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Aviation Safety and Automation Technology for Subsonic Transports

James A. Albers, Ames Research Center, Moffett Field, California

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National Aeronautics and
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Ames Research Center
Moffett Field, California 94035-1000

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SUMMARY

The major challenges facing the Air Transportation System today include reducing congestion and delays, enhancing safety, and expanding the capacity of the National Aviation System. This report discusses aviation safety human factors and air traffic control (ATC) automation research at NASA Ames Research Center directed toward these challenges. Research results are given in the areas of flight deck and ATC automation, displays and warning systems, crew coordination, and crew fatigue and jet lag. In addition, accident investigation research and an incident reporting system that is used to guide the human factors research is discussed. A design philosophy for human-centered automation is given, along with an evaluation of automation on advanced technology transports. Intelligent error-tolerant systems such as electronic checklists are discussed along with design guidelines for reducing procedure errors. Implementation of the current research results can offer significant improvements in the current Air Transportation System. Study results indicate that significant improvements in aircrew planning and decision making could be realized with the use of display-based communications transmitted by data link. Initial studies on three-dimensional (3-D) auditory displays indicate that these displays could improve situation awareness for both crew members and ATC controllers. It was found that a 40-minute pre-planned rest period for long-haul operations can offer a safety valve to mitigate the effects of sleep loss and fatigue. The data on evaluation of Crew Resource Management (CRM) training indicates highly significant positive changes in appropriate flight-deck behavior and more effective use of available resources for crew members receiving this training. Simulation evaluation of ATC automation tools for single runway operations provided 4-6 minutes delay reduction per aircraft depending on traffic mix with significant reduction in controller workload.

INTRODUCTION

The increase in demand for air transportation has tripled worldwide traffic since 1970, and is expected to double again by the year 2000 (ref. 1), resulting in the need to transport as many as 650-800 million passengers in the United States in a single year. This rapid growth will place increased stress on the already strained National Aviation System. The demand for access at major airports serving scheduled air carriers is increasing much faster than airport capacity. Unless improvements are made, increased congestion and more flight delays can be expected at the major hub airports. Costs associated with congestion-related system delays already equal $5 to $6 billion per year, because of lost time for passengers and airlines (ref. 2). Instrument operations due to weather also are a major capacity bottleneck. The Federal Aviation Administration (FAA) is attempting to alleviate the problems by upgrading equipment and automating some functions within the Air Traffic Control (ATC) system. However, this is not adequate to meet the anticipated traffic growth.

Also identified as a major national problem is the number of aviation accidents and safety-related aviation incidents attributable to human error. In the last decade the number of near misses reported to the NASA Aviation Safety Reporting System (ASRS) has more than doubled. A review of the data on commercial aviation accidents since 1978 reveals that approximately 65% of commercial jet accidents, and 85% of general aviation accidents have been directly attributed to human error as the probable, or a contributing, cause (ref. 3). These factors, coupled with increasing congestion, have led to a growing public concern for safety of commercial air transportation in the National Aviation System.

The new generation of automated aircraft has increasingly used technology on the flight deck to enhance factors such as safety of flight and economic performance. Despite the success of the new aircraft, a number of incidents and accidents were attributed to problems of crews operating automated equipment according to ASRS data and National Transportation Safety Board (NTSB) reports. The increased range of the new generation of long-haul aircraft with reduced crew sizes and highly automated cockpits can be expected to heighten concerns about crew fatigue, complacency, and boredom. Information transfer problems within the cockpit and with air traffic control has been the cause of numerous incidents in flight operations. During periods of high workload and emergency situations pilots have complained of information overload. Economic pressures and increasing demand for more frequent flights will only serve to increase the potential for operational inefficiency and decreased flight safety. The problems of advanced automation, information transfer, fatigue, increasing congestion, increasing demand, and the limited capacity of the Air Transportation System present new challenges to both human factors and flight systems research communities.

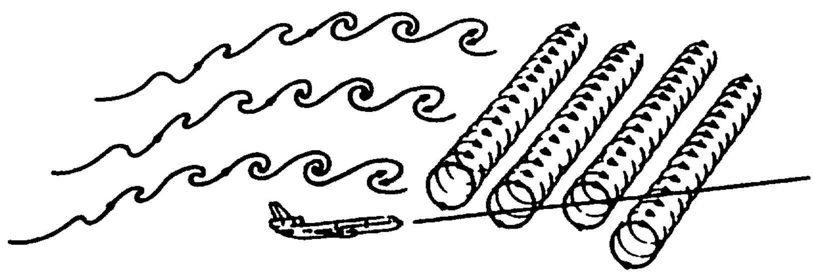
NASA initiated an Aviation Safety/Automation Program in fiscal year 1989 to address the problems of aviation safety and automation of aircraft and the ATC system. This program augmented the funding in the existing research and technology base that was directed toward safety and ATC automation. The primary goal of the Aviation Safety/Automation program is to enhance the safety of the National Aviation System through development and integration of automation technologies for aircraft crew and air traffic controllers. The major thrust of the program is to develop and integrate technology that can assist, support, and monitor human performance in the aviation context and thus reduce human error and its consequences.

This report discusses the aviation safety and ATC terminal area automation research at NASA Ames Research Center. The aviation safety research includes accident investigation, incident reporting, and human factors of flight-deck automation, displays and warning systems, crew coordination, and crew fatigue and jet lag. The research discussed in this report is complemented by research at the NASA Langley Research Center and is closely coordinated with the FAA.

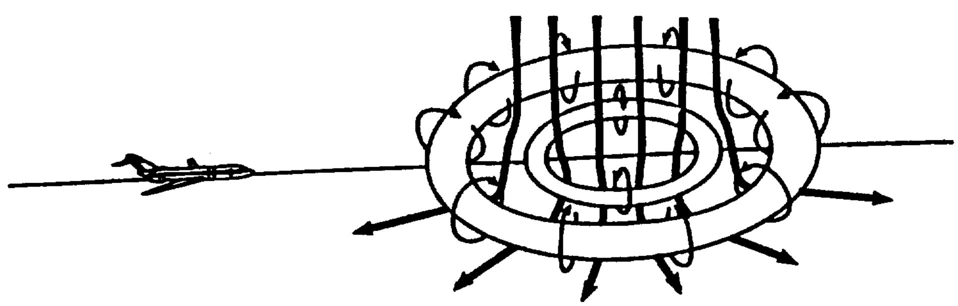
ACCIDENT INVESTIGATION AND INCIDENT REPORTING

Accident Investigation

Flight encounters with severe atmospheric disturbances are a continuing problem that must be better understood to improve safety. In conjunction with the NTSB, researchers from Ames have analyzed a series of atmospheric disturbances encounters involving airlines equipped with digital flight data recorders (refs. 4 and 5). The severe atmospheric disturbances studied included high-altitude turbulence and low-level microbursts. High-altitude turbulence is usually referred to as "clear-air turbulence" and is associated with a strong inversion in air temperature and a strong vertical shear in horizontal winds. These conditions are often in the regions of the tropopause and the associated jet streams. The most severe encounters are frequently above mountains or thunderstorms. Microbursts are intense downdrafts that impact the surface and cause strong outflows. They are associated with thunderstorms, and usually occur during the summer. The atmospheric disturbances were modeled (fig. 1) to investigate the nature of these disturbances and to study their effects on aircraft operations. The winds of clear air turbulence can be represented by a Kelvin-Helmholtz vortex-array model. The winds of a microburst can be represented by a multiple-vortex ring model.



a) Vortex model of high altitude turbulence



b) Vortex-ring model of low level microburst

Figure 1. Models of severe atmosphere disturbances.

The wind time histories for a given flight can be determined after the fact from digital flight records along with ATC tracking data (fig. 2). The accelerations measured aboard the aircraft are integrated to determine the time history of the flight path that provides the best match to the ATC radar position data and the digital flight data recorder barometric altitude data. The aircraft data are generally obtained from the manufacturer. The wind velocity is computed as the difference between the vehicle inertial velocity and its velocity with respect to the airmass.

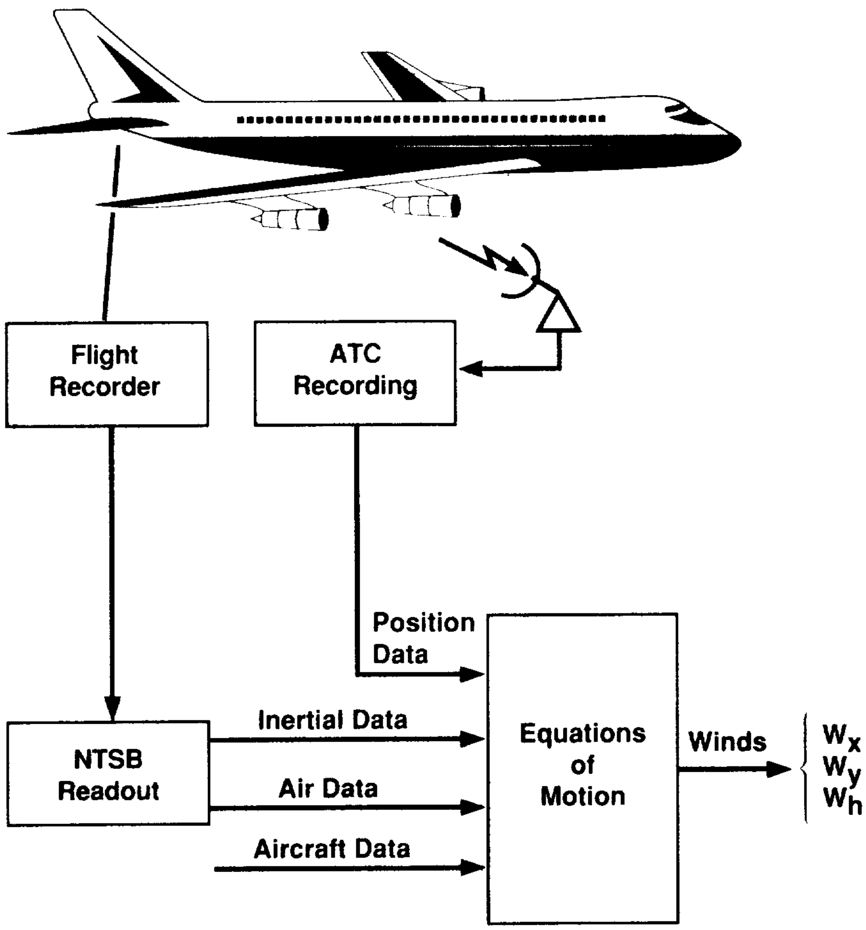
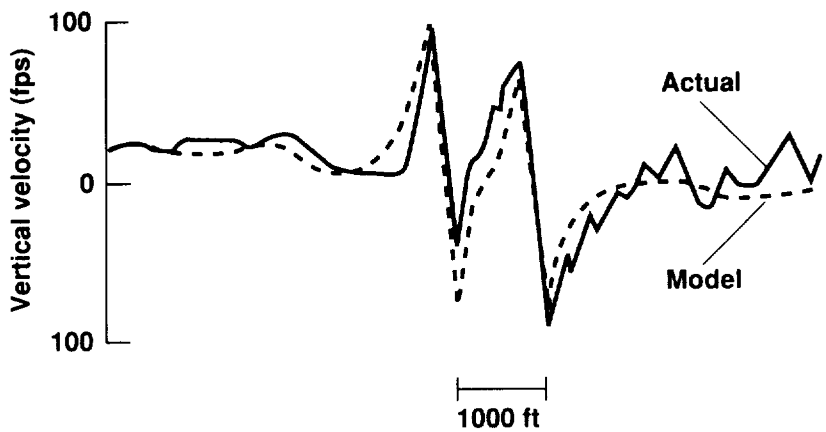


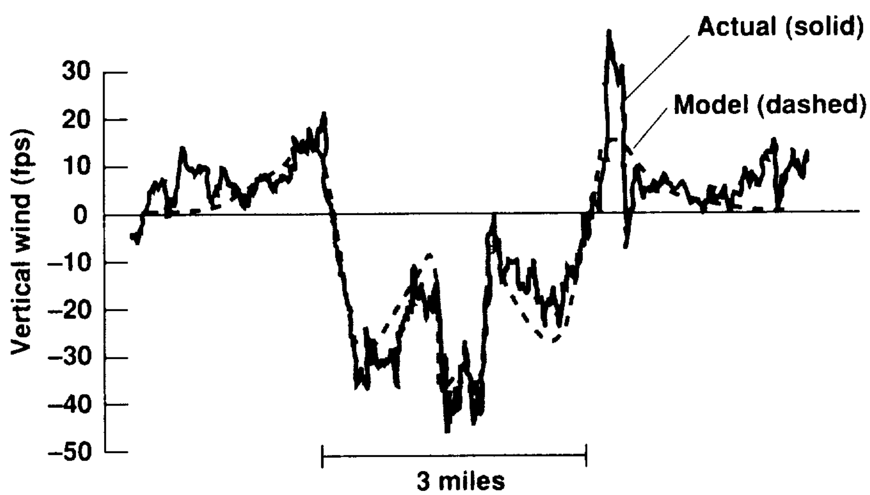
Figure 2. Reconstruction of winds from flight and ATC records.

A comparison of modeled vertical wind perturbations with the measured winds for a severe turbulence encounter over Hannibal, Missouri, April 1981, is shown in figure 3(a). Reasonably good agreement was obtained between the model and actual winds. The vortex model provides a means of studying the effects of these wind hazards on aircraft response and gravitational (g) load. Simulations have provided information on the effects of these reconstructed vortices on the flight behavior for three types of aircraft: a large commercial airliner, an executive jet, and a remotely piloted vehicle.

Analysis of digital flight data from the landing approach accident at Dallas/Fort Worth in 1985 indicates that the aircraft encountered a microburst with rapidly changing winds embedded in a strong outflow near the ground. The results are shown in figure 4. Data from the Delta 191 accident show that the aircraft encountered a strong microburst downflow followed by a strong outflow accompanied by large and rapid changes in vertical wind. American 539 passed through the center of the microburst during a go-around maneuver about 100 sec after Delta 191. Data from American 539 indicate a broad pattern of downflow in the microburst with regions of upflow at the extreme edges. The wind pattern in the Dallas/Fort Worth microburst has been identified through the development of a multiple-vortex ring model. A comparison of the modeled vertical wind perturbations with the measured winds shows reasonably good agreement (fig. 3(b)).



a) High altitude turbulence



b) Low level microburst

Figure 3. Comparison modeled and measured vertical wind velocities for severe atmospheric disturbances.

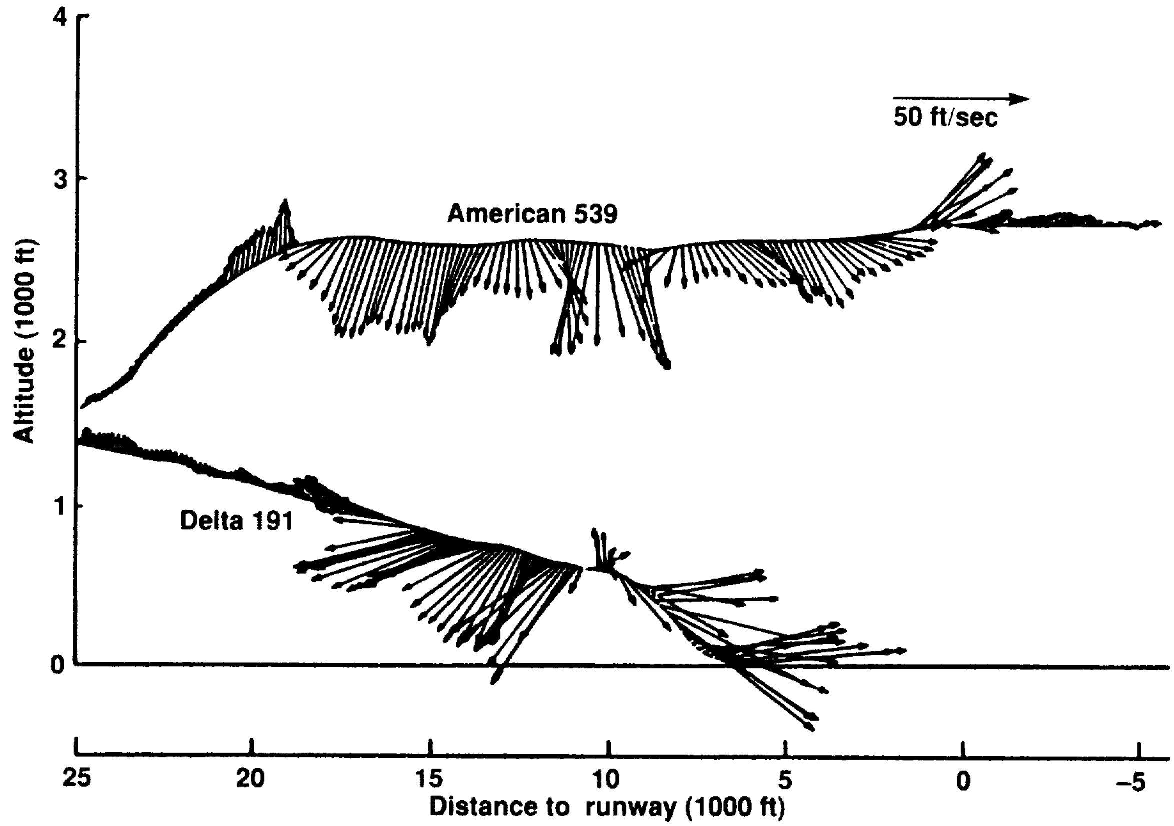


Figure 4. Wind vectors for two aircraft, Dallas/Fort Worth, August 1985.

For the first time, with modern digital flight data recorders, sufficient data are available to separate atmospheric disturbance and maneuver-induced g loads. Investigations are planned in flight simulators to better understand control problems for severe turbulence encounters and to determine methods to reduce the maneuvering loads. These investigations will examine the use of both automatic and manual control modes, and will consider the nonlinear aerodynamic effects at high positive g loads where the aircraft is in the Mach buffet region.

Incident Reporting

The ASRS, established in 1976, is managed by NASA at the request of the FAA (ref. 6). The ASRS receives, processes, and analyzes voluntarily submitted aviation incident reports from pilots, air traffic controllers, and others. The aviation community is fully supportive of the ASRS program; in fact, both government and industry organizations act as integral elements in the incident-reporting system's input and output phases (fig. 5). These reports describe both unsafe occurrences and hazardous situations. The ASRS uses an epidemiological model where human errors could be considered as symptoms of a variety of underlying disorders either in the aviation system, in the human operator, or both (fig. 6). These errors could lead to a variety of outcomes depending upon the environment in which the error occurred. The ASRS offers incident reporters confidentiality, and the FAA provides limited immunity to the reporter for unintentional aviation safety transgressions. In exchange, the program receives unique safety information which can be used to remedy reported

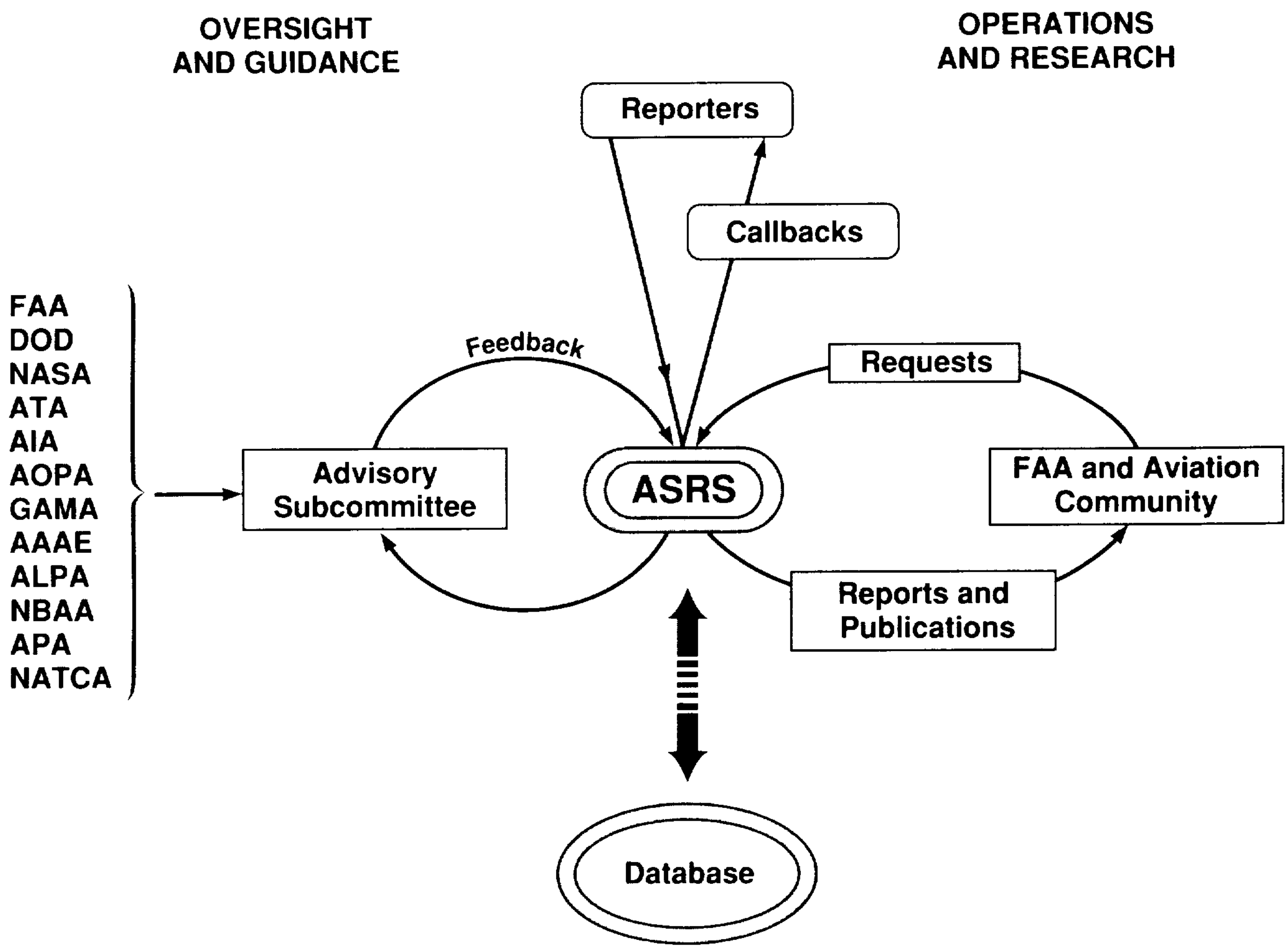


Figure 5. NASA Aviation Safety Reporting System.

hazards, to provide data for planning and making improvements to the National Aviation System, and to conduct research on pressing safety problems. The ASRS's particular concern is the quality of human performance in the aviation system.

