

# A Flight Control System Architecture for the NASA AirSTAR Flight Test Infrastructure

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A flight control system architecture for the NASA AirSTAR infrastructure has been designed to address the challenges associated with safe and efficient flight testing of research control laws in adverse flight conditions. The AirSTAR flight control system provides a flexible framework that enables NASA Aviation Safety Program research objectives, and includes the ability to rapidly integrate and test research control laws, emulate component or sensor failures, inject automated control surface perturbations, and provide a baseline control law for comparison to research control laws and to increase operational efficiency. The current baseline control law uses an angle of attack command augmentation system for the pitch axis and simple stability augmentation for the roll and yaw axes.

## Nomenclature

$\alpha$	=	angle of attack, degrees
$\delta$	=	control surface deflection, degrees
$C_z$	=	force coefficient in the aircraft body Z-axis, positive down
$C_{z\alpha}$	=	derivative of body Z-axis force coefficient with respect to angle of attack
$C_{z0}$	=	body Z-axis force coefficient bias term
$N_z$	=	body Z-axis load factor, positive down, g
$\bar{q}$	=	dynamic pressure, pounds per square foot
$S$	=	reference wing area, square feet
$W$	=	aircraft weight, pounds
<i>AirSTAR</i>	=	Airborne Subscale Transport Aircraft Research
<i>AvSAFE</i>	=	Aviation Safety Program
<i>CAS</i>	=	Command Augmentation System
<i>COTS</i>	=	Commercial Off The Shelf
<i>DOF</i>	=	Degree Of Freedom
<i>FCL</i>	=	Flight Control Law
<i>FCS</i>	=	Flight Control System
<i>FCU</i>	=	Flight Control Unit
<i>GPS</i>	=	Global Positioning System
<i>INS</i>	=	Inertial Navigation System
<i>IRAC</i>	=	Integrated Resilient Aircraft Controls
<i>IVHM</i>	=	Integrated Vehicle Health Management
<i>LaRC</i>	=	Langley Research Center
<i>LPS</i>	=	Load Protection System
<i>MOS</i>	=	Mobile Operations Station
<i>NASA</i>	=	National Aeronautics and Space Administration
<i>SAS</i>	=	Stability Augmentation System
<i>STS</i>	=	Stick-To-Surface
<i>UDP</i>	=	User Datagram Protocol

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## I. Introduction

THE Integrated Resilient Aircraft Controls (IRAC) project and the Integrated Vehicle Health Management (IVHM) project, both part of the NASA Aviation Safety Program, are focused on flight research of transport-category aircraft during adverse flight conditions such as upsets, damage, and failures. One of the key research areas is developing adaptive control algorithms and strategies for transport-category aircraft during adverse conditions. An important part of this research is flight validation of controller performance and stability in realistic scenarios. Full 6-DOF simulation can play an important role in the validation process<sup>1</sup>, but flight testing is ultimately required due to the complex and relatively unexplored nature of transport aircraft dynamics in the flight regimes of interest. However, flight testing a full scale manned transport aircraft in adverse flight conditions has unacceptable safety risks and would be prohibitively expensive. To address these challenges, NASA has developed the Airborne Subscale Transport Aircraft Research (AirSTAR) flight test facility<sup>2,3,4</sup>.

## II. AirSTAR Overview

AirSTAR is an integrated flight test infrastructure which utilizes remotely piloted, powered subscale models for flight testing. One particular use of AirSTAR is flight testing research control laws in adverse flight conditions. AirSTAR consists of a remotely piloted subscale test article, the Mobile Operations Station (MOS) (an integrated ground station and control room), and a test range. Under the current AirSTAR Concept of Operations (CONOPS) (Figure 1) a safety pilot, using a hobbyist radio control transmitter, performs the takeoff and climbs to a specified altitude, where control of the aircraft is transferred to a research pilot through a handoff maneuver.

The research pilot executes the flight test plan from a research cockpit located in the MOS, which utilizes synthetic vision displays driven with aircraft sensor data. The research pilot uses a ground-based flight control system (FCS) that is connected to the aircraft through an L-band telemetry uplink and S-band telemetry downlink. Once the flight test maneuvers are complete, the safety pilot resumes control of the aircraft and performs the landing. The safety pilot is the pilot-in-command of the aircraft and determines who is in control of the aircraft (physically and procedurally) at all times via a switch on the safety pilot's transmitter. When the onboard flight control unit (FCU) receives the appropriate command from the safety pilot, the FCU begins responding to the research pilot's commands received through the L-band telemetry uplink. The command state of the FCU (i.e. who actually has control of the aircraft) is part of the data on the S-band telemetry downlink.

