X-43A Flight Controls

Ethan Baumann
NASA
Dryden Flight Research Center
Edwards, California

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A Little About Myself

- Graduated from Purdue University December 1998
  - B.S. in Aeronautical/Astronautical Engineering
  - Physics Minor

- Dryden Flight Research Center (DFRC)
  - 2 Co-op terms
    - Worked in Controls & Aerodynamics Branches
  - Hired as Controls Engineer January 1999
    - Worked January ’99 – June ’05 on Hyper-X Program
      - Ended up as GNC lead for X-43A Ship 3
  - Currently Dryden’s Principle Investigator and GNC lead for putting a JPL Synthetic Aperture Radar and a precision autopilot on one of Dryden’s aircraft

Topics

- NASA Dryden
  - Overview
  - Current & Recent Flight-Test Programs
- UAVSAR Program
  - Program Overview
  - Platform Precision Autopilot
- Hyper-X Program
  - Program Overview
  - X-43A Flight Controls
  - Flight Results

NASA Dryden Flight Research Center

Flight Research separates "the real from the imagined," and makes known the "overlooked and the unexpected."
- Hugh L. Dryden

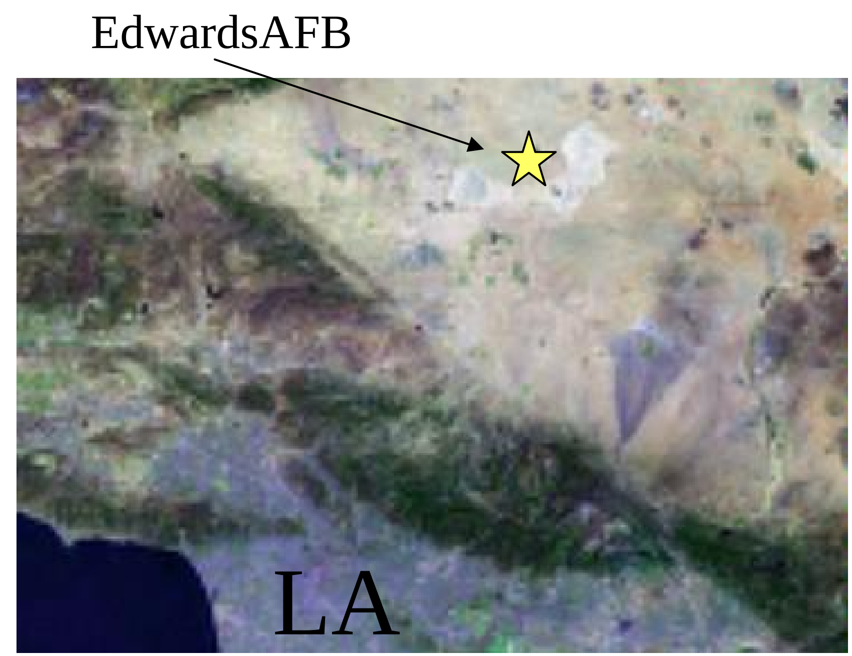
- NACA Engineers first showed up Fall of 1946 to support X-1

- Named for Hugh L. Dryden
  - NASA Deputy Administrator

- Located on Edwards AFB, California
  - Excellent Flying Weather
  - Dry lake beds serve as natural runways
  - Middle of the Mojave Desert
  - 80 miles Northeast of Los Angeles
  - Middle of Nowhere

- NASA's atmospheric flight test facility

- Alternate landing site for Space Shuttle



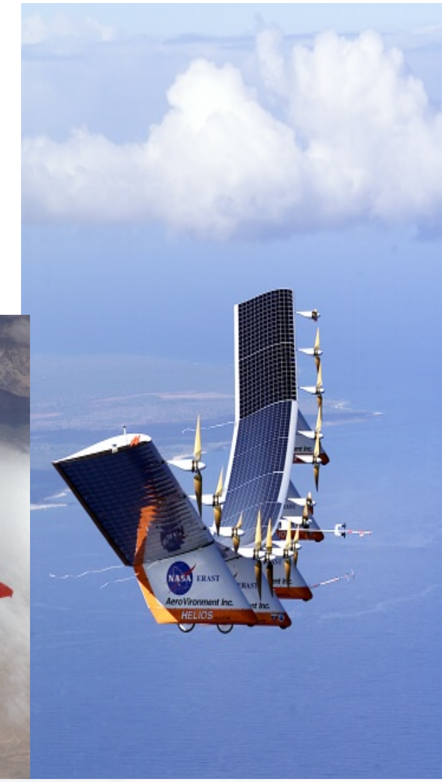
NASA Dryden Flight Research Center

Past Projects

- Space Shuttle
- X-1
- X-15
- XB-70
- X-29
- X-31
- F-8 DFBW
- F-8 Super-Critical Wing
- F-18 HARV
- Lifting Bodies
- SR-71

Current & Recent Flight Research Projects

- Airborne Aerial Refueling Demonstration (AARD)
- Active Aero-elastic Wing (AAW)
- Earth Science
  - Altus
  - Ikhana (Predator-B)
  - Helios
- G-III
  - UAVSAR Program
- F-18 Systems Research Aircraft
- F-18 chase planes
  - Also used for research
- Intelligent Flight Controls (IFCS)
- F-15B Research Test Bed
- Hyper-X
  - X-43A
- Shuttle Support



NASA Dryden's G-III Aircraft

- Aircraft Goal
  - » Provide a research test-bed for NASA, the Air Force, and other government agencies with a long-term capability for efficient test of subsonic flight experiments.
    - "Shirt sleeve" environment
    - Research Infrastructure

- Aircraft Performance
    - Max Mach - 0.85
    - Max Operating altitude - 45Kft
    - Normal cruise – 459 kts
    - Max payload – 4500 lb
    - Payload, full fuel – 2610 lb
    - Takeoff performance – 5,500ft (SL)
    - Range – 3400 nautical miles (full passengers)
    - Climb – 4,049 fpm
    - Large Internal Volume (1500 cu. Ft.)

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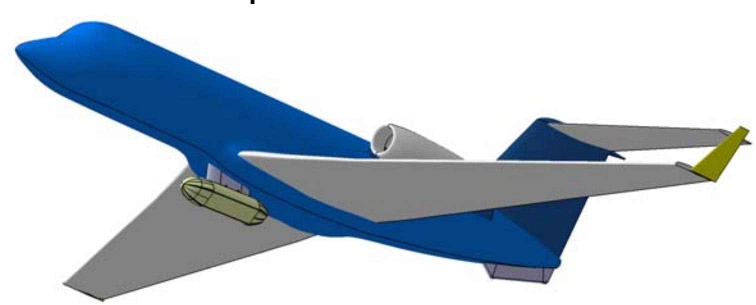
UAVSAR

- The primary objective of the UAVSAR Project are to:
  - » develop a miniaturized polarimetric L-band synthetic aperture radar (SAR) for use on an unmanned aerial vehicle (UAV) or minimally piloted vehicle
- Roles & Responsibilities
  - » JPL
    - Lead center that will design, fabricate, install and operate the radar instrument, develop processing algorithms and conduct data analysis
  - » Dryden
    - Manage the development of pod design, fabrication and delivery to JPL
    - Deliver RPI interim platform and long term operational platform
      - –NASA's G-III selected as the interim platform
    - Lead the platform modification effort and head up flight operations of the platform
    - Develop Platform Precision Autopilot (PPA) capability
  - » Total Aircraft Services, Inc. (TAS)
    - Under contract to perform G-III modifications and pod fabrication
- First Flight of SAR on G-III in Fall '06



Platform Precision Autopilot

Interface to G-III autopilot through Instrument Landing System (ILS)*

IMPLEMENTATION

GOALS

- Achieve required trajectory performance
    - Repeat Pass Flight within 10 m tube
- Meet UAVSAR schedule requirements
- Facilitate software development and deployment
- Minimize impact to G-III Flight Management System (FMS)
- Provide for safe and simple operation
- Facilitate migration to UAV platform

JUSTIFICATION

- Makes use of inherent accuracy in ILS
- Simple modification to insert RF switches between ILS signals and PPA, isolating PPA from G-III FMS
- PPA control is easily disabled by disengaging autopilot
- PPA control algorithms relatively simple

*Approach used by Danish Center for Remote Sensing (DCRS) for a similar application

Instrument Landing System

- ILS consists of two radio transmitters each with a signal at 90 Hz and 150 Hz
  - » VHF transmitter for Localizer
  - » UHF transmitter for Glideslope
- Localizer and Glideslope receivers on aircraft measure Difference in Depth Modulation (DDM) of the 90Hz and 150 Hz signals.
  - » DDM of localizer signal indicates if aircraft is left or right of centerline
  - » DDM of glideslope signal indicates if aircraft is above or below glideslope
  - » DDM of zero indicates aircraft is along centerline or glideslope