Since its inception, the ASRS has published more than 40 research studies based on its data covering the full spectrum of aviation activity. The program has processed over 160,000 safety reports, issued 1,400 alerting messages, and responded to 1,800 special information requests. This database has become a major resource to guide NASA human factors research and is heavily used by the FAA, NTSB, Department of Defense, and other government, industry, and safety organizations, both nationally and internationally. This U.S. incident-reporting system has proven to be so effective in improving safety and in stimulating safety awareness that it has been used as a model for similar programs in four other countries.

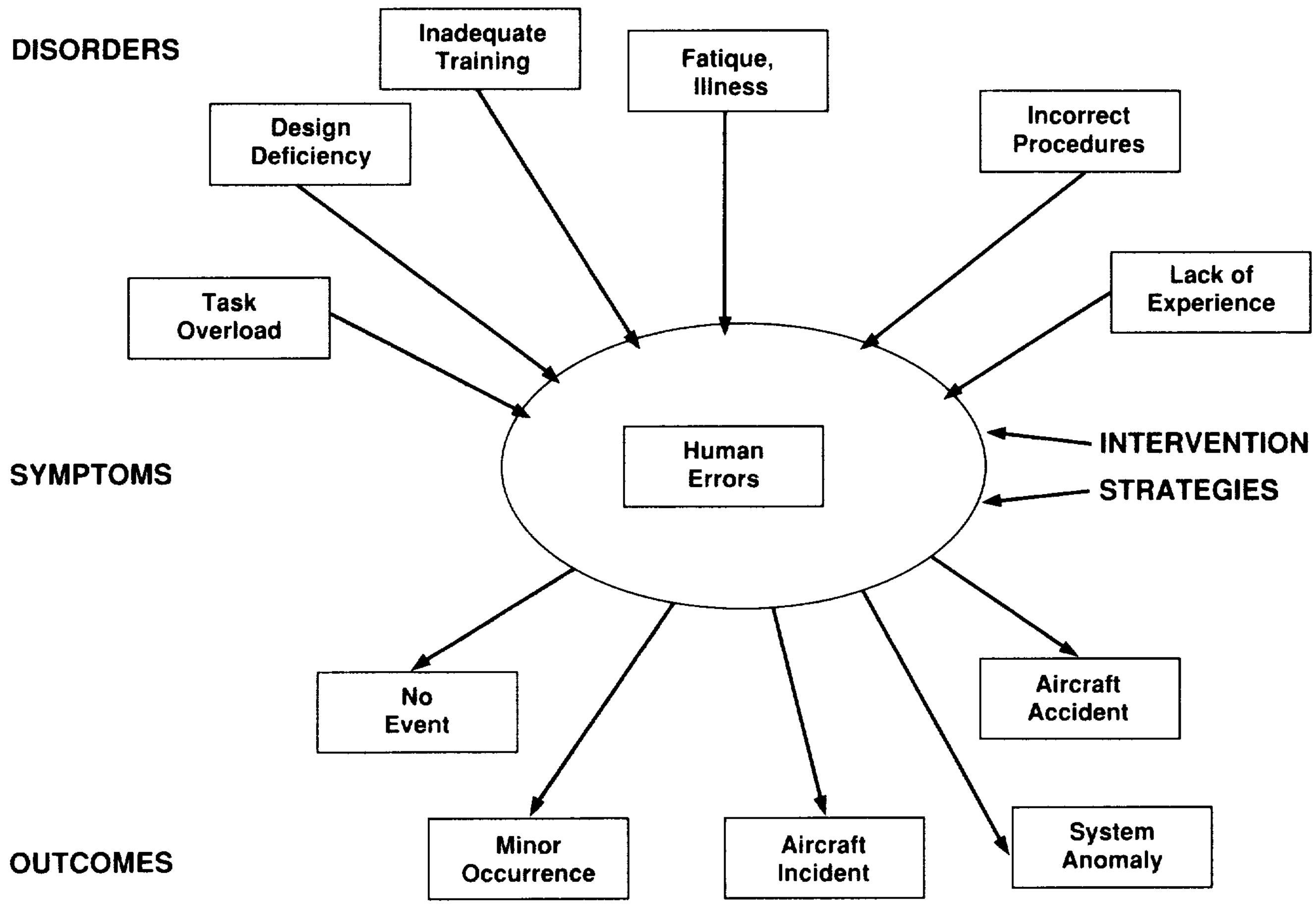


Figure 6. ASRS model of human error.

AVIATION SAFETY HUMAN FACTORS RESEARCH

NASA's aviation safety human factors program is directed at understanding and mitigating the problem of human error in aviation. Research is directed in the area of flight-deck automation, display and warning systems, crew fatigue and jet lag, and crew coordination research.

Flight-Deck Automation

The flight-deck automation research consists of two elements: (1) human-automation interaction and (2) intelligent error-tolerant systems. The human-automation interaction element is concerned with the role of the human in the automated environment. Intelligent error-tolerant systems focuses on development of cockpit systems that intrinsically tolerate human error.

Human-automation interaction– The Air Transport Association's National Plan for the Enhancement of Safety through Human Factors (ref. 7), has identified the lack of a scientifically based philosophy of aircraft automation as an important shortcoming in planning for the future aviation system. In an attempt to redress the shortcoming, Ames, in consultation with colleagues at Langley Research Center, and Boeing and Douglas Aircraft Companies, is developing an appropriate automation philosophy and guidelines for the design and evaluation of automated system interfaces for pilots and controllers. This philosophy makes extensive use of examples from previous and current aircraft automation applications and addresses, in particular, conceptual and philosophical issues in the context of aircraft automation as it has evolved over the past 70 years. An initial report discussing some of this philosophy is in reference 8.

Humans will continue to manage and operate the National Aviation System through the first part of the 21st century. Therefore, the technology requirement is for automation to assist humans in attaining increases in performance within the flight deck or ATC work station, to monitor human performance, to detect and warn of human errors, and to assist humans in the management of contingencies. We speak of such automation as being human-centered, in that its function is to assist rather than to supplant the human. The concept of being human-centered is one in which the pilots perceive themselves as being at the focus of control, regardless of the control modalities in use. The pilot controls and manages the resources in the aircraft and aircraft systems to aid in situation awareness. These resources are illustrated in figure 7.

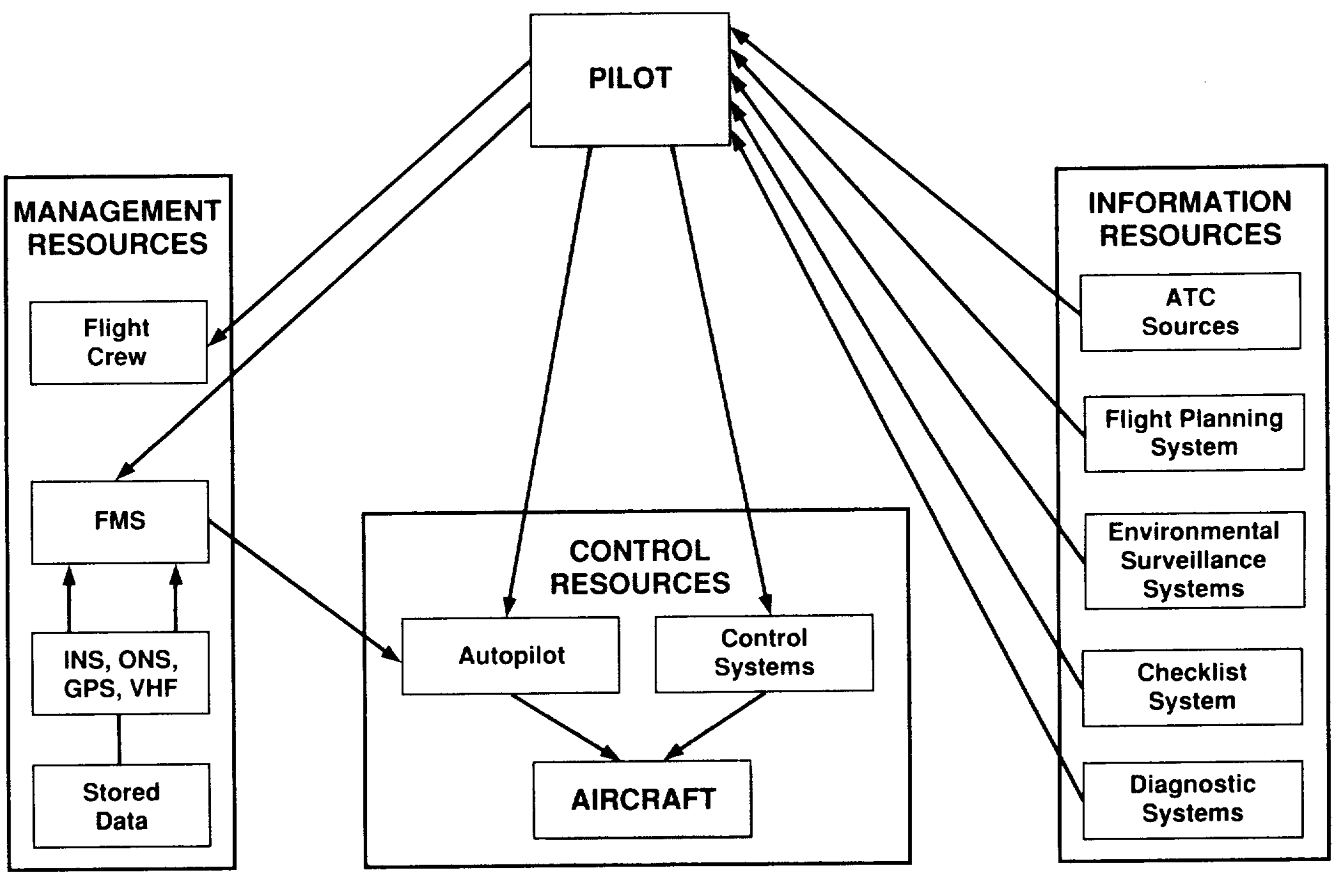


Figure 7. A concept of human-centered automation. (FMS = flight management system, INS = inertial navigation system, ONS = omega navigation system, GPS = global positioning system, VHF = very high frequency)

The first principle of human-centered automation is that the pilot bears the ultimate responsibility for the safety of a flight operation and the human operator must be in command. From this principle, the following corollaries were developed: (1) to command effectively, the human operator must be involved; (2) to be involved, the human operator must be informed; (3) the human operator must be able to monitor the automated systems; (4) the automated systems must also be able to monitor the human operation; and (5) each intelligent agent must have knowledge of the other's intent.

Because the trend has been to automate more systems, modern aircraft automation has become extremely complex (fig. 8). The trend toward greater complexity has the potential to decrease awareness with respect to the state and status of the automation and results in the pilots becoming increasingly peripheral to the aircraft systems. To counteract the effects of peripheralization, human-centered automation systems must be designed to allow for human interaction and involvement with a system which is consistent with human intellectual abilities, skill level, and responsibility; allow for the joint and collaborative interaction and responsibilities of flight crews, controllers, and ground personnel; and enhance unique human capabilities. Implicit in human-centered automation is the development of designs which (1) fully utilize and enhance the unique human capabilities of pattern recognition, information integration, learning, and adaptation; and (2) protect the system from

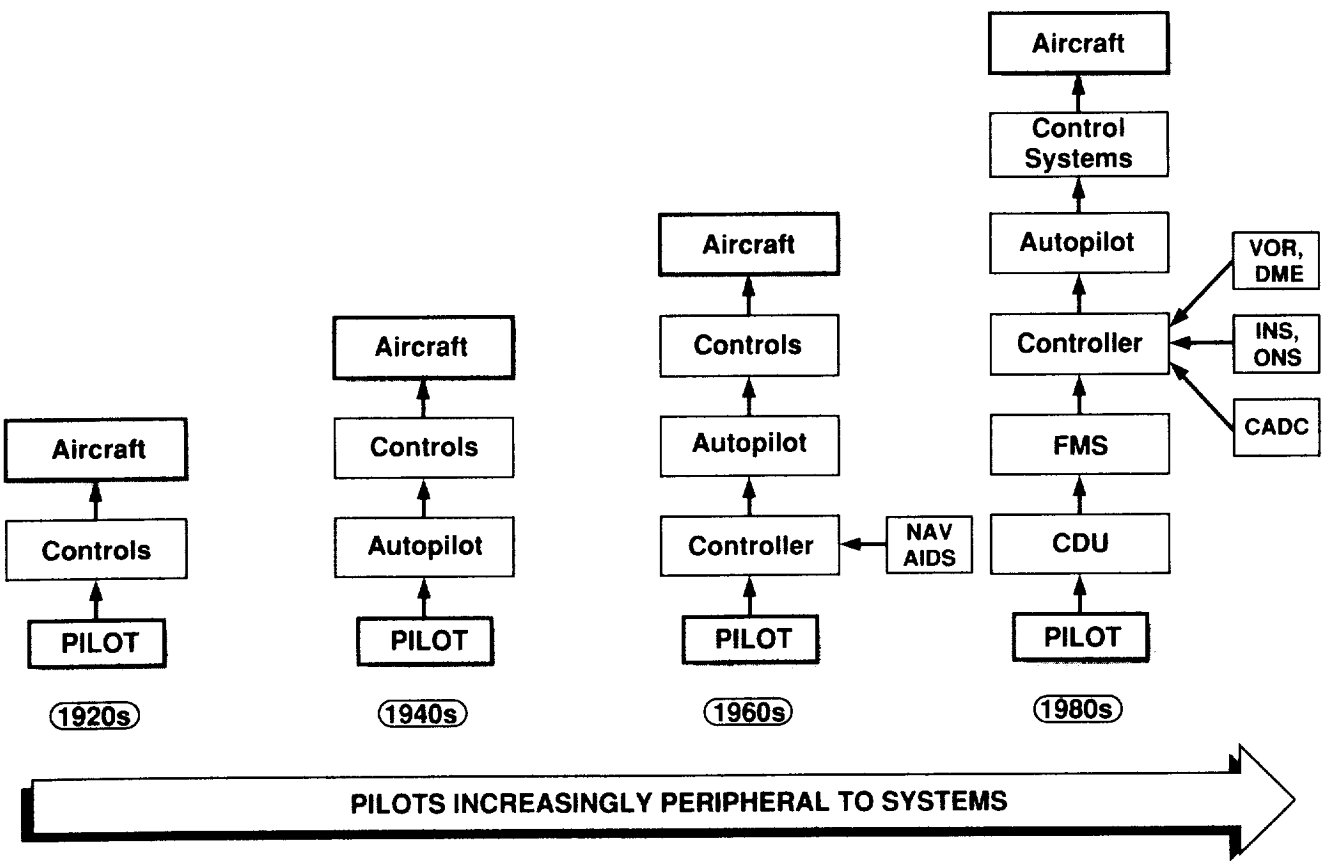


Figure 8. Trend of aircraft automation, 1920-1989. (FMS = flight management system, CDU = control data unit, VOR = very high frequency omnirange, DME = distance maneuvering equipment, INS = inertial navigation system, ONS = omega navigation system, CADC = central air data computer)

human limitations such as systematic human error tendencies, unreliable monitoring skills, decision-making biases, and limitations of working memory and processing speed.

A recent NASA/FAA/Industry workshop was held to discuss the design, training, and procedural aspects of flight-deck automation, as well as the crew's ability to interact and perform effectively with the new technology (ref. 9). Several themes were repeated in the working group report. The participants felt that the ability of the flight crew to understand automation is a key concept. This includes the way it works, the system intent, the control laws, normal versus irregular operations, and implications of system status. They also indicated that automation necessitates closer crew communication as well as closer interaction in all elements of design, training operations, and ATC.

A major field study was performed to investigate the effects of automation on advanced technology transport aircraft (ref. 10). The Boeing 757 which has a "glass cockpit" (electronic cathode ray tube displays) was selected as a representative modern aircraft for this study. The results indicated that, in general, the pilots exhibited a high degree of enthusiasm for the aircraft and their training. However, pilots indicated some reservations in the areas of safety and workload reduction. As far as safety, pilots were concerned there is too much head-in-the-cockpit time and were concerned about degradation of their manual flying skills. With respect to workload, there was strong disagreement, but at least half of the respondents reported concern that automation increased workload during phases of flight characterized by high workload, and automation decreased workload during routine operations.

The results also indicated that the highly automated cockpit may require scrutiny for crew coordination and cockpit resource management, both in the assignment of tasks, and standardization of their performance. Numerous pilots complained that there was a lack of clarity on "who does what," a problem usually not present in well-standardized traditional cockpits. Supervision by the captain or the first officer may be more difficult: at the very least, it may be considerably different than that in traditional three-pilot cockpits. In addition, the pilots were concerned that the ATC system did not take advantage of the advanced navigation and guidance capabilities of the aircraft.

In summary, the field study has shown that the modern advanced technology transport aircraft are being effectively and safely operated by two-pilot crews, but that numerous human factors problems, as well as some problems external to the cockpit, prevent the safest and most effective utilization of the aircraft.

Intelligent error-tolerant systems– Research in intelligent error-tolerant systems includes evaluations of a normal flight-deck checklist, development of touch-panel-operated electronic checklist, and the development of a cockpit procedure monitor.

The improper use, or non-use, of the normal checklist by flight crews is often cited as the probable cause or at least a contributing factor to many aircraft accidents, including the recent Northwest MD-80 accident at Detroit and the Delta 727 accident at Dallas/Fort Worth. A field study was conducted to analyze the normal checklist, its functions, format, design, length, usage, and limitations of the humans who must interact with it (ref. 11).

It was found that the currently used paper checklist has several design weaknesses: the lack of a pointer system, the inability to store skipped items, space limitations, and a limited branching and tracking capability. However, the study results indicate that this is only the outer shell of the checklist problem. The real problems that emerged were the design concepts and social issues surrounding checklist usage. Checklist designs that do not "run parallel" with activities of external agents such as gate agents, cargo loaders, refueling agents, and flight attendants may be a problem. Omission of checklist items sometimes occurs when an item that could not be completed in sequence is deferred by the crew to be accomplished later. In addition, checklists should be tightly coupled with other critical tasks such as takeoff, taxiing, and landing. Every effort should be made to provide buffers to help recover from a checklist error.

