

The NASA Advanced Concepts Flight Simulator - A unique transport aircraft research environment

Matthew W. Blake

NASA, Ames Research Center, Moffett Field, CA

**AIAA Flight Simulation Technologies Conference, San Diego, CA, July 29-31, 1996,
Technical Papers (A96-35001 09-01), Reston, VA, American Institute of Aeronautics and
Astronautics, 1996**

We address the current and planned capabilities of the NASA-Ames Advanced Concepts Flight Simulator (ACFS) located at Moffett Field, California. The ACFS is used to study many aspects of human factors in aviation safety as well as methods to improve aviation operational efficiency. The ACFS provides full mission functionality and appears similar to high fidelity training simulators, but is unique in that no flight hardware is used; the entire simulation is programmable. This capability allows the simulator to be reconfigured to meet any research requirement. This paper describes the current and planned capabilities of the ACFS, elaborates some of the unique features available to the aviation research community, and describes some of the specific research programs completed recently. (Author)

THE NASA ADVANCED CONCEPTS FLIGHT SIMULATOR: A UNIQUE TRANSPORT AIRCRAFT RESEARCH ENVIRONMENT

Matthew W. Blake, NASA Ames Research Center

ABSTRACT

This paper addresses the current and planned capabilities of the NASA Ames Research Center Advanced Concepts Flight Simulator (ACFS) located at Moffett Field, California. The ACFS is used to study many aspects of human factors in aviation safety as well as methods to improve aviation operational efficiency. The ACFS provides full mission functionality and appears similar to high fidelity training simulators but is unique in that no flight hardware is used; the entire simulation is programmable. This capability allows the simulator to be reconfigured to meet any research requirement. This paper describes the current and planned capabilities of the ACFS, elaborates on some of the unique features available to the aviation research community, and describes some of the specific research programs completed recently as well as some future research plans.

INTRODUCTION

Modern commercial transport aircraft are extremely complex systems. In addition to the conventional control stick or yoke, rudder pedals, and thrust lever, the modern flight deck is comprised of numerous computer displays, keyboards, and cursor control devices. Rather than describing a flight as "flying from point A to point B", the task of piloting a commercial aircraft from one location to another is now more aptly referred to as "managing the flight".

The current Air Traffic Control (ATC) environment is also very complex. The airspace is rigorously controlled and there are very complex procedures and rules regulating operation of aircraft in the airspace. Utilizing current procedures, the ATC environment is near capacity. New ground based automated ATC systems hope to significantly increase capacity, and rapid changes in satellite navigation and on-board computational capability have provided aircraft with the ability to determine more efficient routes than the current ATC system. These possible changes to the airspace system all require thorough development and test prior to the fielding of a new system.

Due to this complexity of the aircraft and air traffic systems, the pilots often have so much flight planning and system management work to accomplish that they let the on-board computers actually guide and control the aircraft during much of the flight. Even when the pilots choose to interactively guide the aircraft, they will often use a combination of autopilot knobs and switches to provide a heading and altitude rather than the conventional stick and rudder approach to control of the aircraft. This use of automation can improve the efficiency of the operation tremendously, however it presents many new problems. These include pilot or ATC controller confusion on what the system is doing, why the system did it, and what the system is going to do next. These changes have brought around a whole new set of potential human-machine interface hazards to the safe execution of commercial transport flight operations.

To accurately study human performance in the airspace operations arena or on the flight deck requires providing the full complexity of the entire environment. To safely study this requires use of a simulation rather than experimentation in the real world. The ability to simulate this complete system is called full-mission simulation. In the early 1980s, NASA scientists recognized the need to perform research in this area and the Crew-Vehicle Systems Research Facility (CVSRF) was constructed at the NASA Ames Research Center. The facility contains three main components; a conventional current technology aircraft simulator, an advanced future technology aircraft simulator, and an air traffic control simulator. The facility has gone through numerous upgrades and changes since this initial capability leading to the current configuration.

