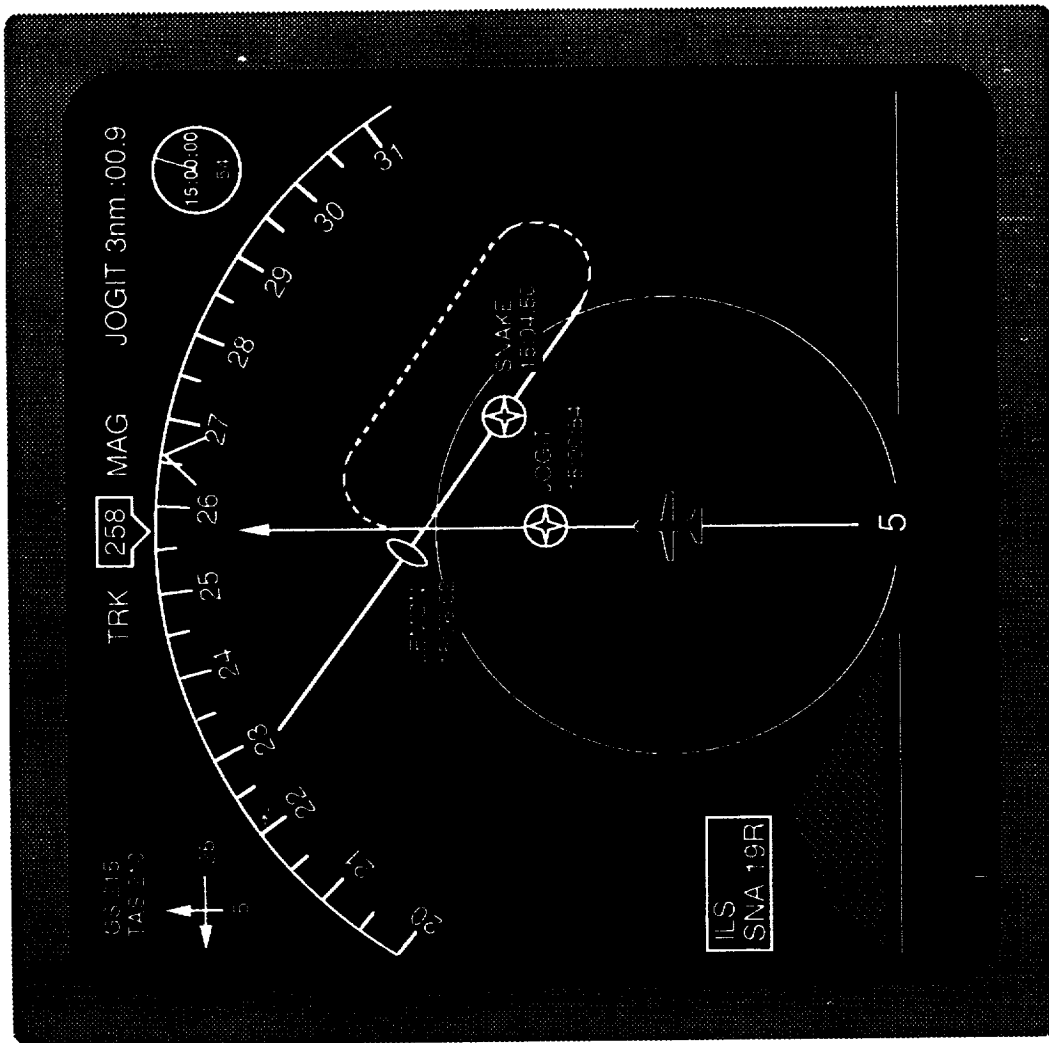


FIGURE 28. NAVIGATION DISPLAY, IN MAP MODE, SHOWING TANDAM-GENERATED RUNNING SOLUTIONS TO SNAKE FROM AB EAM LEMON

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
		Crew acknowledges clearance; informs ATC aircraft can comply.		Crew edits SYS-controlled flight plan with expedited deceleration to 180 KTS; executes deceleration with automatic speed break deployment.
			SYS accommodates crew edit and initiation of deceleration, calculates ETA and position of 180 KTS. Data is displayed on ND.	
				Crew notes ETA and position for 180 KTS.
			SYS automatically displays slat, and flap reconfiguration points; informs crew.	
				Crew notes points for configuration changes, and prepares to execute changes.
15:01:22	JOGIT/D1.5 180/4000	Crew informs ATC that aircraft is at 180 KTS and will cross above final approach course in 25 seconds; reminds ATC it can give, or work to, ETAs to SNAKE.		
		ATC acknowledges receipt of crew's message		

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
15:02:07	ABEAM LEMON/D1 180/4000		SYS modifies running solutions to SNAKE.	Given time requirement for ATC/crew communications, crew decides to edit SYS's running solutions to SNAKE to allow a 10 second (.5nm) lead to turn initiation for downwind legs. Also, crew directs SYS to now have race track solutions reside in pre-select mode.
		ATC asks if aircraft could make SNAKE between six and seven minutes from now.		Crew monitors passing first possible downwind turn; notes ETA to SNAKE increase at approximately a 2 to 1 rate as aircraft continues toward SLI VOR (heading of 255 degrees).
		Crew says it can make any time to SNAKE after approximately 15:07:33.		Crew glances at ongoing solutions to SNAKE to see soonest current ETA (ETA:15:07:13) and, mentally adds a time buffer (~20 sec) for communications, calculations, and execution.

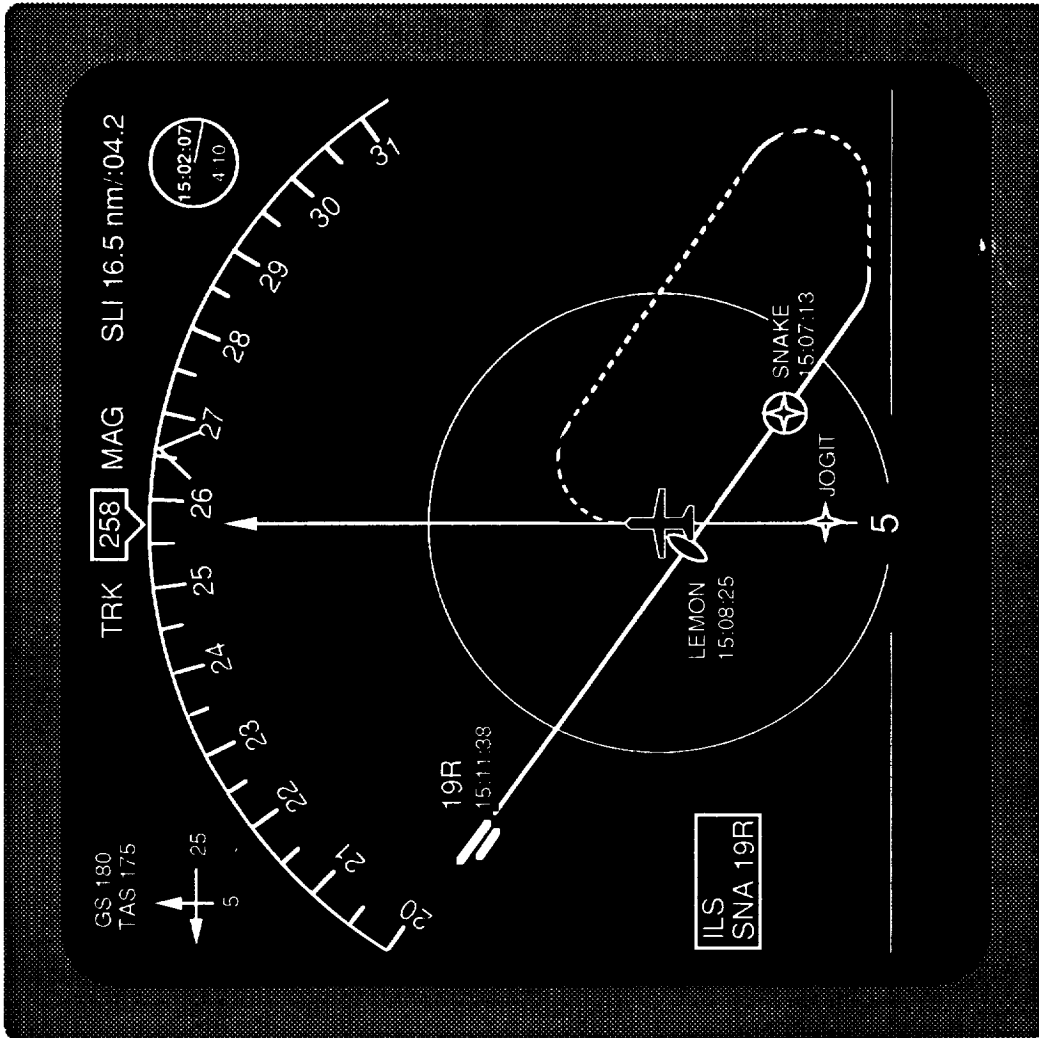


FIGURE 29. NAVIGATION DISPLAY, IN MAP MODE, SHOWING TANDAM-GENERATED RUNNING SOLUTIONS TO SNAKE FROM ABEAM LEMON/D1

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
		ATC directs crew to generate a solution to SNAKE at 15:07:45 and contact them with flight path and time specifics.		Crew commands SYS to generate a solution to SNAKE, holding to the constraint of arrival at 15:07:45.
			SYS -- consulting approach data base, and selecting a race track pattern (and rejecting a shortest route solution since it would take the aircraft unnecessarily far away from the terminal space) - - generates the commanded solution and displays it to crew.	
		Crew describes race track solution to SNAKE at with 15:07:45 ETA.		Crew inspects the solution and decides to communicate with ATC.
		ATC thanks crew and clears aircraft to SNAKE.		
15:02:31		Crew ROGERS clearance; informs ATC that turn to downwind will commence immediately.		Crew selects SYS-calculated solution to SNAKE.

