AIAA Meeting Papers on Disc, 1996, pp. 374-384
A9635043, AIAA Paper 96-3517

The NASA 747-400 flight simulator - A national resource for aviation safety research

Barry T. Sullivan
NASA, Ames Research Center, Moffett Field, CA

Paul A. Soukup
NSI Technology Services Corp., Sunnyvale, 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 describe the NASA-Ames Current Technology Glass Cockpit Flight Training Simulator, located at Moffett Field, California. This unique simulator is used to conduct aviation human factors and airspace operations research. The simulator is an exact replica of a cockpit of one of the most sophisticated and advanced aircraft flying in the world today. Although the simulator replicates a typical flight training simulator, it has unique research capabilities above and beyond the normal training simulator that is used to train today's airline pilots. We describe the NASA simulator and its advanced features, including its unique research capabilities. We also describe some of the research that has been conducted in the cab since its installation, and review some of the upgrades that are currently in progress or will be conducted in the near future. (Author)

96-3517

A96-35043

AIAA-96-3517-CP

THE NASA 747-400 FLIGHT SIMULATOR: A NATIONAL RESOURCE FOR AVIATION SAFETY RESEARCH

Barry T. Sullivan, NASA-Ames Research Center *
Paul A. Soukup, NSI Technology Services Corp. **

ABSTRACT

This paper describes the NASA Ames Research Center's Current Technology Glass Cockpit Flight Training Simulator located at Moffett Field, California. This unique simulator is used to conduct aviation human factors and airspace operations research. The simulator is an exact replica of a cockpit of one of the most sophisticated and advanced airplanes flying in the world today. Although the simulator replicates a typical flight training simulator, it has unique research capabilities above and beyond the normal training simulator that is used to train today's airline pilots. This paper will describe the NASA simulator and it's advanced features, including it's unique research capabilities. It will also describe some of the research that has been conducted in the cab since its installation, and will also review some of the upgrades that are currently in progress, or will be conducted in the not too distant future.

INTRODUCTION

During recent years commercial airplanes have transitioned from cockpits equipped with analog instruments, gauges and switches to highly automated computer driven glass cockpits. Despite numerous advances in technology, most aviation accidents are still the result of human error. In order for scientists to study these types of errors a unique facility was needed which would enable them to examine the types of issues that are existent in today's modern cockpits. In late 1993, a unique Current Technology Glass Cockpit Flight Simulator was installed at the NASA Ames Research Center's Crew-Vehicle Systems Research Facility (CVSRF). This simulator provides researcher's and scientists with a means to explore issues pertaining to aviation human factors and airspace operations in a full-mission simulation environment. This unique simulator is but one integral component of the CVSRF. The CVSRF, located at Moffett Field in California, is a national research facility which was built in the early 1980's to study aviation safety issues.

The CVSRF is comprised of two full-mission flight simulators - an Advanced Concepts Flight Simulator (ACFS) and a Current Technology Glass Cockpit Flight Simulator, as well as an air traffic control (ATC) simulator. The ACFS represents a "generic" operational flight deck of the future, while the Current Technology Glass Cockpit Flight Simulator reflects a state of the art aircraft equipped with today's latest technological advances. Each of the simulators are integrated with the facility's ATC simulation providing the capability to perform complex full-mission human factors and airspace operations studies. This paper will focus strictly on the features and capabilities of the Current Technology Glass Cockpit Flight Simulator and how these features are utilized in supporting national research programs related to improving aviation safety.

The NASA Current Technology Glass Cockpit Flight Simulator is an exact replica of a United Airlines Boeing 747-400 airplane cockpit. It represents a modern commercial transport aircraft incorporating highly advanced autoflight and guidance systems, including a sophisticated integrated avionics and warning system (A picture of the 747-400 simulator cockpit is shown in Figure 1). All systems within the simulator function and operate just as they do in the actual airplane, allowing researchers and scientists to conduct studies examining the human-to-human and human-to-machine interfaces encountered in the flight deck environment with a high degree of fidelity and realism. Unlike the typical flight training simulator used by the airlines, the NASA 747-400 simulator is enhanced with special research capabilities to support the many programs utilizing the cab. Customers originate from within NASA, industry, the airlines, universities and other government agencies such as the Federal Aviation Administration (FAA). Research objectives include developing fundamental analytic expressions of the functional performance characteristics of aircraft flight crews; formulating the principles and design criteria for aviation environments of the future; evaluating the integration of new subsystems in contemporary flight and air traffic control scenarios; and the development of new training and simulation technologies that are required by the continued technical evolution of flight systems and of the operational environment.

* NASA 747-400 Simulator Manager, AIAA Member
** 747-400 Simulator Project Engineer

SIMULATOR DESCRIPTION

The NASA 747-400 Simulator was built by CAE Electronics Ltd. and was installed at the CVSRF in September 1993. The 747-400 simulator is configured to United Airlines Tail #RT612 and is certified to the Federal Aviation Administration's (FAA) Level D requirements in accordance with *Federal Aviation Regulation (FAR) Part 121 Appendix H* and *Advisory Circular AC120-40B,* dated 29 July 1991. The simulator is also certified to the International Civil Aviation Organization's (ICAO) Level II International Qualification Standards, as defined in the international advisory circular, *International Standards for the Qualification of Airplane Flight Simulators,* dated January 1, 1992. These levels of certification are recognized by the FAA and industry as the highest possible levels of certification for airplane simulators in the world and provide immense credibility to the numerous research programs that are conducted in the NASA 747-400 simulator. The simulator compartment includes the cockpit flight deck, observer seats, an experimenter operator control station, and an engineering terminal. A floor mounted access stairway is provided to allow access to and from the flight deck compartment. Simulator features include a VITAL VIIe visual system, a digital control loading and motion system, a weather radar system simulation, and a traffic alert and collision and avoidance system. Other key features which will be described include the 747-400 cab's advanced aircraft avionics, integrated display system, digital sound/aural cues system, the simulator's hardware and software architecture, and it's unique research specific capabilities.