The current CVSRF conventional technology aircraft is a Boeing 747-400 simulator. The 747-400 utilizes computer driven all glass display instrumentation and the latest in avionics systems. This is an exact replica of a current state of the art aircraft. The simulator adheres to FAA Level D certification standards, the highest certification standards available. In addition to all conventional 747-400 aircraft features, the simulator includes several capabilities not available on a training simulator. These include programmable flight displays and extensive data

collection capabilities. The 747-400 simulator is an excellent platform for studying proposed near term airspace operations changes and human factors issues related to incremental system changes.

The ACFS has evolved over the years and is currently being completely rebuilt. Recent upgrades to the ACFS include a new multi-processor host computer, a new instrument panel including flight displays and computers, an updated digital communication network, a new aural cue system, and a new cockpit center pedestal and throttle system. The new ACFS includes a complete full-mission simulation of a mid size, mid range transport. Unlike the 747-400 simulator that utilizes aircraft avionics units, the entire ACFS is simulated on general purpose computers and is therefore completely re-programmable. Any system can be changed to address specific research areas. The ACFS includes a relatively conventional baseline flight deck environment that can be easily reconfigured for any research design. The Flight Management System (FMS) is also fully programmable, providing a unique research capability. The ACFS is an excellent platform for studying significant changes to the airspace system or major new concepts in human interfaces.

The ATC environment is a significant contributor to pilot workload and, therefore, to the performance of crews in flight. Full mission simulation is greatly affected by the realism with which the ATC environment is modeled. The CVSRC ATC simulator provides the capability to integrate the aircraft simulators into a very complex airspace environment. This environment includes several ATC sectors, dozens of pseudo aircraft, and an elaborate communication and data-link system to simulate the large traffic load experienced in the real world. The ATC simulator can also tie in with other simulators and the NASA Ames developed Center/Tracon Automation System (CTAS). This system is designed improve the safety and efficiency of traffic flow in the terminal area.

The ACFS and 747-400 simulators can be configured to operate together and with the ATC simulator. Additionally, both the CVSRC simulators can be linked to outside simulation facilities.

SIMULATOR DESCRIPTION

The ACFS was originally developed as a joint effort between NASA Ames, NASA Langley, and the Lockheed Georgia Company. Three simulators were built and located at each site. This paper describes the NASA Ames simulator.

The ACFS is currently configured to simulate a generic advanced twin engine mid-range transport aircraft, similar to a Boeing 757. The ACFS consists of a re-configurable cab on a 6 degree-of-freedom motion platform with a Link Image II Out The Window (OTW) visual system. The cockpit includes a conventional center console with throttle levers and aircraft system control and display devices, an overhead panel for control of many other aircraft subsystems, and, following the current upgrade, 8 video display screens across the main panel for flight, guidance, navigation, and status information. There is a Mode Control Panel (MCP) in the glare shield for autoflight control and 2 Control Display Units (CDU) for interfacing with Flight Management Computers (FMC). A time lapse photograph of the simulator in motion is shown in figure 1.

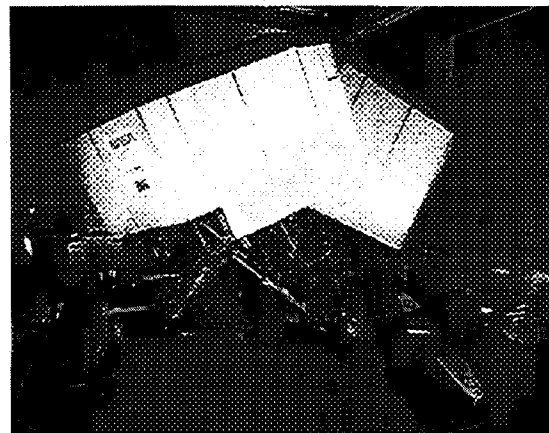


Figure 1: Time lapse photograph of ACFS in motion

AIRCRAFT PERFORMANCE

The ACFS performance and behavior can be tuned to a particular experiment's requirements. The default configuration is a low wing airplane with twin turbofan engines. General operating characteristics include:

