

Real-Time Pilot-in-the-Loop and Hardware-in-the-Loop Simulation at Gulfstream

Stephen Landers
Gulfstream Aerospace
Savannah, Georgia

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1 Abstract

Increasing system complexity and interdependence have driven Gulfstream to build real-time, pilot- and hardware-in-the-loop facilities for product development and production support. The Advanced Design Research Lab (ADRL) and Integration Test Facility (ITF) Labs, which support this function, are described. At the core of the real-time simulations are Applied Dynamics International's rtX and rtS computers running Simulink models and additional software developed at Gulfstream. Examples of how these facilities have successfully supported production and internal research projects are presented.

2 Introduction

Gulfstream Aerospace produces the world's premier business jet aircraft. The company's first corporate aircraft was the twin-turboprop G-I which entered service in 1959. Subsequent versions of the aircraft evolved through improvements in jet propulsion, swept wings, aerodynamics, avionics and systems.

In recent years simulations have been used extensively in the product development process. As system design complexity and interdependence have increased on recent Gulfstream aircraft, the fidelity of the engineering tools has improved as well. Desktop simulations are executed in a non-real-time environment and are primarily limited to subsystem testing. Gulfstream's Integration Test Facility (ITF) and Advanced Design Research Lab (ADRL) have constructed test facilities that provide real-time pilot- and hardware-in-the-loop integration test capabilities. By integrating visual systems, force-feedback control systems, aircraft hardware and simulations, the ITF and ADRL facilities provide increasing levels of fidelity to best represent the aircraft based on the user's requirements.

With the development of new advanced aircraft, early systems integration testing becomes more critical to program success. The amount of systems testing required to validate and verify these systems also increases with complexity. Flight testing is expensive and in some cases hazardous, so simulations are used as a means to reduce both risk and cost. Through simulations, tests can be performed under controlled and repeatable conditions. Data from aircraft can be played back through the simulation to identify root causes of anomalies and develop appropriate solutions.

Central to the ITF is a flexible simulation architecture utilizing in-house developed applications in conjunction with products from Applied Dynamics International (ADI) and The MathWorks. To maximize traceability and commonality during the engineering process, simulation components have been developed that can be used in any of the facilities.

Gulfstream engineers and flight crews have successfully utilized the various simulation, hardware, and lab configuration capabilities provided by the ITF and ADRL test facilities on recent development programs. Use of these integration tools enabled the product development teams to identify and resolve issues early in the process and mitigate previously unforeseen integration issues prior to actual aircraft level tests.

2.1 Abbreviations

AD	Analog to digital
ADI	Applied Dynamics International
ADRL	Advanced Design & Research Lab
AFC	Advanced Flight Controls
CAS	Crew alerting system
CASE	Conceptual Advanced Simulation Environment
COTS	Commercial, Off The Shelf
DCU	Display Control Unit
DU	Display Unit
FBW	Fly by wire
IG	Image Generator
I/O	Input/Output
ITF	Integration Test Facility
LRU	Line Replaceable Unit
OTW	Out-the-window
PVCS	A revision control application
REU	Remote Electronic Unit
SCT	Simulation Control Technologies
UDP	User Datagram Protocol
USB	Universal Serial Bus

3 Simulation Objectives/Purposes

With the development of new aircraft, the systems integration testing becomes more critical to program success. The amount of systems testing required to validate and verify these systems also increases with complexity. Flight testing is expensive and in some cases hazardous, so simulations are used as a means to reduce both risk and cost. Through simulations, tests can be performed under repeatable conditions. Data from aircraft can be played back through the simulation to identify causes of faults in order to remove errors.

4 Simulation Architecture

Three different groups within Gulfstream contributed to the building of the overall simulation. Because it is necessary to have fully integrated simulations, it was decided to create a common simulation core that each group could use and insert their components. When unit testing of the group's model is complete, it can be brought into the Integration Test Facility simulation, using the same core, and all the simulation components can be integrated to form one coherent total aircraft simulation. Traceability from the desktop simulation through each of the lab facilities can be maintained.

The simulation core contains:

- 6-degrees of freedom dynamics and equations of motion
- atmosphere and winds
- mass properties
- ground reaction
- radio navigation aids database
- propulsion

Different aircraft projects can utilize the same core functions. Simulations for a G550 can use the same core as G150. The mass properties equations are data driven, so although the data feeding that part of the simulation changes, the equations do not. The same is true for ground reaction and propulsion. A block diagram is shown in Figure 1 depicting the general layout of the simulation. Blocks shown in blue are core elements.

One of the design criteria maintained throughout the development of the simulations was to have the ability to inject failures into the models during testing. In the initial versions of the simulation a simple switch from a control panel was activated and the failures inserted. With hardware-in-the-loop an external breakout box is implemented which causes the line replaceable unit (LRU) to think a failure has occurred. Unit testing of the specific LRU is not the objective of the integration labs, therefore it should be possible to remove the breakout box and create failures by intercepting data transmitted from the LRU, modifying it, and then retransmitting it back into the system.