Several checklist philosophies currently used in the industry do not accommodate the limitation of the human operators, leading some pilots to misuse them or not use them at all. The checklist is highly susceptible to production pressures ("making schedules"). These pressures encourage substandard performance when the crew is rushing to complete the checklist. Furthermore, under production pressures, checklists are sometimes relegated to second place status to save time, thereby leading some pilots to shortcut part of, or even the entire, procedure. It was also found that the sociotechnical environment in which the pilot operates has a substantial effect on checklist performance. If the individual captain chooses not to use the checklist for any reason, no one can force its use. As a result of this field study, researchers have produced guidelines for checklist design, management, and usage.

Recent field studies and research in the area of cockpit procedures has shown that one of the disadvantages of a paper checklist is the lack of an explicit display of pending and completed procedural steps, as well as the inability to switch reliably between multiple active procedures. The problems can be overcome by use of an electronic checklist (fig. 9). Two levels of electronic checklists have been developed and are currently running on a touch-screen display in the Advanced Concepts Flight Simulator (ACFS) at Ames. They are the pointer checklist and a sensed checklist. The pointer checklist aids the pilot in conducting the normal or emergency procedures by providing feedback for accomplished items as well as intentionally or inadvertently skipped items. The checklist display automatically calls up the appropriate sub-system display. The system is designed to allow the pilot to branch from checklist to checklist without losing track of uncompleted checklists and without getting lost in the electronic procedure manual. A sensed checklist has all the capability of the pointer checklist, but goes one step further. The sensed checklist system has the capability to sense the state of configuration items such as flap position, gear position, wing/engine anti-ice, etc., thereby providing redundant monitoring and feedback to the flight crew on the state of the system and checklist items.

Full-mission Line Oriented Flight Training (LOFT) scenarios have also been developed to test the effectiveness of different electronic checklist designs in reducing procedural errors. A series of experiments is being conducted on the ACFS to evaluate the usefulness to the crew of electronic checklists of varying degrees of sophistication and intelligence for performing normal procedural tasks and coping with on-board malfunctions.

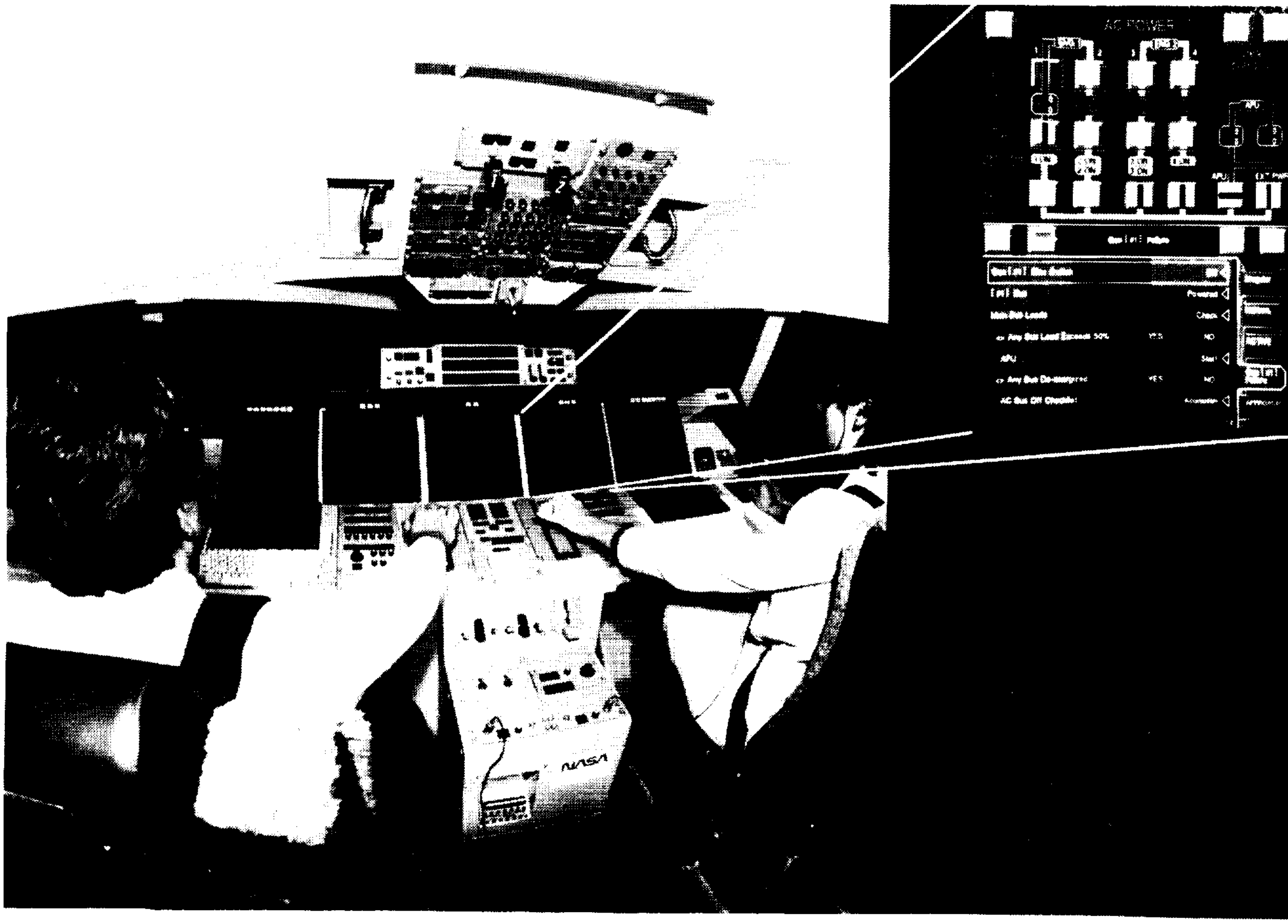


Figure 9. Electronic checklist display in the ACFS.

Electronic checklists can be used as cockpit procedure monitors. A cockpit procedure monitor has been developed that incorporates a model of expected pilot behavior, a key feature of error-tolerant systems. The goal is to develop an "electronic check pilot" that can intelligently monitor pilot activities. NASA is investigating a number of alternative techniques to track pilot activity including (1) a rule-based script of flight phases, (2) operator function models, and (3) Bayesian temporal reasoning.

Under a grant to Georgia Institute of Technology (refs. 12 and 13), an activity tracking system that was originally developed for a satellite communications operator was modified to track the action of the crew of the B-727 simulator. The objective of this system is to track pilot actions, detect errors, determine error consequences, and provide real-time pilot feedback. The system architecture of the script-based model is illustrated in figure 10(a). The system architecture uses aircraft state, pilot actions, script model, aircraft model, and flight plan as input. The script-based model (fig. 10(b)) represents the various levels of flight activities which requires pilot actions. The technology developed for this script-based cockpit procedures monitor has been used to develop the interactive touch panel operated electronic checklist display for the ACFS.

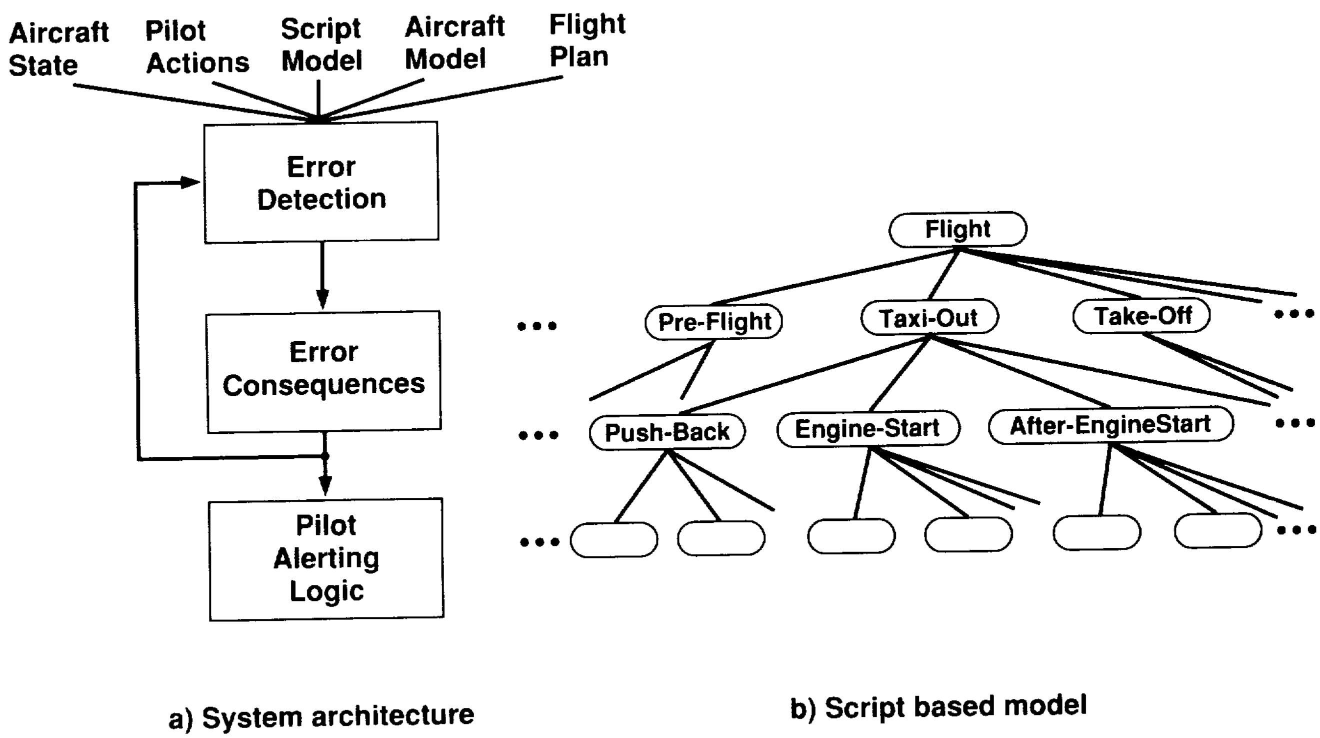


Figure 10. System architecture and script-based model of cockpit procedures monitor.

The electronic checklist has been designed to provide a graphic display of the status of checklists and checklist items (pending, skipped, or completed). The checklist program also can sense the state of many aircraft controls and systems. The checklist can thereby provide a redundant check that procedural steps have in fact been completed.

A cockpit procedure and decision aid is being developed that will monitor pilot actions, system status, and resources for any threat to achieving critical flight functions for current and future flight phases. If threats to critical functions are detected, the system will suggest alternative procedures for completing the flight. The system will also provide the crew with immediate feedback on the effect of actual or planned crew decisions on future flight phases. A prototype flight and configuration plan monitoring system of this type is discussed in reference 14. The cockpit procedure and decision aid will be implemented and evaluated in full-mission simulation in the ACFS.

Displays and Warning Systems

Display and warning systems research consists of flight-deck information management systems, traffic alert collision avoidance system, and 3-D sound displays.

Information management– Today the pilot has an increasing amount of information available from both air traffic and the aircraft systems. Also, there is an increase in the complexity of aircraft systems due to technology improvements and advanced systems available for improved information management. For these reasons, Ames has an ongoing research program to develop design principles for advanced flight-deck information management systems and computer-aided design technology to facilitate the integration of new information. To attain the program goals, a multifaceted approach has begun. This approach includes (1) development of methodology for quantifying aircrew information requirements and information-processing capacity, (2) identification of current operational problems that could be eliminated by improved system design, (3) development and evaluation of prototypical information management systems, (4) development of part-task simulation technology as a low-cost design and evaluation tool, and (5) development of computer-aided design technology based upon information management principles.

A number of efforts were successfully completed in support of program objectives. Analyses of ASRS incidents of information transfer factors related to aircraft and ATC communication were completed (refs. 15 and 16) as was a comprehensive survey of air carrier aircrew weather information requirements. The most common communication problems in air-ground communications were attributable to pilot misunderstandings of ATC clearances or a failure to remember the message caused by preoccupation with other duties. The ASRS incident reports indicated problems with ground-air information transfer due to lack of information 45% of the time and inaccurate information 25% of the time. In addition, an analysis of information from frequency monitoring (party line data) from ASRS incident reports was conducted to examine the impact of information transfer and management. Party line-related incident reports indicated information transfer problems due to aircraft call sign confusion 20% of the time.

Research efforts include examining the effectiveness of conventional versus data link weather transmissions, examining the data link interface issues, developing guidelines for the design and implementation of digital information transfer, and determining the impact of data link upon situational awareness and workload. The results of a full-mission flight simulation comparing voice and display-based communication modes in advanced transport aircraft is discussed in reference 17. The results of this study indicated that a display-based mode of information transfer does not result in significantly increased aircrew workload, but does result in substantially increased time the pilot took to acknowledge the message when compared to conventional voice transmissions. User acceptance of the display-based communication system was generally high, replicating the findings of previous studies.

A flight simulation study was conducted along with pilot surveys to evaluate the effectiveness of ground-air transmission for delivery of ATC clearance amendments and weather information (ref. 18). Results of the pilot opinion survey on workload associated with clearance amendments in the terminal area are shown in figure 11. The pilots indicated that clearance amendments in the terminal area almost always induced high workload. The study revealed that significant improvements in aircrew planning and decision making could be realized with the use of data link-transmitted weather information. Also, part of the survey were pilot rankings of possible relay/presentation modes for ground-generated wind shear alerts (fig. 12). The pilots preferred an electronic flight information system (EFIS) display over the other modes of communication such as ATC voice, graphical display, alphanumeric display and Automatic Terminal Information System (ATIS).

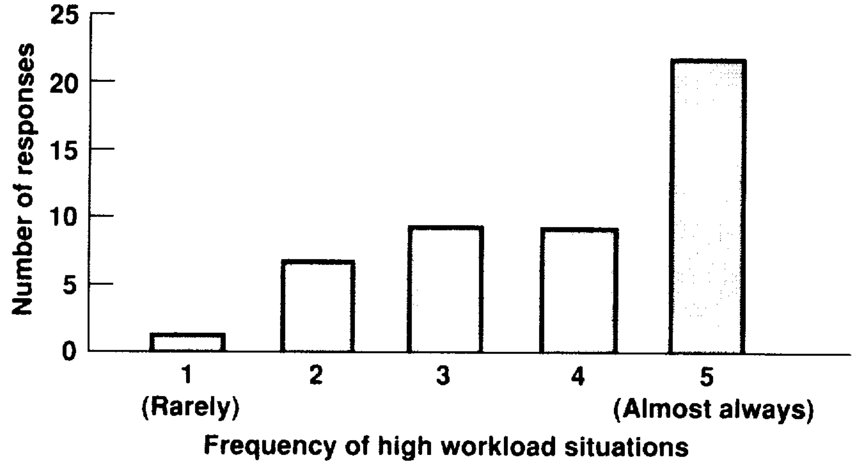


Figure 11. Pilot survey of workload associated with clearance amendments in the terminal area.

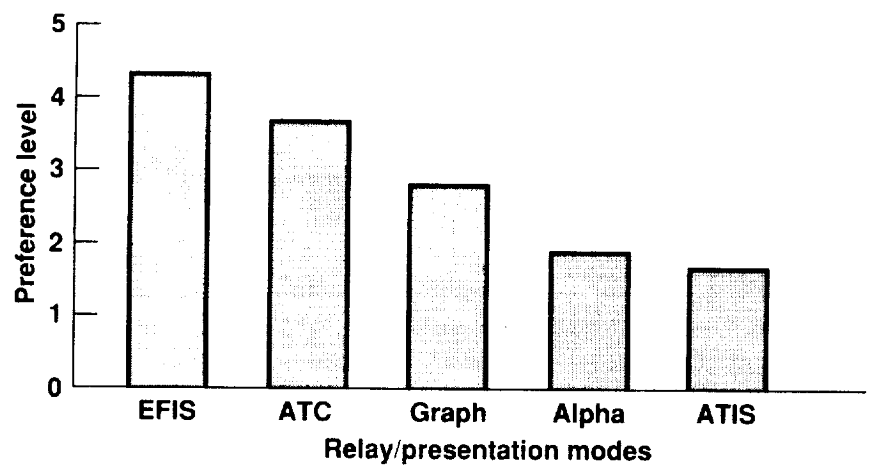


Figure 12. Pilot rankings of relay/presentation modes for windshear alerts.

In support of advanced communications management system development, prototype data entry and retrieval systems were developed to provide support of digital air-ground communication. Study results indicate graphical interfaces using clearance information transmitted by data link provide significant enhancements in flight management systems operations. Part-task simulation results indicated pilot preference for graphical presentation mode over verbal or textual mode (fig. 13). Survey responses indicated that location and intensity of microbursts are clearly the most important information items.

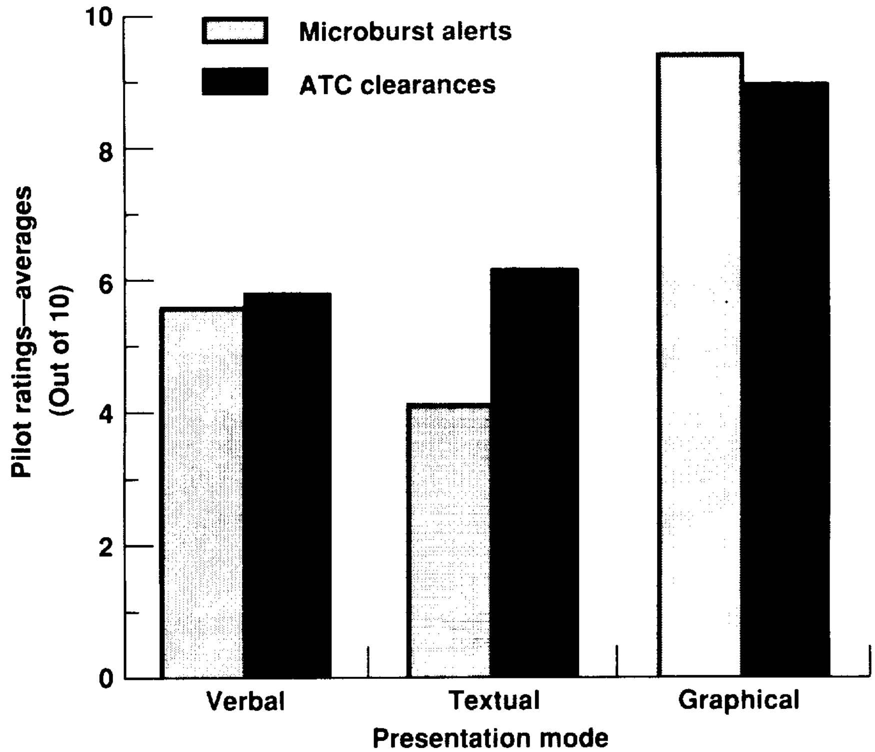
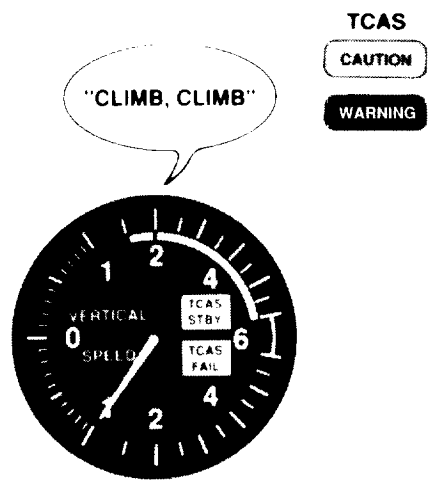


Figure 13. Part-task simulation results of pilot preference by presentation mode.

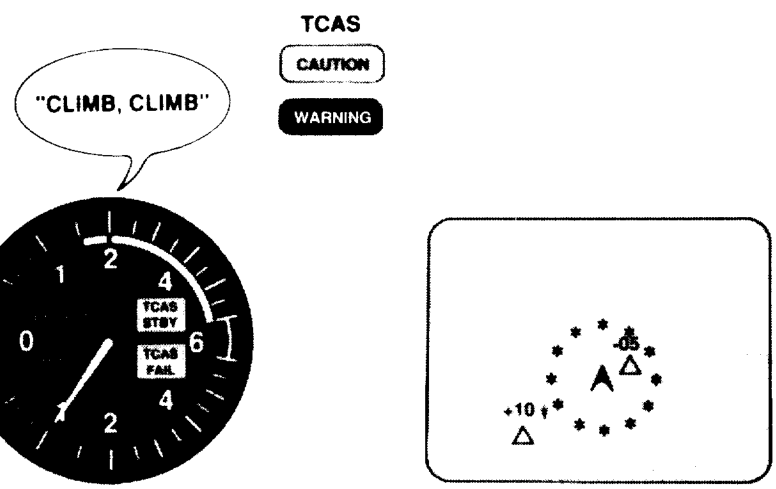
Current and future research will examine pilot/controller communication errors in actual flight operations. Results of these studies should provide a better understanding of the potential impact of data link communications and provide a basis for subsequent flight-deck display design, as well as provide guidelines for phraseology for data link communication. Finally, there is an ongoing effort to develop a part-task simulation that would provide a realistic means of exploring issues relevant to the evaluation of different methods of information transfer and management within the cockpit.