VITAL VIIe VISUAL SYSTEM

In compliance with FAA Level D requirements, the 747 cab is equipped with a Flight Safety International VITAL VIIe visual system. The VITAL VIIe with photo texturing and superior scene quality depicts out the window scenes in either day, night, dawn or dusk conditions. The visual system is a 3 channel, 4 monitor cathode ray tube (CRT) based system driven by a Motorola Delta series computer providing a 36 degrees vertical by 88 degrees horizontal field of view, using zero gap optics. The CRT monitors are raster-calligraphic and are capable of producing approximately 500,000 pixels and between 600 to 750 textured polygons per channel, as well as 1,000 calligraphic lightpoints for a day scene, and 5,000 lightpoints for night/dusk/dawn scenes. Numerous customized airport visual database scenes are simulated including airport scenes for San Francisco, Atlanta, Los Angeles, Boston, Chicago, Denver, Dallas-Fort Worth, New York, Honolulu, Hong Kong, Melbourne and Heathrow to name a few. Other customized databases can be developed through the use of an off-line visual modeling station. The ability to model terrain profiles is also possible. In addition, a generic airport scene capability is also provided in order to simulate non-customized airport scenes. Special weather scenes including weather fronts, thunderstorms, rain, lightning, hail, snow, fog and patchy fog are also available. Control of visibility, runway, airport and ambient terrain lighting, as well the presentation of other ground and air traffic is also available.

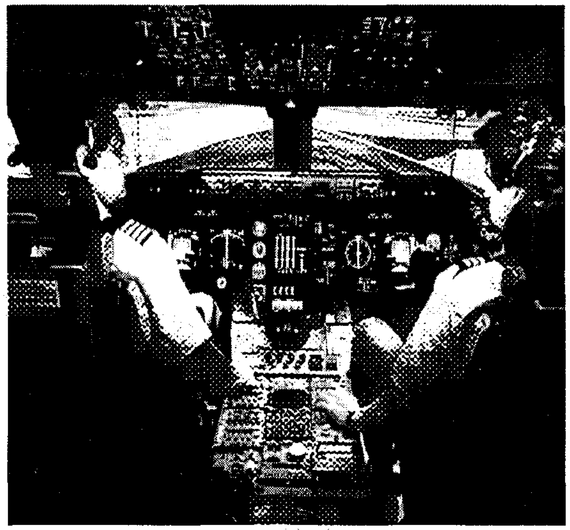

Figure 1 - Picture of 747-400 Simulator Cockpit

CONTROL LOADING and MOTION SYSTEM

Also in compliance with Level D requirements, the simulator includes an advanced digital control loading and six degree-of-freedom motion system. This system utilizes hydrostatic actuators powered by a remotely located hydraulic power supply to provide accurate motion and control feel forces. The hydraulic system consists of a CAE 600 series motion hydraulic supply unit consisting of two motor pump units connected in parallel. The hydraulic supply unit, connected to the motion base frame hydraulic system by flexible hoses, feeds the six servoactuator assemblies and the control loading actuators. The motion base frame hydraulic assembly consists of one pressure line, one return line, two drain lines for upper and lower servojack drains, and three precharged accumulators so that the system pressure does not fall below safe operational levels during worst case conditions. Hydraulic pressure required for control loading is supplied by the control loading pump in the hydraulic power supply unit. In the event of a control loading pump failure, the motion pump is also capable of supplying the control loading system with no adverse effect on motion performance. The cabinet housing the digital control electronics also serves as an interface to the host computer driving the simulator. This stand-alone DN1 cabinet houses the digital electronics, associated controls, display panels, power supplies, and test features required to control the motion and control loading systems. A CAE customized C30 board is the primary computing element in the DN1 based motion and control loading systems. The C30 computes aircraft manufacturer control surface models at a rate greater than 500 Hz. Control loading and motion servo loops run at an iteration rate of greater than 2 kHz. The software for the C30 is downloaded from the simulator host computer at load time. The C30 software communicates with the host-resident control loading and motion simulation through a serial ethernet link.

The motion system software provides cockpit movements in six degrees of freedom with movement in space of the cockpit of the simulated aircraft. The cockpit location is calculated as a moment arm from the aircraft's dynamic center of gravity. An adaptive filter software driver program is used to generate motion commands from linear and angular accelerations from the flight equations. The motion system provides physical sensations felt at the onset of an acceleration, which is then followed by low-level acceleration washout. Sustained longitudinal and lateral acceleration cues are created by use of the earth's gravity vector, and pitch and roll tilts of the cockpit. Buffet characteristics occur during appropriate flight conditions and match aircraft flight test data within very tight tolerances as determined in the *FAA Advisory Circular AC120-40B*. Special effects include the simulation of body accelerations, flap and gear buffets, stall buffets, high speed buffets, spoiler buffets, thrust reversers, engine vibrations, ground reaction forces, and weather effects such as turbulence, thunderstorms, and windshears.

The CAE 600 series motion system has an actuator stroke length of 54 inches and is capable of supporting a load of 22,000 lbs. It can simulate accelerations of +/- 1 g in the vertical direction and +/- 0.7 g's in the lateral and longitudinal axes. The maximum excursion is at least -37.5 deg to +32.5 deg in the pitch axis, +/-32 deg in the roll axis, and +/-37.5 deg in the yaw axis. The maximum velocities are at least +/-30 deg/sec in the pitch axis and +/-32 deg/sec in the roll and yaw axes. The maximum accelerations are at least +/-250 deg/sec/sec in all three rotational axes.

The simulator also includes automated testing and tuning features to assure control loading and motion system fidelity. In addition, the simulator is man-rated to ensure that the simulator is safe and that all possible precautions have been implemented for all users and participating subject pilots using the cab. A series of interlocks have been implemented to ensure operational safety. In order for the motion system to be activated each of the interlocks must be closed. Should any of the interlocks be opened, the motion system will deactivate and come to a rest position, thus ensuring operational safety. Figure 2 depicts the 747 simulator on motion.