The design of the ADI ADvantage interface allows direct manipulation of the data to easily inject failures. Updates to the HostPC application will provide the ability to inject failures and control the other aspects of the simulation from one central application.

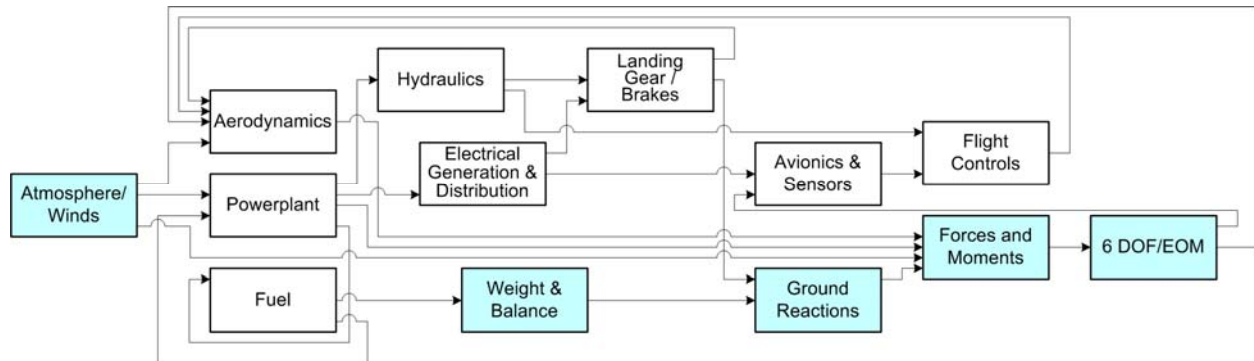


Figure 1. Basic simulation architecture.

Previous simulations used within the ITF and other areas have used Fortran and other programming languages. The latest simulations have been developed using The Mathworks' Matlab, Simulink and Stateflow.

Direct access to the data flowing through the simulation during runtime provided a powerful capability to the system designers during testing. The previous version of the simulation running in the CASE lab had one of the Simulink models running in interpreted mode which allowed users to change gains and switches during run time. ADvantage's ability to inject values directly into the simulation provides that same capability, all while running the simulation in true real time.

4.1 Simulink

Where the block diagram of Figure 1 shows the general arrangement of the simulation, Figure 2 shows the actual top level Simulink diagram used for the Advanced Flight Controls program. Each major function is represented by a block in the diagram. The use of reference models for each of the blocks provides a manageable means of updating and controlling each block. Reference models are stored as separate models so they can be developed and maintained independently and controlled through a revision control system. The models are stored in PVCS for configuration control and to retain the revision history.

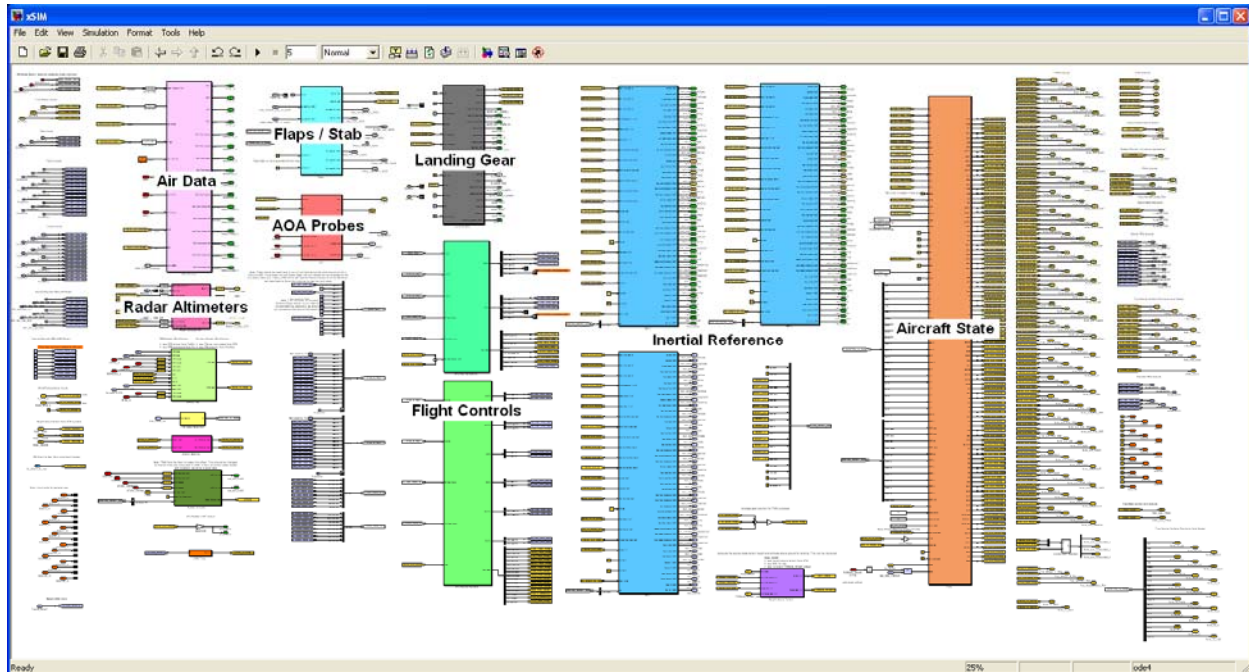


Figure 2. Top-level Simulink diagram.