- Maximum gross weight - 224,000 lbs.
- Payload 60,000 pounds; capacity - 200 passengers
- Twin engine - 41,000 pounds rated thrust per engine
- Speed - 0.78 Mach; range - 2500 miles
- Fuel capacity - 42500 lbs. usable

AIRCRAFT SYSTEMS

The ACFS aircraft represents a combination of current state of the art systems and some improved systems. New or modified systems can be incorporated easily to meet research objectives. The basic features of the current existing simulated aircraft systems are described here.

The flight control system consists of conventional flight surfaces (rudder, ailerons, elevators, flaps, slats, and spoilers) employed in both normal and innovative ways (continuous adjustment of ailerons to reduce wing bending, adjustment of flaps and ailerons to reduce drag, and the use of spoilers coupled with the elevator to maintain glidepath). Wing tip devices are also employed to alleviate twisting forces. Manual and automatic trim of aileron, stabilizer, and rudder are available. Flight control is purely fly-by-wire. The Stability Augmentation System (SAS) is active in the pitch, roll, and yaw axes.

The engines are advanced technology high bypass turbofans with electronic engine control. Features include full function from startup through shutdown including fire detection and extinguishing. The fuel system includes full authority digital fuel control, integral fuel heating system, boost pump, APU fuel control, isolation and fuel shutoff valves. Engine status is displayed on a compact engine display similar to the Boeing 757.

The Auto Flight System (AFS) consists of the Autopilot Flight Director System (AFDS) and the Autothrottle System (A/T). When engaged, the Flight Management Computer (FMC) automatically manages pitch, roll, and thrust through simultaneous control of the AFDS and A/T. Control of the AFDS is accomplished through the MCP. The AFS functions very similarly to an advanced Boeing commercial transport.

The Flight Management Computer (FMC) is one of the most advanced programmable FMCs available anywhere in the research community. The system includes accurate vertical and lateral flight planning, navigation, and guidance. There is currently a major development effort underway to increase the simulated FMC capability.

Warning systems include an Engine Indication and Crew Alerting System (EICAS), a stall warning system, a Ground Proximity Warning System (GPWS), and a Traffic Collision Avoidance System (TCAS).

Communication and Navigation systems include dual Very High Frequency (VHF) transceivers, dual VHF

Omnidirectional Range (VOR)/ Distance Measuring Equipment (DME) receivers, dual Instrument Landing Systems (ILS), and an Inertial Reference System (IRS) consisting of three Inertial Reference Units (IRU). Frequency control of receivers is through a digital entry panel and includes active and standby capability.

Electrical system components include four engine driven generators, an auxiliary power unit (APU) with two generators, external power capability, emergency circuit breakers, air-conditioning, heating, avionics, and associated controls and displays. Power is distributed over six separate buses and can be re-routed in several ways.

Aircraft exterior lighting includes landing, taxi, strobe, navigation, and anti-collision lights. Interior lighting control includes panel, overhead, and instrument intensity. The environmental systems include cabin pressure and temperature and emergency oxygen and de-pressurization control. Adverse weather systems include engine ice detection, anti-ice, continuous engine ignition; and pitot, Angle of attack sensor, and windshield heat. The landing gear system includes manual gear extension/retraction, anti-skid braking with carbon composite brakes, and a parking brake system.

FLIGHT DECK

The ACFS flight deck is designed for operation by a two-pilot crew. The instrument panel can easily be re-configured to a particular experiment's requirements. The default configuration is:

- McFadden hydraulic control loading sidearm controllers for pitch and roll control
- McFadden hydraulic control loading rudder pedals
- Back-driven throttle levers with reverse thrust, very similar to a Boeing 757
- MCP on the glare shield for autoflight control, very similar to a Boeing 757
- Two CDUs in the center pedestal for interfacing with the FMC
- Mechanical switches/knobs in the overhead panels and the center console for miscellaneous aircraft system control

The physical location of the flight displays in the instrument panel can be altered to meet research requirements. What is displayed on each display can also be reprogrammed to meet research requirements. The display installation conforms to ARINC specifications.