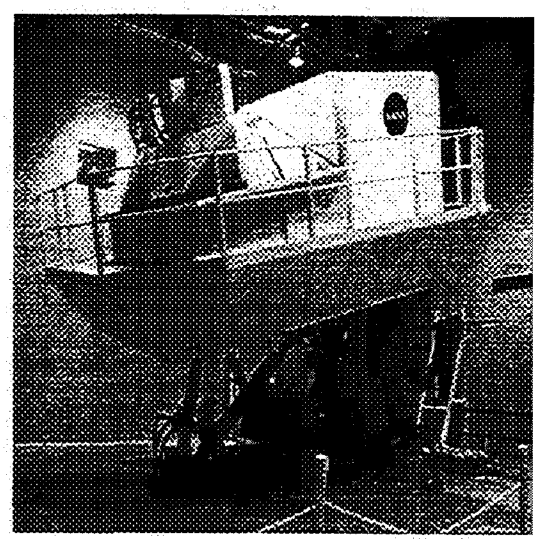

Figure 2 - Picture of 747 simulator on motion.

WEATHER RADAR SYSTEM SIMULATION

The 747 simulator includes a weather radar system simulation which is based on using stored weather cell shapes, which are scanned under software control to present a realistic radar display of a weather front. These fronts must be closely coupled with the 747 simulator's visual and motion systems to ensure simulation fidelity and realism and include precipitation and turbulence effects. Weather radar display information is presented to the pilots via the navigation system displays. Each of the weather cells has a vertical profile enabling the simulation of antenna tilt effects by displaying the projected image of the cloud horizontal plane at the intersection of the antenna boresight and the centerline of the weather cell. Special effects such as visibility, lightning and thunder can also be selected for added realism. Range attenuation and weather cell occultation are also simulated. Sensitivity time control and path attenuation compensation are also simulated with respect to receiver characteristics. Up to 20 weather fronts can be built and stored in the NASA 747's weather radar system simulation. Each weather front can contain up to 20 weather cells, with a maximum of 5 cells along any azimuth. Nonadditive mixing of weather cells is also possible to create new shapes by overlapping existing shapes. The weather radar system software resides partly in the host computer and partly in the weather radar processor board. The host resident software performs database management, radar control monitoring and data processing. The board resident software performs the weather cell scanning and the radar beam processing for occultation, range attenuation and compensation.

TCAS

The 747 simulator includes a Traffic Alert and Collision Avoidance System (TCAS II) which has been implemented according to the Minimal Operational Performance Standards (MOPS) RTCA DO-185. A TCAS II processor which provides the necessary interface to drive the 747 TCAS displays and the corresponding aural warnings for traffic and resolution advisories is simulated in the simulator's host computer. The host computer simulation software generates the flight paths for intruders and other traffic, as well as controls and formats all TCAS processor inputs and outputs. The 747's navigation display and primary flight display are used to depict traffic and resolution information. TCAS intruders can be controlled by one of two methods on the 747 simulator. The first is by the simulator's own TCAS control utility which can generate as many as 12 intruders at one time within a 15 mile radius. The second is by sending intruder information via the CVSRF's air traffic control simulator. Typical threats include traffic advisories, resolution advisories with no climb/no descend commands, resolution advisories with climb/descend commands, resolution advisories with further crew action required commands, and resolution advisories with further crew action required in the presence of a second threat commands. Transponder equipment for intruder aircraft can be selected by an operator as either mode A, mode C, mode S, or none. Intruder aircraft with mode A transponders provide only bearing and range information on the TCAS displays. Mode C and S transponders provide relative altitude, bearing and range information, and nontransponder equipped intruders do not generate any display information. Resolution advisories are provided for only mode C and mode S transponder equipped aircraft.

AIRCRAFT AVIONICS

The B747-400 simulator's advanced avionics includes seven aircraft Line Replaceable Units (LRUs) - two Flight Management Computers (FMCs), three Multi-function Control Display Units (MCDUs), an ARINC Communications, Addressing and Reporting System (ACARS) Management Unit, and a Ground Proximity Warning System (GPWS) Unit. The Honeywell FMCs handle flight performance management, navigation, guidance, thrust control, and display data processing. Through an ARINC interface, the FMCs receive information from other LRUs such as the MCDUs and the ACARS, and also from simulated systems such as the Inertial Reference System (IRS), Global Navigation Satellite Sensor Units (GNSSUs), radios, Air Data Computers (ADC), and fuel system. The data received by the FMCs must behave exactly as in the aircraft. Any discontinuity or irregularity will result in the FMCs acting abnormally. However, certain actions that do not occur in the aircraft cannot be avoided in the simulator. For example, maneuvers such as repositioning the simulation from point to point in a single iteration or freezing the simulation will cause undesired effects such as winds or inaccurate trajectory calculations. Software in the FMCs called SIMSOFT handles these situations by using an ARINC 610 protocol which will inhibit certain FMC inputs and computations. Outputs from the FMCs go to the host computer on the ARINC interface to be used as inputs to the various simulated systems such as the Integrated Display System (IDS), the Central Maintenance Computer (CMC), and the autoflight system. The FMCs also send outputs to the MCDUs, the ACARS, and the cockpit printer. The FMCs are loaded with operational software and a navigational database. The operational software also contains a performance database in order to provide the FMCs with data it needs to calculate pitch and thrust commands. The navigational database includes information that would be contained on navigational charts such as location of navigational aids, airports, runways and other selected airline information. New operational software can be loaded when required, and a new navigation database is normally updated every 28 days.

The three MCDUs, which are also built by Honeywell, allow the pilots to interact with the FMCs through a keypad and display. The majority of system messages and warnings are displayed through the IDS. However, the FMCs can generate forty-two different messages to be displayed in the scratch pad of the MCDUs. These messages are related to guidance and navigational items that require action by the flight crew. The two forward MCDUs permit the Captain and First Officer to interface with and monitor the FMCs, the navigation radios, the ACARS, and SATCOM. The center, rear MCDU only interacts with the ACARS, SATCOM, and CMC. SATCOM is a voice and data satellite based communications system that represents a significant improvement over HF radio for connectivity, voice quality, and traffic volume capacity, especially in the oceanic environment. The CMC software simulation is limited to warning system confidence tests and selection of various aircraft system maintenance pages.