Simulink has proven to be a powerful tool for developing applications covering a variety of fields. Aircraft systems can be rapidly modeled and data flows graphically depicted.

An additional benefit of using reference models and maintaining them through a revision control system is that the models can be used in a number of different versions of the simulation. The original developers create the models for use in a desktop simulation that runs either in a batch mode or in real-time using The Mathworks' Real Time Workshop. The same models are used in each real-time facility, thereby reducing development time and potentially reducing errors by using the same methods in each model. Model dynamics are the same in all instances.

Models developed between the different groups are expected to follow the Gulfstream Integration Test Facility Standards for Matlab, Simulink and Stateflow for Software Development. That document contains specifications on which versions of Matlab can be utilized, naming standards for signals, files and directories, as well as guides on formats for representing conditionals, which blocks to use, and the representation of ARINC 429 data. It is strongly suggested that suppliers to Gulfstream use the standard for developing models to be used within the Integration Test Facility.

4.2 Aircraft LRUs and Components

Real hardware can be connected into the simulations. Using a number of different analog to digital (AD) boards, electrical signals can be converted into values which can be used within the simulation. An easy-to-use Simulink blockset is available from ADI to use within simulation models. The models are designed to provide the capability of connecting either the hardware or using the simulation. The details of hardware implementation are detailed in subsequent sections.

4.3 Control Stations

Each of the different facilities has a control station configured uniquely for each lab. In the CASE lab a Windows XP computer running at 3GHz with 2 GB RAM runs ADvantage. A HostPC application has been developed internally at Gulfstream to provide control over several aspects of the simulation from a single point.

4.3.1 Gulfstream HostPC Application

Developed at Gulfstream, the HostPC application is a Windows Forms C++ Application. It contains several different tabbed pages that have data organized by systems, similar to the aircraft synoptic pages. The initial conditions page (Figure 3) provides a means to quickly set the simulation state. An airport selection drop down menu allows rapid positioning of the aircraft relative to a landing environment. The aircraft can be placed on a taxiway or runway, or in the air on an approach or at any altitude. With the simple press of a button, the simulation can be reset to the initial conditions. Test conditions can be saved and reloaded. Other facility support equipment and simulation parameters can be monitored and controlled from the same control panel.