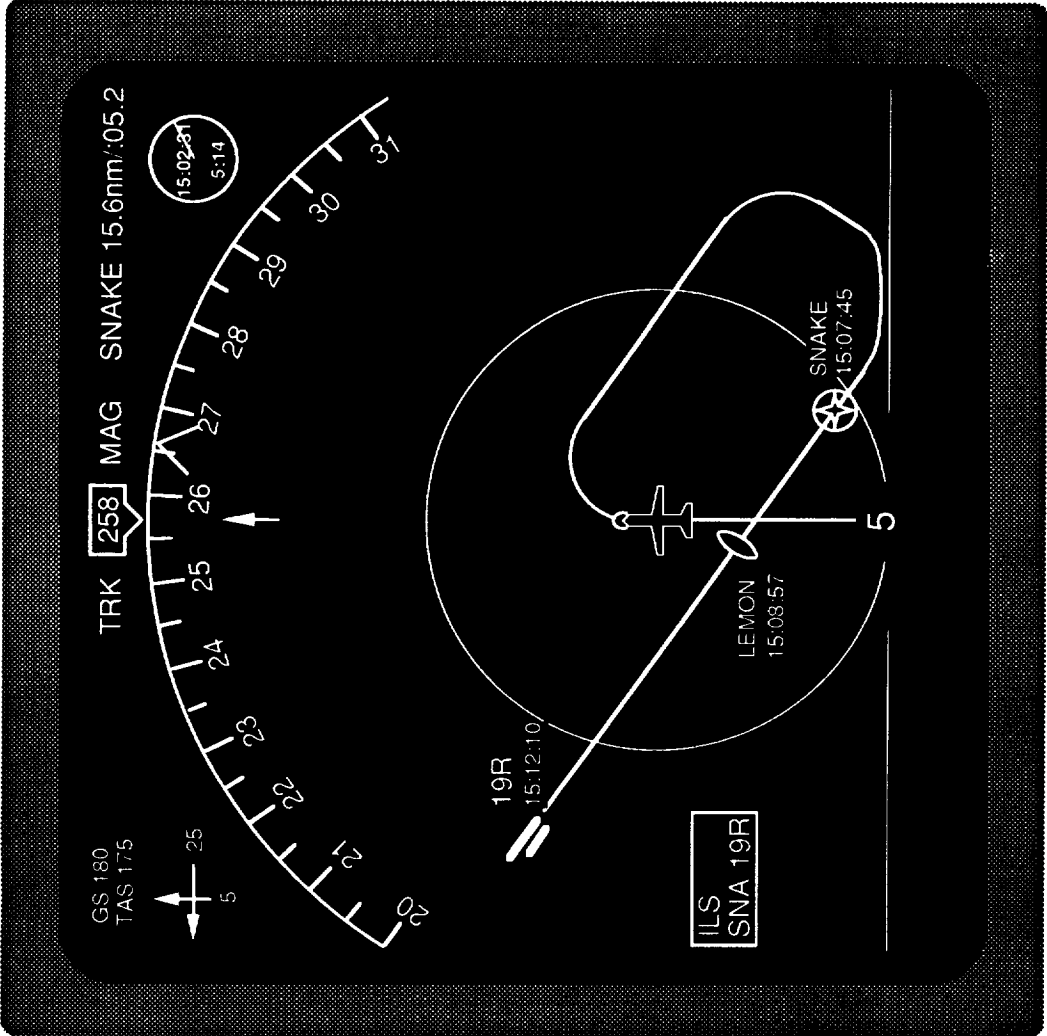


FIGURE 30. NAVIGATION DISPLAY, IN MAP MODE, SHOWING CLEARANCE TO SNA RUNWAY 19R

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
			SYS initiates solution; commences first turn.	
		<Pop-up traffic enters airspace and appears in potential conflict with several cleared aircraft. This traffic's presence forces ATC to rapidly re-meter a number of approaching aircraft. ATC decides to vector 4D aircraft off of current clearance.>		
		ATC cancels 4D clearance to SNAKE; directs aircraft to stay on present northerly heading and expect clearance to SNAKE soon; ATC apologizes for unavoidable change in plans.		
		Crew acknowledges new clearance; states it will maintain heading of 317 degrees, and will await clearance to SNAKE.		Crew rolls out of turn, maintaining new heading of 317 degrees.
			Since aircraft is now off typically prescribed routes in this terminal area, SYS queries crew as to whether it would like to see modified race track or shortest path solutions to SNAKE.	
15:03:38				Crew directs SYS to calculate running 4D solutions for the shortest path to SNAKE.

Preparations for a Possible Runway Change During an Approach to LAX

This third scenario (depicted in Table III) describes a portion of a standard profile descent and approach (the LAX CIVET TWO Arrival) in order to demonstrate how the TANDAM system might assist the crew in preparing for a possible change in assignment from the currently active 25 Left runway to the possible alternate 24 Right runway (please see Figure 32). Both CTAS and Data Link are fully operational. However, in this scenario, the local conditions quickly become significant factors, with the aircraft flying a moderate headwind and flying into steadily worsening weather as it approaches LAX. In fact, the crew's (and ATC's) major concern involves the possibility of a change in runway assignments from 25 Left to 24 Right necessitated by airport-area visibility threatening to drop from Category II to Category III ILS status. In this scenario, the TANDAM system assists the crew in preparing for the possible side-step to 24 Right. The TANDAM system monitors positions and times from each of the runways, and helps the crew perform preparatory activities when they need to be done, and in an order that optimizes workload and preserves crew options. These activities -- calculating a running solution for the step-over maneuver to 24 Right, following all approach constraints, noting significant maneuvering changes necessary if the alternate runway is assigned, establishing the last safe point for the step-over maneuver, and setting up for ILS changes, etc. -- are all critically supported by the capabilities of the TANDAM system.

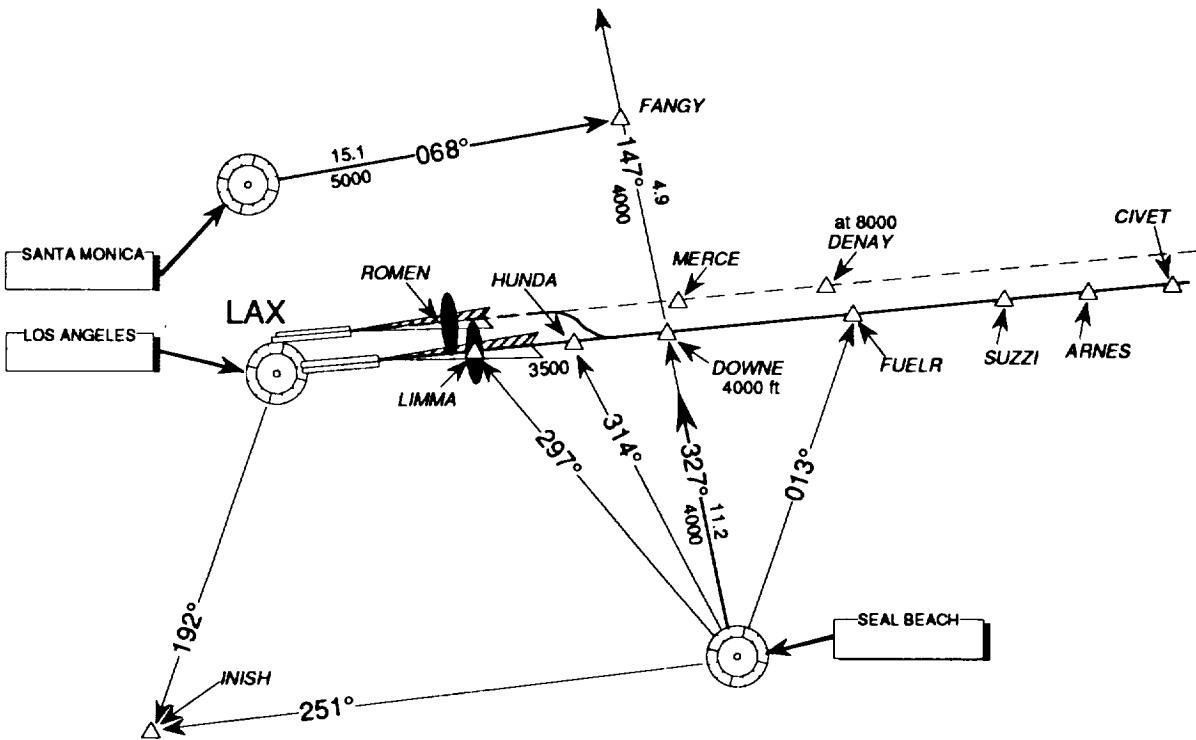


FIGURE 32. SCHEMATIC FOR A POSSIBLE RUNWAY CHANGE DURING AN APPROACH TO LAX

TABLE III. A POSSIBLE RUNWAY CHANGE DURING AN APPROACH TO LAX

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
		<p><On the CIVET2 Profile Descent into LAX, the aircraft is assigned runway 25L. Given worsening weather conditions, crew is told to fly an ILS Category II approach.></p>		
	<p>CIVET/D13 330/12940</p>		<p>SYS tunes Localizer frequency for LAX 25L; informs crew.</p> <p>SYS, adding runway assignment, ILS category information, and current uplinked weather data, to current descent clearance, determines that 24R will be designated alternate since it is the only remaining Category II runway (in current approach direction). SYS informs crew that 24R is likely alternate (and why); recommends it commence developing a running solution to 24R since aircraft is about to enter typical range for ATC-directed runway changes.</p>	<p>Crew notes (and agrees with) SYS prediction of 24R as alternate; directs SYS to calculate running solutions, in pre-select mode, to 24R.</p>

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
			<p>SYS consults MCDET for data on upcoming winds, weather conditions, and proximal traffic. ILS category II approach fixes, altitudes, speeds, and Localizer frequency for 24R accessed from the LAX area data base. A standard "S" turn step-over maneuver is customized to fit current and future parameters of possible runway change. Step-over is also modified for passenger comfort, given altitudes, speeds, and environmental conditions.</p>	<p>Crew decides to have SYS operate in a "Guidance Only" mode after ARNES (11,000 feet).</p>
12:25:03			<p>SYS readies for display its current solution to 24R.</p>	<p>Crew elects to display running 24R solutions, and also show proximal traffic. Crew notes current "window of opportunity" for safe transition to 24R.</p>
			<p>Given current and anticipated weather/winds, SYS begins to determine last safe point to execute runway sidestep maneuver.</p>	

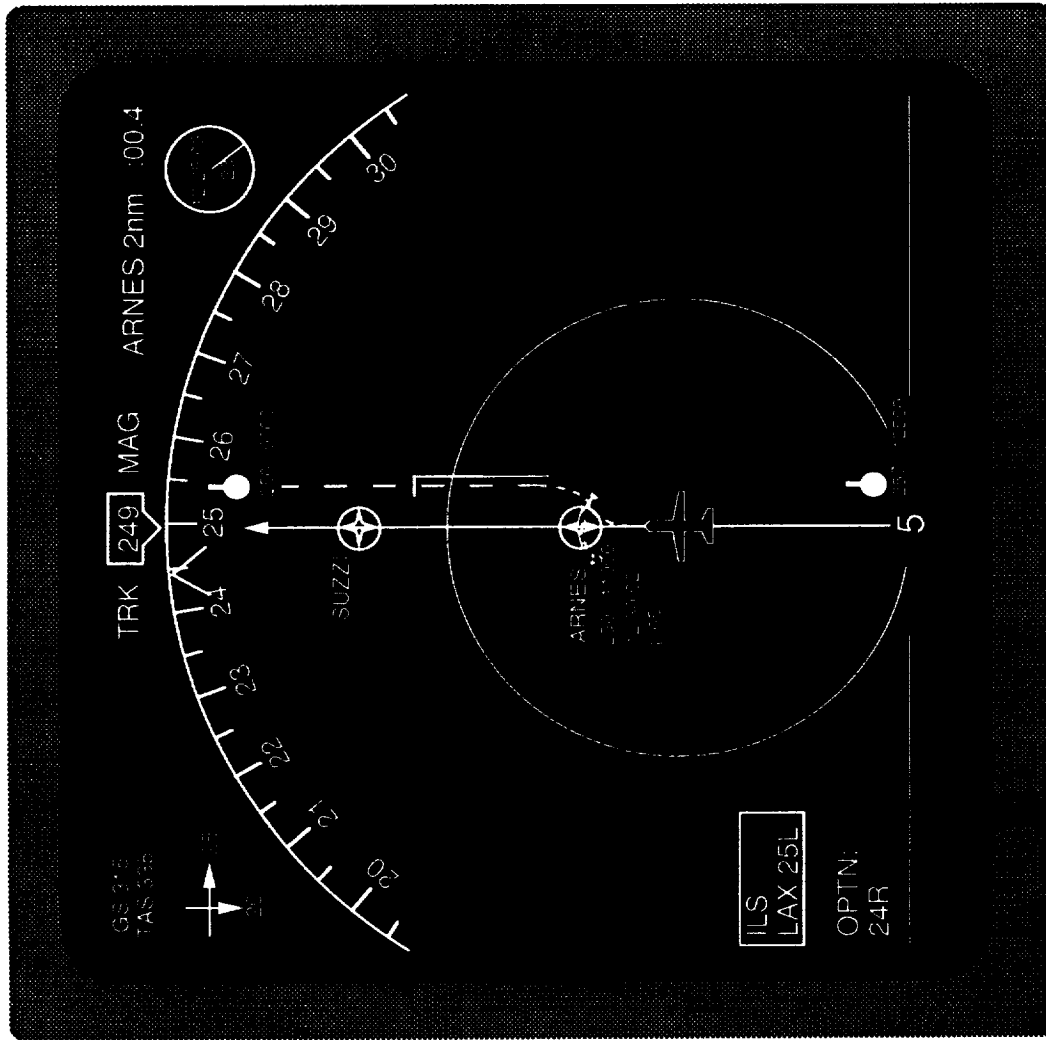


FIGURE 33. NAVIGATION DISPLAY, IN MAP MODE, SHOWING TANDAM-GENERATED EARLIEST SOLUTION FOR SIDESTEP MANEUVER TO LAX RUNWAY 24R

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
12:25:26 E:02	ARNES 315/11000		Upon comparison of vertical profiles for 25L and 24R, SYS identifies altitude differences prior to glideslope intercepts; recommends crew inspect approaches for altitude and offset differences; readies information for display, including automatic change in ND range scale.	Crew notes SYS message regarding alternate to 25L (and its priority level); plans to inspect SYS information after crossing ARNES.
				Crew monitors altitude, speed, and time crossing ARNES, notes 2 seconds early; commands SYS change to "Guidance Only" mode.
			SYS modifies speed setting to make SUZZI on time instead of early.	Crew acts on SYS recommendation and views approach paths and profile information; notes lower pre-glideslope intercept altitude for 24R, and different glideslope intercept points for approaches.