The Collins built ACARS unit serves as a method of communication between a ground station and the B747-400 aircraft using VHF radio or SATCOM. The ACARS interfaces directly with the FMCs, the MCDUs, the VHF/SATCOM receiver, and the cockpit printer. ACARS has a voice and data mode, respectively. In the voice mode, conventional audio techniques are employed. While in the data mode, the flight crew transmits and receives data from a ground station via a digital data-link. The flight crew can send (downlink) position reports, fault reports for maintenance, and requests for information to the airline dispatcher. Information such as departure details, dispatch release, or free text can be sent (uplink) to the flight crew. In the simulator, information is data-linked via a dedicated interface card to the experimenter operator station (EOS). The simulated ground station on the EOS has the capability of receiving downlinks and generating uplinks.

The Sundstrom GPWS unit provides ground proximity warnings with appropriate voice, and other aural and visual indications.

DIGITAL SOUND/AURAL CUES SYSTEM

An 8-channel sound system with 19 speakers implemented throughout the entire flight compartment simulates the various sounds and aural warnings that are audible within the 747 flight simulator. Simulated sounds are generated, processed and controlled digitally using digital signal processing techniques. Attention to direction, frequency and amplitude of simulated sounds ensures realism. Controls have been provided for overall sound system volume, as well as software control to adjust the relative levels of simulated sounds. Simulated sounds are automatic and are representative of typical sounds heard throughout all phases of flight. These include aerodynamic hiss, engine surge, reverser sounds, compressor stall, runway rumble, explosive decompression, crash, rain, hail and thunder. The sound system produces the appropriate noises through a series of frequency generators, noise generators, and sound look-up tables. The sounds are derived from audio tapes supplied by the aircraft manufacturer. Data obtained from the spectral analysis of these recordings is entered into the host computer using various utilities. A serial ethernet and a Datapath C Microprocessor Controller DMC-16 card links the host computer to the sound cards in the sound chassis. Pure sounds are generated on a dedicated circuit card and sent to the appropriate loudspeakers via mixers and amplifiers. Other cards are dedicated to producing noise such as white noise and impact sounds. Using host based sound frequency analysis tools, sound measurements can be taken and verified against flight test results ensuring fidelity and realism. This is a requirement for FAA Level D certification.

The audio interface is composed of an audio chassis and a Digital Audio System Interface Unit (DASIU). In the audio chassis, signal generator cards produce various tones for communications and avionics including aural alerts generated as part of the Modular Avionics and Warning Electronics Assembly (MAWEA) system. These include bells indicating an engine or APU fire, unsafe warning sounds, caution sounds, selective calling, ground proximity warnings, altitude alerts, and stall warning alerts. A personal computer based digital voice system simulates the ATIS and VOICE.

SIMULATOR HARDWARE ARCHITECTURE

The simulator is composed of computers that simulate on board systems and stimulated computers that exist on the B747-400 aircraft. Taking advantage of IBM's latest technology over the last few years, the host computer driving the majority of the simulation, is a single processor IBM RISC 6000, Model 580. The host is networked to various computers including a separate data collection computer which is an IBM RISC 6000, Model 560, and four Silicon Graphics Inc. (SGI) Indigos which control the graphics for the two experimenter operator stations. Using a non-standard ethernet protocol for real-time and higher bandwidth, the host is connected to an interface that drives the simulator hardware. The simulation system interface includes a CAE standard input/output (I/O) interface, a special ARINC interface, a High Resolution Graphics Card (HRGC) interface, a control loading and motion system interface, a visual system computer interface, and an audio and sound system interface.

The CAE standard I/O interface handles analog signals for such systems as the flight instruments and discrete signals such as push buttons and circuit breakers. The ARINC-429 interface is a serial data bus that connects the host computer to the busses of stimulated aircraft components that utilize the ARINC-429 standard. The ARINC-429 protocol specifies a serial system for data interchange between different aircraft LRUs. The hardware portion of this interface is based on three types of boards that exchange and format data between the host computer via the ethernet and the ARINC DMC card.

The HRGC interface between the host computer IDS simulation and the six high resolution CRT displays in the cockpit consists of three chassis containing eleven High Resolution Graphics Cards and five DMC-16 boards. The HRGC is a microprocessor based card that has computing power comparable with an SGI IRIS workstation. It displays 1280x1024 pixels at a refresh rate of 60Hz. It is capable of simultaneous display of 256 colors and draw rates of 117,000 vectors per second and 44,000 filled triangles per second. The DMC-16 boards provides control and communications between the HRGCs and the host computer system. Eight HRGCs are used to drive the IDS pages and three are used for weather radar system applications. The HRGCs contain all the graphics information needed to drive the CRTs. A videoswitcher carries the red, green and blue (RGB) signals from one set of HRGCs to a given CRT. A block diagram depicting the 747