The default flight display configuration is:

- 8 inch Primary Flight Displays (Pilot and Co-pilot), similar to Boeing 777
- 8 inch Navigation Flight Displays (Pilot and Co-pilot), similar to Boeing 777
- 8 inch Engine/EICAS display in the centerline
- Additional 8 inch display below Engine/EICAS for researcher use
- Two 6x7 inch displays for system status and control for Pilot and Co-pilot
- Touch screens and cursor controls for interaction with systems displayed on 6x7 inch device

Figure 2 shows the flight deck as used until recently. Figure 3 shows a diagram of the flight deck that is currently under construction and is described here.



Figure 2: ACFS flight deck prior to overhaul

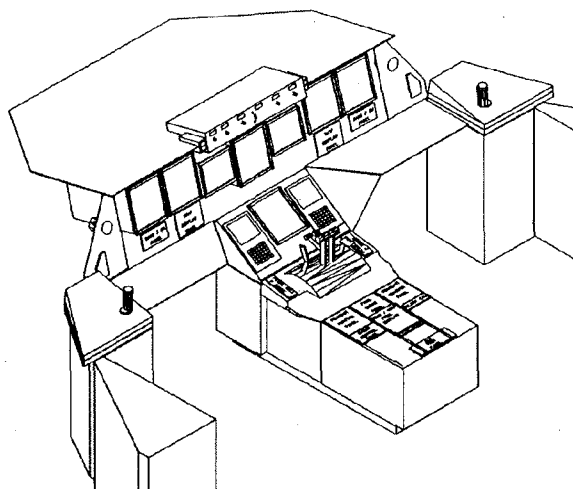


Figure 3: New ACFS flight deck design

SIMULATION CUEING SYSTEMS

In addition to the flight deck instrumentation and control devices, to pilots are cued by a high fidelity visual, aural, and motion cueing system.

The Out-the-Window (OTW) visual image is generated by a Link-Miles Image II visual system. The Image II visual system is a compact flight simulator attachment which presents computer-generated color scenes representing the outside world. These scenes depict specific airports and their surroundings as viewed at dusk, twilight, or night from the cockpit. Enroute visual scenes are also simulated as are other aircraft.

The aural cues are provided by a new Advanced Simulation Technology Inc. (ASTi) sound system. This system generates general aircraft sounds (engines, wind, landing gear in transit), aircraft warning sounds (GPWS alerts, EICAS alerts), and communication/navigation sounds (VOR identifiers, Automated Terminal Area Service (ATIS) messages).

The motion cues are provided by a Link Flight Simulation hydraulic hexapod motion platform. This system is capable of providing motion cues in all six axes. The motion of the crew station in the simulated aircraft is calculated in the host computer and that motion is filtered to create a smaller version that can be reproduced with the limited travel of the simulator motion system. The translational and rotational motion is converted into leg movements and sent to the motion system. The motion system is capable of providing acceleration and velocity cues in excess of:

- Vertical 0.8g acceleration, 24 inches/sec
- Lateral 0.6g acceleration, 24 inches/sec
- Longitudinal 0.6g acceleration, 24 inches/sec
- Pitch 60 deg/sec², 20 deg/sec
- Roll 60 deg/sec², 20 deg/sec
- Yaw 60 deg/sec², 20 deg/sec

SIMULATOR ARCHETECTURE

The simulation is distributed over many subsystems. A majority of the simulated systems are running on the host computer, a Silicon Graphics Inc. (SGI) Challenge multi-processor machine. The flight displays are all running on separate SGI single processor computers. There are separate systems for sound generation, OTW visual image, cockpit control signals, and other miscellaneous devices. Figure 4 shows a high level diagram of the major subsystems in the simulator.