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
		<p>Crew informs ATC that it has a running solution to 24R (for alternate) up to HUNDA intersection.</p> <p>ATC ROGERS crew's message; thanks them for the information.</p>	<p>From MCDET, SYS learns that LAX weather conditions rapidly worsening; determines that likelihood of switching to 25L has increased substantially because of possible Category III conditions; informs crew.</p>	<p>Crew notes worsening weather, higher likelihood of 25L use.</p>
			<p>SYS evaluates LAX approach data base for any Category III requirements not already accommodated in current 25L alternate; finds no significant modifications necessary.</p>	

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
12:26:25	SUZZI 284/9500	<p><Previously issued clearance to 25L involved a descent from FUELR (at 8000 feet) to DOWNE, at crew's discretion, as long as aircraft crossed DOWNE at 4000 feet and was prepared to continue descent to 3500 feet before HUNDA.></p>		<p>Crew continues descent toward SUZZI; verifies that crossing altitude at SUZZI will be between 9000 and 10000 feet; notes latest ETA matches planned (i.e., 2 second early at ARNES has been compensated for).</p> <p>Crew notes crossing SUZZI at 9500 feet, on time.</p> <p>Crew commands descent schedule to be at and to maintain 8000 feet by FUELR.</p>

TIME EVENT COMMUNICATIONS TANDAM SYSTEM CREW INVOLVEMENT

SYS, in consideration of upcoming descent from FUELR to DOWNE, and in preparation for now more likely change to 25L course, recommends aircraft attain 4000 feet at 5nm past FUELR (and, consequently, 2nm before speed reduction to 200 KTS) instead of originally planned 7 nm past FUELR.

<SYS recommendation automatically includes any speed adjustments, etc., needed to stay within 4D requirements and reflects compliance with altitude restrictions.>

SYS informs crew of reason for recommendation: Earlier attainment of 4000 feet should allow crew more preparation and maneuvering time (especially vertically) in the event of a runway change clearance.

Crew acknowledges recommendation and concurs with its logic; directs SYS to edit approach accordingly.

SYS edits approach profile between FUELR and DOWNE.

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
	FUELR 272/8000 12:27:20 L:02		SYS notes aircraft is 2 seconds late to FUELR; initiates adjustment to regain 2 seconds by DOWNE.	Crew notes crossing FUELR at 8000 feet, 2 second late of ETA (due to worsening weather, winds); observing 4D bug on DOWNE, knows SYS is automatically adjusting to make up lost time.
	FUELR/D4 265/4800		SYS's latest 4D calculation to DOWNE predicts 5 seconds late, unless aircraft increases speed; considering distance/time to touch down, spacing of proximal traffic (on both approaches), general rule of thumb against increasing speed, and consequent reduced time for crew procedures, SYS recommends accepting late ETA to DOWNE. SYS also suggests delaying slow down to 180 KTS and initial flaps until 1nm after DOWNE to make up 2-3 seconds.	
				Crew acknowledges SYS message; declines to use delayed slow down suggestion, given concerns about safety in current weather conditions.
				Crew directs SYS to inform ATC/CTAS about revised ETAs.

SYS downlinks revised ETAs for approach.

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
	FUELR/D4.5 263/4400 12:28:20 L:02		<p>SYS displays last safe maneuver point for step-over to 24R, and proximal traffic on both approaches.</p> <p>SYS informs crew that all preparations for 24R are up to date and ready in pre-select:</p> <ul style="list-style-type: none"> •Set up for localizer and glideslope autotuning, and capture •Speeds, descent modifications/flight path angle adjustments •Markers, centerline, and touch down point -- estimated from data base, global positioning system, nav aids -- ready for display •Relevant checklists for 24R •Communication radio frequency change •Go Around procedure readied for automatic insertion into pre-select if 24R is selected 	<p>Crew inspects ND presentation of step-over maneuver and information regarding differences in vertical profiles for two approaches.</p>
		<p>Crew tells ATC that running solution to 24R has been re-estimated, given weather; current calculations place last safe point of side step initiation 1 nm prior to HUNDA intersection.</p> <p>ATC acknowledges crew's message; still believes 25L will stay above minimums.</p>	<p>SYS, on ND, emphasizes GS capture points and altitudes that significantly differ for two approaches.</p>	

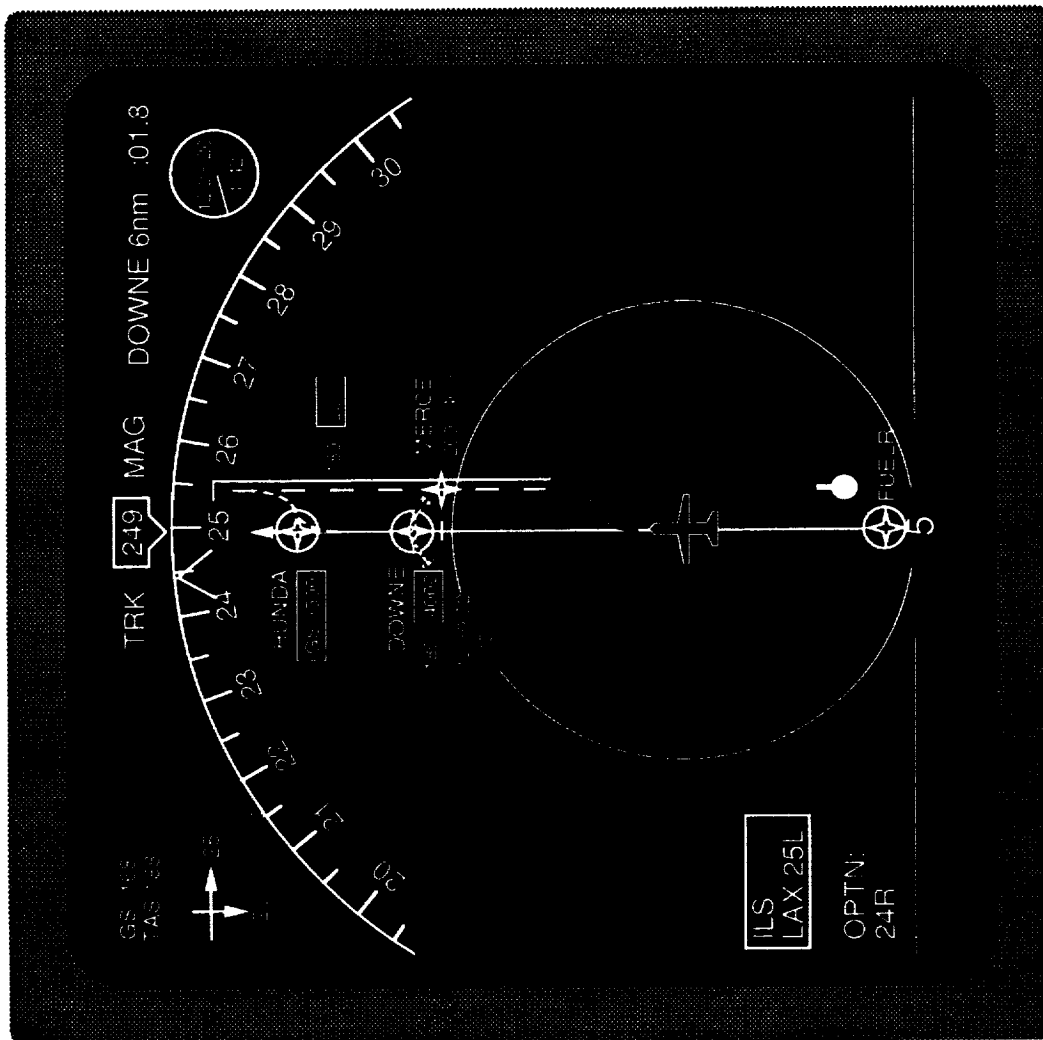


FIGURE 35. NAVIGATION DISPLAY, IN MAP MODE, SHOWING TANDAM-GENERATED RUNNING SOLUTIONS FOR SIDESTEP MANEUVER TO LAX RUNWAY 24R FROM FUEL/D4.5

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
			SYS calculates taxi and at-dock times for both approaches; readies information for DL to company and terminal.	Crew continues to execute 25L approach; mentally re-evaluates likelihood of change to 24R.
	FUEL/D8.5 243/4000 12:29:32 L:05		SYS readies for display final checklists for 25L; reminds crew that Go Around procedure for 25L is loaded in a buffer and can, at crew request, be inspected on ND.	Crew inspects ND as GS intercept and OM (ROMEN) appear for 24R. Crew notes upcoming commit point for 25L, and SYS message regarding 25L Go Around.
				Crew prepares for deployment of slats and initial flaps settings; monitors deceleration schedule and checks that revised ETAs remain unchanged.
	DOWNE/D.5			Crew deploys slats; continues to monitor deceleration schedule.

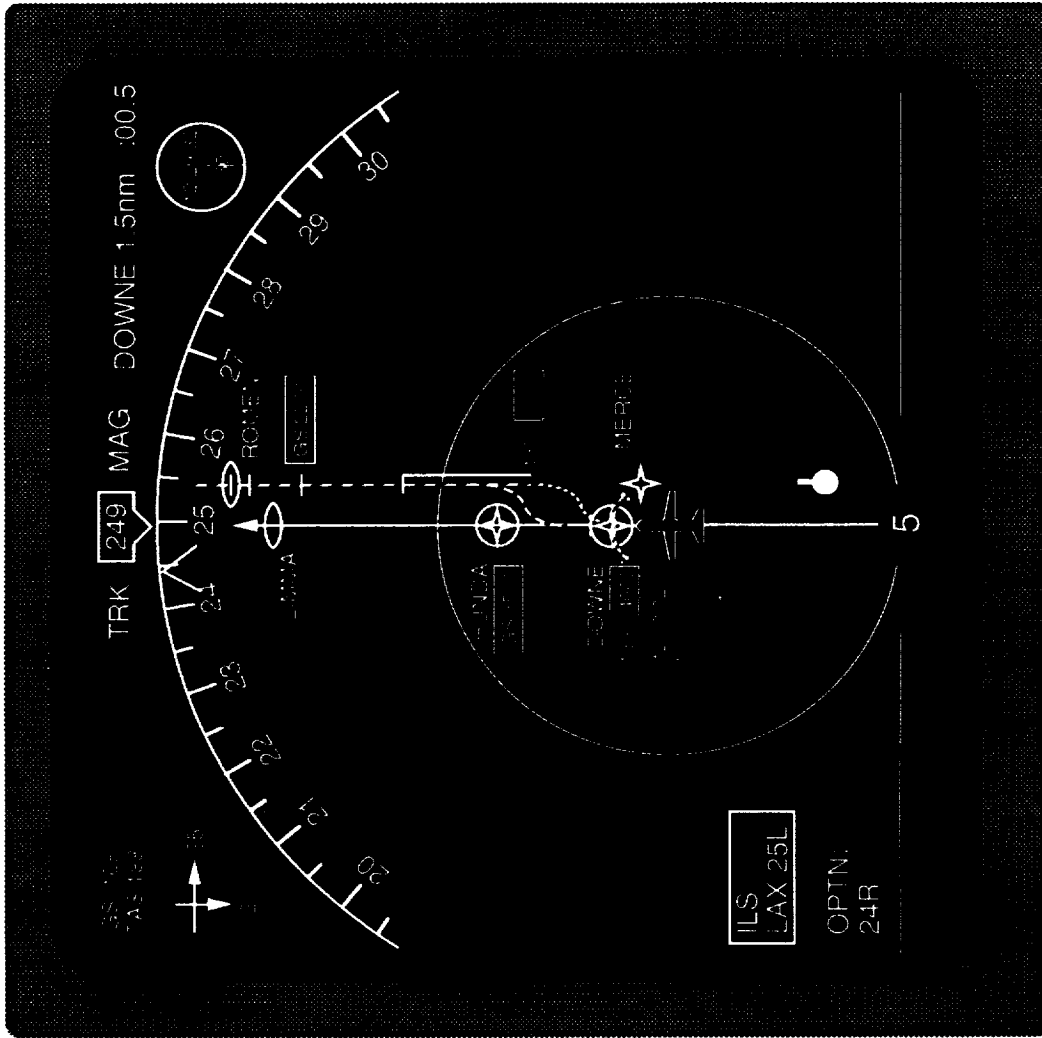


FIGURE 36. NAVIGATION DISPLAY, IN MAP MODE, SHOWING TANDAM -GENERATED LATEST SOLUTION FOR SAFE SIDESTEP MANEUVER TO LAX RUNWAY 24R

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
12:30:44	DOWNED/D1.8	Crew tells ATC it no longer has a safe side-step maneuver to 24R; aircraft is committed to 25L.	SYS, noting aircraft position, informs crew of loss of safe side-step; recommends putting Go-Around for 25L in pre-select.	Crew removes 24R alternate; installs 25L GoAround procedure into pre-select.
				Crew notes closure on final approach course.
			SYS informs crew of 25L GS autotuning.	
		MCDET uplinks runway conditions; LAX remains at Category II visibility.		Crew notes 25L GS capture point.
			SYS re-estimates flap and gear deployment points; displays them.	