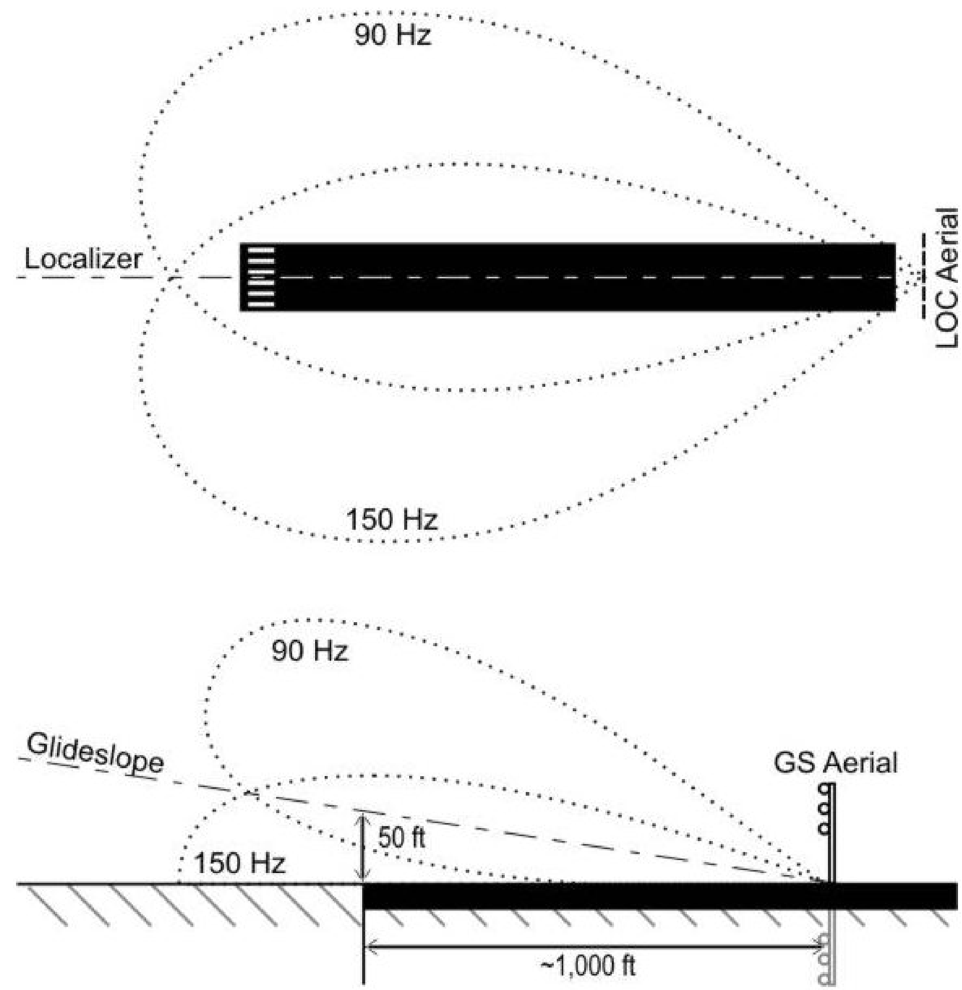
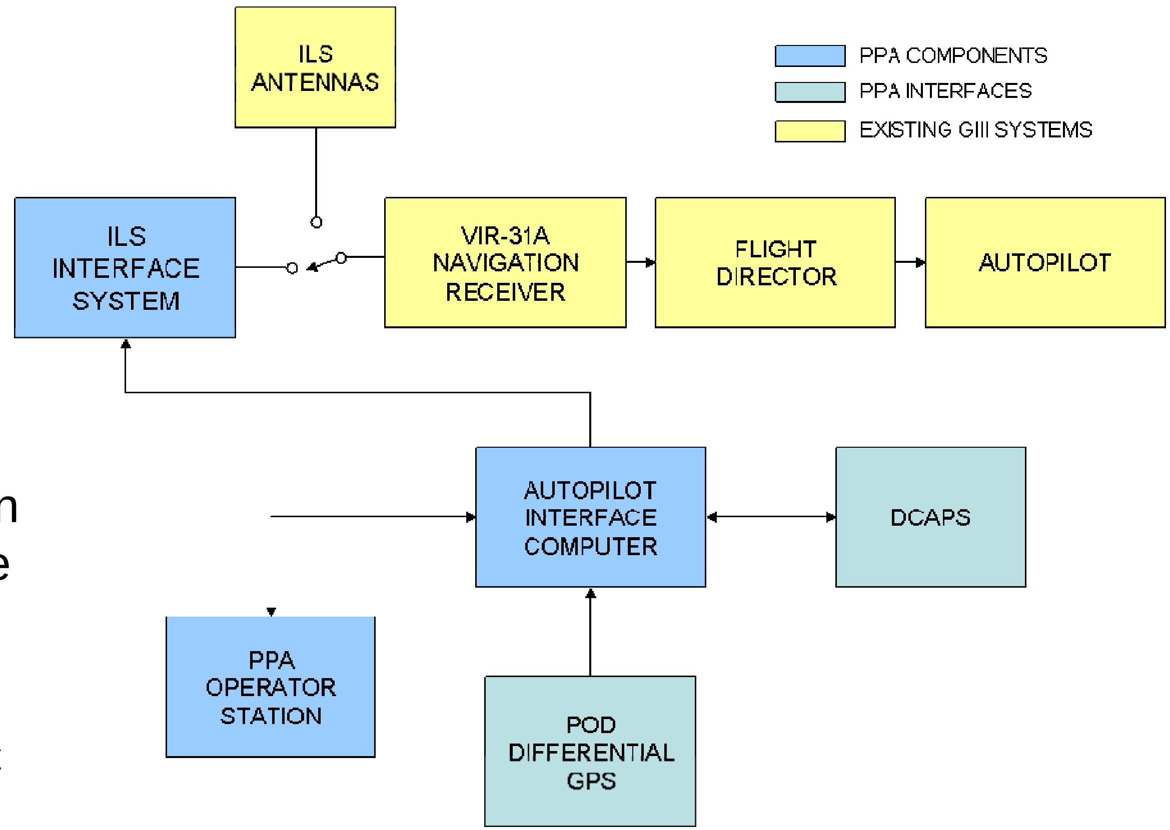


Illustration Source: Wikipedia.org

Platform Precision Autopilot Hardware Interfaces

- Autopilot Interface Computer (AIC)
  - » Provide interfaces to external data sources
  - » Host the control algorithm
  - » Drive the IIS
  - » Provide interface to operator station of G-III for waypoint upload, gain control, and data archive
- ILS Interface System (IIS)
  - » Modulate the ILS signal based on input from AIC
  - » Provide the ILS glideslope (GS) and localizer (LOC) RF signals



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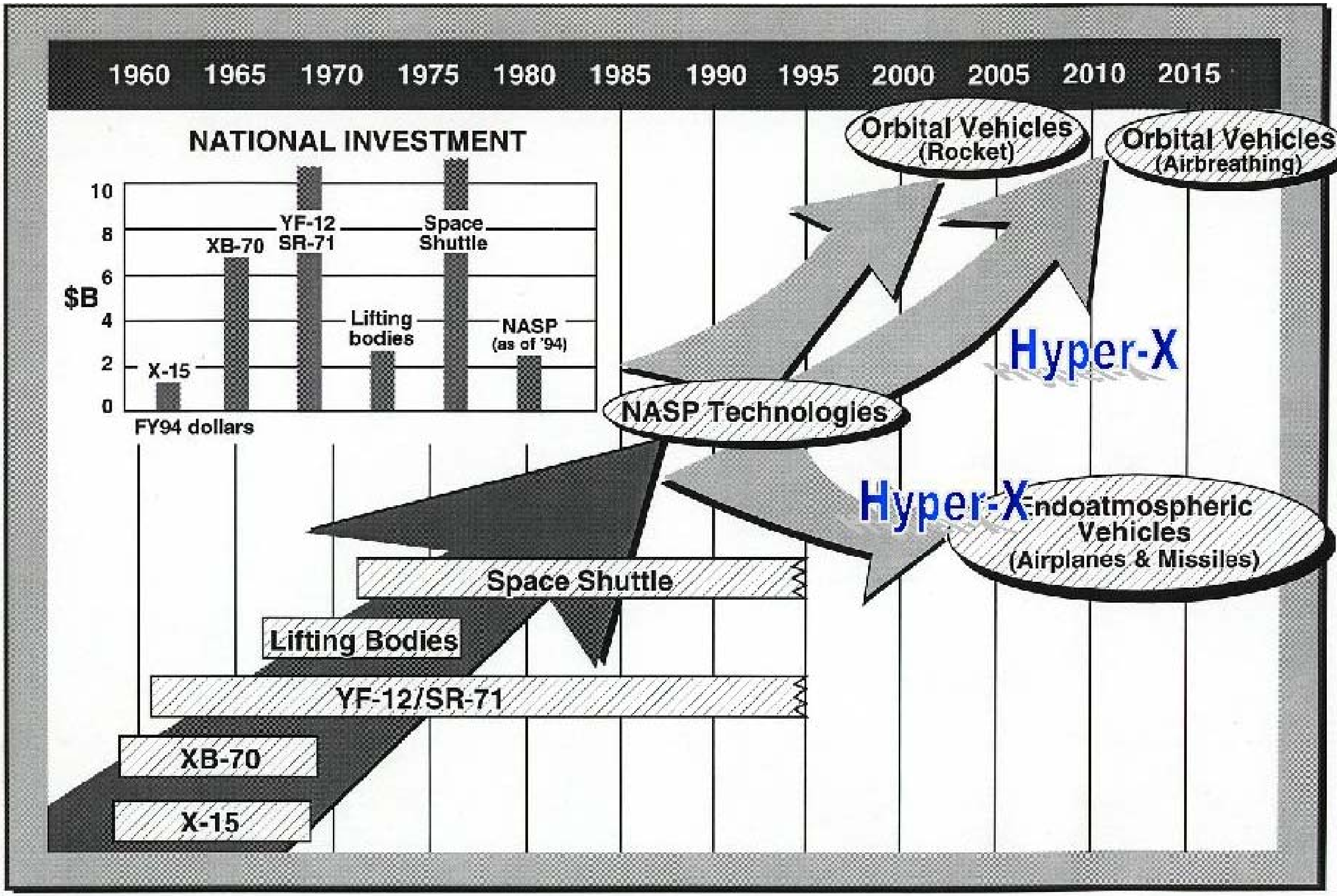
Project Overview