Traffic Alert Collision Avoidance System– The Traffic Alert and Collision Avoidance System (TCAS) is a stand-alone system that can detect the presence of nearby transponder-equipped aircraft. It is designed as a backup to ATC and the pilot's ability to visually sight other aircraft. As the skies get more congested, collision avoidance is increasingly important. TCAS II is mandated by the FAA for all large commercial transport aircraft by 1993. TCAS II provides the pilot with (1) a display of traffic in the immediate vicinity, (2) an advisory of traffic approaching too close within 40 sec, and (3) an advisory of how to avoid traffic approaching within 25 sec. To ensure safe separation of aircraft, TCAS II commands a climb, or a descent, or a reduction in the rate of climb or descent.

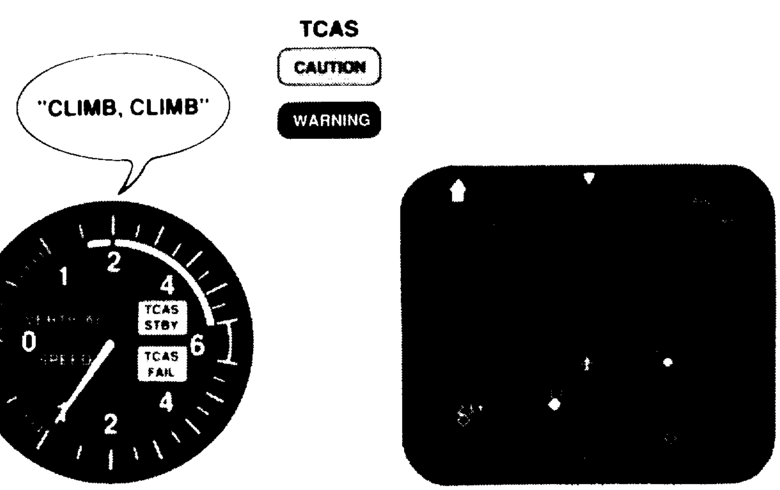
NASA conducted three studies to determine pilots' performance in responding to advisories given by the TCAS II (refs. 19 and 20). The cockpit displays used in the TCAS experiment are shown in figure 14. The "climb, climb" on the figure indicates a voice command to climb when it is necessary to maneuver to avoid a collision. In the first study, normal TCAS II operations were evaluated in simulated air carrier line operations. Study results indicated that pilots were able to use TCAS II correctly within the response times allocated by the system and that TCAS II is effective in ameliorating the severity of the simulated traffic conflicts. The 12 crews flying with TCAS had no



a) MINIMAL TCAS DISPLAY



b) TCAS WITH TRAFFIC DISPLAY ONLY DURING CONFLICTS



c) TCAS WITH CONTINUOUS TRAFFIC DISPLAY

Figure 14. Cockpit displays used in the TCAS experiment.

conflicts involving separation of less than 1000 ft horizontally and 200 ft vertically; 3 of 4 crews flying without TCAS did experience such conflicts.

The second study tested pilots' responses to proposed changes in the avoidance advisories. Results of this study provided performance parameters, pilot reaction times, and aircraft accelerations, for the TCAS logic. The recorded reaction times suggest that pilots are able to make a second or revised response when required within the 2 sec targeted by the TCAS logic. The success rate in reaching vertical velocity by advisory duration is illustrated in figure 15. The figure shows the success rate for "increase advisories" and "reversal advisories." An increase advisory requires a pilot to increase the rate of climb or descent from 1500 ft/min to 2700 ft/min. A reversal advisory requires the pilot to change from climb to descent or descent to climb. The pilots were at least 80% successful in reaching commanded vertical speed when the duration of the resolution advisory was greater than 10 sec.

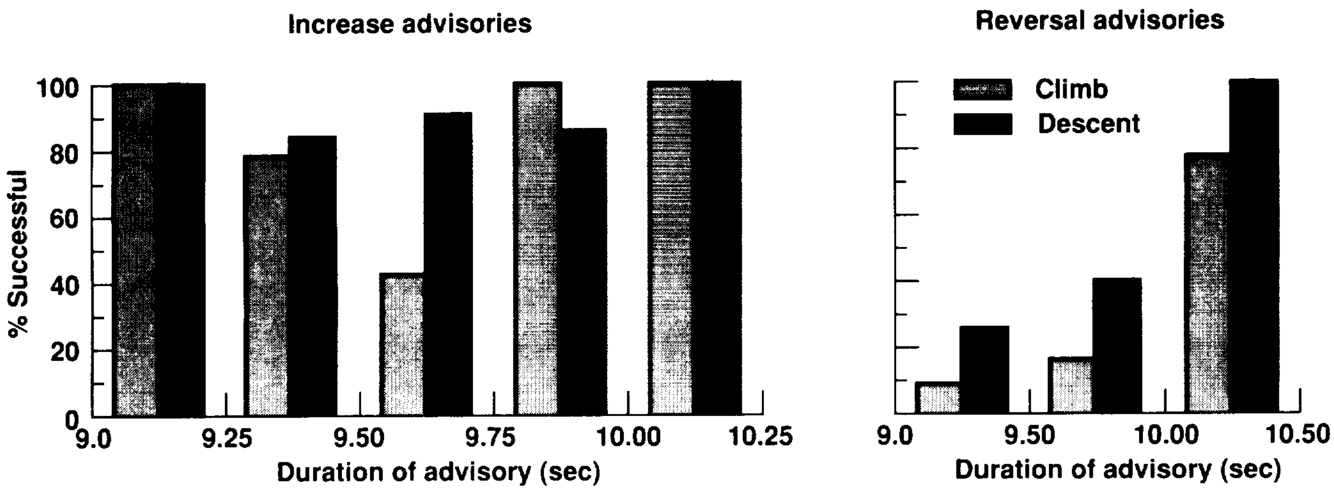


Figure 15. Success rate in reaching vertical velocity by advisory duration.

The third study evaluated three alternate resolution advisory displays as illustrated in figure 16. Displays included a target red-only region on the vertical speed, a red and green region on the vertical speed, and green-only on the vertical speed. The green area designates a safe range of vertical speeds to be achieved and the red area depicts a range of vertical speeds to be avoided. The results indicated that the red and green color format of a TCAS II resolution advisory display was more effective than the red-only display. NASA research improved the maneuver displays, which resulted in both speed and accuracy increases for the pilots' responses. The industry standard was changed to reflect NASA's contribution of adding a target (green) region on the vertical speed display. Through industry and FAA interaction, NASA (by means of a workshop) established airline/manufacturer consensus for TCAS in the glass cockpits. NASA personnel continue to provide human factors expertise to the FAA and airlines on an as-needed basis, e.g., serving as panelists for the TCAS Installation and Federal Deadlines Workshop conducted by the Office of Technology Assessment of the U.S. Congress.

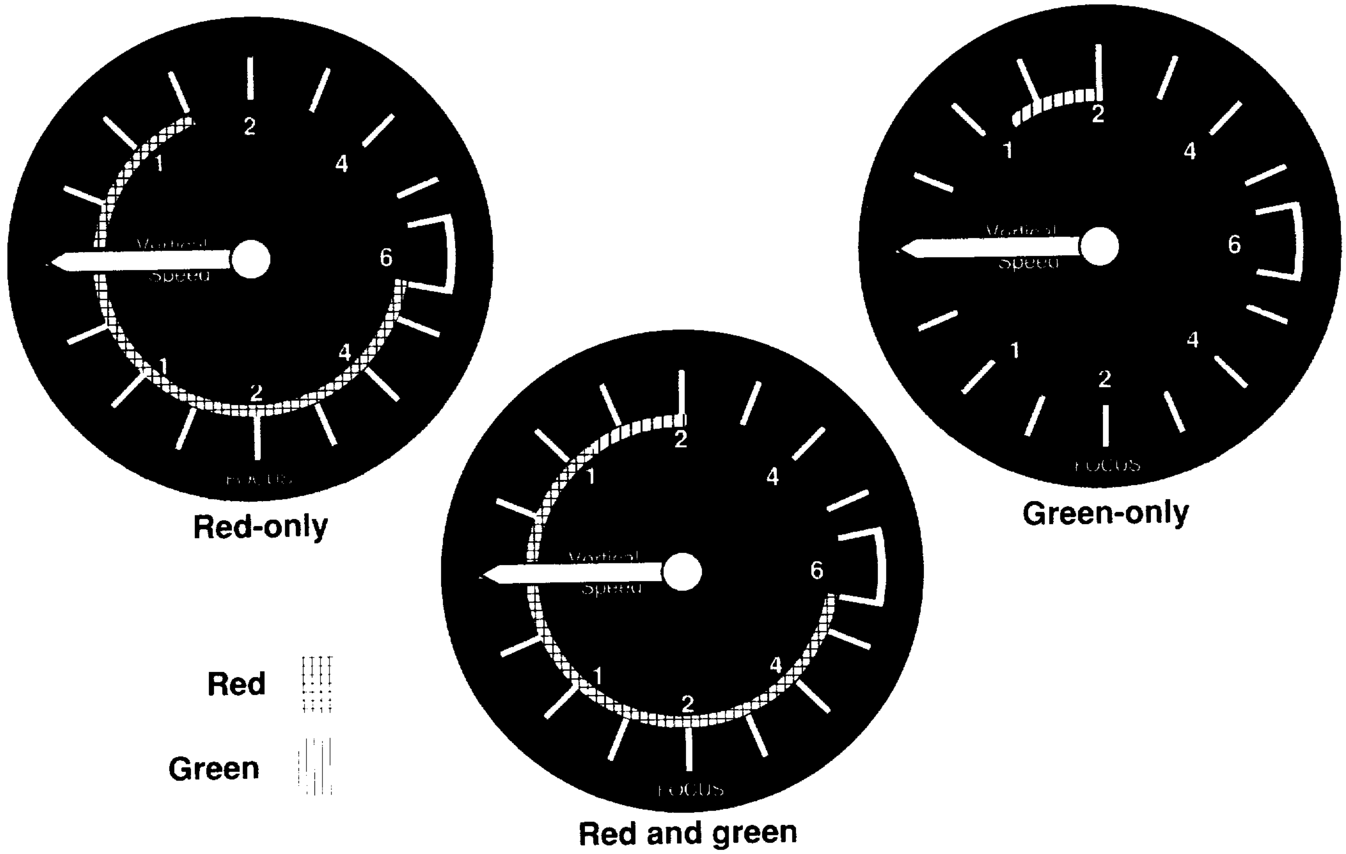


Figure 16. Three versions of the resolution advisory display.

3-D auditory displays– As with most research in information displays, current aviation displays have emphasized visual information. However, a significant body of research has clearly demonstrated the importance of the auditory system as an alternative or supplementary information channel. Indeed, in today's flight environment, successful operations are critically dependent on accurate communication between air/ground personnel and among crew members. ATC controllers and crew members are being required to work under conditions which increasingly tax their ability to manage, interpret, and act upon information in a timely and accurate manner. The 3-D auditory displays may provide improved situational awareness and enhanced intelligibility for a wide range of applications for crew members and ATC controllers. These applications include aircraft warning systems, traffic alerts, acoustic glide path and altitude deviation displays, aircrew and air-ground communications, and ATC communications (fig. 17). NASA has initiated research in a number of these applications.

Research is under way to provide a prototype real-time acoustic display which will allow an ATC controller to immediately, accurately, and inexpensively monitor three-dimensional information through the use of sound. Two types of displays are being considered because of their conceptual simplicity and the likelihood that they will provide significant benefits to current ATC systems. One example is an ATC display in which the controller hears communications from incoming traffic in positions which correspond to their actual location in the terminal area. In such a display, it may be evident to the listener when aircraft are on a potential collision course if they could be heard in their true spatial locations and their routes could be tracked over time. A second example involves alerting systems for ATC. A non-speech sound or auditory icon, such as a complex

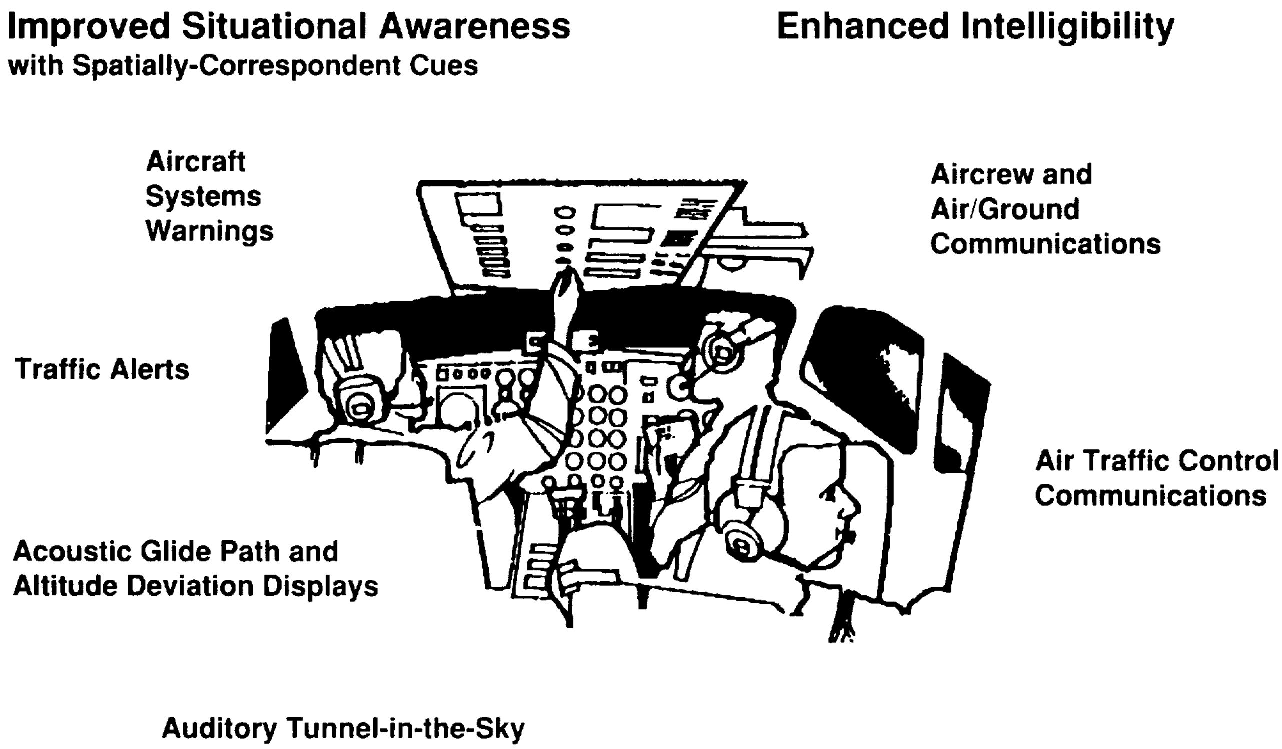


Figure 17. Application of three-dimensional auditory displays.

signal with a unique temporal rhythm, could also be used as a warning of urgent situations like potential runway incursions. Again, the signal could be spatialized to convey true directional information and urgency could be emphasized by placing the warning close to the listener's head, e.g., within the boundaries of his or her "personal space."

The goal in the research is to develop a spatial auditory display, which is both multipurpose and portable, by synthetically generating localized, acoustic cues in real time for delivery through headphones. This involves developing the signal-processing technology required to implement the synthesis technique and to validate the technique with psychophysical studies (refs. 21-25). The synthesis technique, illustrated in figure 18, involves the digital generation of stimuli using head-related transfer functions (HRTF) measured in the ear canals of individual subjects. In the real-time system, up to four moving or static sources can be simulated in a head-stable environment by digital filtering of arbitrary signals with the appropriate HRTFs. A reasonable approach is to use the HRTFs from a subject whose measurements have been "behaviorally calibrated" and are thus correlated with known perceptual ability in both free-field and headphone conditions. In a recently completed study, 16 inexperienced listeners judged the apparent spatial location of sources presented over loudspeakers in the free-field and over headphones. The headphone stimuli were generated digitally using HRTFs measured in the ear canals of a representative subject. For 12 of the subjects, localization performance was quite good, with judgments for the non-individualized stimuli being nearly identical to those in the free-field.

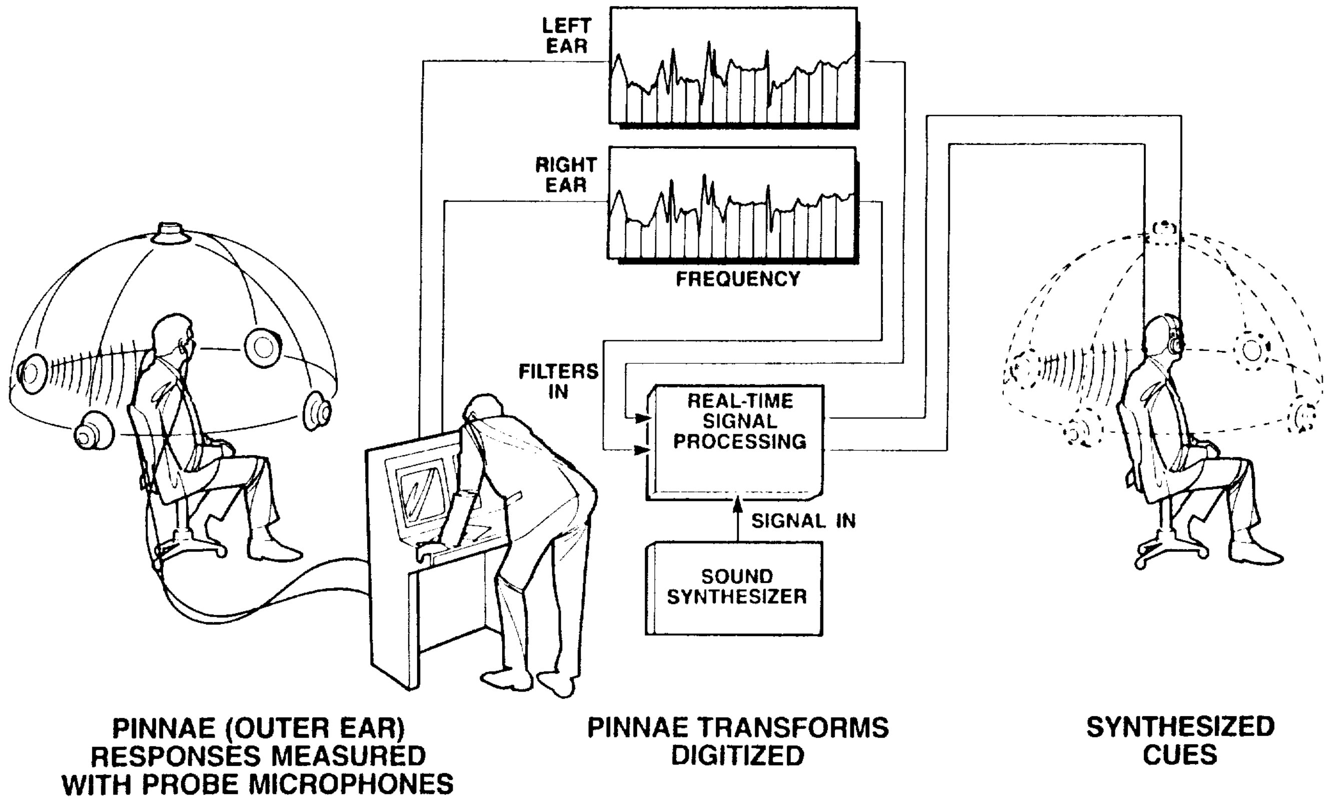


Figure 18. Synthesis technique of three-dimensional auditory display.