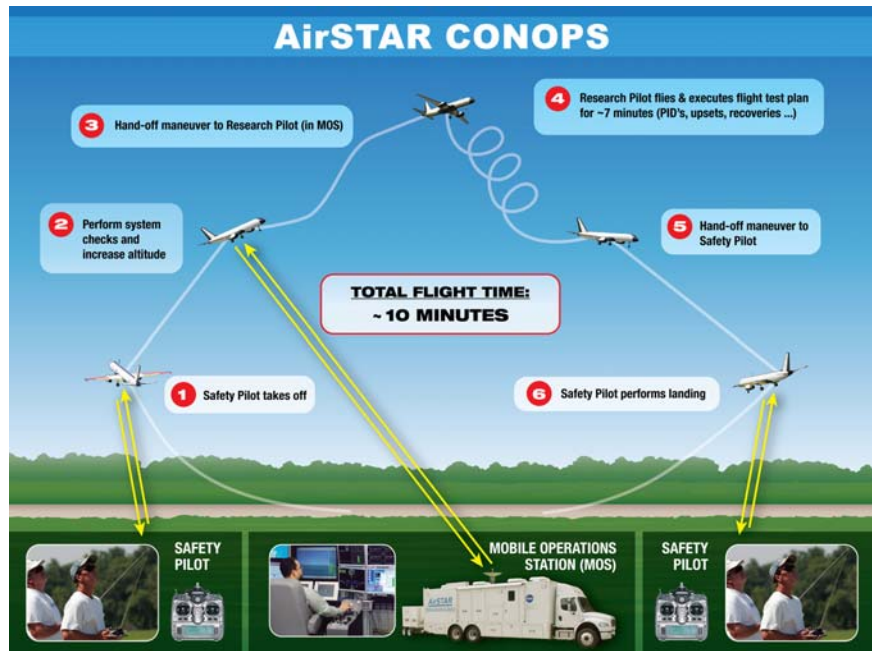


Figure 1. AirSTAR Concept of Operations.

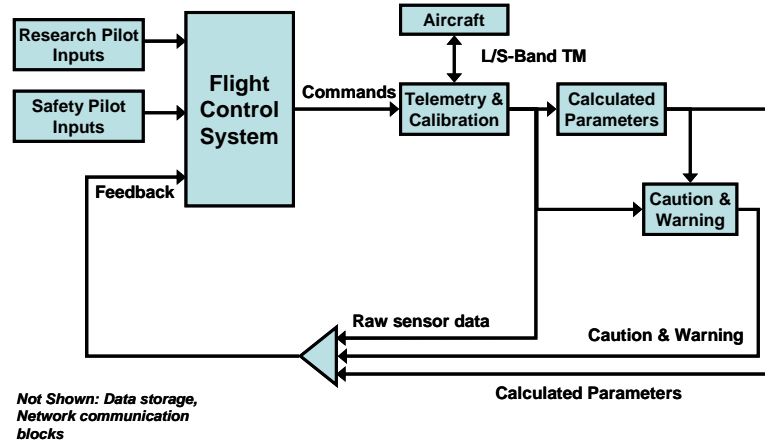
### A. Test Aircraft

Currently, AirSTAR operates two fully instrumented test aircraft. The primary test aircraft is a 5.5% dynamically scaled (i.e. Froude-scaled) twin-turbine powered generic transport model (GTM). Dynamic scaling allows subscale flight test results to be applied to full-scale aircraft. This model (tail number T2) has a 6.5 ft wingspan, weighs 54 lbs at takeoff, and has a flight time of approximately 10 minutes. The secondary test aircraft is a 48 lb single or twin-turbine powered commercial off-the-shelf (COTS) airframe kit modeled after the Lockheed L-1011 TriStar aircraft. This model (tail number S2) is neither geometrically nor dynamically scaled to the full scale aircraft and functions as a surrogate model for the GTM aircraft for system checkout and flight test technique development. Both aircraft have identical engines, components, systems, and instrumentation to facilitate transfer of lessons learned during

developmental flights with the surrogate model. Each aircraft is outfitted with full flight test instrumentation, including angle of attack and angle of sideslip vanes, static and dynamic pressure, control surface positions, rate gyros and accelerometers, a 6-DOF INS/GPS package, and engine instrumentation. Downlink data update rates vary from 5 Hz on the GPS data to 200 Hz on the analog sensors. Uplink commands are received at 200 Hz.