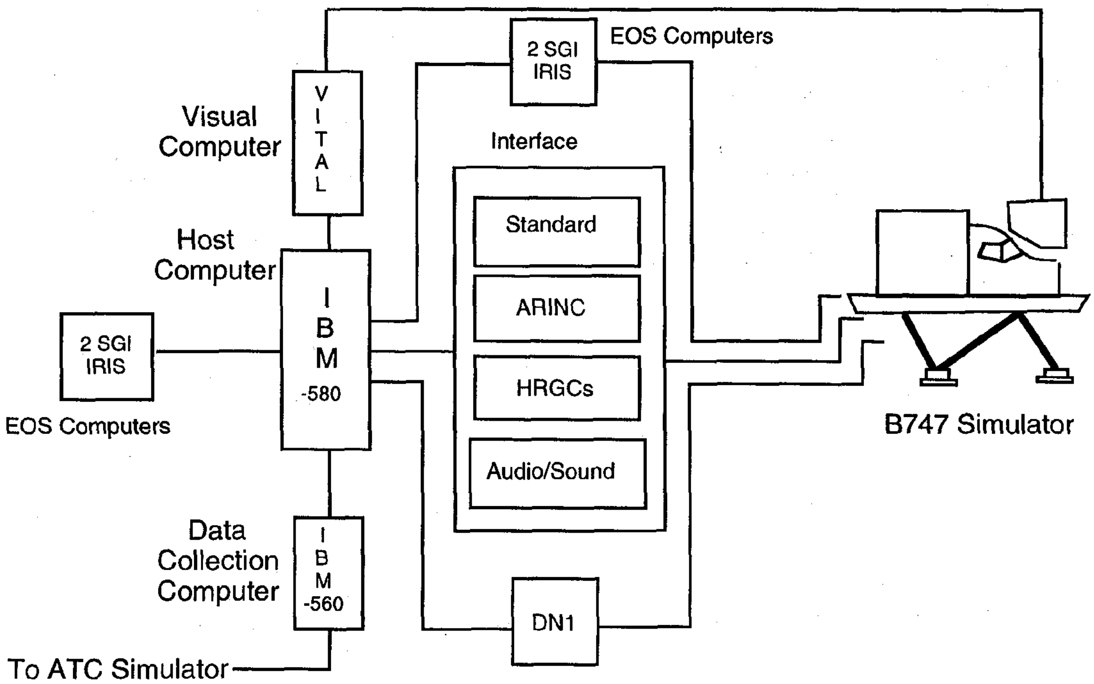

Figure 3 - NASA 747-400 Simulator Hardware Architecture

simulator's hardware architecture is shown in Figure 3.

SIMULATOR SOFTWARE ARCHITECTURE

All software on the IBM 6000s and SGI Indigos operate in a UNIX environment. The simulation software programs are written in high level languages such as FORTRAN or C, and are structured in a modular fashion. Configuration and control of the software is performed by a CAE developed real-time executive called SIMEX-Plus. It controls the linking, loading, executing, and scheduling of software modules. For configuration control the utility uses the load module concept. Each load module is a complete and independent package of the simulation called a configuration. Therefore, a configuration can be developed and maintained for an experiment without impacting other experiments. SIMEX-Plus also ensures that software resident on the simulator is properly controlled and that a history of changes is kept. Other utilities include a computerized test system which enables users to monitor, set, or plot global variables. The performance evaluation utility monitors the timing of all modules and processes so that users can be sure that no excessive computation is occurring. Also, a navigational database development tool allows users to create or modify navigational features such as radio aids or runways. There are also utilities for software maintenance and simulator status reporting.

All critical simulation models such as flight controls, aerodynamics, motion, flight instruments, aircraft position, and visuals execute at the critical rate of 30 Hz. The scheduling is dictated by two dispatcher programs, one for synchronous operations and the other for asynchronous operations. Modules are called at defined intervals anywhere from 33 to 266 milliseconds on the synchronous dispatcher, and from 50 to 300 milliseconds on the asynchronous dispatcher. A module's position in the dispatcher depends on the nature and significance of it's computations. Precise and balanced scheduling on the IBM RISC 6000-580 ensures that the facility enjoys a fifty percent spare time capability that can be used for development and other external purposes.

RESEARCH SPECIFIC CAPABILITIES

The NASA B747-400 simulator is unique in that its purpose is to support human factors and airspace operations research rather than being dedicated to flight crew training. This requires differences primarily in three areas - the ability to modify the flight displays and other flight crew interfaces, enhanced control over external effects, and the capability for powerful but flexible data collection and performance measurement.

PROGRAMMABLE FLIGHT DISPLAYS

The 747-400 is equipped with an Integrated Display System (IDS) which is composed of the Electronic Flight Instrument System (EFIS) and the Engine Indication and Crew Alerting System (EICAS). The EFIS portion of the IDS is composed of the Primary Flight Display (PFD) and the Navigation Display (ND) for both the Captain and First Officer. The PFD displays attitude/direction/altitude/airspeed information, while navigation, performance, and weather radar information is displayed on the ND. The EICAS displays engine data, caution and warning messages, and subsystem data and faults. On the B747-400 simulator, the IDS is programmable to support the development of new or revised flight displays and/or system synoptics to support aviation safety research. The actual aircraft IDS is normally comprised of six integrated display units (IDUs), which are driven by three EFIS/EICAS Interface Units (EIUs). The information displayed on the IDUs is controlled by the unique IDU location, control panel command, and automatic or manual source switching. On the simulator, the IDUs are simulated through the use of six commercial, raster-based CRT displays which are driven by the HRGC chassis. When the simulator is loaded, the HRGCs contain down load files which include all the EFIS and EICAS display information. The down load files can be modified in order to create or alter IDS display pages. The files can be edited using a CAE developed utility called TIGERS on a remote graphics workstation. The TIGERS utility is a windows based tool that allows the user to create or modify dynamic objects with attached attributes such as color, scale, or position that can be driven from the host computer. The IDS simulation model, resident on the host computer, provides the EFIS and EICAS system logic to drive, in real-time, the HRGC graphics software on the IDS pages. The software also provides for EIU functions, including data processing and formatting for EICAS message generation, and interfacing with other simulator hardware and software systems. Using the videoswitcher, there is no limitation as to which IDS page can be displayed on which IDU, giving the user even greater flexibility. The IDS simulation facilitates system modifications on an experimental basis without being dependent on aircraft hardware. The NASA 747 simulator was the first U.S. simulator with programmable flight displays to receive FAA Level D certification.

EXPERIMENTER OPERATOR SYSTEM

The Experimenter Operator System on the NASA B747-400 simulator, not unlike training simulators, provides the capability to initiate, monitor, and control activities in the cockpit during a simulator session. However, the NASA 747 flight simulator has additional features such as an off-board experimenter operator station (EOS), repeater monitors, data collection facilities, and the ability to connect with the CVSRF ATC simulator and other simulators outside the facility. Each EOS is composed of two touch-screen SGI IRIS display systems providing both display of current information and user friendly, touch screen controls for manipulating the simulator. In addition, both the on-board and off-board stations provide control of the simulator through programmable control panels (PCP's) and various buttons and switches. Each EOS enables the operator to manipulate or control a variety of variables via different pages and windows, (i.e. the position set page establishes the simulator on the runway or gate, or trimmed in flight at any airport in the world that can support a B747-400 aircraft). Weather is altered on the weather set page where winds, temperatures, turbulence, and special effects such as lightning, thunder, or blowing snow can be set. Aircraft weight and balance are controlled on the aircraft configuration page. Approximately three-hundred system malfunctions are accessible through individual malfunction control pages. However, the primary means by which an operator can control an experiment and the flight tasks in a repeatable manner are through scenarios developed off-line in advance of the experiment, using a PC-based Scenario Editor Utility (SEDU). Scenarios provide the researchers with the ability to automate and control configurations and events during a simulation by preprogramming a series of EOS functions. Another important tool available on the EOS is the capability of creating a "snapshot" of the simulator that can be recalled at a later time. Snapshots can be permanently saved as "setups" and then used within a scenario. This feature is important in the research environment so that a researcher can repeat a procedure from a precise initial starting point in order to attain reproducible results. An additional benefit to the researchers are the off-board EOS station repeater monitors which display all six cockpit displays and an out-of the-cockpit scene to allow the researchers to observe, in real-time, exactly what the pilots are seeing inside the cab.