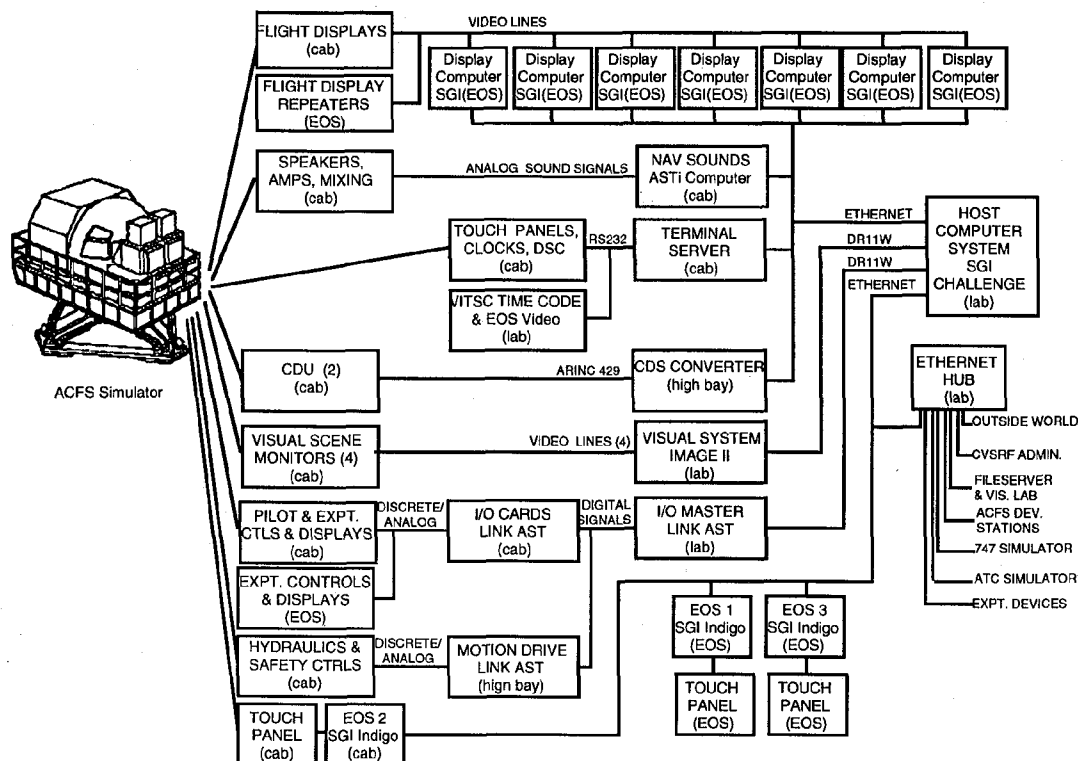


Figure 4: High level diagram of the major ACFS subsystems

Within the multi-processor host computer the software is separated into functional units and run on separate processors. The general load is configured as follows:

- Processor-0: UNIX Operating System, Experiment Operator Stations (EOS), Asynchronous Input/Output (I/O), background processes
- Processor-1: Main aircraft simulation (Controls, Aerodynamics, Equations of Motion, etc.) synchronous I/O
- Processor-2: Data Collection
- Processor-3: FMC process

The host computer is capable of utilizing 12 processors. We are currently using only 4. The majority of the data communication between computers is accomplished utilizing socket protocols over Ethernet lines. The ACFS software includes

approximately 500,000 lines of code, split approximately evenly between FORTRAN and C.