## B. Software

Software for AirSTAR is developed in The MathWorks MATLAB®/Simulink® environment and implemented on a ground-based dSPACE real-time computer located in the MOS. A block diagram of the ground-based software is shown in Figure 2. The commands from both pilots are input to the FCS, in addition to the aircraft sensor data, the



**Figure 2. Block diagram of ground-based flight software.**

(defined as no data for 0.75 sec). The FCS outputs control surface and throttle commands in engineering units, which are calibrated to actuator commands and sent to the aircraft via the L-band telemetry uplink.

Simulation is used extensively in the AirSTAR software development process. Desktop simulation is used for designing and initial checkout of control laws. Hardware-in-the-loop simulation using the MOS systems and the dSPACE computer is used for testing, checkout, flight profile planning, and mission rehearsals.

## III. AirSTAR Flight Control System

The vehicles and operational concept used by AirSTAR present some unique challenges: First and foremost, dynamically scaling an aircraft results in increased model airspeed, angular rates, wind loading, and increased pilot workload relative to a model that is only geometrically scaled. These factors make a dynamically scaled model more challenging to fly and less forgiving of mistakes. Second, under the current AirSTAR CONOPS, the aircraft must remain within visual range of the safety pilot, effectively limiting the test volume to an approximately 1/2-mile radius circle around the safety pilot, extending to ~2000 feet above the surface in altitude. Limited test volume combined with the relatively high airspeeds of the test aircraft adds to the pilot's workload. Third, the primary purpose of AirSTAR is to perform flight research and flight validation of multiple research control laws in adverse flight conditions, which presents unique challenges to flight testing in an efficient and safe manner.

The AirSTAR FCS uses a reversionary build-up approach to mitigate the risks associated with flight testing complex research control laws. Complexity is added in distinct stages that can be quickly transitioned using a two-switch "arm" and "engage" process. The FCS is separated into three flight control law (FCL) modes, shown in Figure 3. These three modes are mutually exclusive; only one can be active at a time. Mode 1 is a stick-to-surface control law composed of stick shaping only; no sensor feedback is used. This mode is the reversionary control law and is simple by design. Mode 2 is the baseline FCL, containing a conventional (non-adaptive) closed-loop controller. Mode 3 is reserved for the research control laws, and can contain any number of FCLs, although only one can be operational at any given time.

The FCS also contains three auxiliary modules that can be used in conjunction with Modes 1, 2, or 3: an Autothrottle, a Wavetrain module, and a Model Tracking & Failures module. The final component in the FCS is a Load Protection System (LPS), which is aimed at preventing the FCS from exceeding the structural limits of the test aircraft. The LPS, Transfer Logic, and Input Selection blocks are always active.

Transfers between FCL modes and activation of other functions are controlled by the Transfer Logic block. The Input Selection block smoothes transitions between FCS modes by using linear faders. When a particular mode is engaged, its commands are faded in and the current commands are faded out at the same rate. All of the FCS components will be described in detail in the following sections.