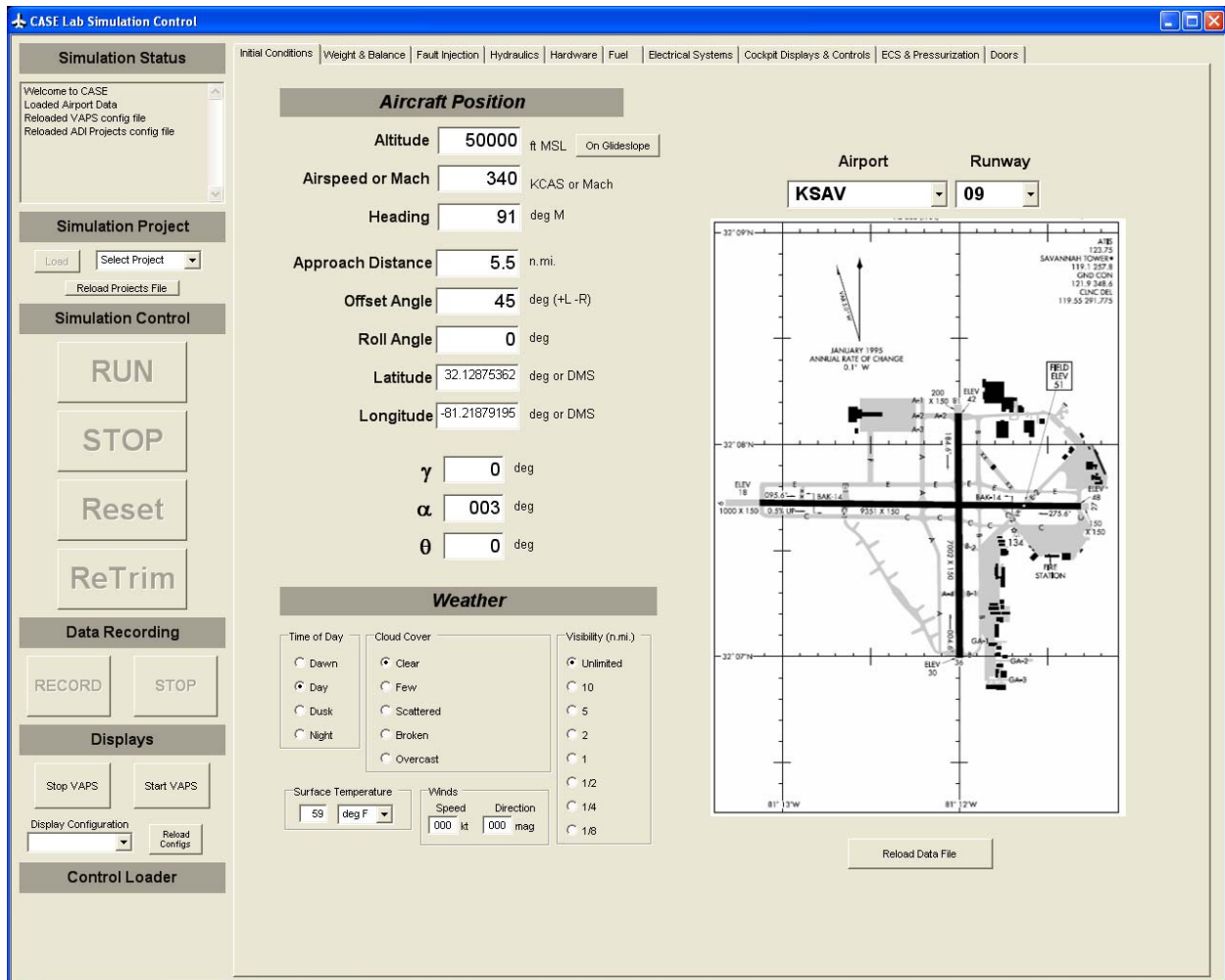


Figure 3. CASE Lab HostPC application initial conditions screenshot.

At the heart of the application is the use of ADI's DasCom. There are three methods for retrieving data from the ADI simulations; DasCom, Com, and COSAPI. Com applications are very slow and require a lot of resource overhead. Each parameter requires an individual "get" command issued to the rtX. The process is extremely slow. ADI's SimPlotter application uses DasCom. By using the Das stream, data can be transferred rapidly to the HostPC application.

Data sent from the HostPC application to the ADI can be organized as high speed and low speed. The most data sent back would be low speed and can be transmitted at rates as low as 1 Hz. Data from the initial conditions page and the simulation control parameters are in this category. A smaller set of data sent at high speed would be for flying the aircraft from the control station. Pitch and roll commands need to be sent at a minimum of 10 Hz.

4.4 ADvantageVI

Gulfstream currently uses ADvantage version 8.2. The Data Dictionary editor allows detailed customization of each model parameter's attributes from ADvantageDE. This permits the ability to create a more user friendly runtime environment. ADI also provides a UDP Manager and ARINC Manger spreadsheet-based tool to create Schedules that package model parameters in any format defined by an ICD. Similar to Schedules, setup files are loaded through ADvantageVI to initialize parameters to different aircraft configurations.

Using an ADI-developed program called CTA, automated testing was implemented to reduce testing time by 50% or more. Test reports are automatically generated. Additionally, the application updates a testing web page accessible through the company intranet.

4.5 ADvantageGP

Although it has not been fully integrated in the development process at Gulfstream, ADvantageGP can be used for desktop development and initial integration testing. Initial integration testing can be completed on the desktop instead of in the lab. Valuable lab time can be conserved for full system integration testing. Engineers at Gulfstream have experimented with ADvantageGP and it has yielded positive results. Further work with GP is expected in the near future.

4.6 ARINC429 Data

Although using the Ballard ARINC429 boards within the lab for ARINC429 data, the data within the models is being prepackaged into an ARINC429 format. This provides the ability to substitute a simulation model for an LRU.

A library blockset was created at Gulfstream for packing and unpacking data to and from the ARINC429 format to allow easy access to the functions and to make the models more common.

Data within the labs can be intercepted and changed or overridden as testing requires. This provides a powerful capability in testing components within the lab.

5 Facilities

Gulfstream is located at the Savannah International Airport. The main campus features a complete manufacturing facility supporting minor, major and final assemblies to produce the "green" aircraft. Final phase manufacturing is also on site facilitating the interiors and completion of the aircraft, including exterior paint.

Engineering for the large cabin aircraft is performed at the Savannah facility. Simulation and experimental labs are co-located within the facility. A complete service center is also on site, providing minor and major maintenance for all Gulfstream aircraft. A flight test group and flight operations group (experimental test and production test pilots) support production and maintenance flight testing of new and existing aircraft.

On-site experimental lab facilities support engineering development and testing. Of these facilities, the ITF and ADRL have been integral for real-time pilot- and hardware-in-the-loop testing of the aircraft systems prior to flight testing. At the conclusion of testing in the lab, the experimental system or software is installed on experimental flight test aircraft. Flight testing is conducted in actual conditions to evaluate whether the system meets the design goals.

5.1 Integration Test Facility

The Integration Test Facility consists of several experimental labs built to emulate the aircraft systems and an additional research lab called the Conceptual Advanced Simulation Environment (CASE) Lab. The labs have been used for production testing and development testing of equipment and software prior to flight testing on actual aircraft. The complete set of avionics has been tested in the ITF before installed into production aircraft. Such testing minimizes the problems encountered when installing hardware on production aircraft and reduces the expense of testing.

5.1.1 Conceptual Advanced Simulation Environment Lab

In support of research and prototyping activities the Conceptual Advanced Simulation Environment (CASE) Lab was established. Initially, its purpose was to support advanced cockpit displays development. As the Advanced Flight Controls program evolved, it became the dominant program within the lab and the simulation was enhanced to provide a more accurate representation of the aircraft aerodynamics, systems and data flows.