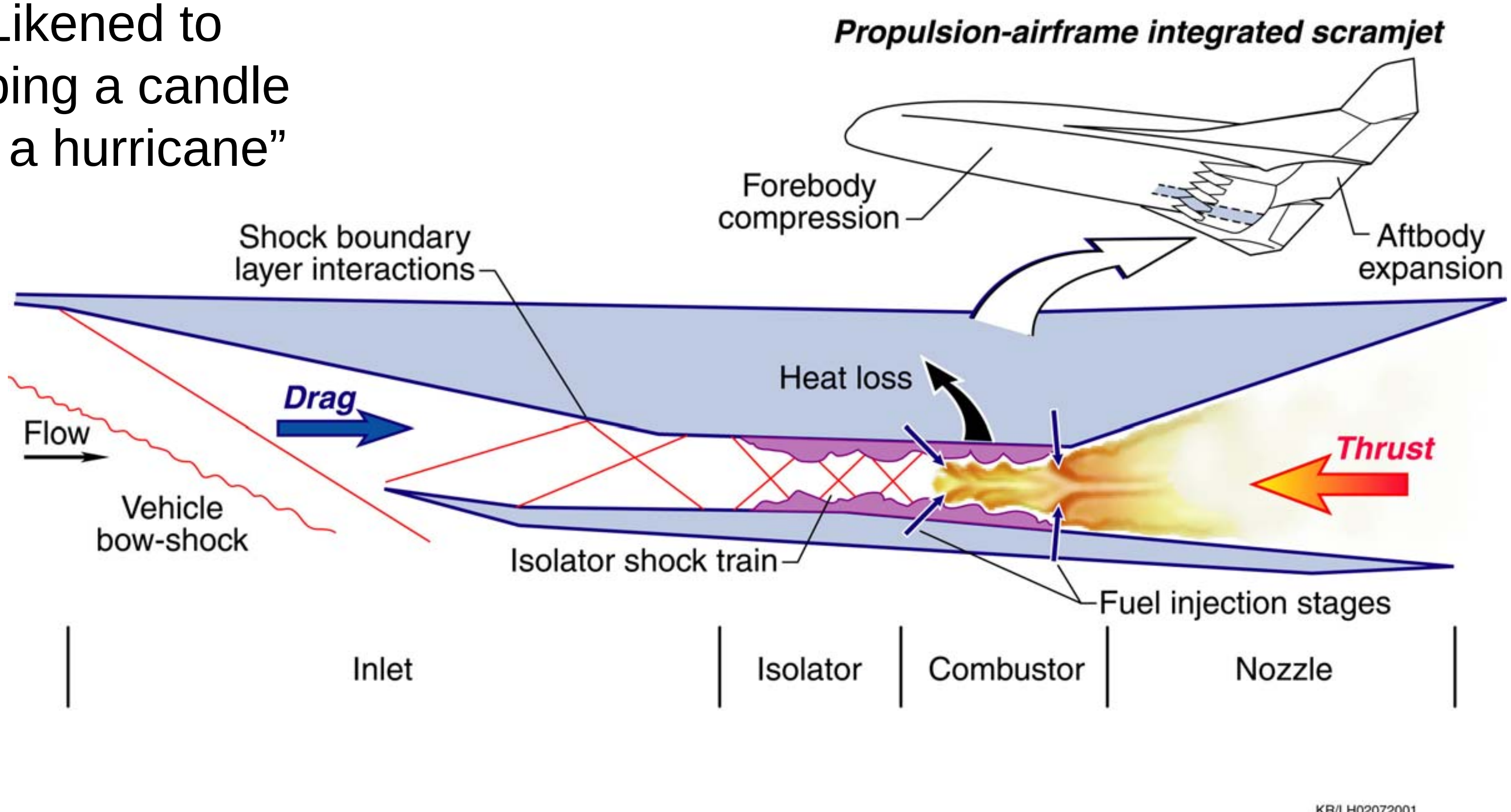
- **X-43A project designed to be the first ever flight demonstration of an airframe-integrated, hydrogen fueled, scramjet powered, hypersonic vehicle**
- **Gather in-flight data in order to validate ground based analytical tools, test techniques and methodologies expected to be used to design future scramjet powered, hypersonic vehicles and their systems**
  - » **Verify predicted scramjet performance**
  - » **Collect dynamics and control, propulsion, aerodynamic, thermal, and structural data**

Hyper-X Legacy



Scramjet Features

“Likened to keeping a candle lit in a hurricane”



Important Scramjet Terms/Concepts

Inlet starting	Combustor/isolator interaction
Ignition/Flameout/Flameholding	Fuel equivalence ratio
Inlet transition	Scramjet-Vehicle Interaction

Project Overview

- A three-flight project
  - » 2 flights at Mach 7
  - » 1 flight at Mach 10
- Top level goal was to accelerate the vehicle
- 7 year program (1996 – 2004)
- ~ $230m investment
- ~ 220+ people working the project

The Effort

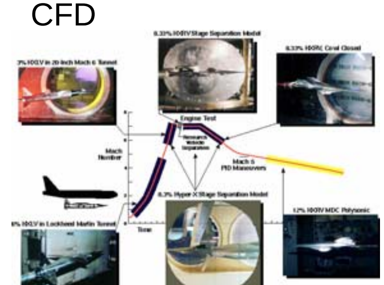
<u>Propulsion</u>
- Fuel system
- Scramjet engine
- Propulsion control laws
- Environmental system

<u>Systems</u>
- Flight computers
- Actuators
- Power
- Software
- V & V testing

<u>Structures</u>
- Aero & thermal loads
- FEM modeling
- Structural analysis & design

<u>LV, Sep, & RV Sims</u>
- GNC & PSC design & testing
- Monte-Carlo analysis
- Vehicle performance
- S/W & H/W testing
- HIL/AIL testing
- Mission control room training

<u>Aerodynamics</u>
- Outer mold line design
- Aero data base – testing & CFD



<u>Stage Separation</u>
- Never been done
- High q, asymmetric bodies

<u>GNC</u>
- LV, Sep, & RV Control laws

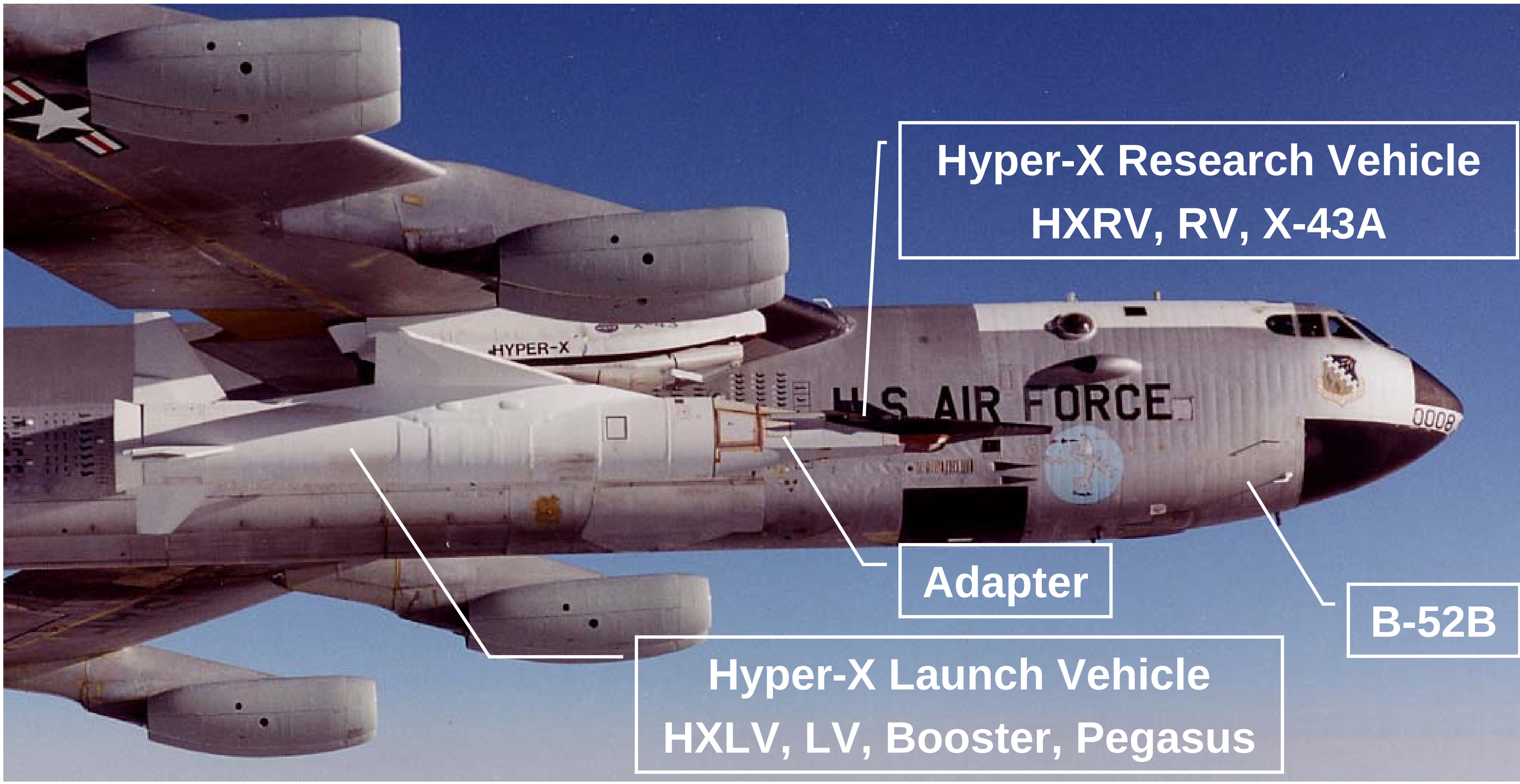
<u>Launch Vehicle</u>
- The ride to Mach 7
- Modified Pegasus booster

<u>Flight Operations</u>
- Puts it all together
- Vehicle integration, fueling, flight, ground, & control room ops