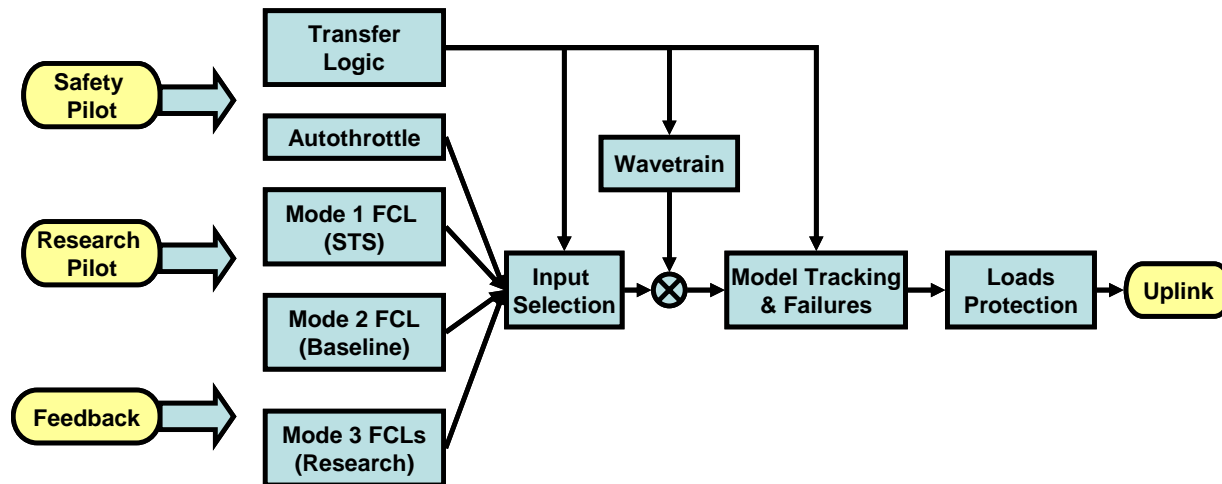


Figure 3. AirSTAR FCS top-level block diagram.

#### A. Mode 1 FCL: Stick-to-Surface

The Mode 1 FCL is a simple stick-to-surface control law that functions as the lowest reversionary mode of the AirSTAR FCS. This FCL applies exponential shaping to the research pilot's side-stick (pitch and roll) inputs. Linear shaping is applied to the rudder pedal commands. The research pilot commands pitch and roll trim rate via a four-position "hat" switch located on the side-stick. A time-modulated gain is applied to the trim rates (i.e. trim rate increases when the hat switch is held in one position) which are integrated to form a control surface command. Rudder trim commands are input directly using an analog knob.

When the safety pilot transfers control to the research pilot, the FCS is in Mode 1 by default. The AirSTAR FCS prevents control surface transients during the handoff by initializing the Mode 1 pitch and roll trim states to the safety pilot's trim commands, which are received via a separate 72 MHz receiver located on the MOS. The safety pilot's rudder trim command simply biases the research pilot's rudder trim command. The safety pilot's trim commands are not explicitly separated from the total surface command and are estimated by applying low-pass filters (time constant = 0.08 sec) to the elevator, aileron and rudder commands. Transients are also minimized procedurally by executing the handoff maneuver in a trimmed, sticks neutral flight condition. Once the control handoff to the research pilot has been performed, the safety pilot's estimated trim commands are held until the safety pilot retakes control.

#### C. Mode 2 FCL: Baseline Flight Control Law

The Mode 2 Baseline FCL is a conventional closed-loop control law intended to improve test efficiency (relative to open-loop control), reduce research pilot workload, and provide a baseline for comparison of research control law performance. The initial design of this FCL utilizes an angle of attack Command Augmentation System (CAS) in the pitch axis and simple rate-feedback stability augmentation in the roll and yaw axes. Augmentation-type research control laws may use the Mode 2 FCL by copying this block into the Mode 3 subsystem. Angle of attack command was chosen for ease of use, simplicity, and suitability for capturing angle of attack set points for modeling experiments. Stability augmentation was chosen for the roll and yaw axes primarily for simplicity.

The angle of attack CAS currently implemented in Mode 2 is a proportional-integral controller designed using the LQR design technique with a linear aerodynamic model derived from flight test data collected at 80 knots equivalent airspeed. Feedbacks are filtered angle of attack and filtered pitch rate, the latter of which is also washed out to remove steady-state pitch rate during turning flight.

The research pilot commands angle of attack using the sidestick inceptor. Trim functionality is similar to Mode 1, except the pitch trim controls trim angle of attack instead of the elevator. When Mode 2 is engaged, the initial trim angle of attack is set to the current angle of attack to mitigate transients. In addition, the integrator state is initialized so the initial Mode 2 outputs will match the current elevator command. If Mode 2 is engaged while the aircraft is in a trimmed, stick-neutral condition, there will be zero elevator transients. Integrator wind-up is prevented by halting integration and holding the integrator output value when the total elevator command is at the actuator limits and the integrator input would otherwise increase the wind-up. In addition, if telemetry dropouts are