EXPERIMENT OPERATOR STATION

Control and monitor of the active simulation is done utilizing a separate process running on the host computer. This process is called the Experiment Operator Station (EOS). This is not a hardware station but rather a program that presents buttons, menus, and diagrams on a color computer display for the engineer or operator to use for control or monitoring of simulation parameters. Many copies of the EOS may be run concurrently, allowing different engineers to monitor different parameters and view different pages of information. There are pages for general simulation control, aircraft configuration, weather, data collection, etc. Generally, additional new pages are created for each experiment's unique requirements.

In the main simulation control room/experimenter station there are also repeater displays of the crew's flight displays as well as mechanical switches and indicators for all safety related simulator controls. There is also an audio station allowing experimenters to communicate with the flight crew during an experiment or with observers located "on-board." Communicating with the ATC simulator is also possible from the experimenter stations. The EOS computer processes are run on two workstations located in the control room. These workstations have touch screen overlays in addition to traditional keyboard and mouse input devices.

There is also an EOS station located in the simulator cockpit. This location has an SGI workstation for running the EOS process as well as simulation control and communication hardware.

EXPERIMENT DATA COLLECTION

Digital data collection of experiment parameters is performed on a separate processor on the host computer. The system is capable of capturing data at multiple frequencies up to 30 Hz. Data is collected on a hard disk and can be processed or transmitted immediately following termination of an experiment run. The maximum recording capacity is 2000 words (8000 bytes) at 30 Hz., up to a maximum of 2 Gigabytes.

In addition to digital data, both audio and video analog data can also be collected. Low light video cameras are mounted in the simulator cockpit and are capable of recording pilot actions and instrumentation status. Audio recordings can be made of all audio channels and mixed with the video. In order to correlate the digital data with the audio and video analog data, a digital time code stamp is recorded and displayed on the video tape. Additional digital data from the simulation can be recorded on part of the video screen if desired.

The combination of audio and video correlated with the digital data provides a powerful tool for analyzing crew-vehicle performance.

SIMULATION DEVELOPMENT AND TEST

The entire SGI based simulation can be run on any SGI workstation in the facility. This "mini-ACFS" system provides an excellent initial development environment. When running on single processor workstations, the simulation cannot run in real-time but the individual processes stay in sequence so

behavior for testing and debug is usually quite adequate. The engineer can run the existing flight displays and EOS as well as a graphical version of the mechanical MCP to provide an essentially complete development environment. Some workstations have been configured with two monitors to provide additional display space for this purpose. This mini-ACFS capability decreases the need for expensive duplicate simulators for development and significantly decreases the need for dedicated time on the main simulator early in the development phase.

The development computer supplier, SGI, provides a state of the art software development environment including a suite of Computer Aided Software Engineering (CASE) tools. This includes a Graphical User Interface (GUI) front end to the debugger, a static code analyzer, an on-line help utility, and much more. The key elements of this environment can be utilized with the real-time system so the user is not forced to develop and test his software utilizing different tools. This cuts down on development and test time and the user does not need to learn and stay proficient at two different environments. Also, the system support staff does not need to support a special (often in-house developed) real-time control, monitor, debug system.

RESEARCH PROGRAMS

The ACFS has been used for a broad spectrum of airspace operations and human factors research. Much of the early use was geared toward full mission studies of many concepts in cockpit design. Some examples include flight deck ergonomic studies on location and characteristics of the sidestick controls, flight display location and content, electronic checklists for coping with onboard malfunctions, and airport surface navigation maps on flight displays. More recent studies have looked at the implications on pilot workload of air-ground data-links and developed autoflight mode change prediction and intelligent cockpit procedural aid tools. The most recent studies are listed below.

Integrated Mode Management Interface (IMMI): This study evaluated an entirely new method of presenting autopilot mode status and control in an effort to improve the pilots awareness of current and projected autopilot actions. This study addressed what is termed "mode confusion" which is rapidly becoming recognized as a major contributing factor in many aviation incidents. The experiment showed the value of vertical situation displays and enhanced mode information.