An example of research on advanced acoustic displays in the cockpit environment includes improving target acquisition time from traffic advisories by spatializing the position of an auditory warning to correspond to the location of the target out of the window. Studies are under way on the ACFS to determine the extent of the improvement with spatial auditory display for traffic advisories. Other planned research involves auditory displays which allow pilots to monitor their locations during landing, particularly during Instrument Landing System (ILS) approaches when visual cues are degraded. Examples include an acoustic glide-path display representing deviations from the approach slope, an acoustic display of deviations from assigned altitude, and an auditory tunnel-in-the-sky corresponding to the computer-generated visual displays. These displays will use spatial non-speech cues which would supplement the visual displays and verbal communications in the current ILS approach system while avoiding additional communication clutter.

Crew Fatigue and Jet Lag

Few aircraft accident reports prior to 1980 had cited fatigue as a causative or contributing factor, though some pilots doing night cargo and long-haul flying felt it to be extremely important. ASRS has received confidential reports from long-haul flight crews describing how fatigue and sleep loss have contributed to major operational errors such as altitude deviations, track deviations, landing without clearance, landing on the incorrect runway, and improper fuel calculations. Also the safety record for long-haul operations has been poorer than for shorter-range flying. These factors led to the initiation of the NASA program on crew fatigue and jet lag in 1980 by congressional request. The program objectives are to determine the extent and impact of fatigue and circadian desynchronization on flight crew performance and to develop countermeasures to minimize the effects.

Studies indicate that long-haul flight crews experience substantial sleep loss due to night flying conflicting with sleep, disruption of layover sleep (jet lag), and large individual differences in adaptability (refs. 26, 27 and 28). One very clear result emerged regarding the direction of flight on sleep: sleep quality decreased more after eastward flights than after westward flights. This directional difference is highly consistent with the fact that the body's natural circadian period is longer than 24 hr. While westward flights lengthen the day, eastward flights shorten it and hence should result in greater circadian-induced sleep disruption. Another finding common to eastward flying airlines was that the crew members sleep for a considerably shorter duration on the second night than they do on the first night in the new time zone (fig. 19).

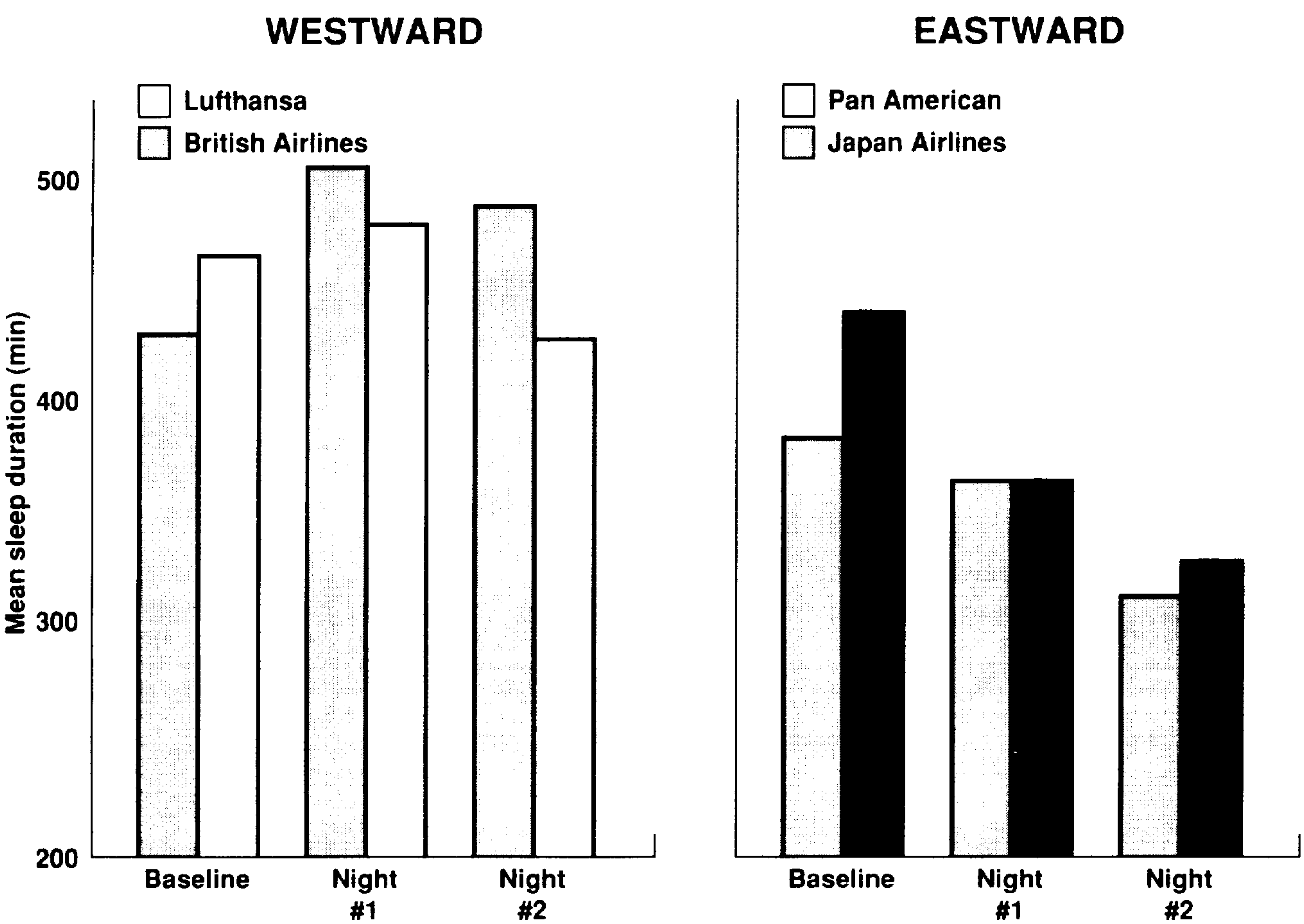


Figure 19. Comparison of nocturnal sleep duration for crew members.

The individual factor of age was found to strongly affect sleep and sleepiness. Age was significantly correlated with an increased number of awakenings and lower sleep efficiency. The sleepiness data led to another finding that has important operational implications. Contrary to popular belief, the results indicated that crew members were not able to predict when they were sleepy. The objective physiological sleepiness scores and the subjects' own subjective ratings of sleepiness just beforehand did not agree (fig. 20). The subjective ratings (Stanford Sleepiness Scale and Analogue Alertness rating) indicate high alertness throughout the day while the EEG-based Multiple Sleep Latency Test (MSLT) score dropped dramatically.

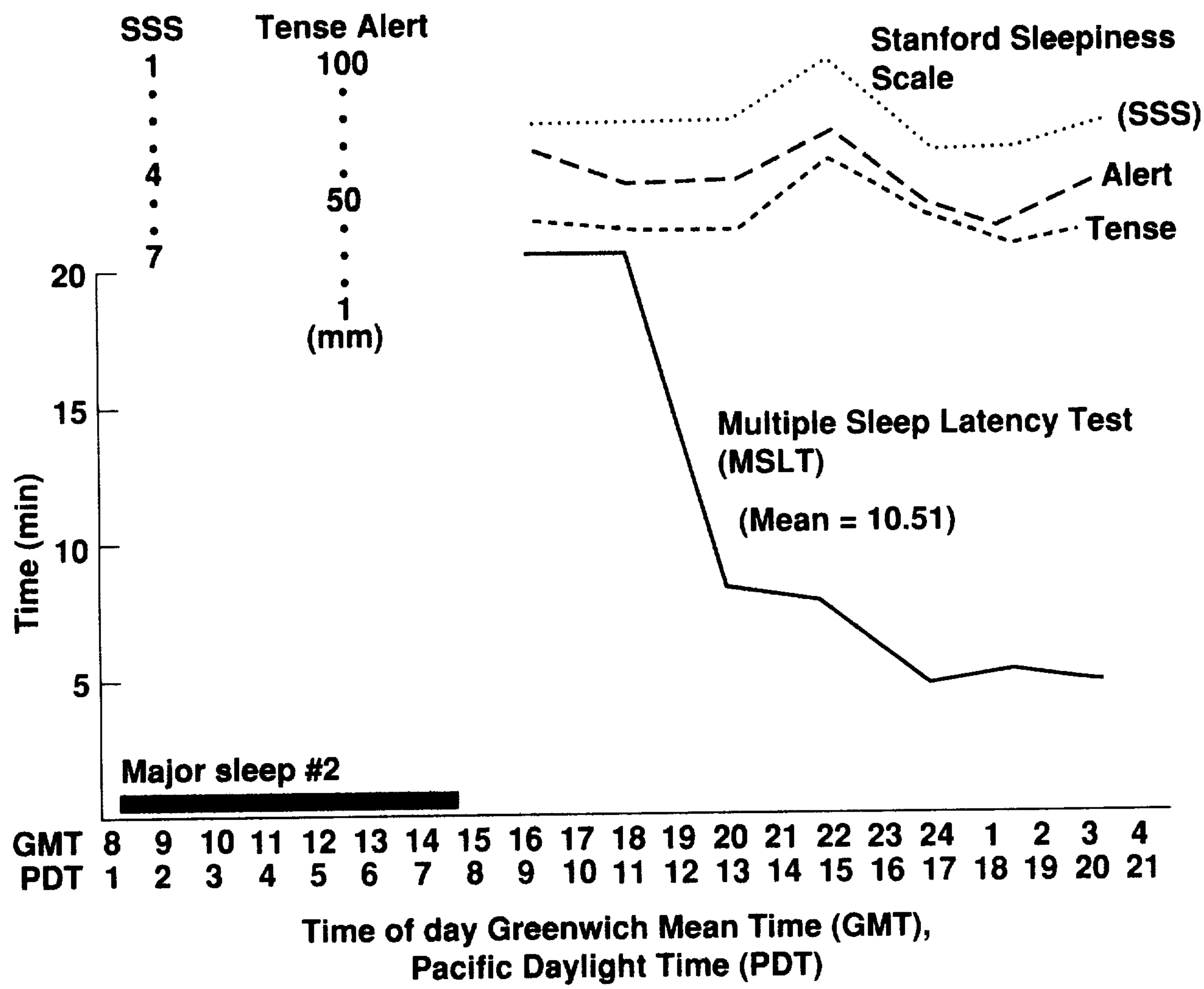


Figure 20. Comparison of subjective and objective estimates of sleepiness/alertness.

The findings of these studies make it not surprising to learn that crew members sometimes fall asleep in their seats during cruise. The incidence of this behavior on selected commercial flights is shown in figure 21, as the percentage of opportunities for cockpit napping (i.e., number in parentheses = number of subjects × number of flights). Only naps lasting at least 20 min were included. The findings are symptomatic of the degree of sleepiness that can develop on the flight deck and suggests that the vigilance of individual pilots may be impaired at least during cruise. However, it should be realized that napping may have a beneficial effect on the overall vigilance level of the crew.

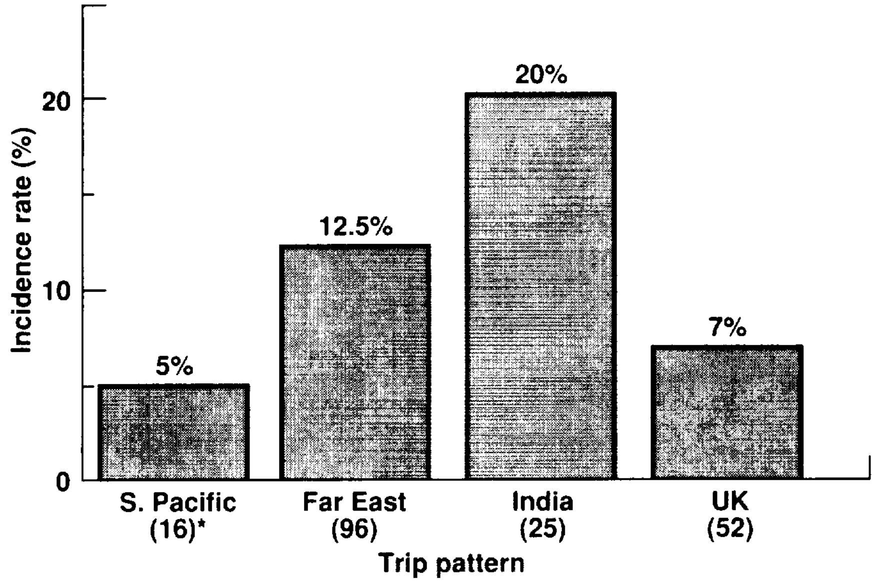


Figure 21. Incidents of cockpit napping during cruise on long-haul trips.

A recent study was performed to evaluate the effectiveness of a preplanned 40-min cockpit rest period to improve crew alertness and performance in long-haul operations (ref. 29). The study involved three-person B747 crews during regular scheduled transpacific flights. Crew members in the Rest Group slept during 93% of possible rest opportunities. The effects of this nap on subsequent performance and physiological alertness were examined (fig. 22). Overall, on the sustained attention/ reaction time test, the Rest Group showed significantly better and more consistent performance compared to the No-Rest Group, especially at night and during later flights in the trip. The Rest Group median reaction time was less than the No-Rest Group which is an indication of increased alertness over the No-Rest Group. An intensive microanalysis during the last 90 min of flight, from an hour prior to top of descent through landing, examined the occurrence of brain waves (EEG) and eye movements (EOG) that indicate reduced physiological alertness (fig. 23). The No-Rest Group had a significantly higher number of events (135) than the Rest Group (37). During the critical landing phase, from top of descent through landing, the No-Rest Group had 24 events, while the Rest Group had none.

In summary, a preplanned rest period during low workload phases of flight (i.e., cruise) appears to act as a "safety valve" for the sleep loss and fatigue that result from the multiple time zone changes and disturbed sleep associated with long-haul operations.

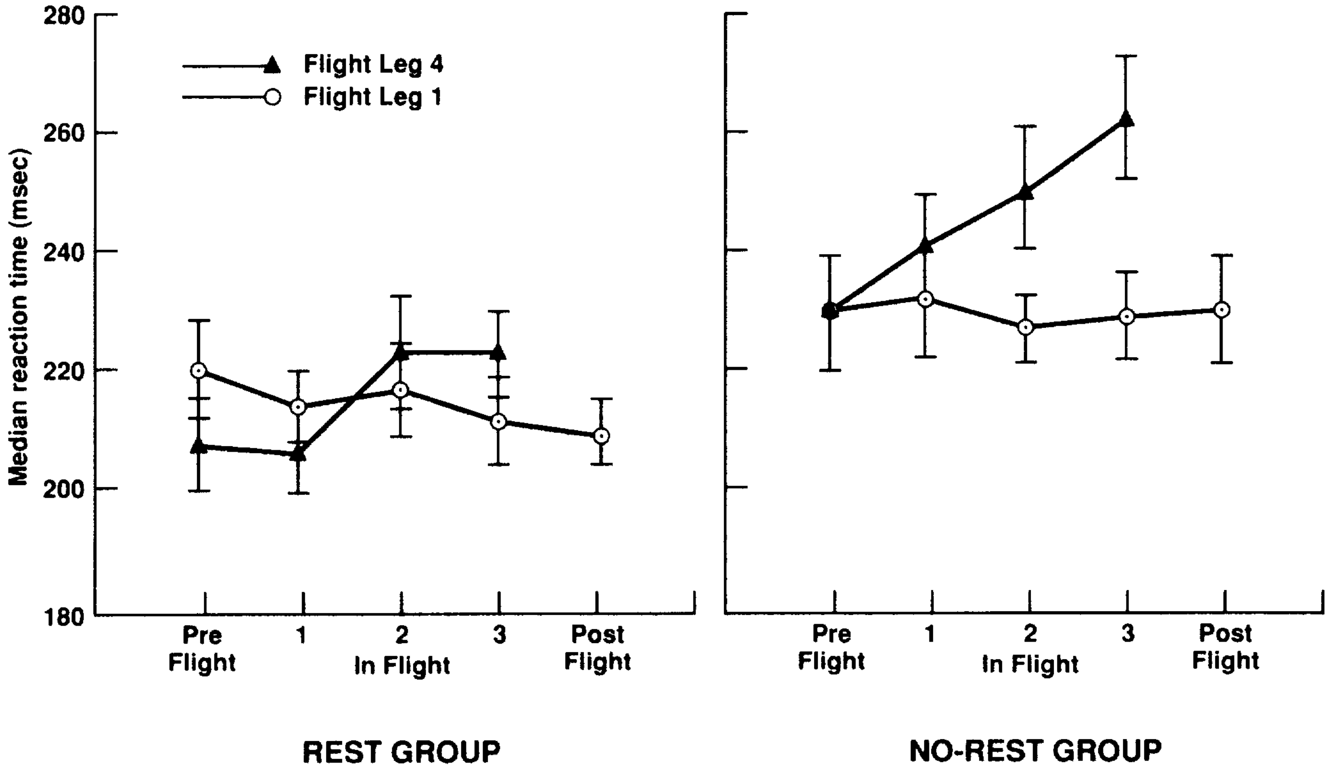


Figure 22. Median reaction times for rest and no-rest groups.

Crew Coordination Research

In the 1970s, evidence was found in accident and incident reports that accidents and incidents were related to problems of crew coordination rather than technical skills. At this time, two airlines pioneered the implementation of a Crew Resource Management (CRM) program and introduced the Line Oriented Flight Training (LOFT) concept. The CRM concept is defined as the utilization of all available resources—information, equipment, and people—to achieve safe and efficient flight operations. The LOFT concept is defined as training that is designed to be as similar as possible to the normal line operations. NASA held a number of workshops to develop a systematic approach to cockpit resource management training. An example of a NASA Ames/Industry conference on Resource Management on the Flight Deck (ref. 30), attended by training representatives from airlines, was held in 1986. During the 1980s, CRM and LOFT programs proliferated throughout the industry but showed great variability in implementation. At this time, NASA began a detailed study of factors influencing crew coordination. The conceptual framework (ref. 31) for this research is shown in figure 24. Crew factor input variables (i.e., personality, leadership, crew composition, etc.) and group process variables (i.e., communication patterns, problem-solving strategies) were studied to investigate the effect on outcome variables (i.e., productivity, safety, group cohesion, satisfaction).

NASA began a series of high-fidelity, full-mission simulation experiments to address crew factors issues. Early research indicated that crew familiarity, leadership, crew composition, and team structure significantly affected overall crew performance often by way of communication processes

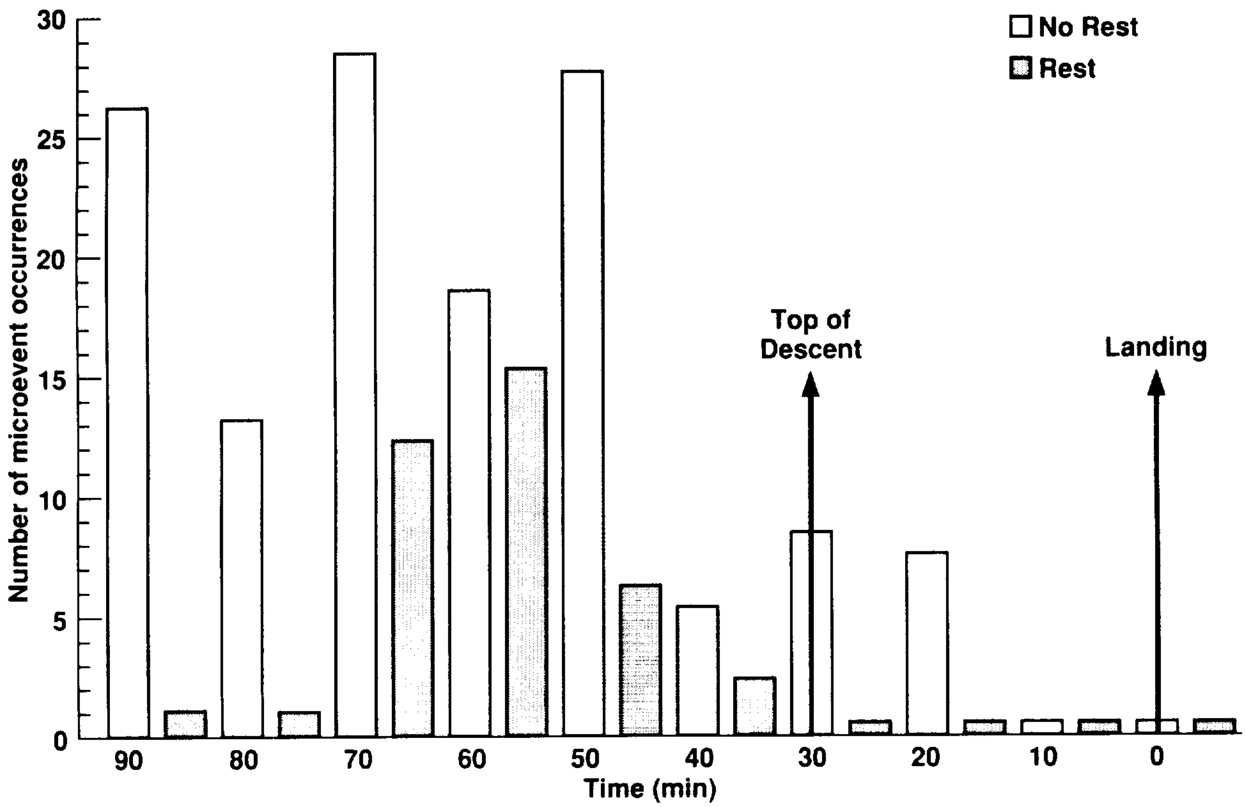


Figure 23. Number of microevent occurrences for crew members with no rest and preplanned cockpit rest.