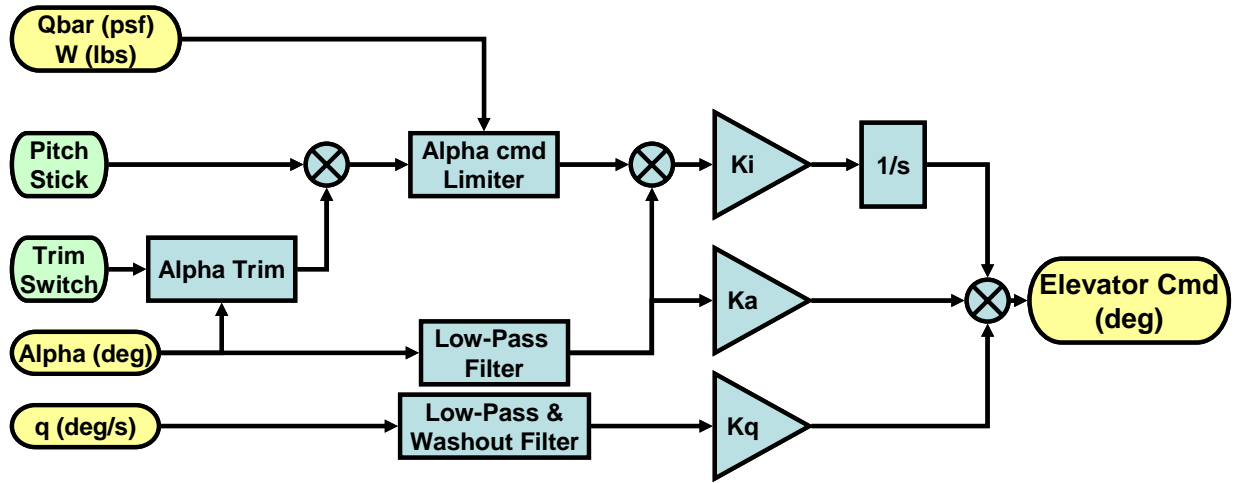


Figure 4. Mode 2 angle of attack CAS structure.

detected by the Caution & Warning system, integration is halted and the integrator output is held until telemetry link is restored.

The angle of attack command is limited to prevent stall and excessive normal load factor. Using a simple linear aerodynamic body Z-axis force model, a maximum and minimum angle of attack can be computed given load factor limits, estimated weight, and current dynamic pressure (Eqs. 1-4).

$$C_Z = C_{Z\alpha}\alpha + C_{Z0} \quad (1)$$

$$N_Z = \frac{\bar{q}SC_Z}{W} \quad (2)$$

$$N_Z = \frac{\bar{q}S(C_{Z\alpha}\alpha + C_{Z0})}{W} \quad (3)$$

$$\alpha = \frac{\frac{N_Z W}{\bar{q}S} - C_{Z0}}{C_{Z\alpha}} \quad (4)$$

The Mode 2 FCL also has simple rate-feedback Stability Augmentation Systems (SAS) in the roll and yaw axes. Both the roll and yaw SAS use filtered, washed out angular rates. Gains are scheduled with airspeed and are zeroed out above 120 knots equivalent airspeed.

#### D. Mode 3 FCL: Research Flight Control Laws

The Mode 3 FCL subsystem utilizes a selectable, enabled subsystem architecture that allows a large number of research control laws to be implemented concurrently and tested individually during a single flight. Research FCLs are disabled (i.e. the code is not executed) until the particular FCL is selected and armed. The selected research FCL outputs are not active until Mode 3 is engaged by the research pilot. Sensor failures can be emulated in the Mode 3 FCL by modifying any or all of the sensor data from the aircraft. Any modification to the sensor data is local to the Mode 3 FCL and does not affect the remainder of the FCS. Finally, 30 channels of user-definable data can be sent out over the MOS network via UDP and observed in real-time during flight operations. Each FCL implemented in Mode 3 can define different parameters for the 30 user data channels, but only the armed/engaged FCL user data is sent out over the MOS network.

#### E. Wavetrain

The Wavetrain module provides the capability to inject arbitrary automated control surface perturbation commands. The perturbation commands are added to the active commands (Figure 3), downstream of the FCLs, but



upstream of the LPS and Model Tracking & Failures modules. A large number of user-defined perturbation profiles can be implemented, which are then selected during flight operations.