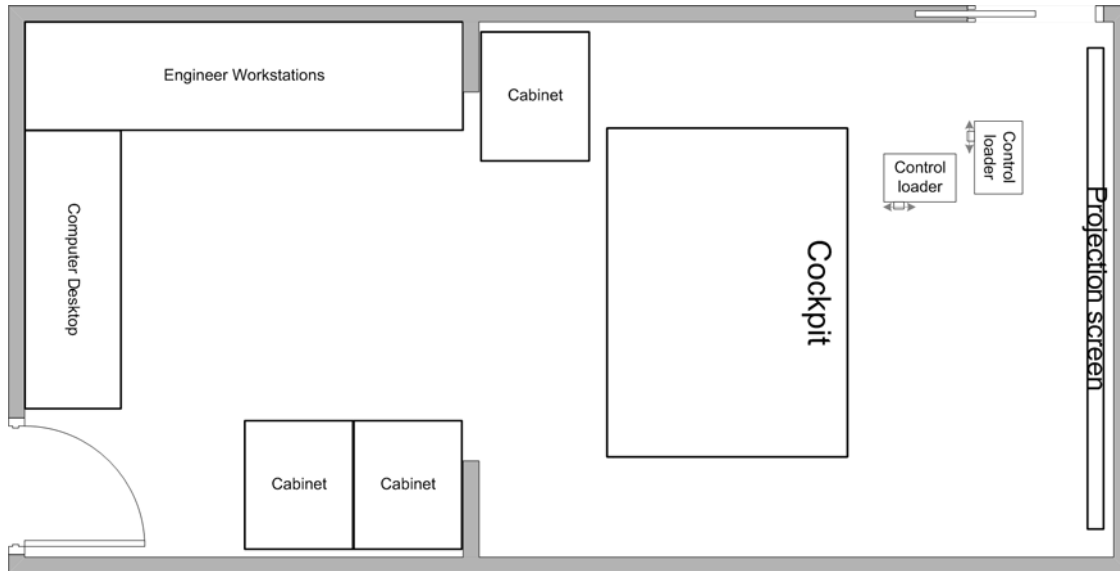


Figure 4. CASE Lab general layout.

5.1.1.1 Simulation Only

The lab was originally designed to be a low-cost development environment with the capability to quickly update the configuration in response to engineering design changes. With the exception of a few control inceptors, described later, simulation is used instead of actual hardware. This also provides for a much smaller facility (Figure 4. CASE Lab general layout. Figure 4).

5.1.1.2 ADI Installation

The ADI computer system is a single core, single processor with 256 MB of RAM. It contains the compiled Simulink models, processes the I/O for switches and controls the UDP to and from the other computers in the lab. In the initial version of the CASE lab, the ADI computer was underutilized because it was used only for capturing the cockpit controls inputs. Electrical signals from the switches and the throttles were connected through PCI-based I/O cards. The original lab configuration consisted of dual Windows XP computers running compiled and interpreted Simulink simulations.

In April 2007 the simulation was re-hosted on the ADI from the two Windows XP machines. Both Host PCs have been retained to allow parallel development while the other computer is used to run the simulation (Figure 5). The electrical connections to the switches and throttles were retained, as well as the network connections. A new Simulink blockset was provided by ADI to read the data from the I/O cards directly. These blocksets also incorporate calibrations for each I/O port and allow orderly connections in the Simulink top level diagram.

Data is input and output to other computers via UDP data streams using ADI's UDP Manger to pack and unpack data in any format specified by an ICD. Display computers use 30 Hz streams. The out-the-window computer UDP stream runs at 60 Hz. The control loader computer UDP is sent at 60 Hz.



Figure 5. CASE Lab engineer's workstation.

5.1.1.3 Electric Control Loader

A two channel electric control loader from Simulation Control Technologies (SCT) of Binghamton, NY was installed in the lab in May 2007 (Figure 6). It consists of a 19" rack mounted 208V electrical controller and supply, a Linux-based control computer, and the two actuators- one for pitch and one for roll. The pitch axis is connected to the actuator by a push rod. In the roll axis, the push rod connects to a pulley wheel, wrapped by a cable connected to the shaft at the top of the column. The rotation of the wheel is translated through the cable to the pulley and then the push rod to the actuator. The control loader is fully programmable, allowing nearly all the characteristics of the aircraft controls to be simulated relatively accurately. The control loader computer can dynamically update the calculated force characteristics based on a given flight condition. The position and forces for the controls are communicated back to the ADI simulation computer via UDP at 100 Hz.



Figure 6. CASE Lab electric control loader.

5.1.1.4 Mock-Cockpit

The placement of displays and controls in the lab is geometrically similar to the production cockpit, although only one or two components are actual aircraft hardware. The displays are COTS displays that have the same resolution as the Large Cabin Aircraft PlaneView displays (Figure 7). The center pedestal has been changed between the production G-IV and production G550 several times in support of a variety of activities.