Propulsion Controlled Aircraft (PCA): This study evaluated an emergency backup Fly-by-Throttle control system for use in the case of a complete conventional flight control system failure (no rudder, aileron, or elevator). The simulation successfully demonstrated tremendous improvement in the ability of the pilot to land safely over manual throttle controlled flight. This effort directly supported eventual flight tests on a McDonnell Douglas MD-11 transport aircraft at NASA Dryden Flight Research Center.

Neural Controlled Aircraft (NCA): This study utilized an active learning Neural Net model of the engine in an effort to further improve the PCA control capability, specifically during higher levels of turbulence and out of trim conditions. This system demonstrated the concept of utilizing active learning Neural Nets to automatically redefine the control system following an unidentified system failure. This experiment also demonstrated the power of a blended control system where all control surfaces and the engines are utilized in unison. For a damaged aircraft, this blended control system provided the pilot with much better performance than the standard flight control system which is based on control of independent axes.

3D Audio for TCAS: This set of experiments studied the use of 3D audio signals to provide directional cues to the pilots for Traffic Collision Avoidance System (TCAS) alerts in a heavily loaded full mission environment. Each crew flew from San Francisco to Los Angeles with standard TCAS monaural warnings and with the 3D Audio warnings. During the flight they were presented with several hundred other aircraft (traffic) and many of these became actual collision threats which activated the warning system. The experiment showed that crews could visually identify the threat following the warning message faster when provided with the 3D spatial cue.

The unique products of these experiments are directly beneficial in commercial aviation and private industry. The general public will see the results of such experiments by the improvement in aviation safety and efficiency. In the next few years, the ACFS will be used extensively in support of NASA's Terminal Area Productivity (TAP) Program and Advanced Air Transportation Technology (AATT) Program. Additional studies will be performed in support of other human factors research and FAA research programs. Some specific planned experiments include use of Head Up Displays (HUD) for improved Low-Visibility Landing and Surface Operations (LVLASO), Free Flight Collision Avoidance, and Free Flight/Flight Plan Negotiation.

FUTURE PLANS

As a research facility, the simulator is essentially always undergoing some form of renovation. The current upgrades were more extensive than is normally done for a specific experiment. These modifications will be completed by the end of August, 1996. In the next year, the simulator will go through the final planned upgrade which includes replacement of the current OTW visual system and cockpit I/O system. A Head Up Display (HUD) system will be installed to support specific TAP research programs.

Other major improvements include a continuing effort to improve the ACFS simulator's software FMC to meet the AATT research objectives. The simulation will be required to support large data-link capabilities in both the ground ATC side and the airborne FMC side. Additional capability for features such as Required Time of Arrival (RTA) and Required Navigation Performance (RNP) will be implemented.

SUMMARY

The ACFS provides full-mission aircraft functionality including elaborate autoflight and flight management systems yet the hardware and software configuration can be changed as needed to address specific research requirements. Unlike most commercial aircraft and training simulators, the ACFS does not include any actual aircraft avionics boxes so the entire simulation is fully programmable to address any research requirements. The unique research capabilities of the ACFS enable scientists to develop and test new concepts in a realistic cockpit environment through the use of full mission simulation. Experimental research performed on the ACFS directly supports many NASA programs in airspace operations and human factors. The ACFS will continue to make an impact supporting basic research as well as focused areas such as the Terminal Area Productivity (TAP) program and Advanced Air Transportation Technology (AATT) program.

References

1. Shiner, R., Sullivan, B., Man-Vehicle Systems Research Facility: Design and Operating Characteristics. AIAA/AHS Flight Simulation Technologies Conference, Hilton Head Island, South Carolina, August 1992.

2. Sexton, G., Crew Systems and Flight Station Concepts for a 1995 Transport Aircraft, NASA Contractor Report 166068, April 1983.
3. Aircraft Operations Manual for the Advanced Concepts Flight Simulator (ACFS), AP-1015, NSI Technology Services Corp., February 1996.