The Team

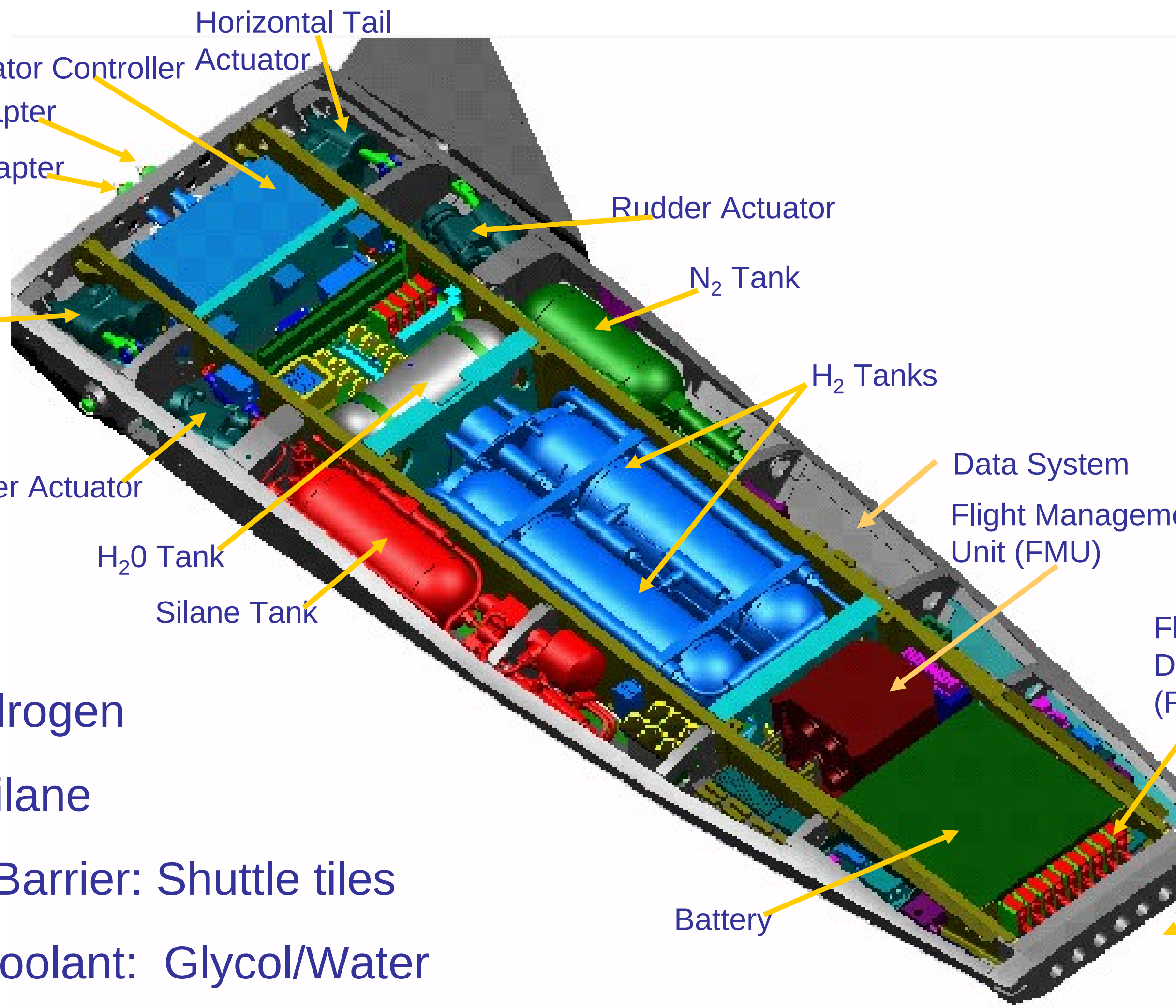
Hyper-X Partnership
NASA Dryden Flight Research Center
Edwards, CA
Research/Flight Operations
Airworthiness, Flight Safety, Range Safety
Air Force Flight Test Center, Vandenberg AFB
Naval Air Warfare Center, Pt. Mugu
Pacific Sea Range
MicroCraft
Ontario, CA
Airframe Assembly
Boeing
Long Beach, CA
Systems/Software Design and Integration
Alliant Techsystems
Magna, UT
Rocket Motor
Orbital Sciences Corp.
Chandler, AZ
Launch Vehicle Development
Lockheed Martin
Dallas, TX
Wind Tunnel Testing
Honeywell
Clearwater, FL
Research Vehicle Flight Computer
Boeing
St Louis, MO
Technology Design
GASL
Ronkonkoma, NY
Engine & Fuel Systems
NASA Langley
Research Center
Hampton, VA
Technology Design and Experimental Test
NASA Marshall Space Flight Center
Huntsville, AL
Architecture Studies and Technology Assessments
NGLT
ATK - GASL
Tullahoma, TN and Huntsville, AL
Research and Launch Vehicle Interface
Stage Separation Testing
Systems Installation

The Hardware



Stack = HXLV + Adapter + HXRV

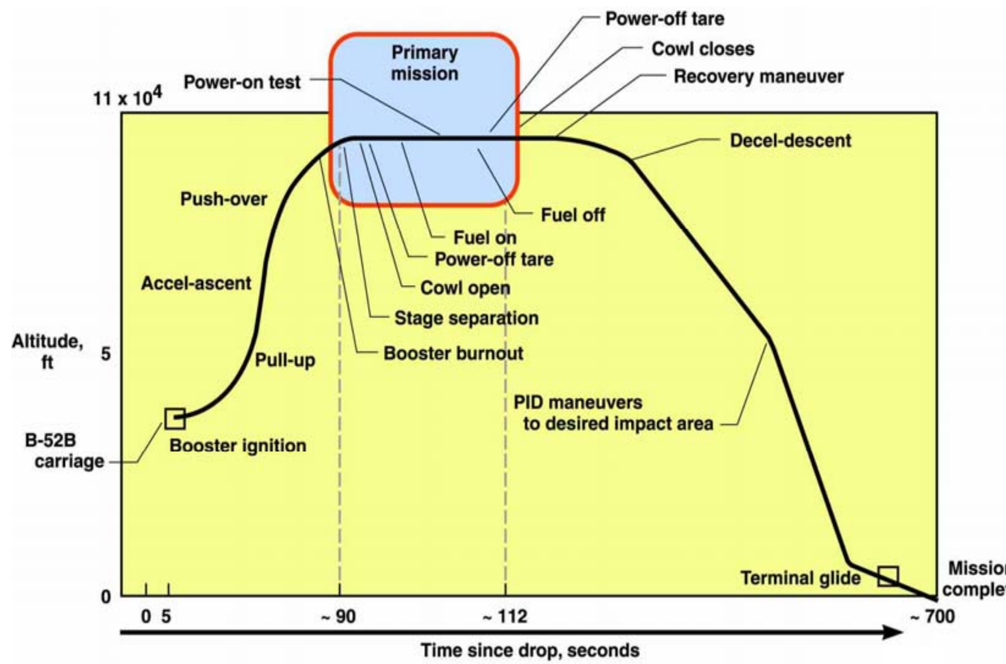
X-43A Systems



- Fuel: Hydrogen
- Igniter: Silane
- Thermal Barrier: Shuttle tiles
- Engine Coolant: Glycol/Water
- Nitrogen Purge
- Electric Actuators

Hyper-X Research Vehicle (HXRV) Mission Profile

- Hyper-X Launch Vehicle delivers HXRV to acceptable separation conditions
- HXRV Guidance & Controls Objectives
  - » Separate from the HXLV
  - » Engine Test (Primary Mission)
    - Maintain RV attitude & control
    - Maintain test conditions
  - » Descent - Post Cowl Closed (Secondary Mission)
    - Arrest dynamic pressure build up and heating
    - Descend along a predetermined descent profile towards an impact location
    - Perform parameter identification maneuvers and frequency sweeps along the descent at Mach 8, 7, 6, 5, 4, 3, and 2.



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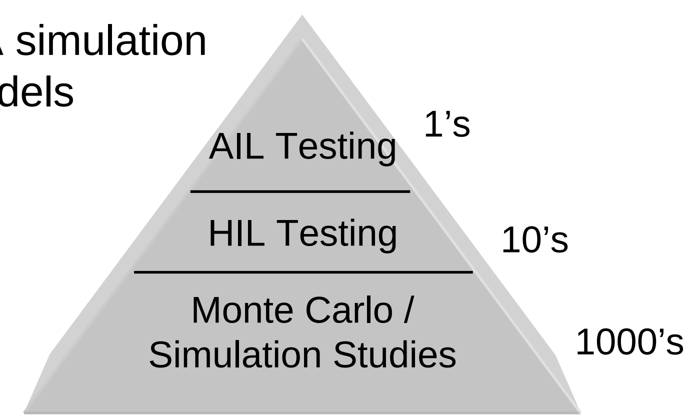
Dryden's Roles & Capabilities

- Responsible for Guidance, Navigation, and Flight Control Software on the X-43A
  - Flight Control Software developed jointly by Langley, Dryden, and Boeing
    - PID controller used for both Longitudinal & Lateral-Directional axes
    - Guidance algorithm commanded vehicle to head west towards an aimpoint
  - Since 1999, Dryden conducted all updates to Flight Control Software
    - Including re-design of the controller for the Mach 10 mission

- Responsible for vehicle and software performance and stability analysis
  - Time history performance
  - Stability margin analysis
  - Software verification & validation supplementing Boeing's V&V

- Dryden developed a number of tools and capabilities to perform the GNC related analysis
  - Linear analysis toolset built in the Matlab/Simulink environment
    - Monte Carlo Analysis Capability
  - High Fidelity non-linear 6 degree of freedom X-43A simulation
    - Including detailed actuator, sensor, timing models
    - Monte Carlo Analysis Capability
  - Hardware in the Loop (HIL) test environment
  - Aircraft in the Loop (AIL) test environment
- Simulation & Monte Carlo results used pre-flight by Aerodynamics & Scramjet IPTs to assess vehicle and engine performance.



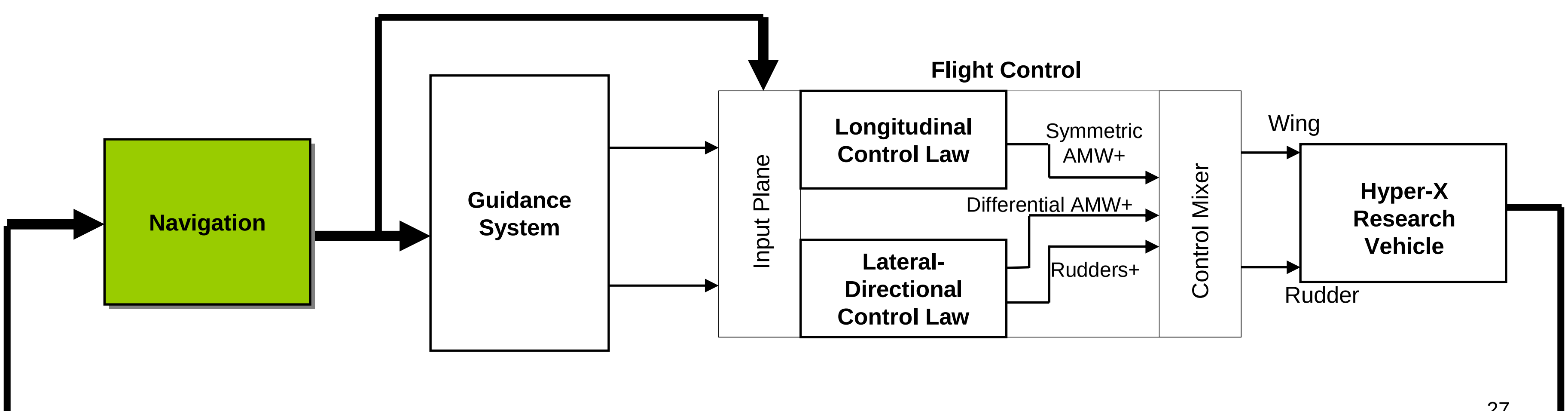
HXRV Free-Flight Requirements

- Deliver RV to acceptable separation conditions
- Successfully separate the RV from the LV
- Engine Test
  - » Maintain RV attitude & control
  - » Conduct the pre-experiment tare
  - » Maintain test conditions
  - » Conduct the post-experiment tare
  - » Conduct the cowl open Parameter Identification Maneuver (PID)
  - » Controlled flight following engine operation
- Descent - Post Cowl Closed
  - » Post engine test pull-up to 8 degrees angle-of-attack (arrest dynamic pressure build up and heating)
  - » Descend along a predetermined descent profile and impact location
  - » Perform parameter identification maneuvers, frequency sweeps and push-over pull-up (POPU) maneuvers along the descent at Mach 5, 4, 3, and 2.