The display control units (DCUs) and guidance panel on the upper instrument panel have been replaced by six 7" Phylon touch screens. The touch screens provide the capability to rapidly switch between a production equivalent DCU and variations without requiring removal and rewiring.

5.1.1.4.1 VAPS Displays

Actual aircraft displays would have been expensive and potentially difficult to modify. By incorporating the COTS displays driven by Windows XP computers and using VAPS by Engenuity Technologies, the displays can be easily modified and configured to emulate the real aircraft displays and behave the same. Through flying the simulation, the behavior of moving components can be evaluated prior to sending the requirements to the displays supplier for production.

In the absence of actual hardware, or where there may be a variation of component styles, touch screens were installed. The display controller units and guidance panels were replaced with by the Phylon displays and an additional display was added on the lower instrument panel next to the landing gear handle. It can be used to emulate buttons or controls that are not available as real hardware components, or additional buttons to control the simulation itself.

During the Advanced Flight Controls program, another touch screen was added above the upper instrument panel to represent the Advanced Flight Controls Control Panel. During the program, at least three iterations were evaluated before any materials were cut.

As the lab continues to evolve and capabilities are added, additional controls are planned. When the aircraft electrical system model is implemented, the overhead panels will be added as touch screens with buttons, switches, circuit breakers and controls as necessary.



Figure 7. CASE Lab cockpit.

5.1.1.4.2 Various Control Inceptors

Several different control inceptors are available within the lab. Early configurations of the lab implemented a simple commercially available joystick. Because Windows drivers and Simulink blocksets were readily available it was easy to add the commercial joystick. The joysticks could be acquired and implemented at very low cost when necessary.

Greater similarity to production aircraft configurations required the implementation of a center column and control wheel. Because of difficulties in acquiring production hardware, the decision was made to manufacture a geometrically similar column installation for the control loader.

Production G550 throttles are mounted in the center pedestal to provide the capabilities of implementing full function of the propulsion system, including thrust reverse and auto-throttles. A production landing gear handle is mounted in the lower instrument panel with lights and the down-lock solenoid implemented, similar to the production aircraft.

5.1.1.5 Visuals

Several different out-the-window image generators have been evaluated in the lab. A dedicated 3 GHz Windows XP computer with 2 GB memory and a high-end video card is installed for image generation. Data communications between the image generator and Simulink simulation is handled via a UDP connection over the gigabit Ethernet connecting all the computers within the lab.

FlightGear, an open-source flight simulator, was evaluated in the lab in 2005. As an open-source application, it was available at no charge and the source code was easily accessed. Microsoft Flight Simulator 2004 was also evaluated at the same time. The graphics and update rates of Microsoft proved better and more consistent than FlightGear.

The visuals are projected onto a flat 115" wide screen located in front of the cockpit structure. The equivalent field of view forward is approximately 84° horizontally and 50° vertically and from either seat.

Experiments were successfully conducted with additional projectors to add side views, but the lab is currently configured with only the forward view.

5.1.2 G550 Lab

The G550 Lab is a full function simulation of the G550 production aircraft avionics. The lab is approximately the same length as the cabin of the G550, which allows installation of aircraft wiring and placement of the equipment in the corresponding locations as on the aircraft (Figure 8). Components which cannot be installed in the lab are simulated. The initial version of the lab used all Fortran models, and was distributed across three different computer systems. As recently as Spring '07, the Simulink versions were integrated into the lab during the Advanced Flight Controls program, described later.

In the G550 lab actual aircraft hardware is incorporated into the simulations. As an example, the real aircraft cockpit with production displays and select equipment is fully integrated into the simulation. The production aircraft data networks are incorporated with the simulation monitoring the data and providing control of the simulation conditions. Faults can be injected into the simulation to identify error handling.

In conditions where production or equivalent hardware cannot be included in the simulation, a model is substituted to provide the corresponding signals. Additionally, the end-to-end systems can be evaluated to insure proper response to flight conditions. Sensors can be tested in the lab under repeatable conditions. In some cases, sensors can be simulated or real for end-to-end system testing. This provides the capability to continue testing when real hardware is unavailable. During the build process, the installation of production wire harnesses can be validated.

5.1.2.1 Production Cockpit

A production cockpit is installed in the lab (Figure 9) and outfitted with production equipment. The flight controls in the cockpit are connected to a hydraulic control loader to provide the correct force feedback and feel to the pilots flying the simulation. Avionics equipment installed in the cockpit functions the same as in the actual aircraft. As new software loads are available, they can be loaded into the avionics and tested prior to flight testing.

5.1.2.2 Hardware-in-the-Loop

The numerous components which make up the aircraft are essential when performing integration testing. Again, some components cannot be located in the lab due to size limitations, hazards, or cost. Simulation drawers were built to emulate the hardware which cannot be installed.

5.1.2.3 Hydraulic Control Loader

Flying the simulation provides the capability to evaluate the various flight control conditions before test flying the aircraft. To provide the simulated forces back to the pilots through the controls, a control loader was incorporated. In the G550 simulation, a hydraulic McFadden control loader was used.

program the simulation models were all written in Fortran. During AFC Phase I, the initial Simulink versions were created and implemented in the lab replacing Fortran models.