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
			<p>SYS readies Final Approach checklist for display; verifies distance to 25L's OM (LIMMA), MM, and IM; re-estimates touch down point; readies guidance information for PFD.</p>	<p>Crew deploys initial flaps.</p>
				<p>Crew notes 25L GS signal being displayed above current altitude; watches GS indication 'move down' ADI.</p>
				<p>Crew initiates final descent, following GS down; deploys landing gear and final flaps.</p>

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
		VARIANT B		
12:30:26	DOWNED/1	ATC, due to Category III conditions at LAX, issues change to runway 24R. Crew WILCOs clearance.	SYS executes (via FMS) cross-over to 24R and modifies displays accordingly; annunciates required descent to 2200 ft by role out from side-step. All preparations for 24R (previously in pre-select) are active; 24R GoAround procedure loaded into pre-select.	Crew selects alternate to 24R; initiates side-step maneuver following SYS-generated guidance (including modifications for configuration change with slats extended, and descent).
			SYS informs crew of 24R LOC autotuning and capture.	Crew notes capture; closes on new final approach course.
			SYS informs crew of 24R GS autotuning.	Crew notes 24R GS capture point; roles out of turn, at 2200 feet and holding until GS capture.
			SYS changes communication radio frequency.	

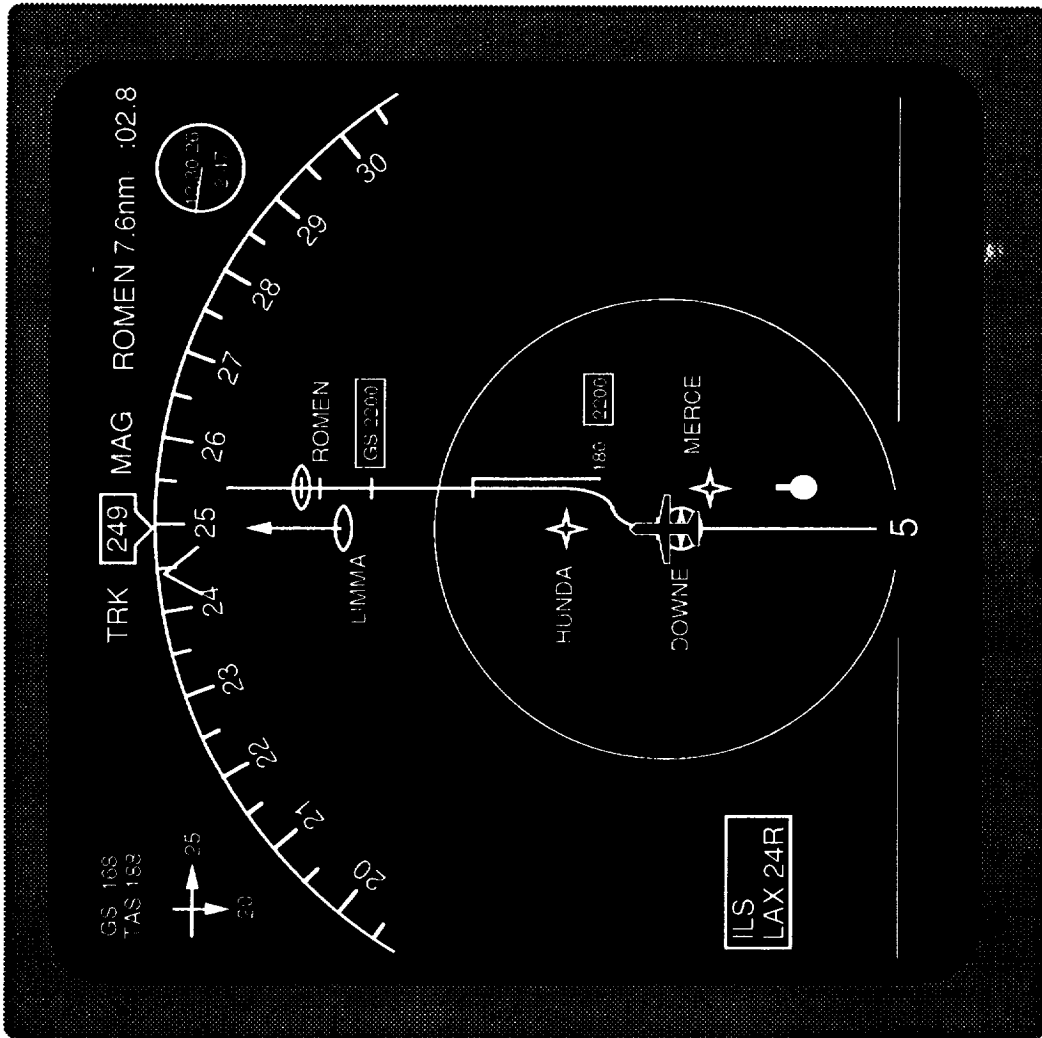


FIGURE 38. NAVIGATION DISPLAY, IN MAP MODE, SHOWING SELECTION OF LAX RUNWAY 24R FOR FINAL APPROACH

TIME	EVENT	COMMUNICATIONS	TANDAM SYSTEM	CREW INVOLVEMENT
		MCDET uplinks runway conditions; LAX remains at Category III visibility.	SYS re-estimates flap and gear deployment points; displays them.	
			SYS readies Final Approach checklist for display; verifies distance to 24R's OM (ROMEN), MM, and IM; re-estimates touchdown point; readies guidance information for PFD.	Crew deploys initial flaps.
				Crew notes 24R GS signal being displayed above current altitude; watches GS indication 'move down' ADI.
				Crew initiates final descent, following GS down; deploys landing gear and final flaps.

PLAN FOR EVALUATION OF THE TANDAM SYSTEM CONCEPT

Content and Scope of the Evaluation

The goal of the proposed test of the TANDAM system concept is twofold: To evaluate the potential for relevant operational benefit of such a system, and to identify possible shortcomings of the system as it is currently defined. As such, this evaluation most appropriately should be limited in scope, concentrating on major functional features of the proposed automation and their potential for utility in operationally critical (and representative) mission events. This test plan, therefore, takes as its objective, the goal of defining an investigation of the system concept's operational value in the context of a limited number of carefully designed flight scenarios depicting the CTAS-controlled commercial aviation environment assumed for the near future.

Owing to the currently preliminary status of the TANDAM system concept, evaluations should entail part-task simulations of its principal functional features exercised in a moderate-fidelity operational environment. The major capabilities of the TANDAM system should be prototyped only to levels sufficient to determine their operational validity, and to determine the effectiveness of their performance in comparison to relevant baseline conditions. Only after success in such part-task/limited-prototype evaluations should the development of a full-scale TANDAM system prototype be considered for more comprehensive investigation. In this light, the test plan proposed herein should be considered a necessary and prudent, but not sufficient evaluation of this system concept.

Preparations for the Evaluation

To conduct the part-task evaluation of the TANDAM system concept, several preparatory activities will be necessary. First, specific, limited implementation of the system concept in the context of an advanced flight deck will involve the development and refinement of an operator interface. This would include creating the actual means by which subjects can interact with the FMCP, FMS, and Data Link control heads to affect commands, call up information, etc. These control activities in turn, will of course need to be connected to software emulations and/or simulations of significant components of the crew station and ATC automation. Software modules must be created that are capable of replicating advanced FMS functions (including 4-D navigation and vertical maneuver management), Data Link communications, CTAS clearances (including 4-D schedule constraints), and (at least) the principal management and assistance functions of the TANDAM system. These modules must have access to a fairly sophisticated relational data base that will contain the relevant parameters of the scenario's flight plan, and all the mission events and situational variables needed to trigger automated response.

In addition to the development of the aircraft and ATC simulation/emulation capabilities, it will also be necessary to specify task timelines associated with the scenarios used in the evaluation. These detailed descriptions of the operational environment will be crucial to the precise, "in situo" definitions of the variables of interest and the associated performance measures used to evaluate them. So,

for example, the factor of "situation awareness" -- a difficult concept to adequately define in the abstract -- could be defined in relation to a particular mission event (e.g., negotiating a clearance), if the operational parameters of that event have been explicated. With "situation awareness" specified for the relevant mission event, the determination of how to appropriately measure it (while not trivial) would follow.

Development of detailed timelines would contribute to two other essential aspects of the evaluation of the TANDAM system. For one, the timelines would be used to help specify the mission-event information stored in the relational data base. Thus, specific timing constraints, maneuver requirements, etc., would be available to assist in the development of the TANDAM system, FMS, and Data Link capabilities. Secondly, the timelines would, of course, allow for task-duration and relative workload comparisons between test conditions.

Research Methodology

Subjects

Subjects will be commercial transport pilots currently flying FMS-equipped aircraft. Subjects will possess average levels of experience with this type of aircraft. They will be recruited from current line service situations, and will be paid for their participation.

Design

The empirical evaluation of the TANDAM system concept will contrast three principal factors of interest: The type of Navigation Management, being accomplished using either an advanced Baseline Crew Station, or the TANDAM System's Crew Station; the type of ATC Governance, considering CTAS- and Non-CTAS-Governed environments; and the type of Mission Function, evaluating performance in an At-Altitude Clearance, a Terminal Area Clearance, and a Preparation for Runway Change. Two different groups of subjects will operate the Baseline and TANDAM system's crew stations. Each group will fly two equivalent descent and approach scenarios, one governed by CTAS and the other by more current (non-CTAS) ATC control. The order in which subjects participate in these two scenarios will be counterbalanced to help control for possible carryover effects. The scenarios will each contain at-altitude and terminal area clearances, and preparations for a possible last-minute runway change. Each type of mission function in the scenarios will have been matched for rough position in the scenario timeline, number of maneuvers required (and their overall complexity), approximate number and type of fixes and restrictions, number and type of clearances involved, environmental conditions, and timing constraints.

Dependent measures will include tracking and waypoint/fix arrival time accuracy, course, and specific maneuver tracking accuracy (in terms of rms errors), overall and clearance-specific fuel savings (in pounds of fuel), estimated workload, speed of responding to ATC clearances, navigation and guidance errors (related to data

input awareness and understanding of system processing, and anticipation of the automation's actions), and communications errors. Where appropriate for purposes of comparison between conditions (where, time, number of maneuvers, etc., may not be exactly equivalent), dependent measures will be analyzed in terms of percentages of deviations from optimal performance.

Materials and apparatus

As was mentioned in this section's introductory remarks, the evaluation will be conducted in a part-task simulation/emulation environment. The principal components of an MD-11-class cockpit will be employed. However, a number of significant modifications will also be required. The FMCP will be modified to incorporate 4-D navigational and guidance capabilities, and a cursor control for the ND. The FMS MCDU (and associated pages) will be modified to accommodate the emulated construction and execution of 4-D navigation, and to provide a control head for the Data Link system. Interface formats and controls for the TANDAM system will also be provided (please see the system design section for details on these modifications).

The evaluation software will have to possess part-task simulations of the two Descent/Approach scenarios, and the TANDAM system's functional capabilities. Additionally, the software will need to be able to (at least) emulate essential aspects of 4-D navigation and guidance (onboard and ground-based), and representative ATC (including CTAS) procedures. A Data Link emulation will be required to execute the resulting clearance negotiation sequences. Data base

support for these functions will need to be available. Flight plan information for the Descent/Approach scenarios will have to be provided to subjects for study prior to conducting the evaluation.

Procedure

Two sets of subject activities will comprise this evaluation. Firstly, subjects will receive thorough training (including practice) in the cockpit configuration to which they have been assigned. For all subjects, this training will include familiarization with the Descent/Approach routes, and with the FMS, FMCP (and associated formats), and Data Link system. All subjects will also be trained in 4-D navigation operations, including clearance evaluation and negotiation. This training will cover CTAS- and Non-CTAS-Governed ATC control. Subjects assigned to the TANDAM system's crew station will learn procedures and capabilities specific to its employment.