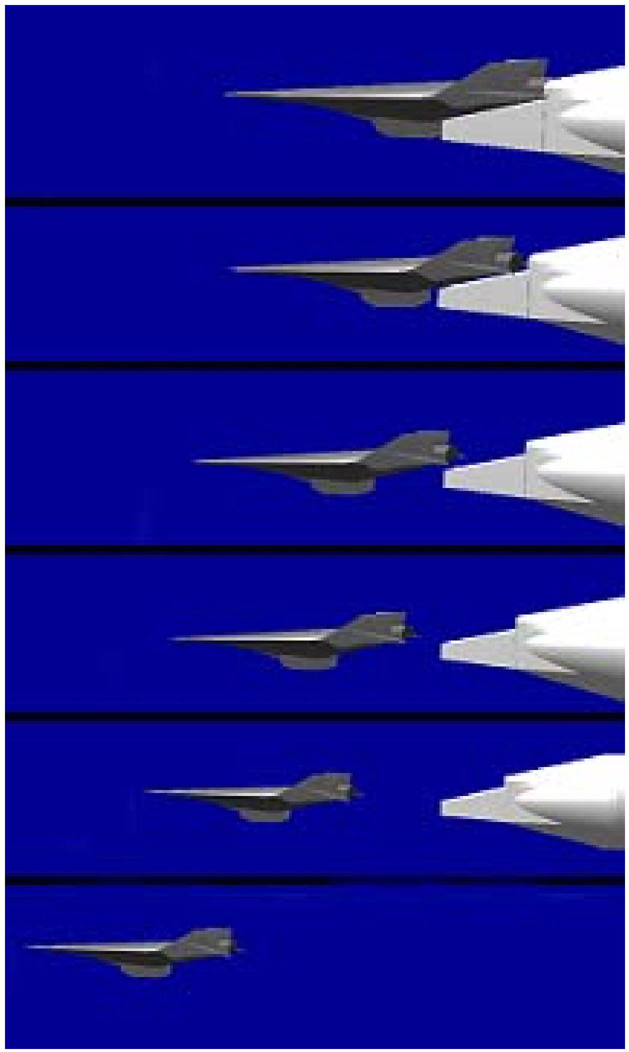
Controlling the X-43A

- X-43A control laws use a PID control architecture.
  - Gains scheduled as a function of Mach & Angle of Attack
  - Gains scaled by Dynamic Pressure
  - Control Laws were designed to be as simple & robust as possible.
    - Only performance requirement was to fly straight and level at a specified angle of attack.
    - Carried ≈ 6 dB Gain Margin & ≈ 45° Phase Margin in all control loops
      - Had to accept less Gain and Phase Margin during portions of the descent
    - Carried large uncertainties which needed to be accounted for.

- Separation studied by LaRC in Separation Simulations.
  - Wings set to a constant deflection for the initial portion of the separation event.
  - Control loops are disengaged at separation and faded in over about 1 second.



Nominal Separation Scenario



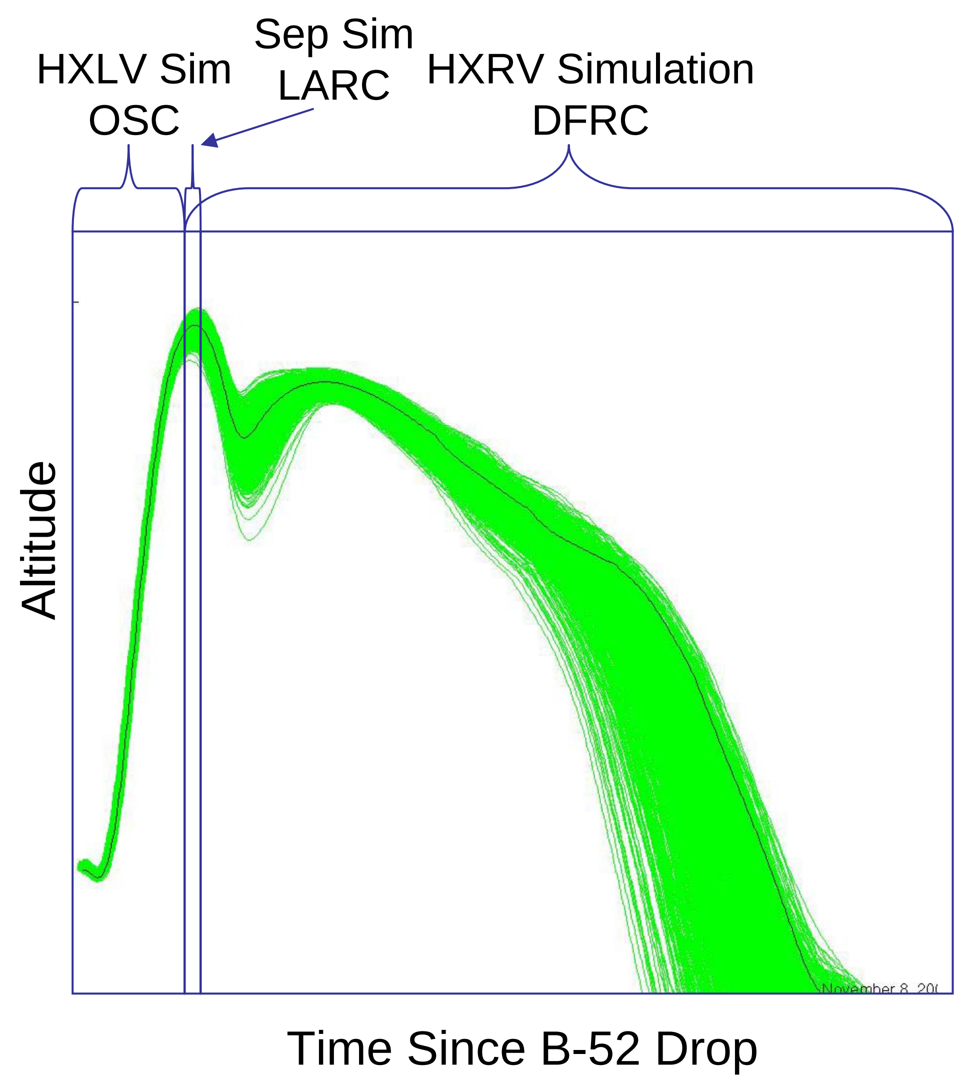
0 msec	**Start of Separation** Mach = 7 q_{bar} = 1066 psf
100 msec	**End of Piston push** 9 in. extension
250 msec	**Beginning Transition to free aero** x_{sep} = -44 in.
350 msec	**Free aerodynamics** x_{sep} = -69 in.
500 msec	**All feedback control loops closed**
2.5 sec	**End of separation / Start of test**

3 Different Non-linear Simulations

- A large portion of the GNC analysis was conducted with the non-linear simulations.

- Early on, the project decided to maintain 3 separate simulations to model the mission.
  - Launch vehicle simulation maintained by Orbital.
  - High fidelity 6 + 6 DOF separation simulation maintained by LaRC
  - High Fidelity RV post-separation simulation maintained by DFRC.

- End States of one simulation used as inputs to the next simulation in the mission.



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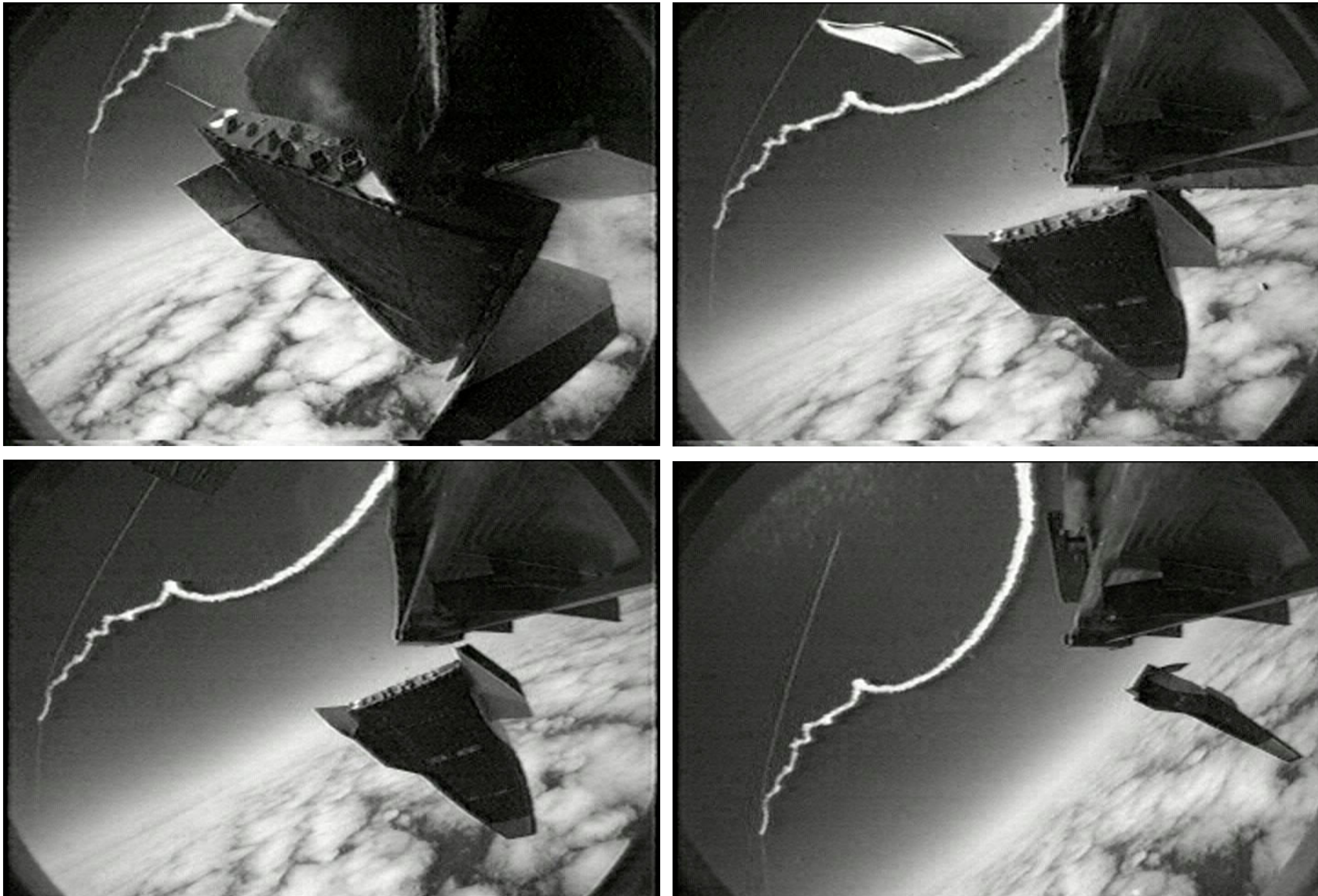
Video Segment