## F. Model Tracking & Failures

The Model Tracking & Failures module, positioned downstream of the Wavetrain input (Figure 3), provides the capability to emulate control surface faults and failures during flight by modifying any of the control surface commands. A large number of user-defined failure profiles can be implemented, which are then selected during flight operations. The present design is focused on simple failures, e.g. a stuck surface, bias, reduced effectiveness, or any combination of the three, which can be applied to any command (Eq. 5). The failures are applied relative to what the control surface commands are when this module is activated ( $\delta_0$ ) to minimize transients.

$$\delta_{out} = \delta_0 + Gain * (\delta_{in} - \delta_0) + Bias \quad (5)$$

Planned development of this module includes a model tracking controller which will enable in-flight simulation of a range of dynamics, such as the aerodynamic effects of structural damage or icing.

## G. Autothrottle

The airspeed-command autothrottle in the AirSTAR FCS can be used in conjunction with Mode 1, 2, or 3 and with the Wavetrain and Model Tracking & Failures modules. The autothrottle is intended to reduce research pilot workload (primarily during turns) by managing throttle commands. The autothrottle is a classically-designed proportional-integral controller which uses calibrated airspeed and washed-out airspeed for feedback data. Integrator wind-up protection is similar to what is used in the Mode 2 FCL; integration is halted and the integrator output is held when the command is at the actuator limits or a telemetry dropout is detected.

## H. Load Protection System

The Load Protection System (LPS) is designed to prevent the FCS from exceeding the structural limits of the test aircraft. The primary focus of the LPS is normal load factor ( $-N_z$ ), with secondary focus on side force loads ( $N_y$ ). The LPS uses a two-step approach to prevent the FCS from exceeding normal load factor limits: the first approach (Plan A) is proactive and limits elevator authority as a function of dynamic pressure. Limiting elevator authority proactively was found to be the most effective way to prevent excessive load factor. Simulation runs showed elevator hardovers resulted in very high g-onset rates which are difficult to reverse quickly enough to prevent excessive load factors. The second approach (Plan B) is reactive and sets the controls to a neutral position if the specified load factor thresholds are exceeded. This approach is intended as a backup in case Plan A fails to limit load factor as expected.

The LPS Plan A elevator limits were set by first creating a database of peak load factor as function of dynamic pressure and elevator inputs by simulating elevator hardovers (step inputs and doublet inputs) from a range of trimmed flight conditions and recording the peak transient load factor. Given a maximum and minimum load factor limit, this database can be used to set the maximum allowable elevator authority as a function of dynamic pressure.

Figure 5 is a plot of peak transient load factor versus equivalent airspeed for elevator hardover inputs (both steps and doublets). The solid blue line is the peak load factor without the LPS activated; these data are used to set the Plan A elevator limits. The dashed green lines show the peak load factors with the LPS (Plan A & B) engaged are below the yield limit (5.0g) and ultimate limit (6.4g) of the S2 aircraft (shown as dotted red lines).

Excessive side force loads are prevented by limiting the rudder authority

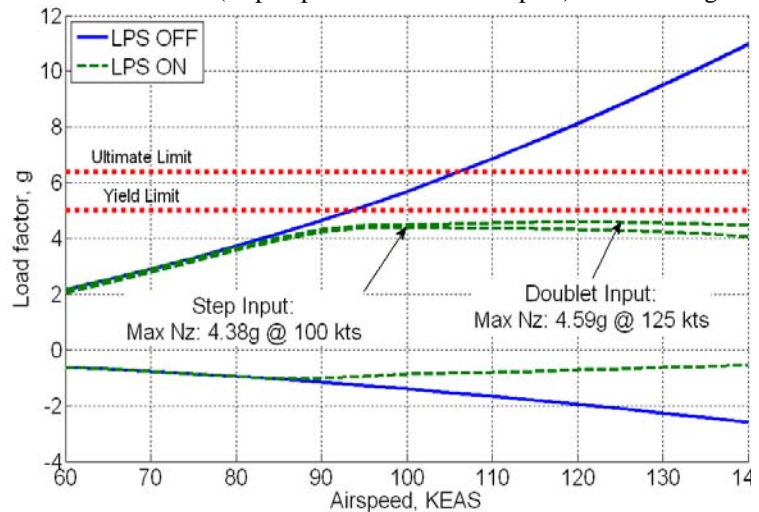
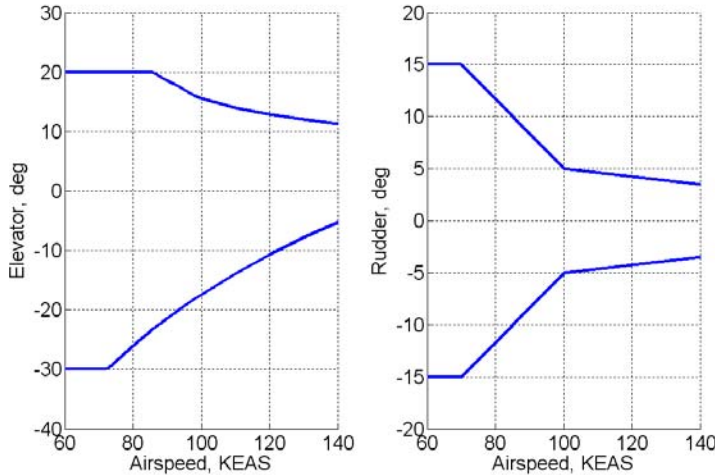