EXPERIMENT DATA COLLECTION

The B747-400 simulator is equipped with a specialized system for collecting run data during a simulator session. A list of variables and the rate at which they will be captured is created on the IBM RISC 6000-560 data collection computer before the session. The name of the list is then entered on the EOS to initiate the recording of the data. The information is recorded by the data collection computer and is stored on hard drives. An average of 2000 parameters (4 bytes) at 30 Hz can be recorded on contiguous disk space of up to 11.3 gigabytes. Experimental data can also be collected in the form of audio and video. The EOS can control the on/off state and vary the volume of up to eight different microphones in the cockpit or at the EOS stations. The audio channels are then mixed together via a digital/audio mixer to provide an analog output to the off-board speakers and the video recorder. In addition, six miniature, low light video cameras are installed around the cockpit giving the researcher the ability to videotape six specific views plus an out-of-the-cockpit view during the simulator session. Time-stamped video/audio recording combined with digital data collection gives the researcher a powerful tool to study the crew and crew-to-vehicle interactions during a simulator session or experiment.

AIR TRAFFIC CONTROL (ATC) SIMULATION INTERFACE

The CVSRF has a separate air traffic control (ATC) simulator which provides realistic air-ground communications and coordinates the appearance of aircraft visible from the simulator cockpit. This system is hosted on a separate computer, a VAX-6310. The ATC simulation consists of four air traffic controller stations and four "pseudo-pilot" stations. Each one of these stations is equipped with multi-channel voice disguisers and are linked to each other, as well as to the 747 simulator. The four "pseudo pilot" stations are able to control numerous pseudo-aircraft at one time. The ATC simulator interacts with the communications, TCAS, and visual systems on the B747-400 host computer. The EOS provides a control switch which determines whether the pseudo aircraft are displayed as TCAS intruders on the B747-400 or whether the intruders originate from the host computer's preprogrammed TCAS scenarios. This gives researchers the option to monitor and record the interaction between the flight crew and ATC, or the flight crew with researcher-designed TCAS scenarios. The ATC simulator is connected to the host computer via the data collection computer through a direct memory access (DMA) link. This link consists of a DR11W interface residing on the data collection computer and a DRB32W interface on the ATC simulator's VAX 6310.

LINKS TO OTHER SIMULATION FACILITIES

The B747-400 simulator is currently linked with two other facilities: the FAA Technical Center in Atlantic City, and the FAA Aeronautical Center in Oklahoma City. The FAA Technical Center includes a unique air traffic control simulation complex which is used to conduct airspace operations research. The facility is linked to several other simulators throughout the country via a high speed digital voice/data communications system. The 747 is linked to the Technical Center by two discrete voice and data lines respectively, which operate at 9600 bps each. These four lines are fed through a multiplexor that combines all of the voice and data communications into a single 56 Kbps dedicated line. The 747 is one of several participating simulator's around the country, each of whose lines are combined into a single 1.544 Mbps T-1 line at the FAA Technical Center. The voice lines transmit all of the flight crew-controller communications. The data lines transmit flight simulator state information such as airspeed, position and altitude to the Technical Center and ATC information such as the time and aircraft designation to the flight simulator.

An additional link to the FAA's Aeronautical Center in Oklahoma City allows FAA personnel to monitor real-time results of an on-going experiment. This link employs a simple modem protocol over the telephone lines. Flight simulator state information such as position, airspeed, altitude, spatial deviations, and auto pilot modes are sent at 9600 bps.

RESEARCH PROGRAMS

Although the NASA 747-400 flight simulator is maintained to the highest recognized certification standards for training simulators, it is not used for training. It is used strictly for aviation human factors and airspace operations research. Participating subject crews are line-qualified 747-400 pilots, thus further validating the value of the results of the research programs conducted in the simulator. Since the simulator's activation in the fall of 1993, over twenty studies have been conducted in the NASA 747 simulator. Typical studies include the following:

Data-Link: A series of studies have been conducted by NASA and FAA to examine the use of digitized information transfer for the presentation of air traffic control information. These studies are concerned with trying to reduce the number of incidents due to communications problems between pilots and air traffic controllers. The results of these studies will help in the future design and development of guidelines and procedures for the implementation of digital information transfer in future commercial transport aircraft.

Converging Approaches: The FAA's System Capacity Office developed a program to focus on the improved utilization of instrument landing system (ILS) converging approaches and examined the related operational aspects towards improving efficiency. Currently, ILS terminal procedures (TERPS) missed approach primary obstacle clearance surface criteria impose capacity constraints on ILS converging approach operations. The FAA investigated procedures utilizing flight management system equipped aircraft to conduct simultaneous converging missed approaches from decision heights between 500 to 700 feet above ground level. Results from these studies showed that converging approaches were possible and could be performed safely using lateral offsets from the localizer between 90 to 100 degrees, thereby allowing decision height minimums to be reduced. Implementation of these new procedures are currently in process for Chicago O'Hare and Dallas-Fort Worth Airports using a reduced decision height of 650 feet.

Center TRACON Automation System Descent Advisories: This experiment examined the compatibility of a new air traffic control Center TRACON Automation System (CTAS) descent advisory clearance with the operational procedures available on current commercial aircraft. The intent of this study was to identify and eliminate any problems with the delivery, timing or execution of successfully flying CTAS descent advisories. CTAS is a new air traffic controller automation tool which helps controllers schedule traffic more efficiently. Results of this study will help develop new phraseology and guidelines for using CTAS descent advisories which will eventually be tested during field tests at Denver International Airport.