5.1.2.5 Visuals

The simulation experience is made more realistic with the addition of the out-the-window visual system in the G550 lab. A CATI X-IG system was acquired in 2004. The 3 channel system projects the out-the-window scene on a 200° x 40° wrap-around cylindrical screen at 60 Hz update rate. Each channel has its own distortion correction to account for installation variations. Two gaming area databases are available; Savannah, Georgia and Juneau, Alaska. The terrain is available out to approximately 20 miles and includes a detailed airport model with buildings, runways and lights. The system is capable of depicting day or night and a variety of weather conditions. Adjustments and configuration changes are made through the dedicated IG computers and the control application.

5.2 Advanced Research & Development Lab

The Advanced Design & Research Lab (ADRL) is a small, highly capable research lab environment. There is a small machine shop with a 3- and 5-axis mill, full welding capabilities and woodworking tools. A full-sized airframe is installed for hardware-in-the-loop systems testing. It is known as the “Phoenix”.

5.2.1 “Phoenix”

The Phoenix test facility is based on a G-V airframe. It was mounted in a hangar and connected to support equipment providing hydraulic and electrical power in place of aircraft engines and generators (Figure 10).



Figure 10. Phoenix test aircraft.

In addition to R&D equipment the airframe has production wiring and actuators. To simulate loads and hinge moments on the control surfaces, hydraulics push back on the surfaces against the flight control actuators. The flight controls can be tested for adequate margin and to verify the actuators are not rate limiting. This type of actuator testing was extensively used during summer 2007 for the AFC program.

The primary system monitoring and simulation controls are conducted through a control room located at the tail of the airframe (Figure 11). Video cameras are installed throughout the facility and within the airframe to allow the test conductors to monitor the test article and ensure safety from the control room.



Figure 11. Phoenix Control Room.

An electromechanical robotic control was designed and fabricated to input commands to the control column and be repeatable. It can be programmed to input a series of different commands at different frequencies and amplitudes.

5.2.1.1 ADI Installation

A multiple processor rtS controls the simulation. Its main purposes are to replicate the data buses needed for operation of the avionics and calculate surface loads. These closed-loop load commands are based on the flight condition and surface positions allowing a pilot to evaluate the handling qualities of different control laws and R&D actuators. Using a real aircraft as a mechanical test rig provides the ability of conducting these tests without modeling the whole mechanical system from pilot to actuator.

5.3 Aircraft 632

Test flights are conducted in an experimental G-V flying testbed. Aircraft serial number 632 (Figure 12) is configured with the PlaneView cockpit and additional test equipment. An experimental flight control computer and actuators were installed to configure the airplane for conducting fly-by-wire testing. The controls on the right side of the cockpit are connected to the FBW equipment, and the left side retains the conventional cable and pushrod connections to the control surfaces.



Figure 12. Test aircraft 632.

The right-most display unit is reconfigured to accept an experimental display driven by a Windows XP computer. The same display software is used in the CASE lab.

6 Recent Applications

In addition to production issues and normal software upgrade evaluations, the labs in the ITF and ADRL have already been responsible for verifying and validating the development of several programs. Two of the more important are the Advanced Flight Controls and a Steep Approach experiment.

6.1 Development Support

During the development of the labs, the wiring diagrams of the aircraft were validated through integration testing. The ITF was generally the first place where new aircraft designs are built into a real assembly of wires and components. As the normal wiring out of the wiring diagrams occurs, errors were identified and corrected before flight of the first test aircraft. Production and development LRUs were integrated into the simulation as they become available.

With the G-V, G-550 and G-450, production LRUs were brought into the ITF labs to verify the LRUs were functioning according to their design specifications before installation onto the aircraft. If errors were found after installation a closer examination of the aircraft wiring could typically be identified as the source of the error because each avionics suite had already been confirmed to be functional against a known wiring configuration.

After the lab was established and functioning properly, LRU problems encountered in the fleet could be tested within the ITF. Certified units already in service can be brought into the lab and thoroughly tested instead of requiring a number of test flights to identify the issues.

Suppliers' products can be evaluated in the lab to determine whether they meet the design requirements and could replace the original units. Testing in the lab does not involve the same issues as a test aircraft regarding safety of flight or certification. Units can be inserted into the lab and tested more rapidly, and a greater number of people can participate or observe the testing than in a real aircraft.

6.2 Advanced Flight Controls

The Advanced Flight Controls Program was undertaken to grow the capability for developing fly-by-wire infrastructure within Gulfstream. A multi-phased approach with increasing complexity required demonstrating capability in the less complex phases before undertaking the more complex tasks.

Phase I involved replacing the hydro-mechanical spoilers with a digital flight control computer, a digital data acquisition unit, remote electronic units (REUs) and fly-by-wire actuators. An experimental flight display was created so the pilots can more closely monitor the FBW system.