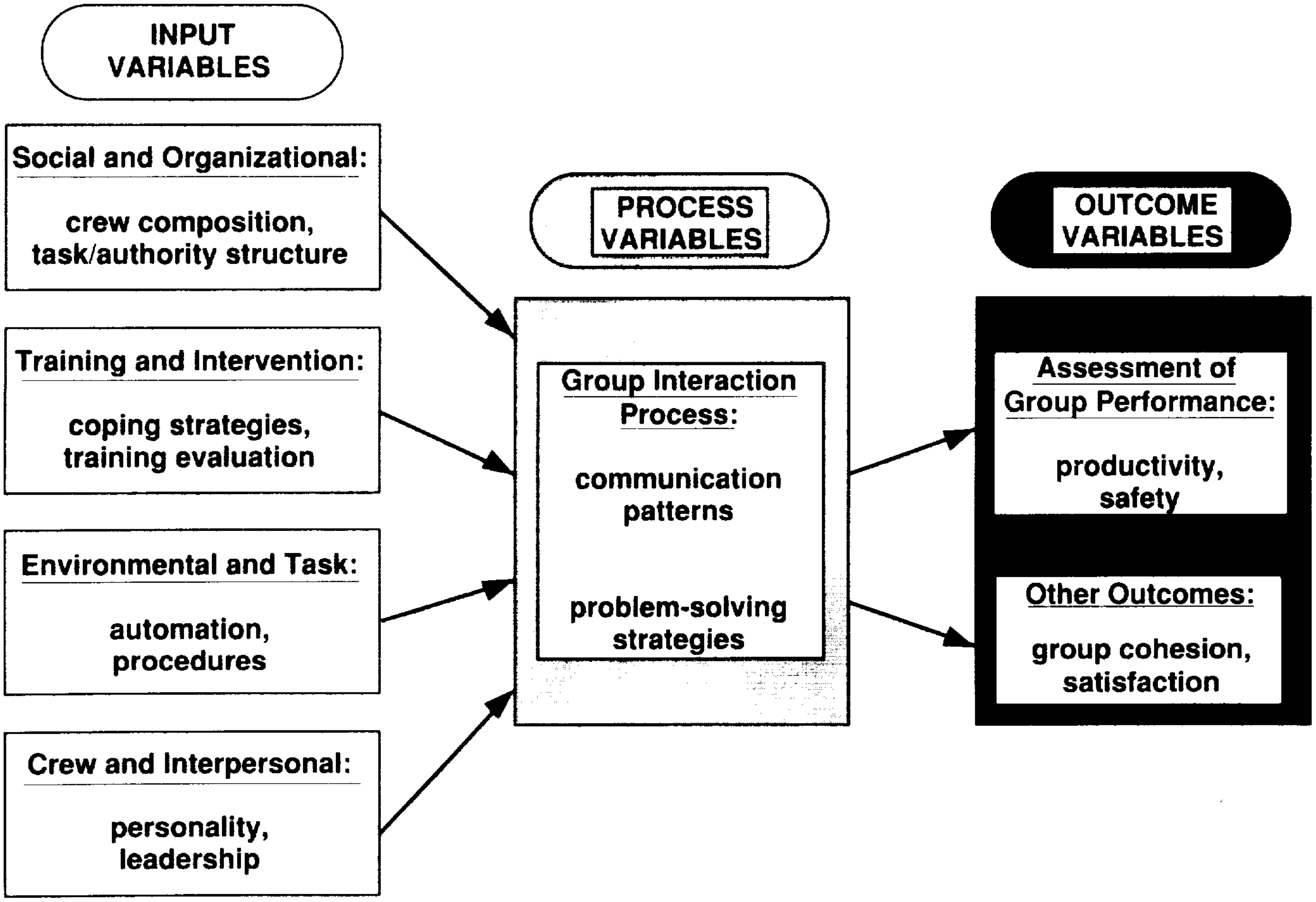


Figure 24. Conceptual framework for crew coordination research.

(refs. 32 and 33). Current crew coordination research is being directed in three major areas: (1) CRM research, (2) automation and crew coordination, and (3) crew communication process.

The objective of the CRM research at Ames is (1) to identify and understand the factors and processes influencing crew effectiveness, (2) to validate countermeasures to crew coordination problems, and (3) to provide assessment tools for evaluating the effectiveness of the CRM programs in accomplishing their desired results. CRM data collection events and training events are illustrated in figure 25. Data are collected using standardized research instruments developed as part of the project, including a survey of crew member attitudes regarding flight deck management (cockpit management attitudes questionnaire), CRM seminar evaluation form, the Line LOFT Worksheet (a form for expert ratings of crew performance in simulator and line settings), and the LOFT Survey (crew member attitudes regarding LOFT). The research design involves repeated use of these instruments to isolate changes as a result of formal CRM training.

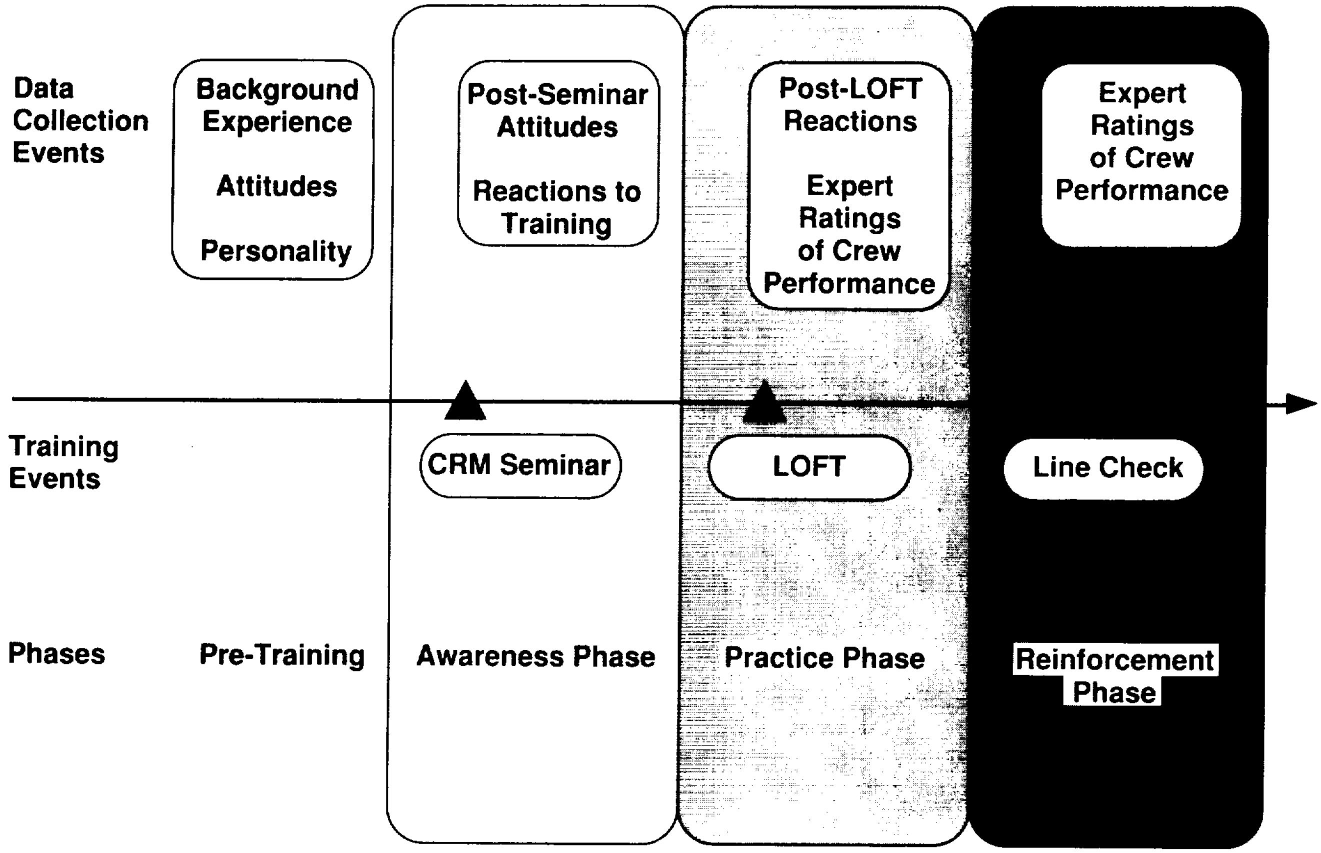


Figure 25. Data and training events for crew resource management research.

A recent paper discussing the effectiveness of CRM training is given in reference 34. Initial findings on CRM impact on crew performance is shown in figure 26. The percentage of CRM-trained crews rated as above average increased while the percent rated as below average decreased. The data indicate that CRM training produces highly significant, positive change in personal attitudes and appropriate flight-deck behavior. Also, CRM-trained crews were found to be more effective in the utilization of all resources in the cockpit (hardware, software, and crew). These findings are the first positive indication that crew coordination training is accomplishing its intended goals. However, this must be qualified by three highly unexpected findings: (1) a "boomerang" effect (ref. 35) in which a subgroup of individuals given CRM training showed less favorable attitudes following training, (2) large differences are found in attitudes and performance within organizations among crew members flying different aircraft and, also, between organizations, and (3) variations in participant reactions to various CRM training seminars presented by the same instructor which appear to relate to both the personalities of participants and to processes that develop within the groups (ref. 36). These kinds of CRM findings have been very useful to the training community.

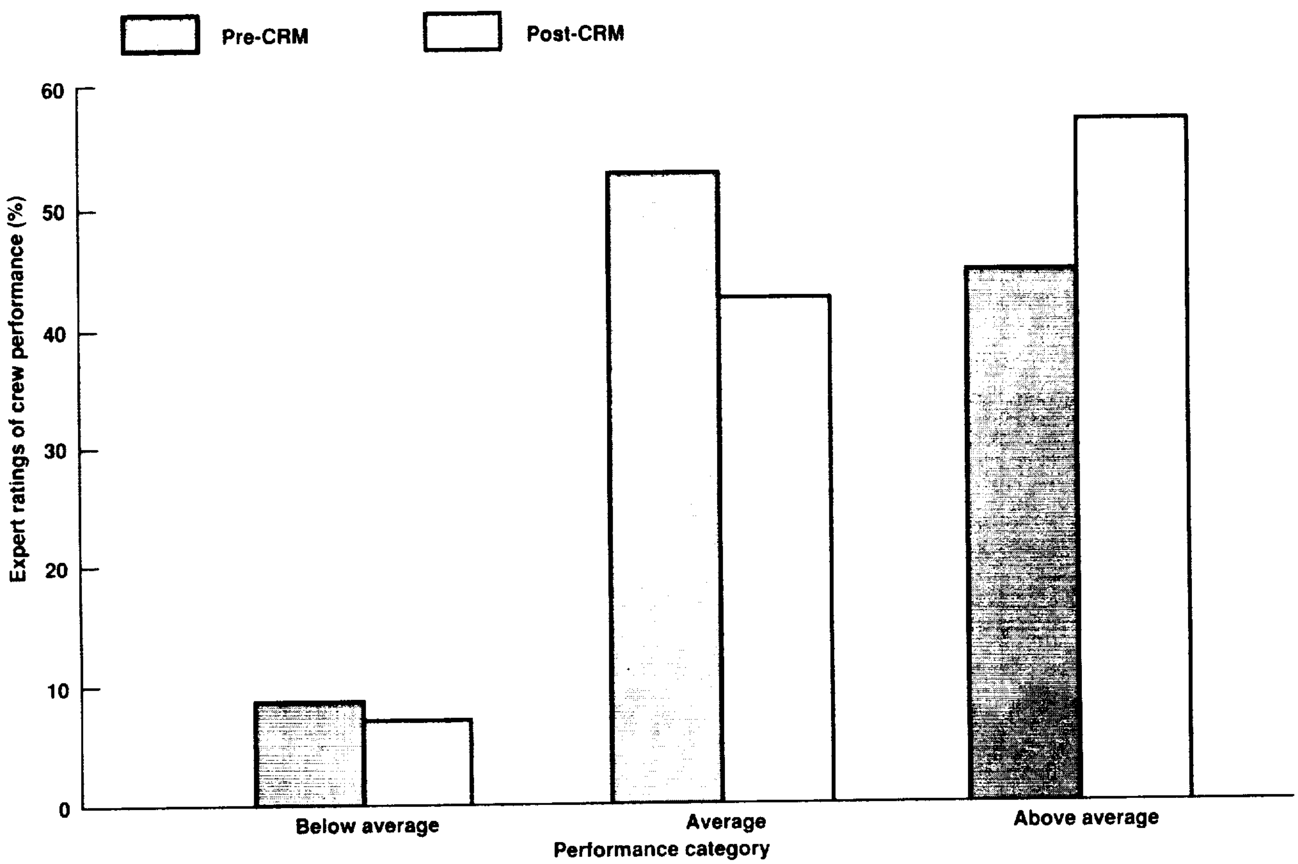


Figure 26. CRM impact on crew performance.

Recently, industry concerns have focused on issues related to automation. One question being asked is whether different levels of automation affect crew coordination and communication in different ways. A related question is whether training methods and materials need to be modified to maintain effective crew performance and to assure a smooth transition from more traditional flight-deck equipment.

To address some of these questions, NASA recently completed a full-mission simulation to compare crew coordination and information transfer within crews in a traditional cockpit setting (represented by a DC-9) and in an automated (MD-80 series) cockpit. This work was based on the results of the extensive field study reported in reference 10. The objective was to identify critical performance issues of automated cockpits (both advantages to be gained and possible limitations). Reflecting an integrated approach of controlled experimentation in real work settings, direct comparison of two contrasting cockpit environments (standard versus automated) was possible through experimentation in simulation facilities provided by an airline's training center. Twelve crews of active line pilots from each aircraft type were selected, flew the same route, and experienced the same problems and environmental conditions while an in-flight observer evaluated crew performance. Results are being analyzed to look for crew behavior patterns which correspond to differences in (1) overall crew performance, (2) aircraft type/automation level, (3) types of errors produced, (4) captain versus first officer and pilot-flying and pilot-not-flying roles, (5) normal versus abnormal flight phases, and (6) the crew's use of a particular automation option.

Crew coordination researchers at Ames have developed a variety of research methods associated with both field and experimental (typically high-fidelity, full-mission simulation) designs. Both settings provide opportunities to explore critical new issues and to assess whether specific variables/ conditions affect crew performance in a systematic way. In both kinds of studies, a close analysis of crew communication processes is critical to understanding crew performance. They are the mechanisms by which crew members coordinate their activities, transmit and receive information, and solve problems. Innovative techniques for documenting group process in the field (during actual operations) have been developed and successfully applied in studying leadership styles and team building in air crews (refs. 37 and 38). In addition, the crew factors program has produced new techniques for analyzing sequential and interactive speech patterns that are now being applied in high-fidelity simulated environments (ref. 39). The communication patterns linked to performance differences have been identified including distinctive differences in the use of question-answer and command-acknowledgment sequences as well as differences in the relative rates of overall communication and non-response. We are currently expanding one communication-based program for analyzing group processes from a number of different perspectives representing different levels of analysis.

The following projects are based upon observations from systematic field research and from transcribed and coded videotape data from several full-mission flight simulations: (1) leadership and team building, (2) communication variations and aircrew performance, (3) shared mental models and crew decision making, and (4) resource management styles. Results from each of these areas have been integrated into a single summary chart in figure 27, and in many cases represent converging evidence from different research approaches. The figure gives a summary of communication processes that correspond to more effective and less effective crew performance. The communication process research has been very fruitful in terms of its specific recommendations for training and there are plans for extending this methodology to the air traffic controller domain as well as other teams with which air crews interact.

More Effective Crew Performance	Less Effective Crew Performance
More predictable behavior • Leader behaves in a standard, consistent way: a. Standard pre-briefing b. Explicit discussion of norms and interface tasks across teams • Conventionalized speech patterns: a. Homogeneity of patterns across all low-error crews b. More command-acknowledgement sequences completed More anticipatory/planful behavior • More planning during all flight phases • Greater attention to environmental cues during normal flight phase and ongoing re-verification of information status	Less predictable behavior • No single characteristic leadership style: a. No standard briefing b. Nonstandard or no discussion of norms and interface tasks (within or across teams) • No single characteristic speech pattern across high-error crews: a. More questions and fewer commands b. Fewer acknowledgements More reactive to emergencies • More planning and information gathering during abnormal flight phases than during normal, low-workload flight phases. • Lack of re-verification of information pertinent to situation assessment

Figure 27. Summary of communication results.

ATC TERMINAL AREA AUTOMATION RESEARCH

Objective and Approach

ATC automation research is aimed at the development and testing of controller-compatible air traffic control automation concepts and methods, their evaluation in both simulated and real environments, and their integration into the ATC system. The main purpose of the research is to provide a variety of computer-aided tools that can assist controllers in achieving safe, orderly, and expeditious movement of traffic within the terminal area. The criteria for designing these tools revolve around the principle of human-centered automation. In the context of ATC this principle requires developing tools that complement the skills of controllers without restricting their freedom to manage traffic manually. The aids assist the controller in solving specific ATC problems and the controller decides when and how to use these tools. In addition, these automation tools must be compatible with future technologies, i.e., four-dimensional (4-D) flight management systems, Microwave Landing System (MLS), and data link.

To ensure desirable characteristics in the human-system interface and gain controller acceptance of automation tools, specific design guidelines were established. They included designing the automation aids to: enrich the controller's work environment, increase situational awareness, and complement the controller's skills. In addition, the designer should involve controllers in the selection and design of the automation tasks. The automation tools are defined as systems that contribute to increased efficiency of controllers in performing their tasks. The controllers interact with these tools by using graphics and mouse input as the primary vehicle for system-human dialogue.

The automation system needs to assist controllers in management of traffic at both the Air Route Traffic Control Center (ARTCC) and at the Terminal Radar Control Facility (TRACON). Typically, arrivals enter the airspace of the ARTCC that is feeding traffic to a major destination airport at least 200 n.mi. from the airport. Initially, the arrival traffic continues along established jet routes at cruise speed and altitude. Center controllers direct the traffic to points in space called feeder gates, typically located about 30 n.mi. from the airport at 10,000 ft above ground level. Some airports use as many as four such gates or corner posts which approximately form a rectangle, with the airport at the center. At the gates, the Center controllers hand the traffic over to the TRACON for final sequencing to the runway.

ATC Automation Tools: CTAS

NASA has designed a set of automation tools to assist air traffic controllers in the efficient management of air traffic (ref. 40). The concept (fig. 28) referred to as the Center TRACON Automation System (CTAS) consists of three principal tools which are Traffic Management Advisor (TMA), Descent Advisor (DA), and Final Approach Spacing Tool (FAST). The automation tools are illustrated in figures 29, 30, and 31. TMA is designed for traffic managers in the Center and TRACON, DA for arrival and descent sector controllers in the Center, and FAST for feeder and final approach controllers in the TRACON environment. The relationship of the three tools is illustrated in figure 32. The functions of each element and the relationships between elements are discussed below.

The TMA coordinates traffic flow through the feeder gates and generates landing schedules that minimize delays. The TMA includes algorithms, a graphical interface, and interactive tools for use by the Center traffic manager or TRACON controllers. The primary algorithm is a real-time scheduler which generates efficient landing sequences and landing times for arrivals within about 200 n.mi. from touchdown. Four scheduling algorithms, selectable by the user, have been implemented in the TMA. They are referred to as first-come-first served with and without time advance, and position shift with and without time advance. A detailed description of these scheduling algorithms is found in references 40 and 41. A unique feature of the TMA is its graphical interface that allows the traffic manager to modify the computer-generated schedules for specific aircraft while allowing the automatic scheduler to continue generating schedules for all other aircraft. The graphical interface also provides convenient methods for monitoring the traffic flow and changing scheduling parameters during real-time operation. In essence, the scheduler is a real-time algorithm that transforms sequences of estimated times of arrival (ETA) into reordered sequences of scheduled times of arrival (STA) using one of several scheduling protocols selected by the traffic manager.