Moving Map Display: This NASA study evaluated the use of an integrated moving map display for presenting ground taxi information which enabled pilots to navigate about the terminal area in low visibility weather conditions. Navigation data to the map display was provided via a simulated differential global positioning system (DGPS). The information was presented to participating flights crews on their navigation displays via data-link. The enhanced map display depicted a topographical view of the terminal area including runways, taxiways, gates, position of other aircraft, ATC clearance information, relative aircraft position, heading and ground speed. Results of this study indicated a definite reduction in crew workload in using the integrated map display versus the use of the conventional paper Jeppesen maps that are typically used today. In addition, crew's taxi time performance was improved as well by using the enhanced map display. Other potential benefits possibly gained by this type of display include improved terminal area capacity by enabling airplanes equipped with this advanced technology to operate in reduced visibility conditions, and a possible increase in safety by reducing the chances of possible ground incursions.

Multiple Parallel Approaches Program: This on-going FAA program evaluated the traffic handling capabilities of conducting multiple simultaneous independent instrument landing system approaches in instrument meteorological conditions. These studies evaluated the feasibility of conducting dual and triple parallel runway operations with varying runway separation distances by taking advantage of advanced radar systems such as the Precision Runway Monitor (PRM). This advanced radar system employs a faster radar sweep, allowing more accurate tracking of terminal area traffic. The 747-400 simulator was one of several simulators connected to the FAA Technical Center's air traffic control simulation complex via a high speed digital voice/data communications system. The results of this study provided the FAA with a new separation standard for parallel approach operations.

3-D Audio: This NASA study evaluated the use of spatialized sound techniques for detecting other ground traffic during taxi operations in the terminal area. For this study, directionalized auditory warnings were briefly enunciated over customized (stereo) pilot headsets to attempt increasing the crew's situational awareness about non-visible hazards such as other nearby aircraft, or as annunciations for intersecting taxiways during taxi operations. The main thrusts of this study were to determine the time to complete taxi routes under spatially-audio assisted and non-assisted conditions, incursion warnings and taxiway announcements. Preliminary results indicated that all participating pilots expressed a strong preference for the ground collision avoidance alert to be included with a future system, hopefully decreasing the amount of time a pilot would need to respond to a possible ground incursion.

Propulsion Controlled Aircraft: This study evaluated the use of a propulsion only flight control system in the event in which an airplane's primary flight control system malfunctioned or became inoperative. This study made use of control laws developed at NASA Dryden to control aircraft flightpath angle by manipulating aircraft thrust to maintain pitch and roll control during approach and landing operations. Results of this study indicated that participating pilots were very excited about the fly-by-throttle concept. A follow-on study is currently being planned that will extend the use of the propulsion controlled flight algorithms to include engine out performance as well as other phases of flight for a four engine aircraft.

These programs are just a representative sample of the type of programs that are supported on the NASA 747-400 simulator. Over the upcoming years, the 747 simulator will be used extensively in support of NASA's Terminal Area Productivity (TAP) and Advanced Air Traffic Technologies (AATT) Programs. In addition, NASA will continue to work with the FAA in trying to resolve human factors and airspace operations issues by supporting the FAA's National Plan for Human Factors and Free Flight Programs.

FUTURE PLANS

Although the NASA 747-400 simulator represents a state of the art aircraft, it too will evolve over the upcoming years. Probably the most significant upgrade to the simulator which is currently taking place in the airplane as well, is the implementation of the Future Air Navigation System (FANS). FANS is an advanced avionics system upgrade that will utilize global satellite based information for communications, navigation, surveillance and air traffic management for the twenty-first century. The FANS upgrade is primarily a Boeing-Honeywell implementation to upgrade the 747-400 with FANS compliant avionics, taking advantage of satellite navigation and communications systems, and technology advances in automation. FANS will utilize Global Positioning System (GPS) information for aircraft tracking and navigation, supporting enroute and terminal area non-precision approaches. In the future, ground based augmentation is expected to extend the GPS capabilities by including precision approaches. Other FANS modifications to the simulator include upgrades to the various installed avionics, specifically the two FMC's, the three MCDU's, the Multi-input Cockpit Printer, the ACARS Management Unit and SATCOM. Also, there are changes integrated as part of the FANS package which require modifications to the appropriate simulated systems including the 747-400's EICAS, MAWEA system for pending data-link messages, and the modification of the navigation displays depicting the use of GPS data for primary navigation. New key features resulting from the FANS upgrade include Automatic Dependent Surveillance (ADS) allowing more precise aircraft tracking, Airline Operational Communications Data-Link (AOC DL) of flight plan information, winds forecast data and route modifications, and Air Traffic Control Data-Link (ATC DL) of air-ground messages including clearance uplinks. In the real world environment the ADS and ATC DL functions are generally hosted on controller workstations with graphical user interfaces for selecting or displaying the data-link information for the airplanes flying in the airspace in the controller's jurisdiction. For the simulated environment, the interaction for ground support functions such as AOC DL, ATC DL or ADS are provided via specially designed control pages on the 747-400 simulator's Experimenter Operator's Station (EOS). All data-link applications have airborne and ground-based counterparts which exchange data through specially formatted messages and are transmitted via an ACARS network. The airborne side of these applications are included as part of the upgraded avionics. The ground based applications required development for a simulated environment. Some of these features include Required Time of Arrival (RTA) utilizing time based navigation, and Required Navigation Performance (RNP) which compares actual position versus required position on a given route. The significance of the FANS upgrade is that it will enable the CVSRF to support important national programs such as NASA's AATT Program and the FAA's Dynamic Aircraft Route Planning (DARP) Program. These two programs will rely very heavily on the new capabilities provided by the FANS upgrade.

Other upgrades envisioned over the upcoming years include the integration of some advanced display symbology depicting potential conflict alerting schemes, enhanced collision and avoidance logic, reduced separation, vertical situation, and advanced ground taxi displays to name a few. These advanced displays will take advantage of the 747 simulator's reprogrammable flight display capabilities, and will attempt to increase aviation safety by hopefully reducing pilot workload. In addition, integration of a heads up display is being considered for the 747-400 simulator. Technology advances in the future will enable the integration of a smaller and less obtrusive HUD system which can be used to study advanced HUD symbologies that will allow pilots to navigate about the terminal in low or zero visibility conditions. As an extension of the FANS upgrade, integration of ADS-B is envisioned to be installed in all aircraft some time in the not so distant future. This will allow aircraft to determine the detection and flight path of other aircraft in the nearby vicinity representing an enhanced traffic and collision avoidance capability.