X-43A Flight 1

02 June 2001

Adapter Camera Flight 1



X-43A Return to Flight

- X-43A Mishap Investigation Board (MIB) convened on June 5, 2001 and submitted draft report March 8, 2002

- MIB Findings
  - Modeling deficiencies caused over-prediction of autopilot stability margins
    - » Fin Actuation System
    - » Aerodynamics
    - » Mass Properties

- Over-prediction of fin actuator torque margin
  - » Mis-prediction of aerodynamic hinge moments
  - » Low torque margin

- 2 year Return to Flight effort commenced March 2002

Return to Flight Risk Reduction

Launch Vehicle

- Higher fidelity models
  - » Aerodynamics
  - » Actuators
  - » Structures
  - » Autopilot
- Lower loads trajectory: booster propellant off-load
- Actuator upgrade for greater torque capability
- Autopilot trades/optimization
- Independent simulation

Stage Separation

- Higher fidelity models
- Additional separation mechanism testing
- Control law refinements for robustness
- Independent simulation

Research Vehicle

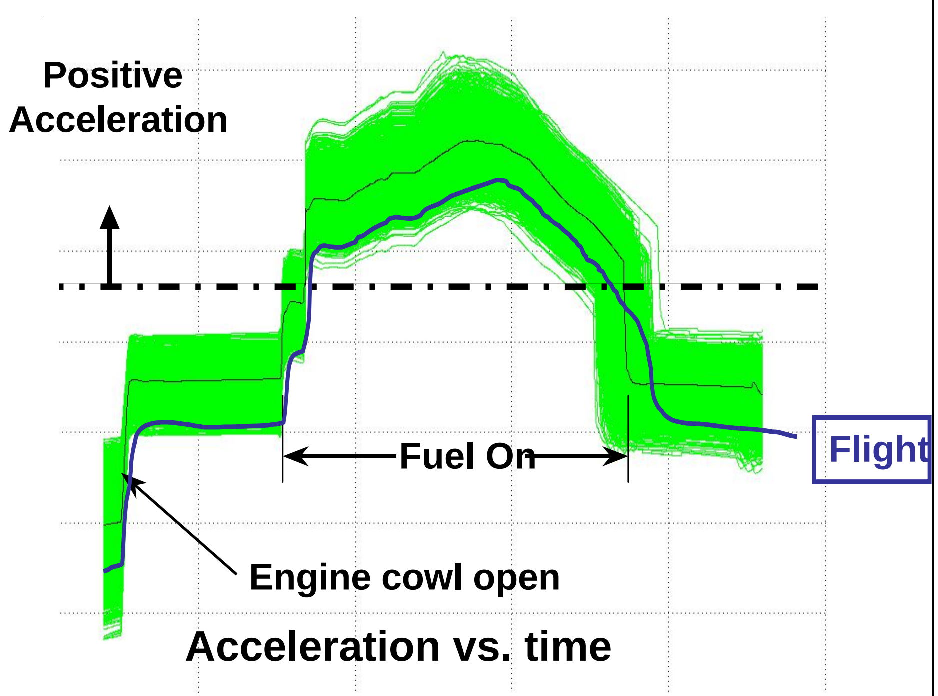
- Higher fidelity models
- Increased AOA for flameout robustness and greater thrust
- Upgraded engine control logic for unstart robustness
- Adapter fluid systems improvements
- Redesign of wing control horns
- Aircraft-in-the-loop timing tests
- Independent simulation

Flight 2 – March 27, 2004

- It was touch & go for awhile
  - » Weather was dicey up until the morning of flight
    - H2 fueling was accomplished with wind gusts up to 60 knots
  - » Frequency conflicts were resolved with the great cooperation of the F-22 program
  - » Last minute B-52 problems resolved
  - » A fire in the range building extinguished without use of water

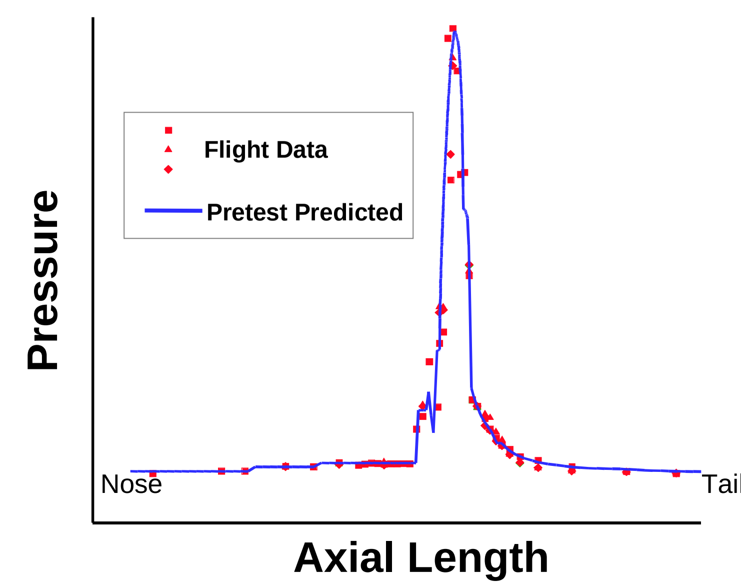
X-43A Research Vehicle Results

Preflight Monte Carlo Predictions vs Flight Data



Acceleration vs. time

Centerline wall pressure



F3 Approach & Philosophy

- The Flight 3 hardware was worked in parallel with Flight 2.
- Final models and analysis were not available until after Flight 2 and initial post-flight analysis was complete.
- The focus of the team shifted to Flight 3 in the beginning of May 2004.

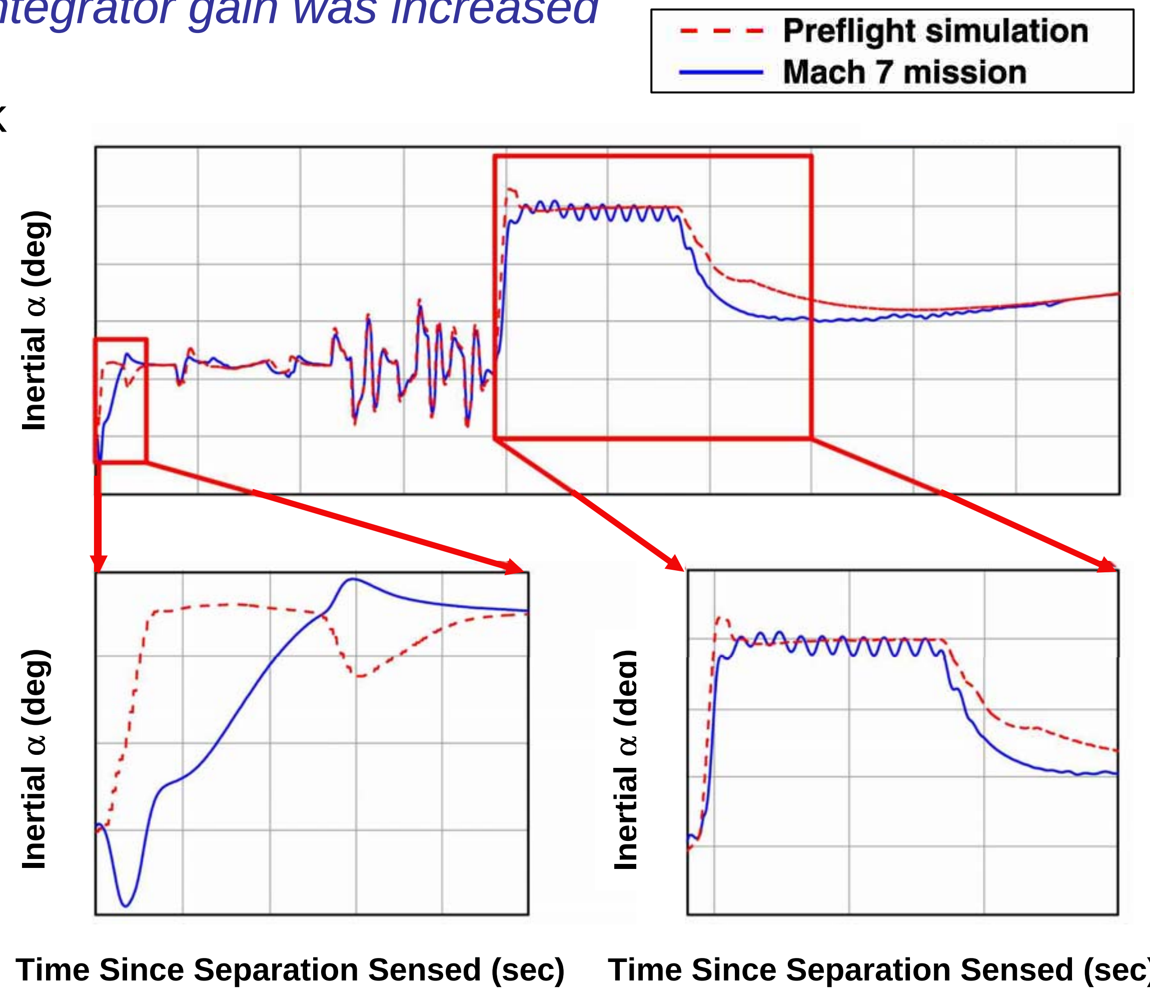
- Quick turnaround, goal for flight was 6 months after initial model release in early April.
  - » Capitalized on recent Flight 2 experience and Return-to-Flight Approach
  - » Work efficiently and quickly without losing attention to detail.
  - » Team remained mostly intact
  - » Tests and procedures went faster than they did for flight 2.

- Assumptions
  - » Do very little independent analysis (i.e. no duplication of effort)
  - » Look at Flight 2 data to determine what Flight 3 modification would be necessary for success.
  - » Models would not be updated based on flight data. The flight data would be used for guidance for modifications and for stress cases.
  - » Engine test region was primary objective and therefore was the highest priority

- Flight 3 approach was success oriented and assumed no major issues.