The second activity, subjects' participation in the evaluation trials, will be conducted in separate sessions adhering to the counterbalancing assignments, etc., described in the Design section. When subjects have completed both scenario runs, debriefing interviews will be conducted.

Predictions

Two general hypotheses are made with regard to this evaluation: Use of the TANDAM system will result in superior crew performance and situation awareness when compared to use of the conventional advanced (i.e., Baseline) crew station; and crew execution of descent and approach functions in the CTAS-Governed environment will be superior to analogous crew activities when not governed by CTAS. These general hypotheses will be supported by several specific predictions.

In the At-altitude Clearance conditions, superior performance for the TANDAM system is predicted to be demonstrated by fewer and smaller deviations from ATC-assigned waypoint/fix arrival times, more accurate tracking and maneuvering, and larger estimated fuel savings. These benefits are predicted to be even more substantial when CTAS is in operation.

Performance resulting from the use of the TANDAM system in the terminal area is also predicted to be superior to performance in the baseline crew station conditions. Again, smaller deviations from ATC-determined arrival times, and more accurate tracking and maneuvering, will evince the TANDAM system's utility. Additionally, lower and better distributed workload should be indicated by pilots employing the TANDAM system.

For functions involved in preparing for a possible runway change, the automation-assisted conditions should, once again, demonstrate better crew

performance and awareness than the conventionally equipped (i.e., baseline) crew stations. While superior time-at-waypoint, and control activity accuracy are once again expected, the critical predictions of superiority here involve the TANDAM system's assistance with preparations in anticipation of a last-minute clearance. As such, it is hypothesized that subjects using the TANDAM system's crew station will exhibit fewer preparation omissions, fewer input and selection errors, and fewer navigational confusions than will subjects using the baseline crew station. Furthermore, cockpit activities in the TANDAM system conditions will more closely approximate ideal sequencing and timing of essential preparations (e.g., adhering to scheduled speed reductions, establishing ILS capture, and correctly setting all maneuver pre-selects for the alternate runway). Because of these preparatory advantages, crews using the TANDAM system should be well aware of crucial altitude, speed, and positional differences between the assigned and alternate runways.

In summary, future real-world implementations of the TANDAM system and CTAS should expect many operational improvements in the National Airspace System. These enhancements should include fewer and less serious errors associated with automation usage, fewer consequent clearance-related violations (e.g., altitude "busts"), improved situation awareness for the crew (and for controllers), and better crew cognizance of navigation and guidance automation, especially with regard to anticipating the automation's actions.

COMMENTS AND CONCLUSIONS

SOME FINAL CONSIDERATIONS

The present study has endeavored to define a concept for an automated system that assists the crew in executing navigation, guidance, and communications functions during descents and approaches. This automated system, the TANDAM system, has been designed to take substantial advantage of situation-specific elements in the aircraft mission. Moreover, the design and development of this system has attempted to follow human-centered design principles in its construction of the automation's operational capabilities and associated interface elements. The functional integration of the TANDAM system with 4-D clearances, and CTAS in particular, reflects a design philosophy of ensuring the development of a design concept well situated in the next generation of the National Airspace System.

This having been said, however, it should be remembered that the automated system defined in this program has been developed in a solely analytical fashion. It is, therefore, a legitimate concern that problems may have been overlooked which were not apparent in the design effort and have remained so, owing to the lack of critical evaluation under dynamic, temporally realistic conditions. For this reason, the test plan proposed in the preceding section (or some derivative thereof) is recommended as the next step in the development of this system. Whatever evaluative means is used, it is readily apparent that there is still substantial work to be done to verify that the system is viable.

Also provided in this research effort is a set of guidelines tailored to the challenges of automation design. Given the design philosophy adopted herein, it was no surprise that many of these guidelines directly addressed issues arising from cases in which automation is designed to take advantage of situation-specific information to operate at its fullest potential. These guidelines have been expressly written for crew system designers, but it is hoped that their applicability will extend to other engineering practitioners as well.

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In the course of conducting these activities, a number of collateral "lessons learned" have emerged. Chief among these is that it has become quite evident that, while future automation will benefit from being responsive to all aspects of the flight environment, none is perhaps more useful than automation that is able to accommodate the rather substantial capabilities of next-generation ATC. The advent of CTAS will enable coordinated, safe, and efficient 4-D navigation for aircraft in virtually every aspect of descent, approach, and landing. CTAS, if allowed to operate as it has been designed, will improve spacing control and sequencing efficiency, while minimizing average scheduling delays for all involved aircraft. But this sophisticated set of capabilities will not be maximally exploited if the modern commercial transport's airborne communication and navigation systems are not equally competent partners in the precise control necessary for accurate 4-D navigation. To consider just one example, an aircraft's airborne systems will need to be capable of rapidly evaluating ATC

clearances and determining the aircraft's optimal response in order to allow negotiation, when desirable. And air traffic controllers, for their part, will need to effectively customize their directives to optimally control aircraft of that vary greatly in their ability to comply with such clearances.

With regard to the flight deck automation itself, it is evident that software systems that can utilize situational cues are at a distinct advantage over systems that cannot. Even without recourse to more sophisticated computational schemes (e.g., using mental models of pilot workload), the TANDAM system defined in this report shows every indication of improving responsiveness to mission plan demands, and to unanticipated events as well. The prospect of eventually employing such advanced computational approaches promises the development of automated systems that more intelligently anticipate and respond to mission objectives and environmental conditions, and that do so in ways that complement, and even enhance, human abilities.

APPENDIX:
**GUIDELINES FOR THE DESIGN OF ADVANCED
AUTOMATED SYSTEMS WITH A SPECIAL EMPHASIS
ON ADAPTIVITY**

ISSUES REGARDING DESIGN PHILOSOPHY AND GUIDELINES

In this appendix, guidelines are presented for the design of automated systems. As the title of the document indicates, special emphasis has been placed on developing guidelines that address design issues relevant to situational and pilot-state variability, and to the automation's ability to adapt to these contextual factors, when necessitated by mission requirements.

For the sake of conceptual continuity, the introductory comments, and the discussion of design assumptions and philosophy presented in the body of the report are now repeated (in modified form) at the beginning of this appendix.

Introductory Comments

Recommendations and guidelines for the effective design of automated systems share a number of important characteristics with other design guidelines. For example, since the human operator often interacts with the automated system, guidelines regarding the design of an interface are typically relevant. And, since the automated systems are specialized software and/or hardware systems residing in the overall avionics system, guidelines for the design of such technologies are,

of course, pertinent. What makes automation design unique, however, is the need to establish guidelines advising designers about translating operational and functional requirements into routines for gathering and interpreting data, applying rules, etc., and subsequently executing advisories and/or commands to the aircraft and crew. In this sense, design guidelines for automation must consider both the system's states and the crew's strategic awareness and understanding of those states.

Thus, the desire to provide specific, concrete guidelines is often, of necessity, replaced with the goal of developing guidelines that keep the designer responsive to the general intent of the design requirement. For example, how a particular system is programmed may be irrelevant from a design point of view; however, how it acts (obtains information, processes it, makes interpretations and informs its users), as a result of that programming, is of central concern to the designer.

It is essential to keep in mind that the designer of an automated system is (or at least should be) driven by one overriding concern: Satisfaction of mission and functional requirements. The means by which this automated system satisfies these requirements must follow two interrelated tenets: The designed system must be able to effectively accomplish the execution of its identified technical tasks (e.g., 4-D calculations to a fix must be accurate and timely), and it must be able to accomplish these tasks in ways that involve, inform, and assist the crew without also resulting in undue levels of workload, and while still ensuring an optimal level of situational awareness. Moreover, this second tenet, often referred to as human-centered design, demands that this inclusion of the human

operator go well beyond mere accommodation of his or her (unavoidable?) presence. Human-centered design endeavors to develop technologies that take advantage of human cognitive and perceptual strengths and preferences, and that help compensate for human limitations. These guidelines for the design of automated systems must direct the designer to remain cognizant of human skills and their possible utility in satisfying the mission and functional requirements.

A human-centered approach to automation presupposes that the human operator possesses the critical skills and knowledge required for safe, efficient flight. Researchers and the pilot community both point to such crew assets as the crew's ability to learn from experience, to make quick, decisive judgements in uncertain, time-critical situations, and to cope with unanticipated, perplexing problems -- even when these problems have, perhaps, never been encountered before, or when there may be no one "correct" solution. It is not surprising, therefore, that most sophisticated efforts in developing artificial intelligence and other "smart" automated systems focus on these same problem-solving and decision-making abilities. It is essential that advanced automated systems assist the transport crew in high-level tasks, if these systems are to be considered genuinely human-centered. But to be able to perform such functions, automated systems must be able to monitor and assess several classes of context-sensitive variables: the rapidly changing situation of the aircraft at any given point in its route, the more strategic elements of the mission plan (and modifications by ATC and other external conditions), the crew's cognitive and physical states, and their anticipated needs and preferences. In these important respects, human-centered automation must be adaptive, responsive, and accurate. It follows, then, that guidelines for

the design of automated systems will only be useful if they encourage designers to remain aware of the mission and its requirements, fully consider relevant human capabilities and limitations, and take advantage of the situational information that will allow them to optimize the functional relationship between the automation and the operators, in service of the mission's goals.

So, to summarize the discussion thus far, the determination of automation requirements should be based on a thorough understanding of mission requirements, operational constraints, and human capabilities and limitations. This understanding is essential since it is on its basis that the designer must determine what functions and activities, in what contexts, should be accomplished or assisted by an automated system. This understanding must be both comprehensive (in terms of mission goals) and procedural (in terms of specific crew and system decisions and activities) so as to provide the designer with both strategic and tactical goals for the system design. The understanding of the mission objectives and operational context -- whether learned from flight phase, environmental factors, or pilot state -- provide the cuing mechanisms for enlisting the assistance of the automated system, and for determining what data must be evaluated and what decisions and actions must be considered.

Assumptions and Choice of Design Philosophy

In any design effort, assumptions must be made regarding mission requirements, relative level of functional advancement over current capabilities, software and hardware capabilities, and extent of the system's impact on the integrity of other

cockpit systems, and on the crew's procedures. These assumptions in large part govern the designer's thinking in the design process, and greatly constrain the design philosophy adopted -- the designer does well to make explicit the assumptions of the design goal and the consequent design philosophy being followed. Determination of these assumptions could come from any number of pragmatic, technical, or theoretical considerations. In human-centered design, assumptions must be the products of mission requirements and human information processing capabilities.

In any automation design effort, several assumptions must be made for coherent, principled designs to be developed. Chief among these are assumptions regarding:

- Software and hardware capabilities -- in any design effort, critical technologies must be operational in the time frame envisioned for the automated system.
- Determination of the extent of automaticity versus extent of human involvement -- One decision crucial to the choice of design philosophy is determining the degree to which the automation will function autonomously, versus the degree to which dependence on human monitoring and intervention will be required. This issue of extent of automaticity is critical since the consequences of a poorly thought out philosophy in this regard can result, at one extreme, in ineffectual (minimal) automation and, at the other, in completely opaque and

surprising (maximal) automated control. Unfortunately, this decision is too often made on the basis of any number of peripheral criteria -- technical feasibility, for example, or even simple expedience. From a human-centered design perspective, only the potential for reduced workload, maintained or increased situational awareness, and the ability to capitalize on mission-enhancing options should be determinants of the applicability and extent of automaticity.

However, determining the appropriate extent of automated functioning is potentially complicated by other tenets of human-centered design. Consider, for example, two of Charles Billings' (ref. 4) general principles for human-centered automation:

"To command effectively, the human operator must be involved. (p. 13)"

"To be involved, the human operator must be informed. (p. 13)"

Taking these principles at face value, one could reason that the more involved (and, by implication, informed) the human operator, the more in command that operator would be. But, since one of the typical motivations for deciding to automate is to unburden the operator from having to be cognizant of all aspects of a function, -- that is, purposefully rendering the operator less informed about every detail of the function's execution -- automating could easily be seen as lessening informativeness and involvement, and therefore being opposed to Billings' design principles.

The resolution to this apparent dilemma, of course, lies in what the operator is informed about. Billings is certainly not recommending that an automated system should tell the operator about every detail of that system's processing. Rather, he is recommending that the system (and any context-sensitive mechanisms supporting it) be crafted such that precisely and only the relevant events, states, etc., be interpreted for, and reported to, the crew.