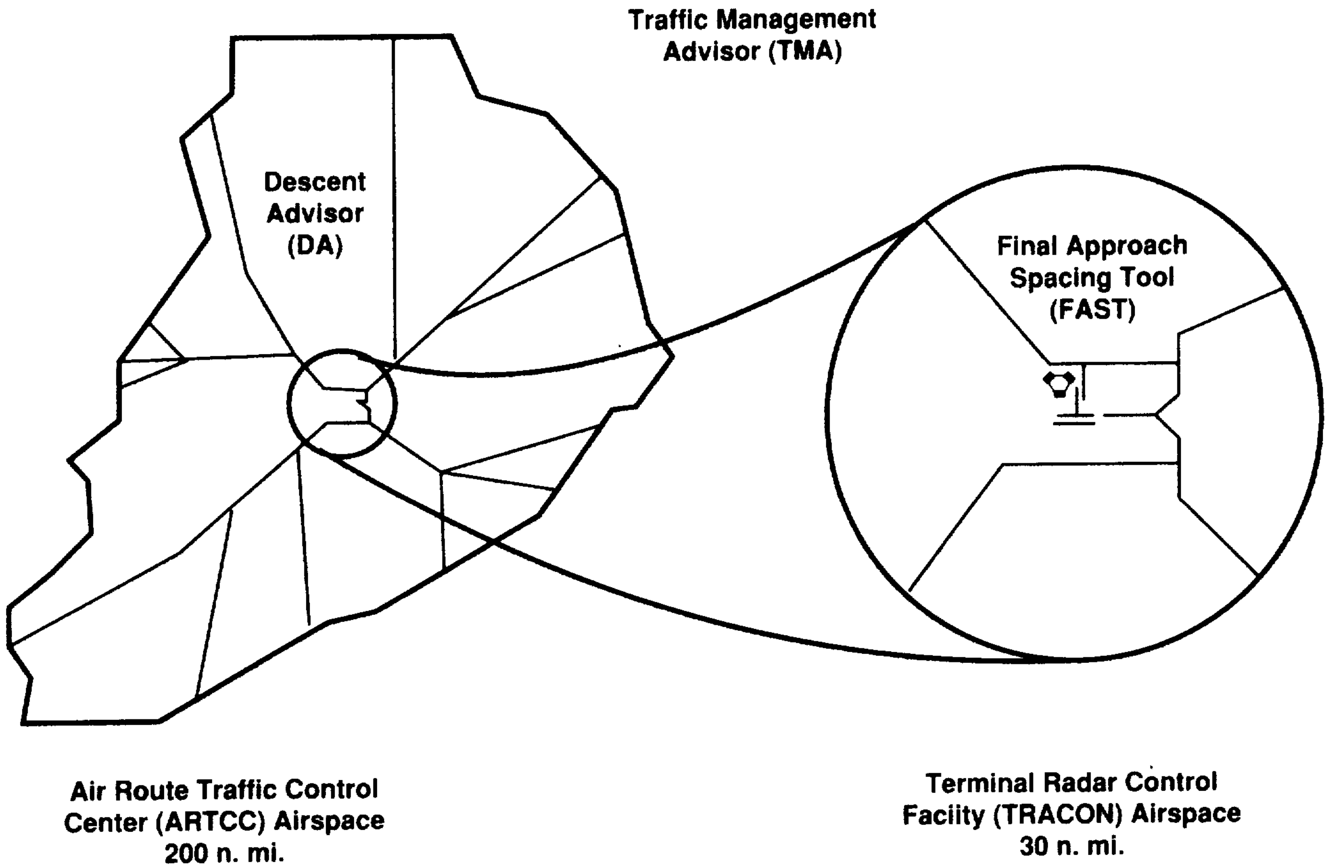


Figure 28. Center/TRACON Automation System.

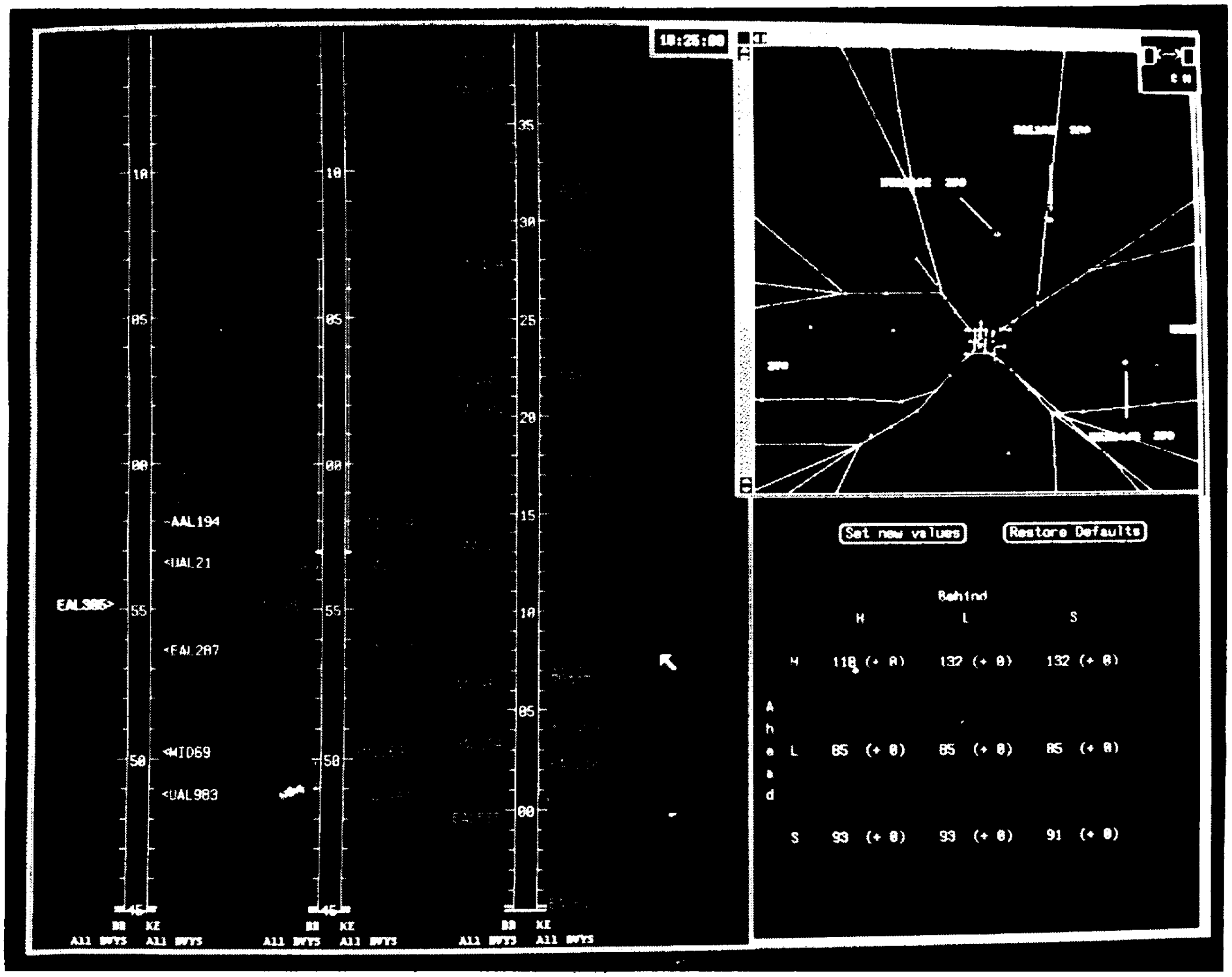


Figure 29. Traffic Management Advisor.

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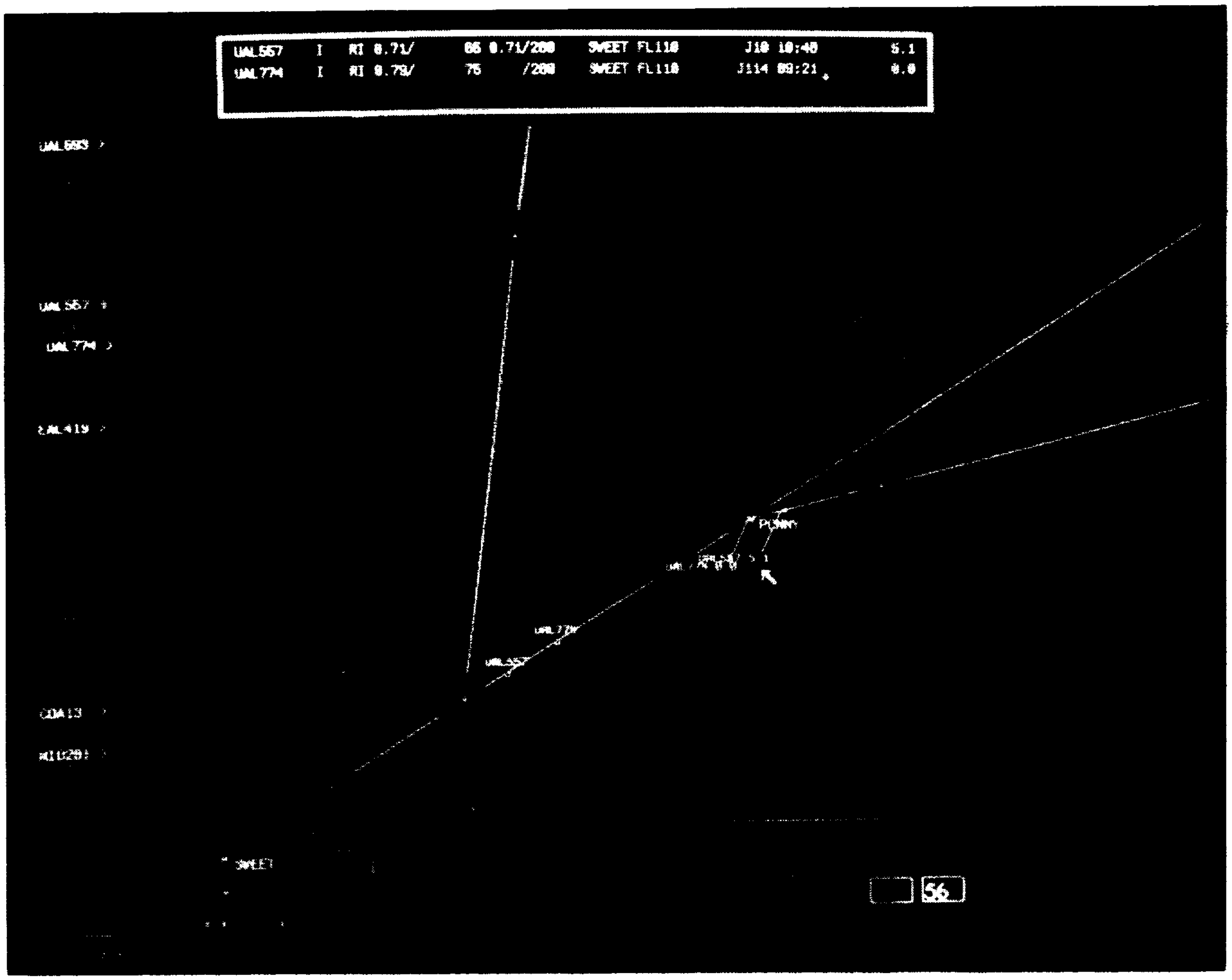

Figure 30. Descent Advisor.

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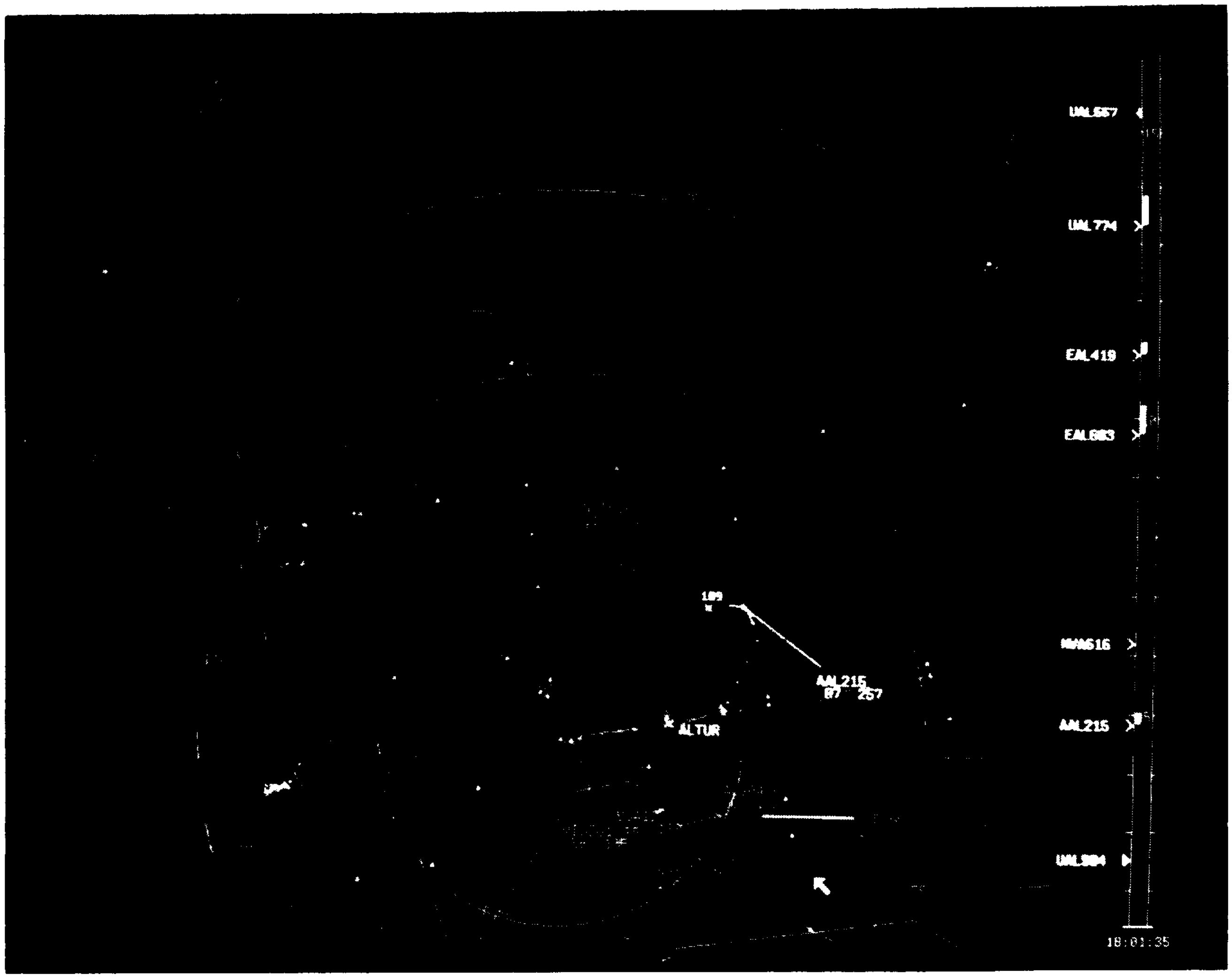

Figure 31. Final Approach Spacing Tool.

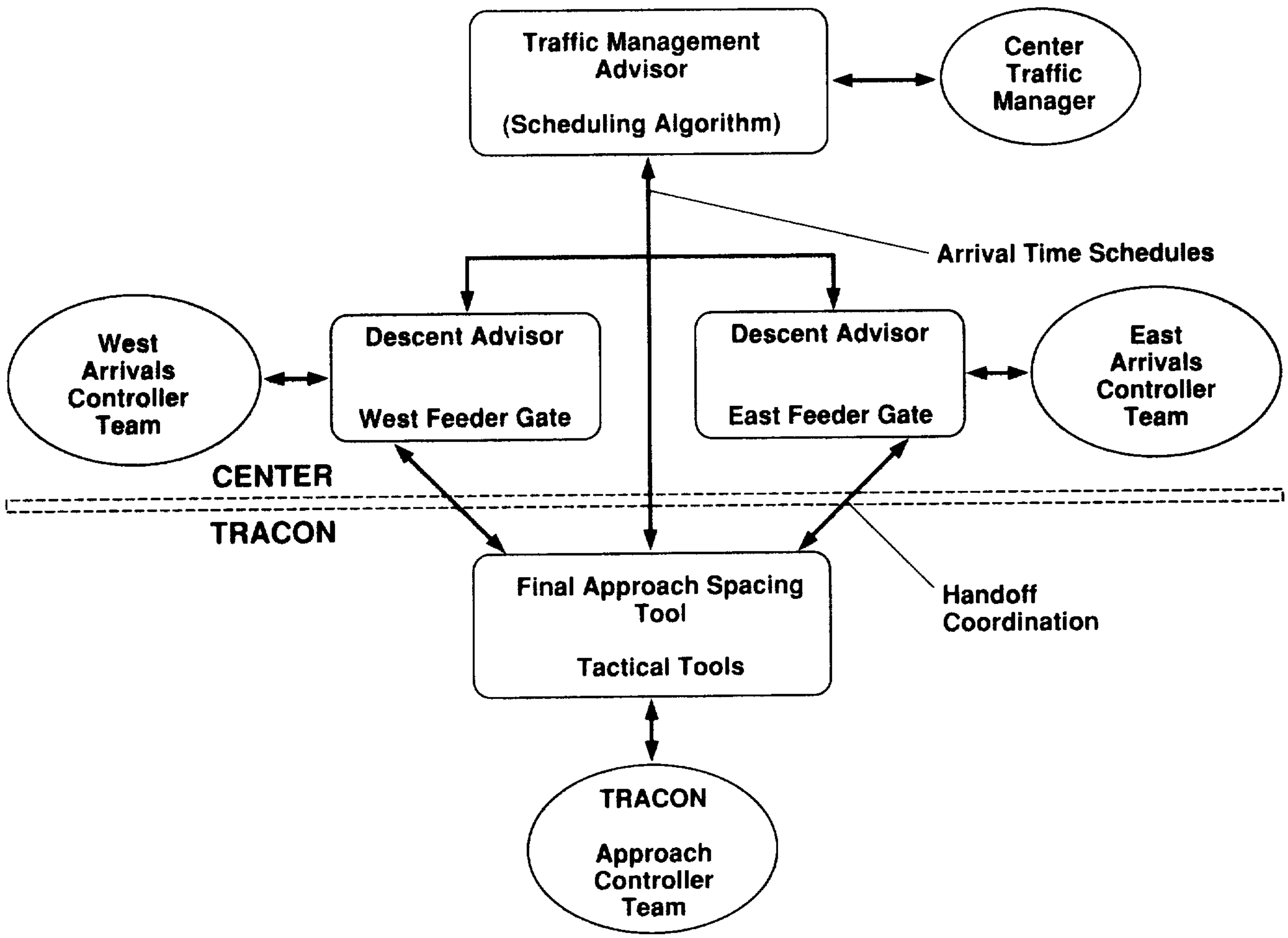

Figure 32. Automation concept and hierarchy of automation tools.

The DA is a set of computer tools designed to assist the Center controllers in accurately controlling the arrival times of aircraft at the feeder gates according to the schedules and sequences determined by the TMA. These tools build upon the Ames-developed collection of algorithms for accurately predicting and controlling aircraft trajectories (ref. 40). The DA provides fuel-efficient and conflict-free descent clearances, adapted to aircraft type, to meet TMA-generated landing times. For all aircraft entering an arrival sector, the DA implemented at that sector computes ETAs at its respective arrival gate. These ETA computations take into account the airspace structure and ATC procedures of each arrival sector. For simplicity, only two DAs are shown in figure 32, but in general there can be four or more, at least one for each arrival gate feeding traffic into the TRACON. The ETAs from all arrival sectors are sent as input to the TMA which uses them to calculate efficient, conflict-free landing schedules. These STAs at the runway are then transformed by the TMA to gate arrival times, and are sent to the DAs at the appropriate arrival areas. Upon receiving these STAs, the DA algorithm generates cruise and descent clearances which controllers can use to keep aircraft on schedule. For aircraft that drift off their planned time schedules, the controller can request revised clearances that correct such time errors to the extent possible.