Updates Addressing Mach 7 Mission Inertial Angle of Attack Performance

- During the Mach 7 mission, the HXRV was slow to arrive at the commanded engine test angle of attack after separation.
  - *The angle of attack error integrator gain was increased to improve performance.*
- A low amplitude angle of attack oscillation occurred during the recovery maneuver.
  - The cause of the oscillations is not fully understood.
  - Prior to the Mach 10 mission, actuator friction and aerodynamic uncertainties were believed to be possible causes.
  - *The angle of attack was lowered throughout the trajectory to avoid flying at the same flight condition.*

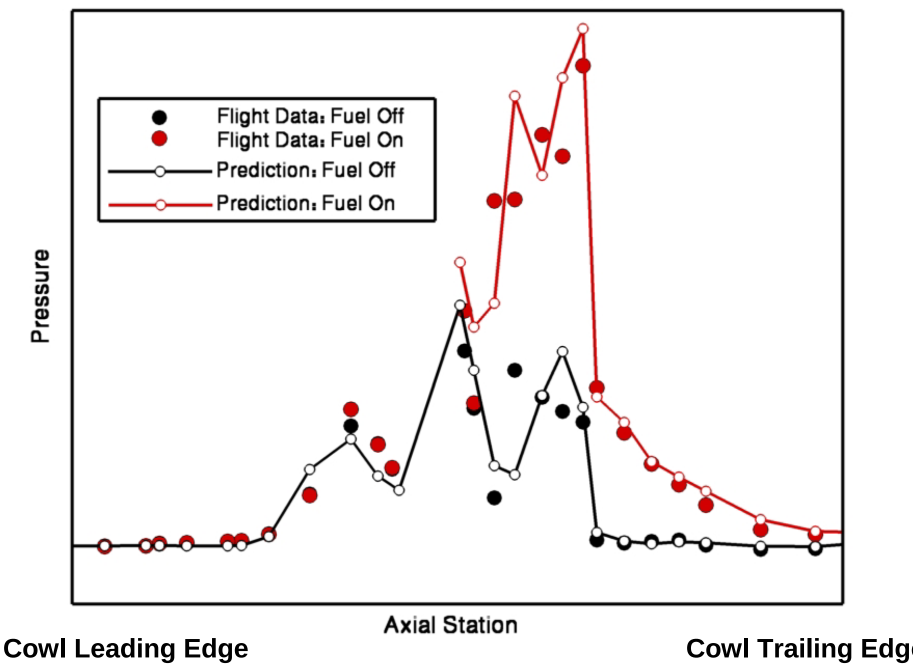


Modified for Mach 10 Mission

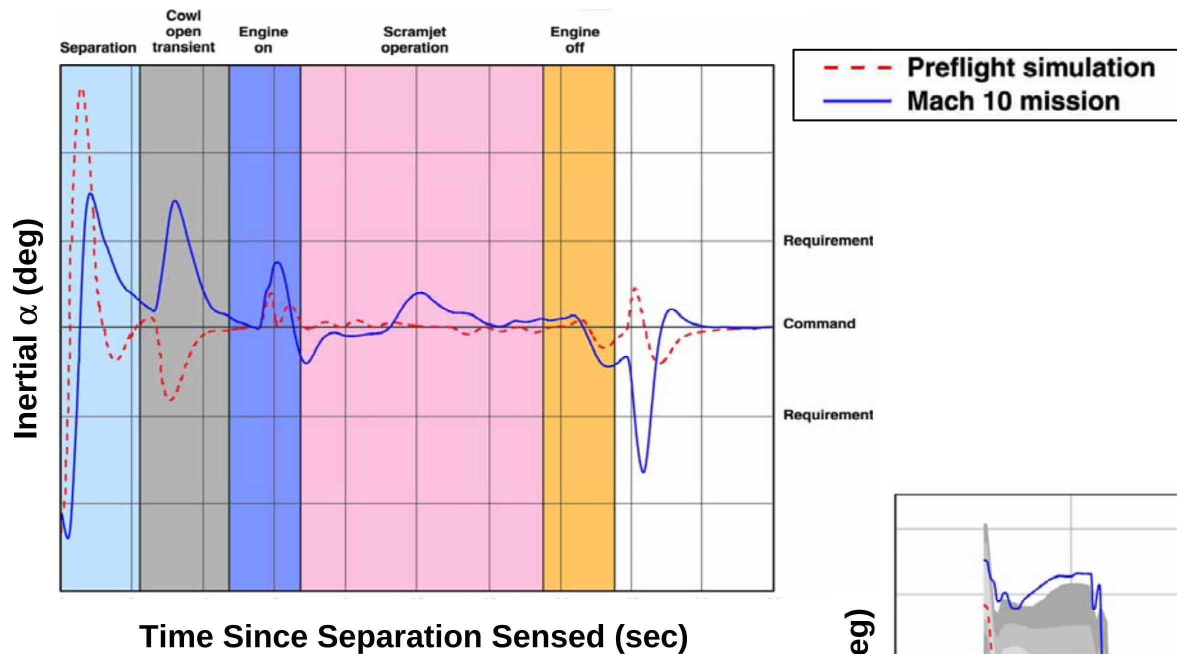
Mach 10 Mission Engine Test Performance Overview

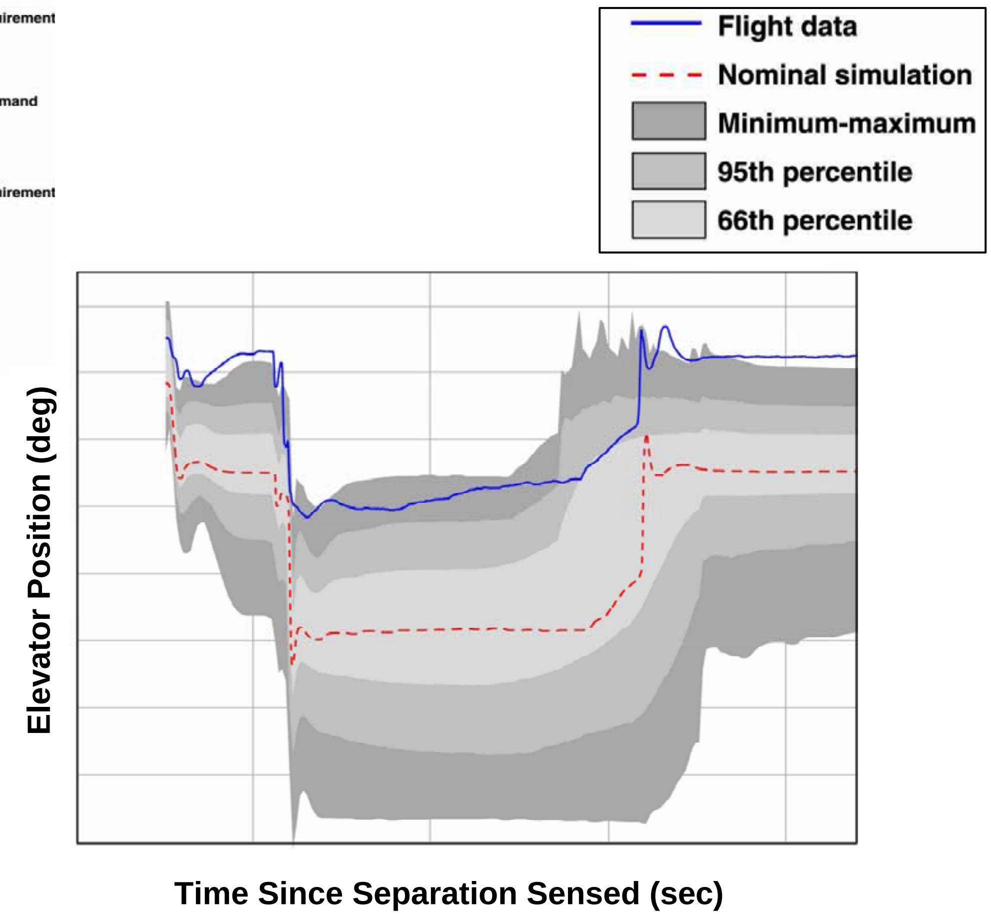
- Successfully separated from HXLV
  - Vehicle pitched up past the desired angle of attack and arrived at the desired condition shortly prior to the cowl door opening.
- Maintained desired angle of attack within 0.2 deg during the engine test.
  - A slight change in the engine performance was seen as the ignitor was removed from the fueling profile. This caused the HXRV to pitch up 0.2 deg and was quickly rejected by the controller.
- Mach & dynamic pressure within acceptable limits.
- Elevator trim settings during the engine test were near the pre-flight Monte Carlo predictions.
  - Likely due to mis-prediction of C_{mo} in unclassified aerodynamic and engine databases.