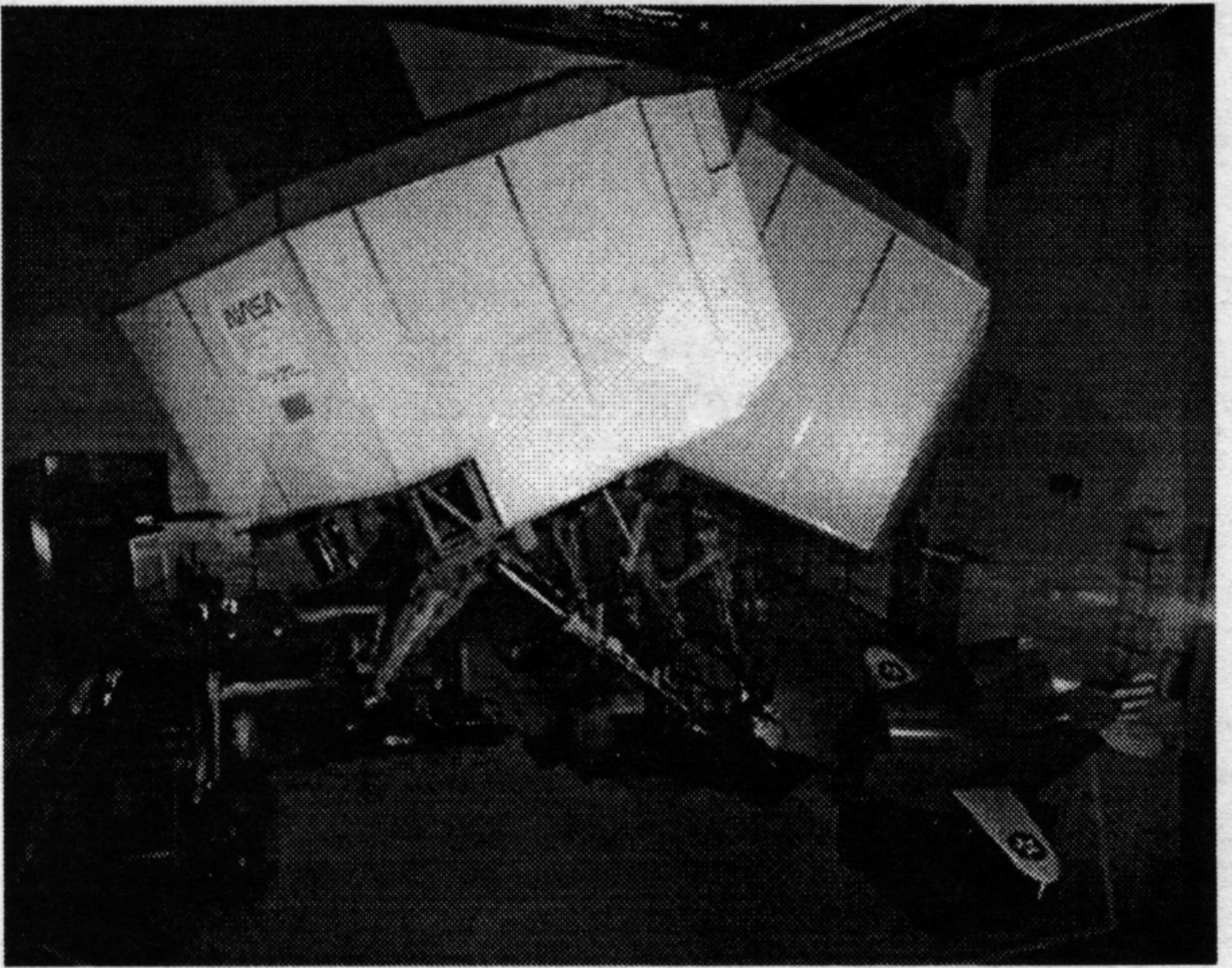


Figure 1: Time lapse photograph of ACFS in motion



Figure 2: ACFS flight deck prior to overhaul