The FAST assists TRACON controllers in sequencing and spacing aircraft for maximum runway throughput (ref. 42). It predicts time to the runway using each aircraft's performance characteristics, current winds, and expert controller rules for choosing the most desirable approach path. FAST's main functional element is a trajectory algorithm similar to that in DA, but extensively modified to solve problems unique to TRACON operations. The algorithm generates a series of speed and heading advisories. These are designed to maintain each aircraft on a desired time-controlled path as the aircraft proceeds from the feeder gate to downwind and base legs and then onto the final approach course. Each new advisory attempts to correct time and position errors accumulated since the previously issued advisory. This technique reduces the effects of wind modeling errors and of differences in pilot response. Speed advisories are appended to the data tags of aircraft. Graphical advisories such as turn arcs are drawn in front of an aircraft's radar position a short time before they are due to be issued. Advisories are also color coded if the controller display has color capability.

Evaluation of Automation Tools

The automation tools are verified in the ATC Advanced Concepts Simulation Laboratory at Ames (fig. 33). The Laboratory is a facility for real-time simulation of advanced ATC systems which uses controllers and airline pilots as evaluation subjects. The unique characteristics of this laboratory are specialized software to allow rapid prototyping of ATC automation tools and a communications network (voice and data) to the Langley Transport Systems Research Vehicle (TSRV) simulator, Ames MVSRF simulator, and to the Denver ARTCC. The ATC facility is capable of receiving radar data from the Denver Center so that current operations can be observed and evaluated. The interactions with the various facilities are illustrated in figure 34.

Several piloted simulations were conducted on the NASA Ames B727 full-mission simulator to evaluate the performance of the ground-based, four-dimensional (4-D) descent advisor algorithm for controlling the arrival time of conventional (unequipped with 4-D flight management system) aircraft. The simulator, which is FAA certified Phase II, has a 6-degree-of-freedom motion system and a night/dusk computer-generated imaging visual system. The first study evaluated the DA performance for a single aircraft executing straight line descents (ref. 43). A follow-on simulation evaluated the performance of the 4-D DA for curved paths (ref. 44). Results indicated that the 4-D descent advisor algorithm has significant potential for accurately controlling arrival times of aircraft not equipped with an on-board 4-D flight management system. Simulation results showed that most pilots executing advisor-assisted descents arrived at the feeder fix within ±20 sec of their scheduled arrival time, which is a necessary condition if a time-based traffic management system is to be maximally effective.

A real-time simulation was conducted to evaluate the effectiveness of the CTAS in assisting controllers with the management of mixed traffic (4-D equipped and unequipped aircraft), and the effect of CTAS on piloted 4-D equipped aircraft operations (ref. 45). The focus of the experiment was to study the operational issues concerning the handling of 4-D equipped aircraft in the arrival flow. The real-time ATC simulation facility at Ames was used to create the ATC environment and traffic scenarios for the controller test subjects (fig. 35). The major components of the ATC simulation included (1) the pseudopilot simulation which generated and controlled the air traffic, (2) the TMA which scheduled all traffic for coordinated flow between the Center sectors and TRACON,

Figure 33. ATC Advanced Concepts Simulation Laboratory.

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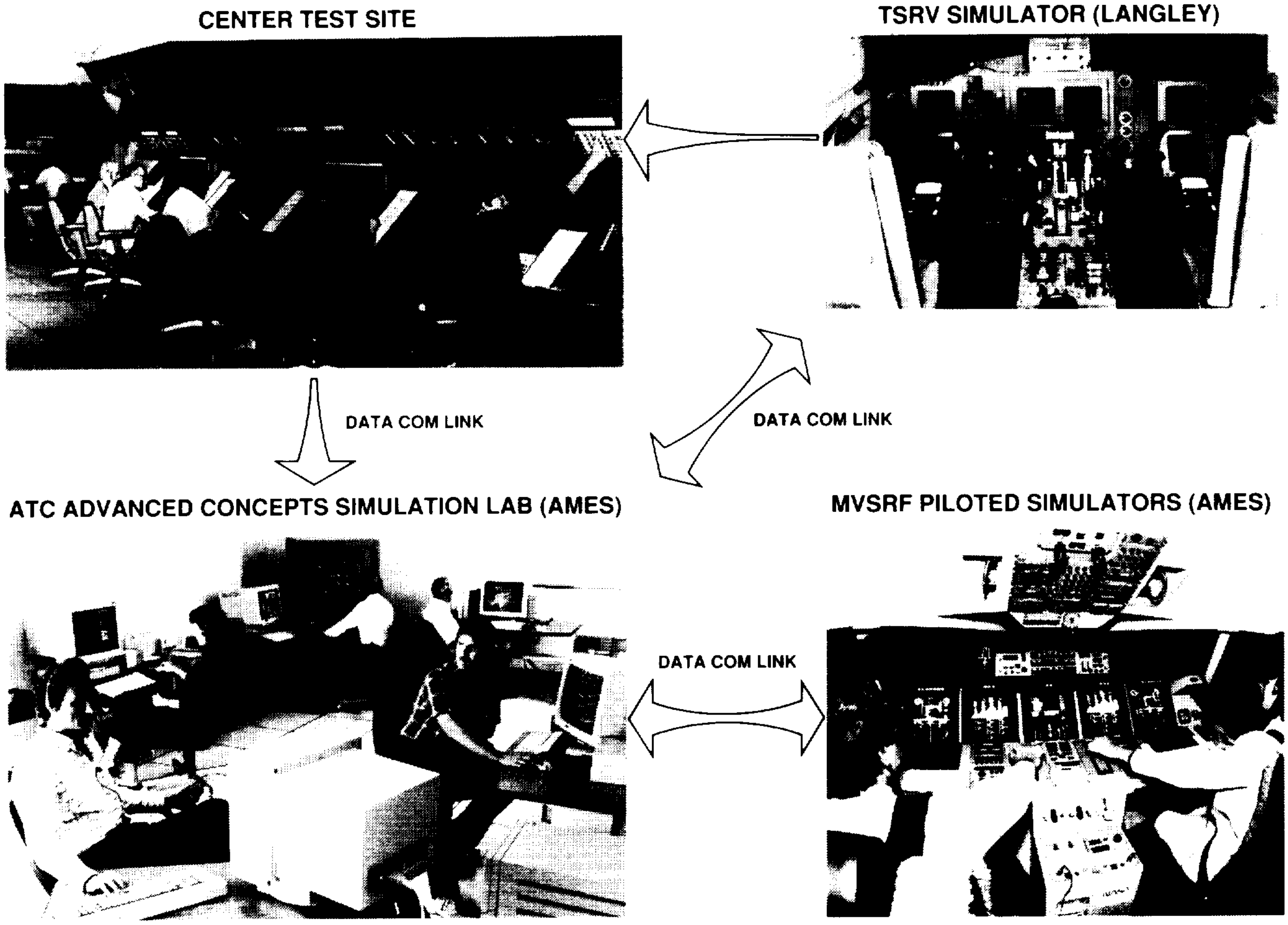

Figure 34. Interactions of various facilities involved in ATC research.

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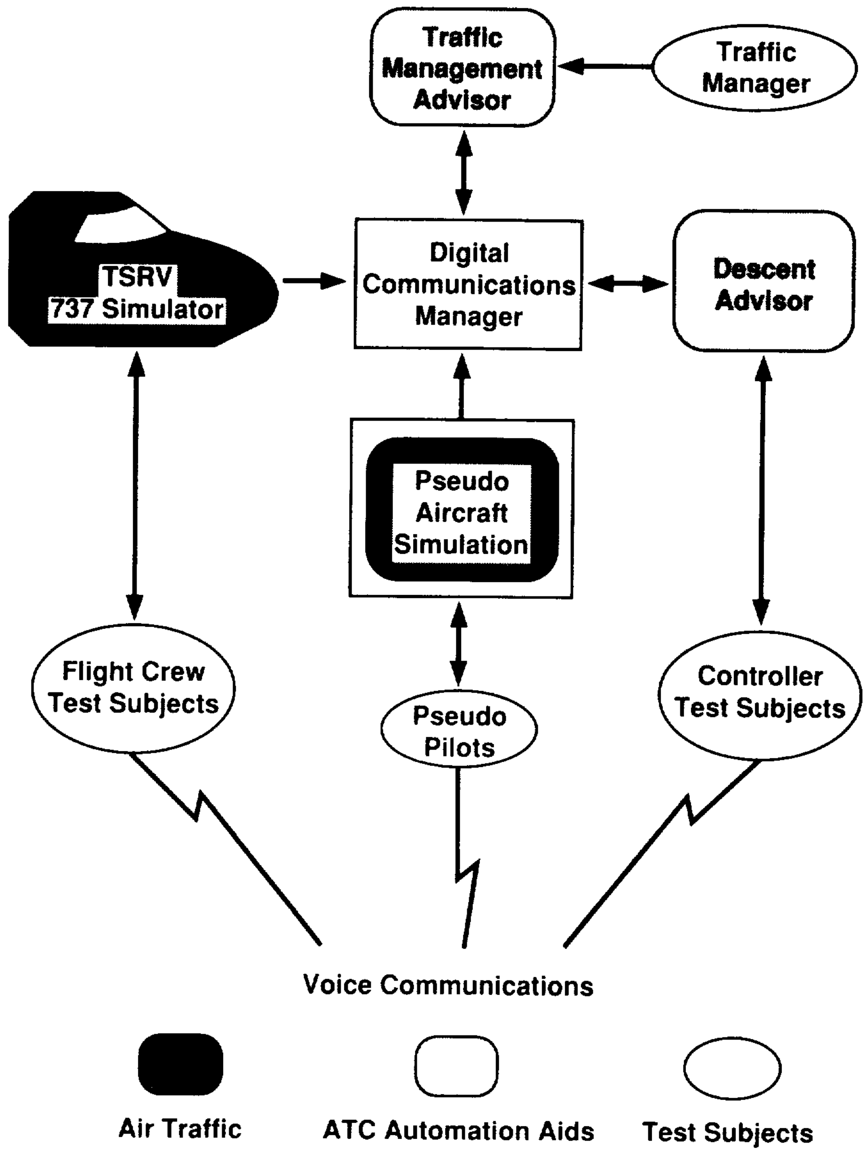
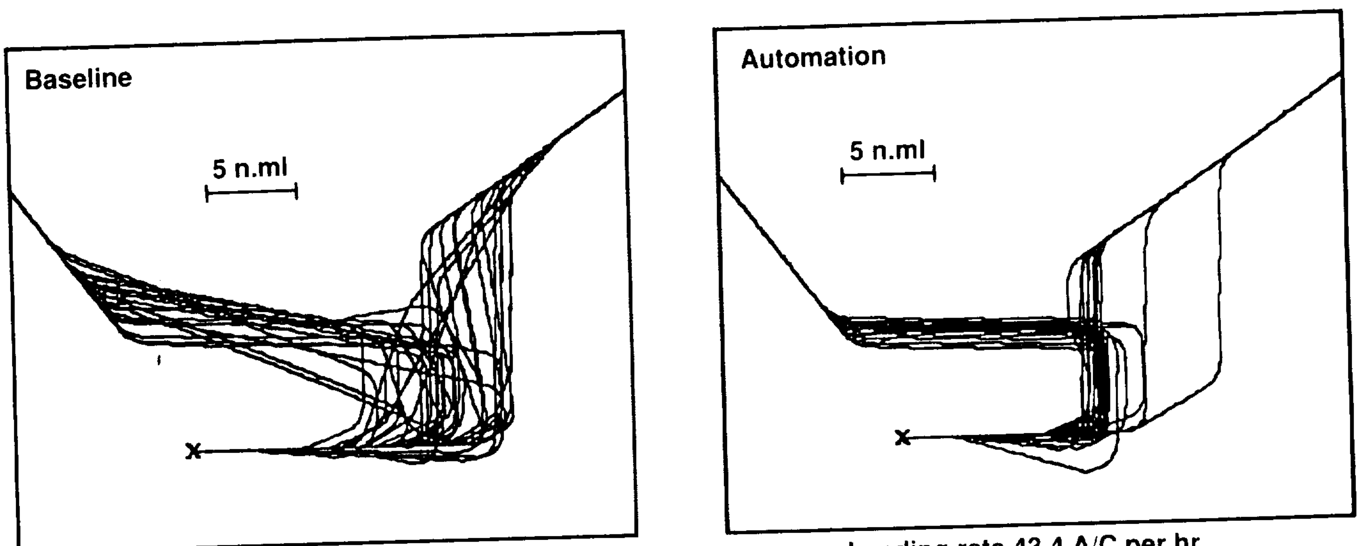


Figure 35. Research system for air traffic simulation.

and (3) the DA which provided the Center controllers with a variety of automation tools for the sequencing of traffic. The FAST, which assists in TRACON operations, was used in an auxiliary capacity to study the TRACON flows generated by the Center arrival activity. The Langley Research Center (LaRC) TSRV 737 piloted simulator was used to introduce 4-D traffic into the arrival flow. The Ames and LaRC facilities were connected via transcontinental voice and data links. It was determined that the accommodation of a 4-D aircraft in the arrival flow requires careful coordination of procedures between the pilot and the controller. Otherwise, conflicts may develop that add to the controller's workload. The experience of the simulation leads to the broad conclusion that a ground-to-air data link may be required for proper integration. The controllers were quite enthusiastic about the 4-D capabilities demonstrated by the TSRV and they appreciated how airborne 4-D capabilities could improve the efficiency of air traffic control.

A simulation evaluation of FAST, in conjunction with the TMA and DA, was conducted in January 1990 (ref. 46). The ATC Advanced Concepts Simulation Laboratory and the B727 full-mission simulator were used for this simulation. The objectives of the simulation were to (1) determine controller performance and runway capacity effects with and without automation tools, (2) evaluate controller acceptance of the FAST concept, (3) evaluate pilot acceptance of flying in the automation environment, and (4) determine the accuracy of the trajectory prediction algorithms in the TRACON. Operational controllers were fed runway capacity-limited arrival rates for Instrument Flight Rules (IFR) conditions with a mix of heavy and large aircraft. The evaluation demonstrated that the automation achieved a decrease in inter-arrival spacing at the runway of 9 sec. This translates to an increase in landing rate of about five aircraft per hour and corresponds to an estimated delay reduction of 4-6 minutes per aircraft depending on traffic mix. In addition, the automation tools resulted in a significant reduction of vectoring airspace (approach intercepts 10-11 n.mi. from the runway with automation compared to 18-20 n.mi. without automation (fig. 36). The results of an evaluation questionnaire following the simulation showed strong controller acceptance of the automation tools.



Landing rate 38.8 A/C per hr

Landing rate 43.4 A/C per hr

Increase of 4.6 aircraft/hour using integrated ATC automation aids

Figure 36. Airspace utilization with and without automation aids.

A summary of payoffs from CTAS is illustrated in figure 37 for single-runway IFR operations. The simulation was performed for 1 1/2 hr traffic rush with a traffic mix of 50% heavy and 50% large aircraft. For these conditions, average delay reduction per aircraft was 2 minutes for TMA and DA combined and 6 minutes when FAST was included. The average fuel savings per aircraft was 450 lb for TMA and DA combined and 1050 lb when FAST was included. In addition, all three simulation tools contributed to a significant reduction in controller workload.

Tools	Average delay reduction per A/C (min)*	Average fuel savings per A/C (lbs)*
TMA+DA	2	450
Fast	4	600
TMA+DA+Fast	6	1050

*Single runway, IFR; A/C mix: 50% Heavy, 50% Large; 1-1/2 hour traffic rush

Figure 37. Payoffs from automation tools.

The FAA is considering the implementation of the automation concepts at one or two FAA-selected demonstration sites. CTAS software and Sun workstations have recently been installed at the FAA Technical Center and FAA contractor labs. Further research will adapt CTAS to operate with MLS and data link. Field evaluations could be conducted first for single-runway operations followed by multi-runway operations. Field evaluations would allow refinement of the automation concepts before committing to a national implementation. However, preparations for national implementation could proceed simultaneously with demonstration implementation. The initial phase would include installing a stand-alone Traffic Management (TM) work station at selected Center and TRACON sites. This would be followed by an integration of the CTAS elements (TM, DA, FAST) at these sites. Finally, national implementation of the automation concepts could be performed if warranted by results of field tests.

SUMMARY OF RESULTS

This report discusses aviation safety, and ATC automation research directed at the challenges of reducing congestion and delays, enhancing safety, and expanding capacity of the National Aviation System. Aviation safety research results are given in areas of incident reporting, accident investigation, and human factors of flight-deck automation, displays and warning systems, crew coordination, and crew fatigue and jet lag. Aviation safety human factors research is directed at understanding and mitigating the problem of human error in aviation. ATC automation research is aimed at the development and testing of controller-compatible air traffic control automation concepts and methods, their evaluation in both simulated and real environments, and their integration into the ATC system.

The principal results are as follows:

1. The NASA Aviation Safety Reporting System has become a major resource to guide human factors research and has been effective in stimulating safety awareness. The system has resulted in numerous safety advisories, has provided quick response to Federal Aviation Administration and National Transportation Safety Board questions, and has published numerous research studies.

2. Analysis of atmospheric disturbances using digital flight data recorders from accidents has led to an understanding of the disturbance characteristics, and accurate models which are being used to improve aircraft countermeasures to atmospheric disturbances.

3. Design philosophy for human-centered automation has been developed and evaluations of automation in advanced technology transports suggests ways to optimize the human performance in the automated environment. The first principle of human-centered automation is that the pilot bears the ultimate responsibility for the safety of a flight operation and the human operator must be in command. The results indicated that the highly automated cockpit may require additional scrutiny for assignment of tasks and standardization of crew member performance.

4. Display-based communications such as electronic checklist, TCAS II, data link, and 3-D auditory displays could provide significant improvements in aircrew situation awareness and decision making. For example, study results indicate graphical interfaces using clearance information transmitted by data link provide significant enhancements in flight management systems operations.

5. Crew Resource Management (CRM) training produced highly significant positive change in personal attitudes and appropriate flight-deck behavior and more effective utilization of available resources. However, a subgroup of individuals given CRM training shows less favorable attitudes following training, large differences are found in attitudes and performance within the organizations, and variations in performance may be related to the personalities of the participants.

6. Studies indicate that long-haul flight crews experience substantial sleep loss due to night flying conflicting with sleep, disruption of layover sleep (jet lag), and large individual differences in adaptability. Results indicated that crew members are not able to predict when they are sleepy. A 40-minute preplanned rest period for long-haul operations can offer a safety valve to mitigate the effects of sleep loss and fatigue.

7. An integrated set of automation tools has been designed to assist air traffic controllers in efficient management of air traffic. The tools are Traffic Management Advisor, Descent Advisor, and Final Approaching Spacing Tool. Simulation evaluation of these tools for single runway operations provided 4-6 minutes delay reduction per aircraft depending on traffic mix with significant reductions in controller workload.

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Point of Contact: J. Albers, Ames Research Center, MS 200-3, Moffett Field, CA 94035-1000
(415) 604-5070 or FTS 464-5070

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16. Abstract

The major challenges facing the Air Transportation System today include reducing congestion and delays, enhancing safety and expanding the capacity of the National Aviation System. This report discusses aviation safety human factors and air traffic control (ATC) automation research at NASA Ames Research Center directed toward these challenges. Research results are given in the areas of flight deck and ATC automation, displays and warning systems, crew coordination, and crew fatigue and jet lag. In addition, accident investigation research and an incident reporting system that is used to guide the human factors research is discussed. A design philosophy for human-centered automation is given, along with an evaluation of automation on advanced technology transports. Intelligent error-tolerant systems such as electronic checklists are discussed along with design guidelines for reducing procedure errors. Implementation of the current research results can offer significant improvements in the current Air Transportation System. Study results indicate that significant improvements in aircrew planning and decision making could be realized with the use of display-based communications transmitted by data link. Initial studies on three-dimensional (3-D) auditory displays indicate that these displays could improve situation awareness for both crew members and ATC controllers. It was found that a 40-minute pre-planned rest period for long-haul operations can offer a safety valve to mitigate the effects of sleep loss and fatigue. The data on evaluation of Crew Resource Management (CRM) training indicates highly significant positive changes in appropriate flight-deck behavior and more effective use of available resources for crew members receiving this training. Simulation evaluation of ATC automation tools for single runway operations provided 4-6 minutes delay reduction per aircraft depending on traffic mix with significant reduction in controller workload.

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