Figure 5. Simulated peak load factor for the S2 aircraft.



**Figure 6. LPS elevator and rudder limits for the S2 aircraft.**

control inputs. As a result, research control laws can run through development and test iterations in a timely fashion with minimal risk to the test aircraft.

### I. Mode Transfer Logic

The engagement of selectable FCL modes (Mode 1, 2, and 3) and modules (Wavetrain, Model Tracking & Failures, and Autothrottle) within the FCS is controlled by the Mode Transfer Logic block, which is designed to prevent inadvertent activation of FCS functions. All of the selectable FCS functions (except the Autothrottle) require the use of an “arm” switch and an “engage” switch to be active. The FCS functions must be armed prior to being engaged. The Autothrottle can be engaged whenever the research pilot has control. In addition, the following rules govern the FCS function:

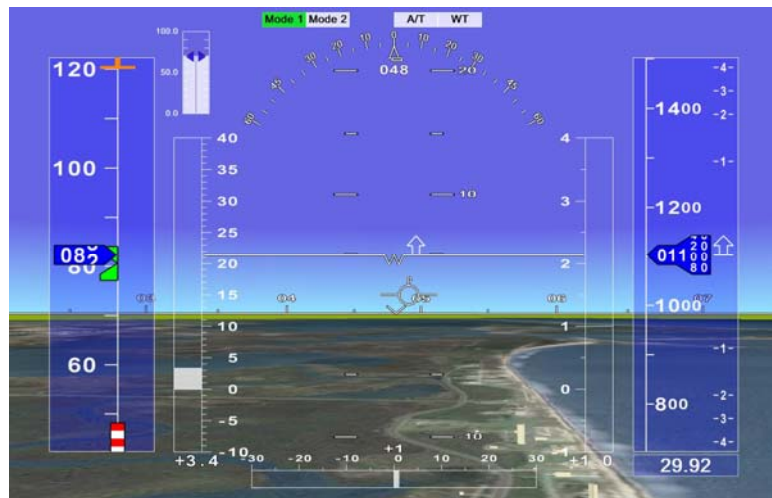
1. The FCS is locked in Mode 1 while the safety pilot is flying OR the telemetry link is inoperative.
2. The FCS will automatically revert to Mode 1 if the safety pilot takes control or the telemetry link fails. All selectable functions are disabled and disarmed, and must be rearmed and reengaged when the research pilot has control again.
3. The research pilot can manually revert the FCS to Mode 1 by pulling the trigger on the sidestick. This will only disengage, not disarm, any active functions.
4. Any selectable function (except the Autothrottle) must be armed prior to being engaged. Disarming while engaged will turn off the function.
5. Mode 2 and Mode 3 FCLs can not be engaged if the current command from these modes is at or beyond the LPS limits.