To re-couch the issue then, it is perhaps more accurate to say that the appropriate degree of automaticity is determined by the designer's success in first identifying the essential operational information required by the operator (for situation awareness), and then effectively presenting that information to the operator in the course of the system's execution of the automated function. In this regard, then, the designer cannot be free to make the arbitrary decision to specify more or less automated functioning -- done correctly, such decisions can only result from an understanding of human information processing requirements, and the mission's functions.

DESIGN GUIDELINES

Analysis of Mission Functions and Determination of Requirements

While not formally part of the design effort, functional analysis and requirements definition activities are (as the previous discussion attests) essential preparatory tasks, the results of which greatly shape the eventual design of the automated system. For this reason, it is recommended that a significant portion of any

design effort be devoted to a comprehensive treatment of these preliminaries. Several guidelines should be considered when conducting these activities.

- Endeavor to identify functions, not tasks. Since the goal of the designer is to develop the optimal automated system, working from the more general information embodied in functions makes it less likely that the new design will be preemptively constrained to resemble existing tasks (i.e., existing means of accomplishing underlying functions).
- When identifying functions, endeavor to identify contextual factors (e.g., phase of flight, weather, crew workload) that may influence how that function is accomplished. Especially note contextual factors that threaten to impede the effective and safe execution of that function and subsequent functions.
- Do not limit functional analysis and requirements definition activities to modified time-line analyses of mission segments. Endeavor to include indirect information from pilot reports, incident and accident data, and reviews of technical research. Also, where appropriate, obtain part-task and in-situo training on relevant technologies and in relevant operational procedures. Periodically consult subject matter experts, and evaluate the opinions of these experts based on differences in line experience and general operational background, beliefs and biases, etc.

- When identifying functions, endeavor to identify functions that appear to be error prone (even when those errors are typically recognized by crews, or by onboard or ground-based systems).
- When identifying functions, endeavor to identify functions (as currently instantiated in tasks) that demand high levels of workload or concentration, take significant amounts of time, or that interfere with, degrade, or do not promote situation awareness.
- When identifying functions, endeavor to note contingency relationships between functions, especially when execution of a function has significant consequences for several concurrent or subsequent functions. In particular, look for cases in which the execution of a function determines or substantially restricts the options, performance, etc., of contingent functions, since such cases are logical candidates for automated assistance.
- When identifying functions in existing systems, endeavor to note cases in which the same or similar functions are accomplished differently. In such cases, attempt to ascertain the reasons for these operational differences (e.g., due to situational changes such as differences in altitude or maneuvering area, or due to artifacts of previous design decisions such as executing a maneuver through an FMS input versus through a FCP command). Such functions may have situation-specific requirements for automated assistance.

- When instances of present-day automation are encountered, endeavor to ascertain the logic behind the automation, including the employment of all its modes and situations of operation. Rather than uncritically accept, question the implicit or explicit design decisions embodied in the automation in order to lessen the tendency to bias the design of new systems.

Automated System Capabilities

When determining the capabilities required of the automated system, the designer must consider (at least) two classes of capability: Capabilities related to mission functions and their operation in coordination with the crew and ATC, and capabilities related directly to the processing and interpreting of situation-specific information to be used in the cuing of automated routines.

Operational capabilities

- When determining operational capabilities required by the automated system, the scope of the automation's functional control must be identified (e.g., automated control of all landing maneuvers via an Autoland system) and every effort must be made to catalog this automated control's consequences on related systems and procedures. The potential consequences of the automation's scope of control can include everything from the designer's intended improvements in operational performance, to unintended control over-rides and inadvertent activation (or inhibition) of

other systems. Test phase evaluative processes such as Failure Modes and Effects Analyses (FMEAs) are often used to identify the consequences of the newly developed system's implementation. Analytic processes similar to FMEAs should be used to evaluate automated system concepts early on in design. (This recommendation, of course, is easier said than done. For such evaluative processes to be effective, a rather sophisticated and comprehensive model of the proposed system [and the overall crew station] must already be articulated to some degree. It is a simple fact of most concept design efforts that this level of system specificity is not yet defined. In this more typical case, it is recommended that the designer endeavor to continually question and explore the potential consequences of the operational capabilities posited for the candidate system).

- When defining operational capabilities of the proposed automated system, the designer should not be quick to abandon design concepts that meet with initial criticism or skepticism that is based on current operational realities or conventions. Instead, the designer should use these comments, objections, etc., as rather decisive feedback about the proposed design, and should consider them seriously and respond to them substantively. (However, this encouragement of innovation notwithstanding, the designer is reminded that the great majority of innovative concepts are legitimately rejected on technically, operationally, or pragmatically sound grounds.)

Adaptive capabilities

- In cases where the designer has determined that context-sensitive automated routines would be advantageous to more effectively accomplish mission functions, the specific contextual cues required for these automated routines must be expressly identified and the feasibility of their implementations assessed.
- When contextual information is under consideration as a cue for automated routines, the designer should endeavor to determine the relative predictive value of that information. While degree of predictability, per se, can not always be easily or accurately characterized, it is often possible to look for co-occurrence or precedence relationships between the to-be-automated function and potentially predictive contextual cues. In many cases, such correlational relationships can be of substantial value, especially in automated systems designed to act as decision aids for crew-executed functions. Partially predictive contextual information is also valuable since it may well form a substantially stronger predictor if paired with other partially predictive contextual information.
- In identifying context-specific information sources, the designer must not only appraise the relative utility of the information as an input source for the automation, but must also endeavor to ascertain the information's veracity, accuracy, and reliability. Such information sources should also be evaluated in terms of possible negative consequences of their

employment. These concerns should include crew complacency, skilled degradation, and over-dependence, especially as they may relate to cases in which such information sources (and subsequent automated activities) are disrupted or lost altogether.

System Interface and Operational Considerations

Several aspects of user interface requirements are relevant to the design of automation. In particular, interface issues related to context-specific cuing of automated systems must be considered by the designer. A relatively comprehensive treatment of these issues is offered by Billings (ref. 4) in his NASA technical memorandum, "Human-Centered Aircraft Automation: A Concept and Guidelines." Guidelines derived from his treatise -- and guidelines inspired by it -- are presented in this section on controls, displays, and formats.

Controls, displays, and formats

- Design automated tasks to be similar to and compatible with pilot task performance.
- Base the decision to announce partial or incipient failures upon pilot needs and system functional redundancy.
- Do not design control automation capable of failing without unambiguous and apparent annunciation to the pilot.

- Consider the consequences of system failures when designing automated systems; if these consequences are significant, design the automation to assist the crew in dealing with the failure(s). Whenever possible, design the automation and its procedures to be understandable in their diagnosis, trouble-shooting, and problem solving activities.
- Design the automation to warn the pilot when the limits of safe operation are being approached.
- Design the automation to either prevent the selection of unsafe operating modes or to warn the pilot of their potentially hazardous consequences.
- Prevent the automation from taking irreversible/irrevocable actions that could lead to hazards or mishap.
- Consider designing the automation to operate under "delimited authority." "Delimited authority" implies that the automated system must be designed to conduct situation assessment sufficiently early to inform the crew of upcoming events, activities, or possible problems -- and yet not so early as to render such information premature or needlessly speculative (due to uncertainties in the ongoing flight situation).
- Do not impose "hard" limits on the pilots' authority to fly the aircraft throughout its operating envelope.

- Provide soft limits which alert the pilot that the normal flight envelope has been reached.
- Clearly annunciate or otherwise indicate to the crew that their actions are in excess of nominal or typical operating limits, and consider informing them precisely as to how long, etc., such limit-exceeding activities can safely be continued.
- Clearly inform the crew as to how to regain nominal operating parameters after such limit-exceeding activities have ceased.
- In general, do not design automated systems to be uninterruptable, either in control execution or in processing activities related to such execution.
- Do not permit easy-access pilot overrides to disengage or nullify systems operating along with or alongside the overridden system; any circumvention of automation must be done purposefully and with adequate knowledge of the consequences of the circumvention.
- Reduce the workload associated with conducting navigation and guidance functions during terminal area operations.
- Consider developing automation which can adapt to the workload situation by providing more or less support as the situation requires. For example,

during low workload periods the automation could solicit crew inputs in decision making and options evaluation, in high workload, such activities could tend to be addressed by the automation.

- Seek to optimize rather than minimize the level of workload, since low workload may also degrade crew performance and awareness.
- Consider providing meaningful tasks to enhance pilot situation awareness and to ensure that the pilot can effectively resume full control of the aircraft in the event of a failure or other contingency.
- Consider requiring pilot consent when it is reasonable to do so as a means of maintaining pilot involvement during largely automated operations.
- Design automated systems to communicate the consequences of inputs, preselects, etc., on aircraft operation, especially those likely to result in errors and out of tolerance conditions not easily detected by casual human observation.
- Increase the error resistance of automated systems and their associated displays by designing clear, simple display formats and by providing unambiguous responses to commands.
- Perform safety hazard analyses of display and control use to identify instances where errors may be committed.

- Consider designing automation to incorporate the highest possible degree of error tolerance by proscribing either potentially hazardous commands or by providing the pilot with unambiguous warning of the hazardous consequences associated with the implementation of such commands.
- When preparing to design or modify an automated system, review accident and incident data on a frequent basis in order to identify and correct human and machine related design deficiencies.
- Design automation to be flexible enough to accommodate the full range of pilot abilities which can be expected to be employed during all phases of aircraft operation.
- Design automation to provide pilots with control and management options appropriate to phase of flight environment, and other situation-specific contexts. Consider having the automation judiciously assist in determining what not to provide also.
- Present information to the pilot in a form that will maintain or enhance situation awareness.
- Determine the information needs of pilots that do not vary from situation to situation, and ensure that this data is available for presentation to pilots in a form which is useful for all flight situations.

- Determine the specific information needs of each flight situation, and evaluate the utility (and consequences) of presenting this data to the pilots only when needed. Ensure that the presentation is in a form which optimally supports the specific task.
- Do not provide flight critical information to pilots unless its level of validity has been ascertained.
- Provide some indication to pilots when questionable data is being presented to them.
- Provide pilots with critical information concerning the status of both the automation itself as well as the components controlled by that automation.
- Design automated systems to assist pilots in dealing with the situation of automation failure, especially in the context of very reliable systems. Have prepared for presentation, information on the consequences of such failures, and on a ready means of executing crew/automation compensatory actions.
- Consider providing warnings to the pilots when their actions are expected to have potentially negative consequences.

- Pilots must be able to accurately predict and understand the automation's actions and processes.
- Design systems, where ever possible, to prevent hazardous interactions from occurring, and where prevention is not practical or feasible, to minimize the effect of their occurrence.
- Pilots should be provided with the information necessary to improve their awareness of potentially serious situations, and to improve their trust in the automated systems. The designer should endeavor to not make this presentation of information (e.g., trend data) degrade overall situation awareness or increase workload.
- When warnings occur which are not time-critical, pilots will attempt to evaluate the validity of such warnings. When of use to them, means should be provided for the crew to conduct these evaluations quickly and accurately.
- Warnings and cautions must be unambiguous. When common signals are used to denote more than one condition, there must be a clear indication of the specified condition responsible for the alert. For example, accompany summary signals, such as a master caution and master warning, with a clear indication of the specific condition responsible for activation of the alarm.

- Consider allowing the automation to take the first corrective action during emergency conditions and then informing the crew of the situation so that they can intervene as required.
- Minimize false or nuisance warnings in order to reduce pilot workload and increase their confidence in the warning systems.
- Provide trend information to the pilots before parameters reach levels requiring immediate pilot action, in order to alert them to the existence of potentially serious situations.
- Provide means for the pilots to quickly and easily evaluate the validity of all warnings.
- Present all warnings and alerts to the pilots clearly and unambiguously.
- When designing information declutter schemes, consider limiting the information presented to the pilots to that which is needed to maintain situation awareness, and to accomplish the tasks required in the current flight situation. The automated system should manage the display of information for subsequent portions of the mission such that the crew can always have strategic look-ahead access.
- Consider providing pilots with the capability to selectively declutter their displays based on their assessment of what is needed in each flight situation.

In such declutter choices, the automation should still alert the crew to any vital information.