The experimental flight display is a VAPS application developed and tested in the CASE Lab. After completing CASE lab testing, the display application was loaded onto the computer targeted for the flight test aircraft, 632. The computer was installed into the G550 ITF bay with the additional hardware required for the AFC program. An alternative to testing in either the CASE lab or the G550 lab would be to test in one of the test aircraft, which would have been cost-prohibitive, as well as difficult to schedule. Use of the labs provided a very flexible and readily accessible environment which minimizes cost and maximizes the engineering development time.

During the integration and testing of the different models and displays, it was possible to quickly identify errors. Through testing there were unit of measure mismatches and incorrectly connected signals identified which could have created significant problems during actual flight testing. During flight testing it would have been difficult to locate the errors because of the inability to quickly and safely repeat the execution of the test conditions. Some of the simulation parameters were also incorrectly connected to the display software resulting in unusual behaviors during simulated flights. Repeated testing using unusual attitudes not permitted in the real aircraft allowed the problems to be safely and rapidly identified and quickly corrected.

By injecting faults into different aspects of the simulation, it was also possible to identify areas of higher risk and create mitigation schemes for minimizing those risks. The FBW crew alerting system (CAS) was tested prior to the program's first flight. Characteristics of the flight control system were also evaluated using the Phoenix facility with a full end-to-end check. Phase I of the program was concluded without major failures and with a minimum of repeated test points because the issues had been identified and alleviated during simulation testing.

6.3 Steep Approach

The normal aircraft glide slope for approaches is 3°. Some airports have obstacles which require a steeper glide slope angle, such as Lugano, Switzerland or London City in England. Nearby terrain at Lugano is compensated for with a 5° approach. London City has buildings very close to the approach path and also has a 5° glide slope. To demonstrate the capability to safely fly the approach, an aggravated case must be demonstrated, which in both cases can be as steep as 7°.

Considering the distance to European airfields, the cost of conducting a test program would involve great expense and require difficult to acquire approvals. With the CASE lab capable of flying anywhere and an out-the-window display that was adequate for providing ground references to the airports of interest, an experiment was conducted in the lab.

The Flight Sciences group at Gulfstream developed an accurate aerodynamics model of the aircraft from wind tunnel and flight test data and implemented it into the simulation. Different aircraft configurations were included such as landing gear down and various flaps settings. Approaches were conducted at the target airports in the simulation and flown multiple times through touch-down. The techniques and aircraft configurations for safely flying the approach were developed and evaluated.

Additional tests were conducted in the simulation to evaluate failure modes and go-around capabilities. Single engine approaches and engine failure cases during the approach were evaluated. Crew procedures were developed from the simulation flight to compensate for the abnormal and emergency situations.

After learning the cues to fly the approach, a steep approach was designed to fly at Cecil Field in Jacksonville, Florida. A multiple approach test mission was undertaken. Additional approaches were

flown in the simulator, and a similar approach was designed for testing at the Savannah Airport. These simulation tests were the basis for the aircraft-level tests.

Approaches were flown at Savannah on a 7° glide slope using the configurations and speeds identified in the simulation. The flight crew's assessment was that the simulation flew like the real aircraft and the techniques developed in the simulation were sufficiently accurate for flying the approaches. Aircraft performance was accurately modeled in the simulation for this dynamic maneuver.

7 Conclusions

Simulation technology has provided a powerful tool for development of advanced programs at Gulfstream. By designing common models which can be used in all the facilities, the programs have moved from conception to flight testing more rapidly and with fewer errors during flight testing.

The labs provide a safe environment for identifying and alleviating issues which could pose risks to air crews. The ability to quickly repeat test points to develop different techniques or to identify the cues to fly test points has proved to be important for crews and a valuable tool for communication (by demonstration) within the development team. The ability to fly highly unusual attitudes in the simulation also reduces the risks to the crew and aircraft while evaluating the expected behaviors of the systems.

Lab testing is less expensive than airborne tests on the aircraft. By testing in the simulators engineers can evaluate a wide variety of test conditions more rapidly than can be accomplished in the actual aircraft. Having the ability to quickly change conditions, or quickly reset to a specific initial condition, maximizes the amount of testing that can be accomplished in a given period of time. The ability to run test scripts on the simulations has dramatically reduced the amount of time required to conduct tests.

Advances in the simulation labs have provided engineers and pilots with greater capabilities than were available in the past and they will continue into the future.

8 Acknowledgements

The labs described in this paper would not exist without the support of Pres Henne, Dick Johnson, and Barry McCarthy. David Powell (previous ITF manager and current ADRL manager) has driven the development of the ITF and ADRL to the excellent facilities they have become. Bob Farrell's support as the current ITF manager has aided in the evolution of the facilities.

Many engineers and technicians at Gulfstream have contributed to the development of the labs. Some of those who have been essential to the success of the lab are Tom Jenkins, Clint Amerson, Sean Davidson, Bob Hartley, Clay Harden, Greg Grosse, Tom Landers, Misty Mehelic, Nomaan Saeed, and Jeffery Porwoll. In the labs, aircraft coordinators and technicians Marcus Schumacher, Dave Dahlke, Steve Urreta and a large number of others have contributed significantly to the success of the ITF and ADRL facilities.