### J. Research Cockpit

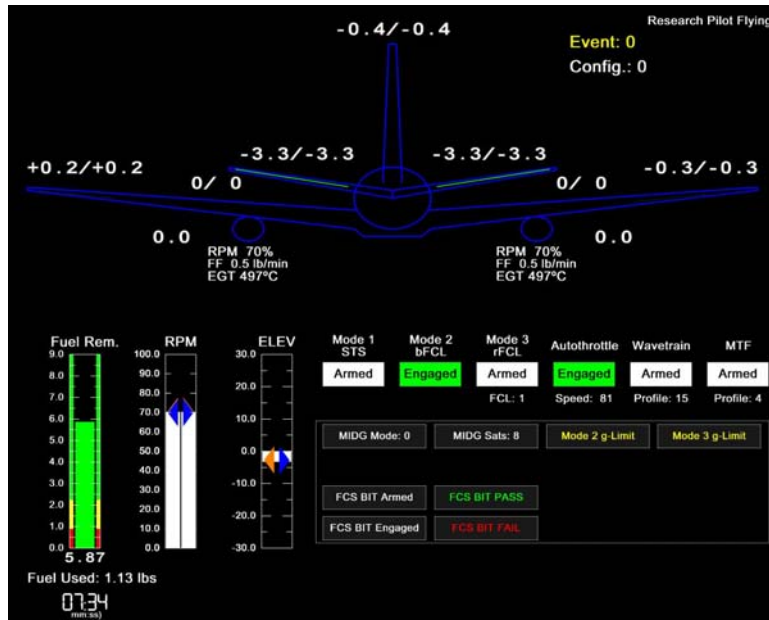
The primary inceptors for the research pilot are a sidestick, foot pedals, and throttle handles. Secondary inceptors include a flap handle, speed brake handle, and a gear switch. The primary interface to the FCS is through a number of hardware switches and knobs in the research cockpit. Due to the time-compressed nature of flight-testing dynamically-scaled vehicles, the Hands-On-Throttle-And-Stick (HOTAS) approach was used to design the research pilot interface to the FCS. The Flight Test Engineer (FTE) assists the research pilot during flight and is responsible for arming FCS functions, selecting profiles

as a function of dynamic pressure. The rudder limits are set so a full rudder reversal at maximum attainable sideslip angle will not exceed the structural limits of the vertical tail at a given dynamic pressure. If the structural limits of the vertical tail are not known (as is the case for the S2 aircraft), the rudder limits are set to the maximum deflections expected to be needed for the maneuvers in the flight test plan. Figure 6 shows the elevator and rudder limits set by the LPS for the S2 aircraft (plotted versus equivalent airspeed for clarity).

If the structural limits of the aircraft are known, the LPS effectively mitigates the risk of structural damage due to excessive



**Figure 7. Primary Flight Display with HUD.**



**Figure 8. Aircraft Configuration Display.**

commands, and angle of attack command bugs. In addition to the visual indicators, one of two distinct audio tones is played whenever a FCS mode engages or disengages. The HUD also displays visual caution and warning indicators, which are accompanied by audio tones.

The Aircraft Configuration Display (Figure 8) shows the current state of the aircraft (control surface positions, gear, flaps, engine data, fuel state) and the current state of the FCS (arm/engage status, profile/FCL selected, airspeed command).

#### IV. Summary and Future Plans

A flight control system architecture for the NASA AirSTAR infrastructure has been designed to address the challenges associated with safe and efficient flight testing of research control laws in adverse flight conditions. The AirSTAR flight control system is a flexible framework that enables NASA Aviation Safety Program research objectives by allowing rapid integration and testing research control laws. Component or sensor failures can be emulated in the FCS, in addition to the capability to inject automated control surface perturbations. A baseline control law is provided which uses an angle of attack command augmentation system for the pitch axis and simple stability augmentation for the roll and yaw axes. A Load Protection System prevents the FCS from exceeding the structural limits of the aircraft.

Future development of the AirSTAR FCS will include envelope expansion of the baseline FCL (Mode 2), addition of roll rate and sideslip angle command augmentation controllers to the baseline FCL, and exploration of alternative control strategies for the baseline FCL (e.g. pitch rate command). In addition, a model-tracking controller will be developed for the Model Tracking & Failures module, allowing in-flight simulation of adverse dynamics.

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for the Wavetrain and Model Tracking & Failures modules, and setting the Autothrottle. The research pilot is responsible for engaging and disengaging FCS functions and handling aircraft configuration changes.

The research pilot and FTE use a number of displays during flight operations. The primary flight display for the research pilot is a synthetic out-the-window view with a Heads-Up Display (HUD) (Figure 7). The HUD displays airspeed, altitude, angle of attack, angle of sideslip, normal load factor, bank angle, pitch angle, heading (both magnetic and ground track), a velocity vector indicator, vertical speed, and engine RPM. The HUD also displays information regarding the FCS, including arm/engage status of FCS modes, an airspeed command bug, autothrottle