- Declutter displays by displaying only that information which the pilot routinely needs to perform the current task, but provide the capability to rapidly access additional information if the need arise.
- Ensure crew awareness of updating of all data bases and system status relevant to mission completion parameters.
- Interpret information requirements with particular emphasis on type of integration prerequisites, information timing, transfer rates, etc.
- Provide a positive high level indication of the automation status of each subsystem.
- Provide information on the status of all controlled components and functions associated with each automated subsystem in the event of an automation failure.
- Develop "graceful" degradation schemes for all automated systems that assist the crew in a broad range of failure conditions.
- Consider locating the most important information in the center of the display.

- Consider reinforcing visual information with auditory or tactile information where high visual workload exists.
- Ensure that there is no interference between voice alerts or messages that might reduce their effectiveness.
- Consider back-driving functionally coupled control systems (e.g., stick and throttle) to increase situation awareness during automatic modes of operation.
- When designing automation that takes the crew through a sequence of inspection or evaluative steps (e.g., with electronic checklists) consider providing the following features:
 - Prompting of the crew when a checklist needs to be performed.
 - Reminding the crew of items still to be completed.
 - Acknowledging pilot confirmation of actions.

Information

- Information requirements must be derived principally from mission/functional requirements. These requirements can be strategic (e.g., flight planning) or tactical (e.g., the capability to make emergency maneuvers) in nature. Information requirements include not only the actual content needed (e.g., airspace sector data, fuel burn rate), but also requirements regarding access speed, size and number of active and background buffers, relational structure and cross-referencing, and updating capabilities. Additionally, all relevant aspects of the data base should be readily accessible to the crew for inspection, and, in appropriate cases, editing.
- When determining the updating scheme, the designer should consider such automation devices as "hot" updating as long as updates are made to all relevant data locations and associated computational routines (e.g., rule systems). In such cases of automated updating, the consequences of the updates should be evaluated by the system and any counterintuitive, unusual or otherwise unanticipated changes of significance to the mission should be communicated to the crew. In such designs for the updating function, every effort should be made to not burden the crew with unnecessary reports.

Human aspects of "intelligent" processing

- When any form of artificially "intelligent" processing is employed, the system must be able to inform the crew about the level of veracity, accuracy, and reliability of the processing, given the data, etc., it is considering. Confidence levels for decisions, etc., and possible consequences of erroneous conclusions of the system's processing must be apparent to the crew.
- When any form of artificially "intelligent" processing is employed, the system's design (and the associated training curriculum) should assist crew members in forming and maintaining a conceptually accurate mental model of all significant aspects of the system's processing. This knowledge of the automated system's processing should include awareness of the system's strengths, weaknesses, characteristic solutions, etc.
- When any form of artificially "intelligent" processing is employed, the system's design should be such that, for relevant cases, the crew can readily determine 'where' the automated system is in a given processing routine (e.g., a decision-making routine). Similarly, the crew should be able to readily determine subsequent steps in the processing of that routine. The designer must determine (from requirements) if and when the crew interface should be able to interrupt or edit an automated system's "intelligent" processing. In such cases, the automated system must be able

to inform the crew members about the effects of their intercession(s) with the processing routine.

Reasoning, judgement, and decision making -- In the design of automated systems employing artificial "intelligence," the designer needs to be aware of human cognitive strategies and biases, and needs to capitalize on, and/or compensate for, these characteristics of human information processing. Human reasoning employs strategies and biases in both syllogistic and conditional reasoning (i.e., logically deterministic), and in information-incomplete situations. A number of these human processing characteristics are relevant to the design of automated systems.

Processing characteristics in syllogistic and conditional reasoning. In situations in which problem-solving and decision-making can be solved by logical syllogism or by conditional ("if-then") reasoning -- that is, by deterministic means -- humans often exhibit processing strategies and biases that deviate from the strict logical appraisal of premises and conclusions. These processing characteristics are particularly likely to be employed in time-critical and high workload situations, and when the number or complexity of decision factors, or potential solutions, is great. The designer is cautioned to keep the following processing characteristics in mind whenever developing decision-making and, in particular, decision-aiding systems, involving syllogistic or conditional reasoning.

- Research shows that people sometimes misinterpret or fail to fully consider the logical premises involved in a decision-making task. For example,

instead of considering all possible meanings of a premise, people will interpret the premise as having only one meaning. Similarly, people will sometimes consider only a subset of the possible combinations of logical premises (based on simplicity or on preferences). In these cases, people will reason from such limited interpretations of the premises, thereby drawing potentially erroneous conclusions.

- There is substantial evidence that, in logical reasoning, people will fail to accurately consider the consequences of negative information about premises. For example, if a given premise is false (thereby logically rendering false the conclusion to the syllogism or condition), people will sometimes persist in accepting the conclusion as valid. Similarly, people tend not to consider counterexamples (to a logical argument) in evaluating the veracity of a conclusion (i.e., in deciding whether a given conclusion could be contradicted). Moreover, there tends to be a cognitive processing bias against seeking any negative (disconfirming) evidence when conducting logical reasoning.
- Research indicates that people sometimes evaluate the veracity of logical conclusions on the basis of their beliefs instead of on the logical grounds supporting or refuting those conclusions. In particular, people have a stronger tendency to accept a believable but invalid conclusion than to accept an unbelievable yet valid conclusion.

- Empirical evidence suggests that a person in a situation of syllogistic or conditional reasoning, will tend to generate a conclusion consistent with the logical problem's premises, accept it as valid, and cease considering other possible conclusions. This "confirmation" bias may, in part, explain why people tend to have difficulty seeking and considering disconfirming evidence (see preceding guidelines for discussion).

Processing characteristics in reasoning under uncertainty. In real-world situations, typical problem-solving or decision-making involves reasoning in the context of incomplete, degraded, or misleading information. The empirical study of such "reasoning under uncertainty" has revealed a number of cognitive strategies and biases characteristically employed by humans. The designer is advised to keep the following in mind when designing automated decision-aiding routines, etc.:

- Research shows that, when people attempt to estimate probabilities of alternative outcomes, they sometimes base these subjective probability estimates on how frequently they have encountered this type of outcome, and not on its probability. Consider the following example: Hypothetical final approach A was a possible outcome in five approaches and was shown to be selected in four of those approaches, and final approach C was possible in twenty approaches and was shown to be selected in ten of those. In such cases, pilots would tend to predict that approach C is more likely to occur in a future clearance than is approach A (even though the probability of A's occurrence, .8, is substantially higher than C's, .5).

- Research indicates that people's judgements of probabilities of occurrence are often influenced by how readily examples of such occurrences come to mind. This "availability" heuristic suggests that subjective probability estimates can be heavily biased by particular personal experience and by memory.
- In assessing the degree of agreement between decision accuracy and decision confidence, it has been shown that people tend to be over-confident in cases of relatively high (but not perfect) decision accuracy. There is some evidence suggesting that this tendency to exhibit more confidence than the accuracy of the decision warrants is due to people's incomplete analyses of the decisions being made.
- When estimating the probability that two independent events (e.g., that accidentally leaving your front door unlocked would occur on the same day that a burglar checks all the doors in the neighborhood), research has shown that people tend to substantially over-estimate the probability that both events will occur. It is believed that such inaccuracies in subjective probability estimation arise from people's tendency to ignore, or not fully consider, the base-rate probabilities connected with each of the events. Instead, people tend to believe some connection or correlation must exist between the events since they co-occurred, thereby (erroneously) increasing their estimates of the conjoint event's likelihood.

- Empirical research reveals that people will greatly over-estimate the likelihood that information obtained in a small number of random observations will be representative of a more general pattern or trend.
- Research shows that, due to memory limitations and processing biases, people do not accurately estimate the degree of relatedness between (i.e., the correlation) events. Nevertheless, when underlying correlations between events are strong, peoples' estimates of relatedness (and therefore, predictability) are largely in accord with actual correlations.

In contrast to this general tendency, it is sometimes the case that people will judge a significant relationship to exist between events when, objectively, there is no correlational evidence of one. This phenomenon of "illusory correlation" is believed to reflect people's tendency to make subjective probability estimates of relatedness (in the absence of actual correlational evidence) on the basis of implicit theories or beliefs -- in effect, people find patterns where they want to. It is significant to note that people's beliefs in such illusory correlations are difficult to change, even being resistant to direct contradictory evidence.

- Research has shown that, in real-world situations, instead of following idealized or optimal decision-making strategies, people prefer to follow strategies that yield clear choices, that involve little or no probability estimating or computation, and that are readily understood and defended. For example, instead of weighing all merits and shortcomings of a

decision's alternatives, people will sometimes evaluate only the relative merits of the alternatives, or only the relative shortcomings in their decisions. In another commonly employed strategy, people choose from among decision alternatives by first ranking important features of the alternatives, and then eliminating alternatives that don't possess the highest ranked feature, then that don't possess the next highest ranked feature, etc., until only one alternative remains.

- Empirical studies have demonstrated that when people engage in real-world decision-making activities, they attempt to take into account the costs involved in making those decisions. People consider the options lost by deciding (therefore sometimes delaying or avoiding the decision), the time involved in evaluating alternatives, the number and complexity of the alternatives (and their relative merit), and the extent of differences (i.e., dissimilarity) between the alternatives. When uncertainty is high, or when the potential consequences of an erroneous decision are serious, people will sometimes hedge their decisions (e.g., selecting a non-optimal alternative that allows options to remain available), or will knowingly take overly conservative, but safe, choices.

Tailored apprising of aircraft systems status, and of consequences of current situation --

- To the maximum extent possible, aircraft system status information, etc., should always be available to the crew upon request. And all standard caution and alert information should be clearly and unambiguously

announced to the crew in accord with established and validated priority/criticality schemes. Such schemes should be able to accommodate any relevant context-specific information which might improve their utilization. In no case, however, should context-specific augmentation of such schemes be able to result in a dangerous, misleading, or otherwise unhelpful modification.

- In cases where it has been determined that context-sensitive automated routines would enhance the capability of a status and alerting system, certain design principles should be adhered to. First, all standard status, caution, and alerting capabilities must not be impeded in any way; therefore, all automated assistance must be limited to advisory functions. Within this role, the automated component of a status and alerting system should evaluate the status of the aircraft in the context of the aircraft's current flight situation. This examination should attempt to evaluate the current and future status of involved systems when such status is not readily determinable by direct sensor readings, equipment tolerance bands, etc., nor by algorithmic system inspection routines. Instead, this evaluation should attempt to use available system status data sources, knowledge of the flight situation, and diagnostic routines designed to predict status in cases of incomplete or inaccurate data. In addition to providing the best possible diagnoses, such probabilistic analyses should clearly and concisely inform the crew about the confidence level of the diagnoses, relevant alternative possibilities, and significant consequences (positive and negative) of accepting or rejecting the diagnoses. The designer should consider that the

automated system may be required to estimate near-term and long range trends in aircraft system functioning, including potential for eventual partial or complete malfunction. Such appraisals should also include predictions regarding collateral effects on interrelated systems.

Extent and type of crew awareness and involvement in automated processes

- In general, the automated system should minimize human involvement in tasks that interrupt or otherwise impede the ability to remain aware of the current aircraft situation and its occupied airspace, or that lessen the extent to which the human can anticipate and speculate about significant upcoming events. This being said, there are some obvious difficulties in heeding this advice. First, many of the tasks implicated above also produce involvement in, and awareness of, important flight-related functions -- minimizing crew participation in such cases could simply improve awareness in one area at the cost of eliminating it in another. Second, determining that a given task or function actively reduces awareness (and, for that matter, that a given automation routine improves awareness), is not always straightforward since actual empirical measurement of situation awareness is, at best, equivocal. For these and other reasons, recommending guidelines for level of awareness, etc., perhaps just acts to obscure the goal of the designer -- to develop a system that exploits human capabilities, compensates for human weaknesses, and robustly satisfies the mission's requirements. In sum,

extent and type of crew involvement should be determined by design efforts sensitive to human-centered principles.

Factors Related to the Automated System's Functional Architecture

While the design and implementation of an actual functional architecture is principally the responsibility of software and hardware developers, the designer can and should substantially influence the direction and scope of such activities since the system's eventual capabilities often pivot on how a design concept is implemented. To this end, the designer should understand the technologies and techniques involved, and should have a reasonably informed appreciation for the kinds of functional requirements, etc., that will drive software and hardware engineers to make the choices they do. Some factors relevant to these concerns are now discussed.