SUMMARY

The NASA 747-400 Flight Simulator is an essential and vital tool for studying issues pertaining to aviation human factors and airspace operations research. Since its inception, numerous studies have been conducted aimed at improving aviation safety and the overall efficiency of the national airspace system. This unique facility has enabled and will continue to enable scientists to develop and test new concepts in a realistic cockpit environment through the use of full-mission simulation. The NASA 747 simulator will allow researchers to conduct studies that examine how crew members interact with each other and how they interface with advanced automation concepts in the ever changing flight deck environment. The facility will continue to make an impact on the current and future aviation environment by it's continuous support of important national programs such as NASA's TAP Program, AATT Program, the FAA's National Plan for Human Factors and Free Flight. This facility will continue to play a vital role in enhancing aviation safety over the years to come.

REFERENCES

1. CAE Boeing 747-400 Full Flight Simulator for NASA, Volume 1: Technical Specification, TPD 08593-1 Rev. 3, CAE Electronics Ltd., St. Laurent, Canada, June 1992.

2. 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.

3. CAE Boeing 747-400 Full Flight Simulator, Software Documentation, Software Avionics, Integrated System Display, 10015347 Rev. 0, CAE Electronics Ltd. St. Laurent, Canada, January 1994.

4. CAE Boeing 747-400 Full Flight Simulator, Audio System Maintenance Manual, TPD 10483 Rev. 0, CAE Electronics Ltd., St. Laurent, Canada, January 1994

5. CAE Boeing 747-400 Full Flight Simulator, Serial Communication System Maintenance Manual, TPD 10485 Rev. 0, CAE Electronics Ltd. St. Laurent, Canada, March 1994.

6. CAE Boeing 747-400 Full Flight Simulator, Sound System Maintenance Manual, TPD 10488 Rev. 0, CAE Electronics Ltd., St. Laurent, Canada, October 1993.

Figure 1 - Picture of 747-400 Simulator Cockpit

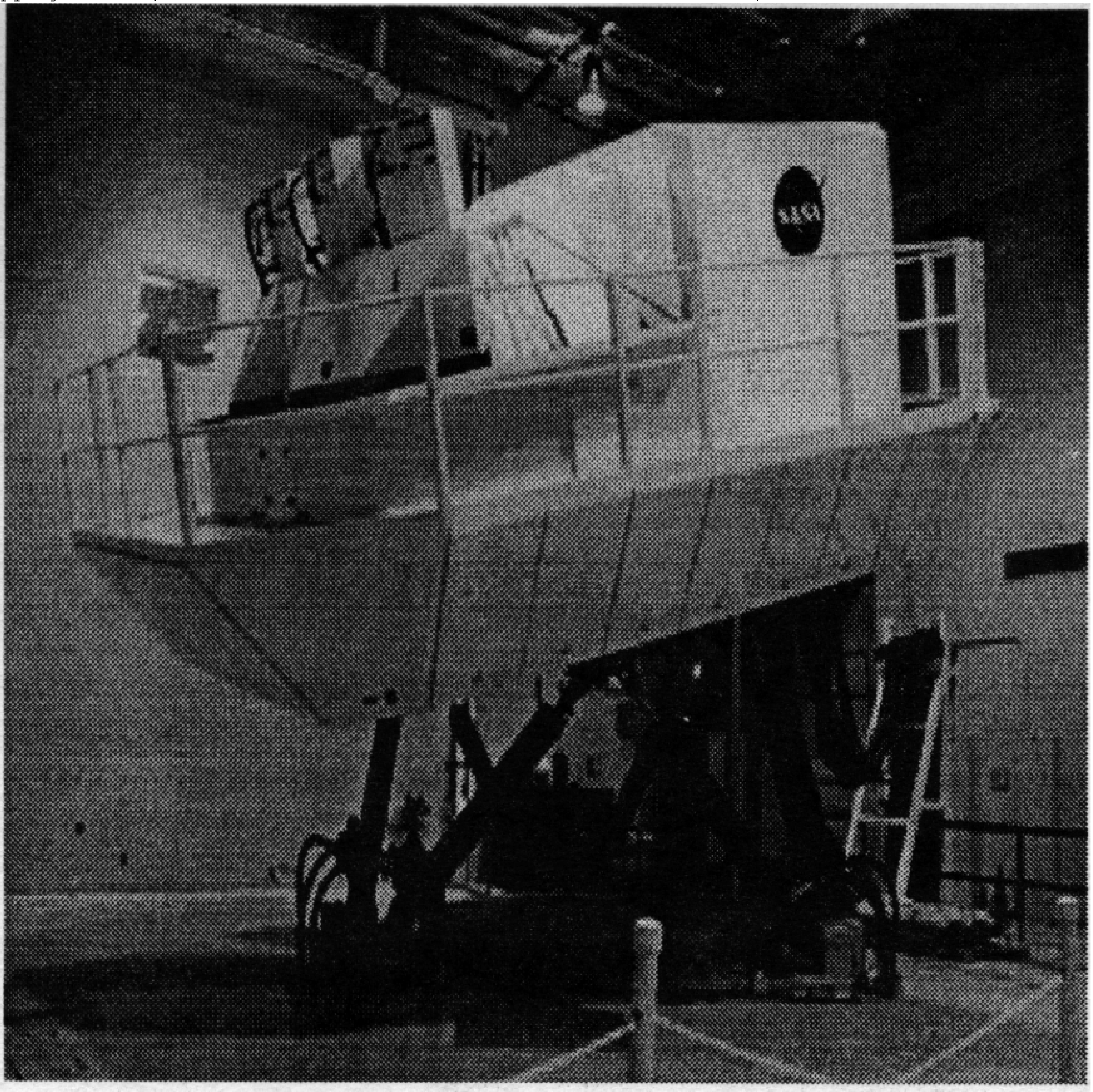

Figure 2 - Picture of 747 simulator on motion.