Types of situation-adaptive mechanism used to cue automated routines

Parasuraman, Bahri, Deaton, Morrison, and Barnes (ref. 15) identify three classes of "adaptive" mechanisms to be considered in the design and implementation of context-sensitive automation: Mechanisms that empirically assess pilot state and performance; mechanisms that model or theoretically represent (and thus predict) pilot state, performance, or intentions; and mechanisms that use mission requirements, events, etc., and situation-specific information. These classes of mechanism are now considered with respect to their potential utility.

Empirical assessment of pilot state and performance -- Empirical evaluation of pilot state typically considers mental and/or physical workload, situation awareness, vigilance, and fatigue. Evaluation of pilot performance generally focuses on aspects of task execution (duration, accuracy, and nature of performance errors), and the effects of this execution on other tasks (done in parallel or subsequent to the task under evaluation). In empirical assessments of state or performance, it is typically assumed that such data will, of course, constitute crucial information for the triggering of automated routines -- however, such obtained data does not, in and of itself, cause the automated routines to be initiated. Instead some rule system, etc., taking this empirical data as inputs, must still specify when and how a given automated routine will be employed. Even so, the designer's critical appraisal of the quality and timeliness of such data is essential since the adaptive decision scheme (e.g., rule system) is largely dependent on it.

- With regard to assessment of pilot state, the designer must decide whether physiological (e.g., heart rate), and/or subjective (e.g., pilot workload ratings) measures will be employed. In either case, the designer must endeavor to use the most technically and statistically reliable, accurate, and non-intrusive measures available. In addition, serious consideration should be given to practical concerns such as: How much and what kind of data is required, signal processing complexity (in the case of certain physiological measures), and the relative discriminability or diagnosticity that these measures are likely to provide (e.g., to date, physiological indices of

mental activity are only able to distinguish relatively general conditions of cognitive processing. Their functional utility with regard to, say, inferring specific intent, is virtually nil.)

- With regard to assessing workload, the designer should determine what aspects of workload would be potentially useful as cuing mechanisms (e.g., visual versus auditory workload; mental workload associated with decision making versus with remembering), and which of these might be reliably obtainable.
- When employing empirical assessment, the system must be able to interpret the functional significance of distinguishable differences in pilot state or performance; differences that are discernable but not interpretable are of little use as cuing mechanisms.

Models of pilot state, performance, or intention -- Parasuraman, Bahri, Deaton, Morrison, and Barnes (ref. 15) identify several types of modelling approaches to representing (and predicting) pilot-related variables: Models that can represent aspects of pilot workload (e.g., involving task-related changes in workload), models of cognitive processing (e.g., "executive" processing models), and models of pilot performance and intention (e.g., queuing theory models, and intent inferencing systems). In some contrast to the empirical mechanisms discussed previously, modelling approaches have often integrally combined the modelling of pilot states, etc., with some set of strategies, rules, etc., for directly triggering an adaptive automated routine. As such, the designer's evaluation of

modelling approaches must consider both how well a given model predicts the relevant pilot variable (e.g., workload), and how effectively the model's strategies, rules, etc., perform their adaptive function for initiating automated assistance.

- When considering the use of a model for predicting a pilot variable, the designer should, whenever possible, obtain statistically rigorous validity and reliability indices successfully comparing the model's predictions with empirically obtained indicants of the pilot variable of interest. Additionally, the designer should verify that the model's input requirements, etc., can be satisfied for the situation (e.g., mission segment) to be modelled.
- When considering the use of a model for predicting a pilot variable, the designer should verify that the model appears to be more efficient than (or otherwise preferable to) representing the pilot variable empirically.
- When considering the use of a model to predict a pilot variable, the designer should compare the modelling approach to rival approaches, evaluating it for strength of predictability, scope of applicability, number and value of beneficial features, ease of implementation, and risks associated with software/hardware technologies and programming techniques employed.

Mission events and situation-specific cues -- Parasuraman, Bahri, Deaton, Morrison, and Barnes (ref. 15) refer to the use of mission events for prompting automated sequences as employing "critical event" logics. These authors adopt Barnes and Grossman's (1985) typology of such logics:

Emergency logic, in which a control process is executed without pilot intervention initiation or intervention...

Executive logic, in which the subprocesses leading up to the decision to activate the process are automatically invoked, with the final decision requiring the pilot's input...

Automated display logic, in which all non-critical display findings are automated to prepare for a particular event, so that the pilot can concentrate on the most important tasks. (p. 18)

Several mission and situation-specific events can be employed in such critical-event logics, among them being:

- Mission phases, segments, etc.
- Current and planned aircraft position and performance data
- Crew inputs (whether correct, erroneous, absent, or delayed)
- ATC inputs
- Current and anticipated environmental conditions
- Time requirements

- Emergencies, malfunctions, and other abnormal conditions

- When considering the use of a critical-event scheme as an adaptive mechanism, the designer should continually evaluate how that critical-event logic satisfies mission functions. Moreover, since critical-event logics are particularly dependent on mission events, this ongoing evaluation should consider the critical-event logic's potential for success in future applications (in which mission functions are likely to change), and in near-term applications involving retrofit issues, operations in mixed fleets, and interactions with variable ATC capabilities.

- When considering the use of a critical-event logic as an adaptive mechanism, the designer must understand the logic's effects on collateral and subsequent events in the mission to the maximum extent possible. This understanding must be both tactical and strategic, and must consider unlikely and critical situations as well as expected nominal performance. And the designer is reminded that, since the rule systems, etc., governing critical-event schemes will typically incorporate some deterministic/conditional logic (e.g., if-then sequences), evaluating the effects of the critical event scheme necessarily entails evaluating all outcome possibilities of these rules (even seemingly innocuous, trivial, or null outcomes).

- When considering the use of a critical event logic as an adaptive mechanism, the designer must have a clear idea of what failures and

malfunctions in the critical-event scheme will look like. The designer must not only have a means for identifying such anomalies, but must ensure that the automated system can, where possible, 'trap' for them (i.e., by programming, etc., preempt their occurrence), announce relevant aspects of their etiologies and effects when they do occur, and provide means for compensating for these occurrences.

- When considering the use of a critical-event logic as an adaptive mechanism, the designer should keep in mind Parasuraman, Bahri, Deaton, Morrison, and Barnes' (ref. 15) criticism of such schemes:

The problem with these [critical-event logic] systems is that they are relatively unsophisticated and are unresponsive to actual operator workload or performance. It is even possible that their rule bases have unforeseen, interactive consequences in a complex environment.
(p. 18)

As such, the designer should consider following a design philosophy that is biased toward relatively low autonomy for the automated system, since, in critical-event applications, the crew and ATC typically constitute vital elements of the system's overall "intelligence" and decision-making capability.

Programming and computational techniques used to control automated systems

Several classes of programming and computation can be employed in implementing automated systems, including the following:

- Standard algorithmic and related rule-based techniques
 - "General case plus variant" modelling (e.g., frame-based programming)
 - "Judgement" and "Reasoning" programming designed to work in circumstances involving uncertain or poorly understood parameters
 - Probabilistic and estimating techniques, including "neural network systems"
-
- When deciding to use a computational or programming technique, the designer should consider the technique's ability to help satisfy the software requirements previously derived from the automated system's design requirements (which, in turn, should follow from the mission's and the human operator's requirements). In many cases, it may turn out that various requirements are better addressed by particular techniques and, thus, different components of the automated system may be supported by different programming approaches. A number of these software requirements are considered below.

- When deciding on a programming approach, the designer should have determined operationally representative estimates of timing requirements for data search, loading, etc., for central processing (e.g., decision-making), and for interaction with the system interface.
- When deciding on a programming approach, the designer should endeavor to ascertain the system's required computational capacity in terms of amount and complexity of computing. This might be achieved by estimating peak calculation rates, number and complexity of parallel computations potentially required, etc.
- When deciding on a programming approach, the designer should endeavor to determine the levels of certainty, accuracy, etc., to be required by the automated system's (operational) functioning.
- Where applicable, when deciding on a programming approach, the designer should ascertain the extent of uncertainty, ambiguity, etc., inherent in the functional phenomenon being modelled or estimated since certain computational techniques are specialized for such situations.
- When deciding on a programming approach, the designer should endeavor to employ the computational techniques least likely to produce erroneous, inconclusive, obsolete, or misleading outputs,

and yet still fulfill the design requirements for the automated system. Such selections of low risk programming techniques must, of course, be weighed against the potential losses in computational sophistication and power that might have been provided by more high risk techniques.

- When deciding on a programming approach, the designer should evaluate the ease, flexibility, and power of the approach to implement operator interact and system integration functions.
- In cases where a requirement has been established for the automated system to produce a solution (e.g., a decision), etc., that resembles or is consistent with the corresponding human solution, the software should mimic the human cognitive processes, strategies, and preferences leading to that solution only when:
 - It is generally believed that some advantage exists (e.g., better solution, faster decision) for the solution obtained by human cognitive processing, and/or
 - There appears to be some collateral benefit afforded the operator (e.g., improved confidence in the solution, improved situation awareness) by him or her recognizing and agreeing with the system's processing.

With regard to this consideration, the designer should endeavor to determine the extent to which the automated routine must be able to report partial solutions (e.g., a best estimate when only half through the required processing) or other interim processing (e.g., at some point in a particular decision-making process, the system has narrowed the number of possible solutions to X alternatives...). This determination should be based on operational and human information processing requirements, not on simple technological capability or practical feasibility.

- For cases in which an Expert System approach is to be implemented, the designer should ensure that the knowledge base from the subject-matter expert include demonstrated expert competence, in terms of actions, safe-guarding procedures, etc., as well as declarative knowledge and opinions about how experts think and act.
- For cases in which an Expert System approach is to be implemented, the designer should ensure that the number and variety of experts consulted, and the contexts in which these experts are observed, be adequate to develop a representative model of the "expert."

Integration of the Automated System with Other Systems

When an automated system is implemented as a component of an aircraft's onboard avionics suite, it necessarily interacts with other components to achieve functional utility. These interactions can range from simple data transfers to complex command and control relationships. whatever the nature of these interactions, their effective execution is essential to advanced aircraft operations. As such, design decisions affecting the functional integration of such component systems must be carefully and thoroughly considered by the designer. To this end, the following guidelines are offered.

Integration among onboard systems for enhanced performance

- System integration schemes should be designed such that crew members are not the sole means of data input, data transfer, etc., between functionally related systems (e.g., Data Link and the Flight Management System). In general, direct system-to-system data transfer (with appropriate user interface, etc., safeguards in place) should always be possible.
- Relevant timing, accuracy, speed, and format requirements for retrieval, transfer, processing, and updating should be compatible between functionally related systems.

- Where advantageous and safe, all related data bases should update adequately to fully support mission, user, and system design requirements. Moreover, such updating should, in general, be "hot" -- that is, data common to several data bases should be updated in all data bases automatically whenever it is updated in one. This characteristic extends to also include the hot updating of the products of any computations, etc., generated from the relevant data.
- In cases where related systems utilize extensive and/or critical amounts of the same data, the designer should consider having the systems share one data base or at least integrate the (partially) redundant data bases for use as mutual backups.

Integration among onboard systems for improved safety

- In all cases of shared data (or shared products of that data), reliable and accurate safeguards regarding error detection, and error propagation must be continuously operational.
- The design of any automated system should endeavor to adhere to all recognized avionics development standards regarding that system's integration with other systems, including any standards concerning processing or computational redundancies, etc.

- The designer should consider providing some degree of functional redundancy among related systems to enable the component systems to perform cross-checking and backup functions. Such capabilities might also be employed in compensatory routines responding to degraded performance, malfunctions, etc. Whatever the use of such functionally redundant capabilities, the source (i.e., the system) responsible for any calculations, estimates, etc., must always be readily apparent to the crew.
- Integration schemes should be designed such that they maximize the probability that vital functions of the aircraft's systems will continue to perform (at some level of adequacy) when related component systems partially or completely fail.
- Integration schemes should be designed such that, in the event of partial failures, malfunctions, etc., every functional level of degraded operation retains essential flight and navigation functions (even if this is at the expense of other capabilities). That is, system integration, even in degraded modes, follows a function prioritization that preserves essential functions at all costs.

Integration with ground-based systems

- The design of the automated system should consider critical features of ground-based systems with which it must communicate. These features can include: Data transmission formats, protocols, and baud rates; transmission and other physical characteristics (e.g., periodicity of message transmission over Mode S data link); and possible sources of error, malfunction, etc.
- The design of the automated system should be such that it does not depend solely on ground-based data for essential functions.
- The design of the automated system should be such that it does not overburden, impede, or otherwise lessen the overall utility of the ground-based system.

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