Flight vs. Pre-flight Propulsion Database



HXRV Mach 10 Mission Inertial Angle of Attack During the Engine Test



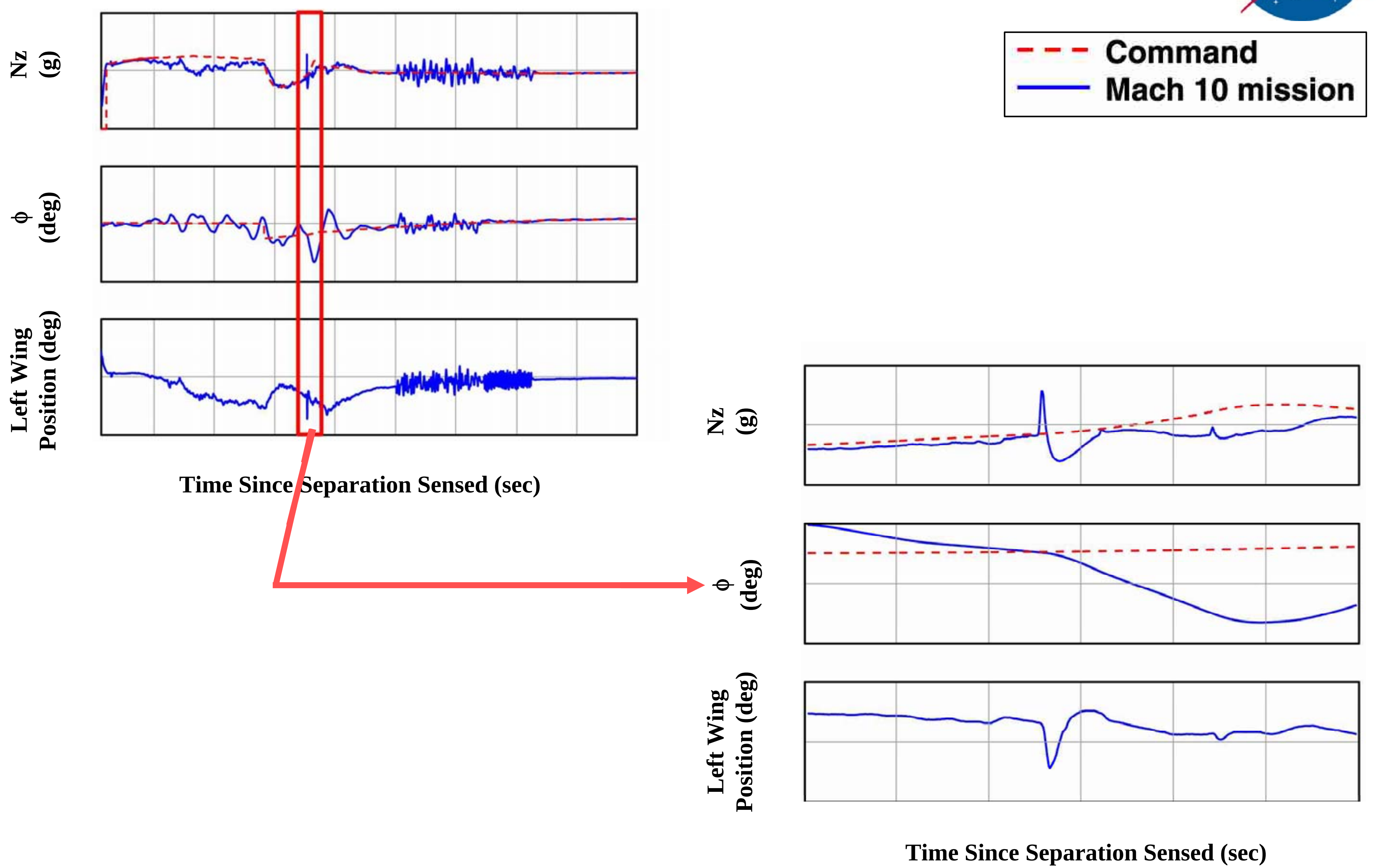


Descent Performance Overview

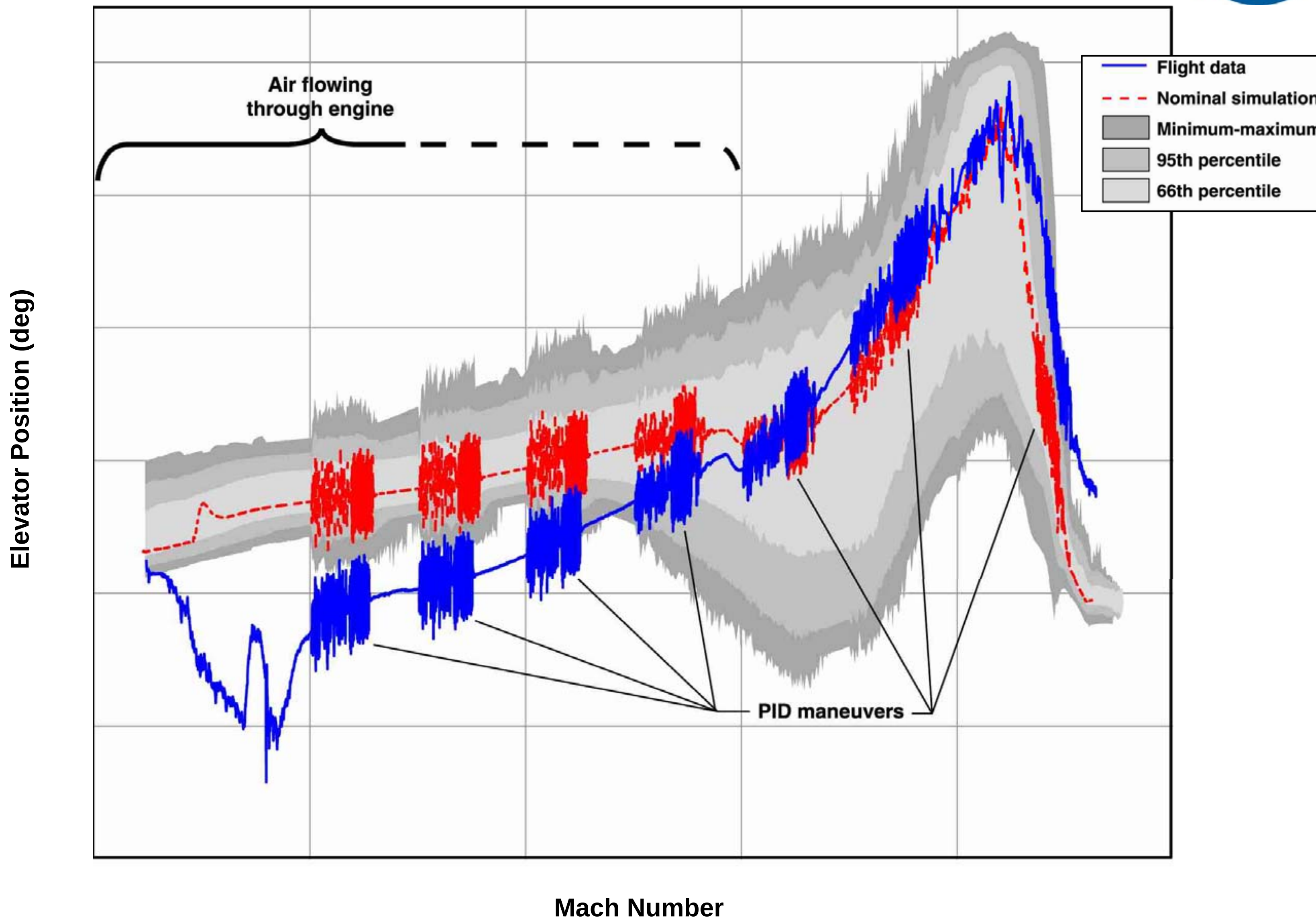
- The HXRV initially achieved the desired angle of attack during the recovery maneuver
  - Shortly into the recovery maneuver, the HXRV began to rock in bank and drop off in angle of attack
    - Elevator trim settings moved outside of Monte Carlo predictions.
    - It is believed that air was flowing through the engine during this time period.
      - Not known how this happened since the cowl door indicated full closure.
    - Appears as if the ignitor ignited when it was vented
    - Vehicle performance improves after venting and flies similar to pre-flight predictions from there on down.
- The longitudinal oscillations seen in the Mach 7 mission were not present during the Mach 10 mission.
- Successfully completed all PID maneuvers
  - HXRV decelerates rapidly during the Mach 2 PID maneuver and some of the inputs are applied in the transonic regime.
- Loss of Signal

Mach	Altitude	Downrange
0.72	918 ft	~600 nmi

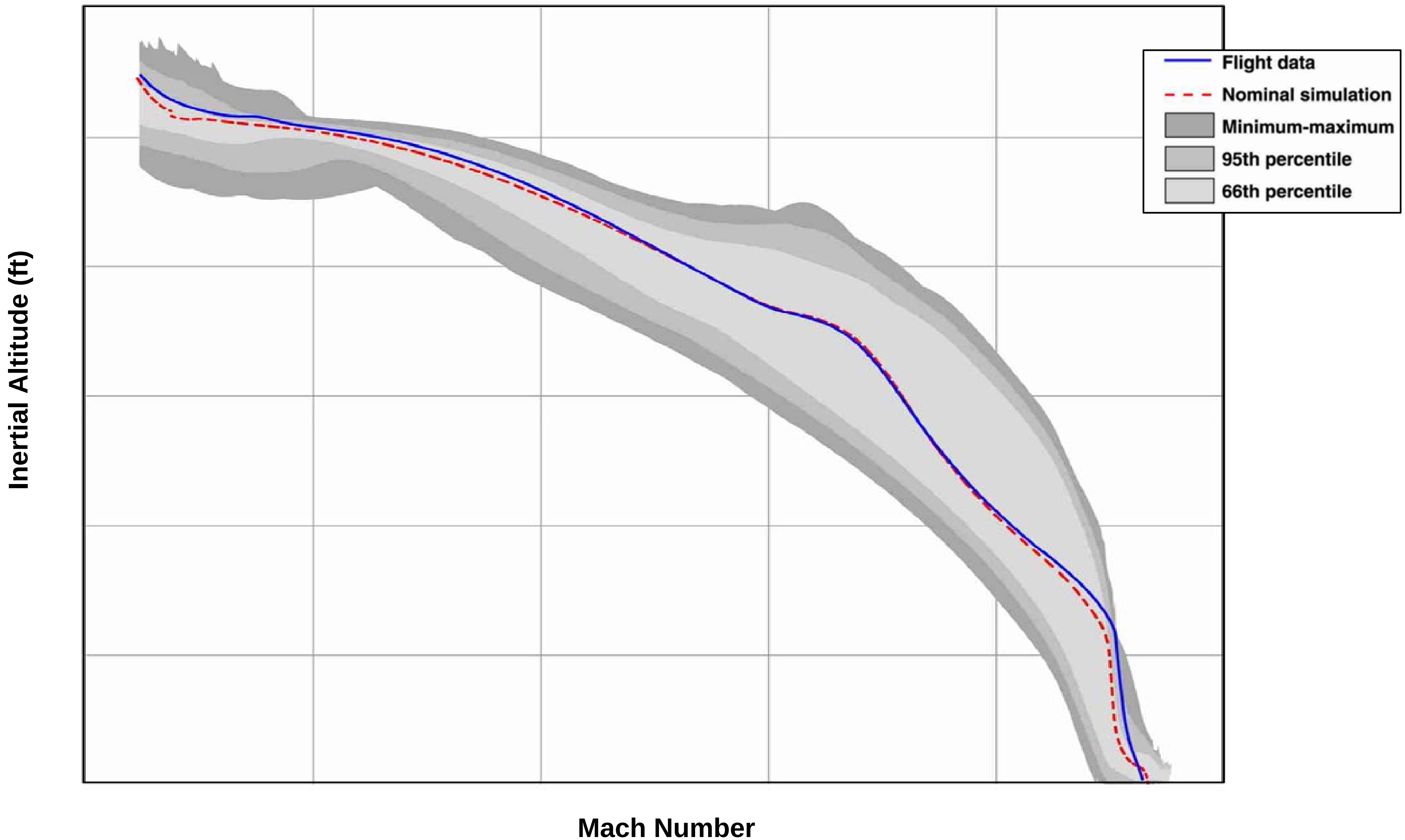
Mach 10 Mission Performance Post-Engine Test



Mach 10 Mission Elevator Position during the Descent

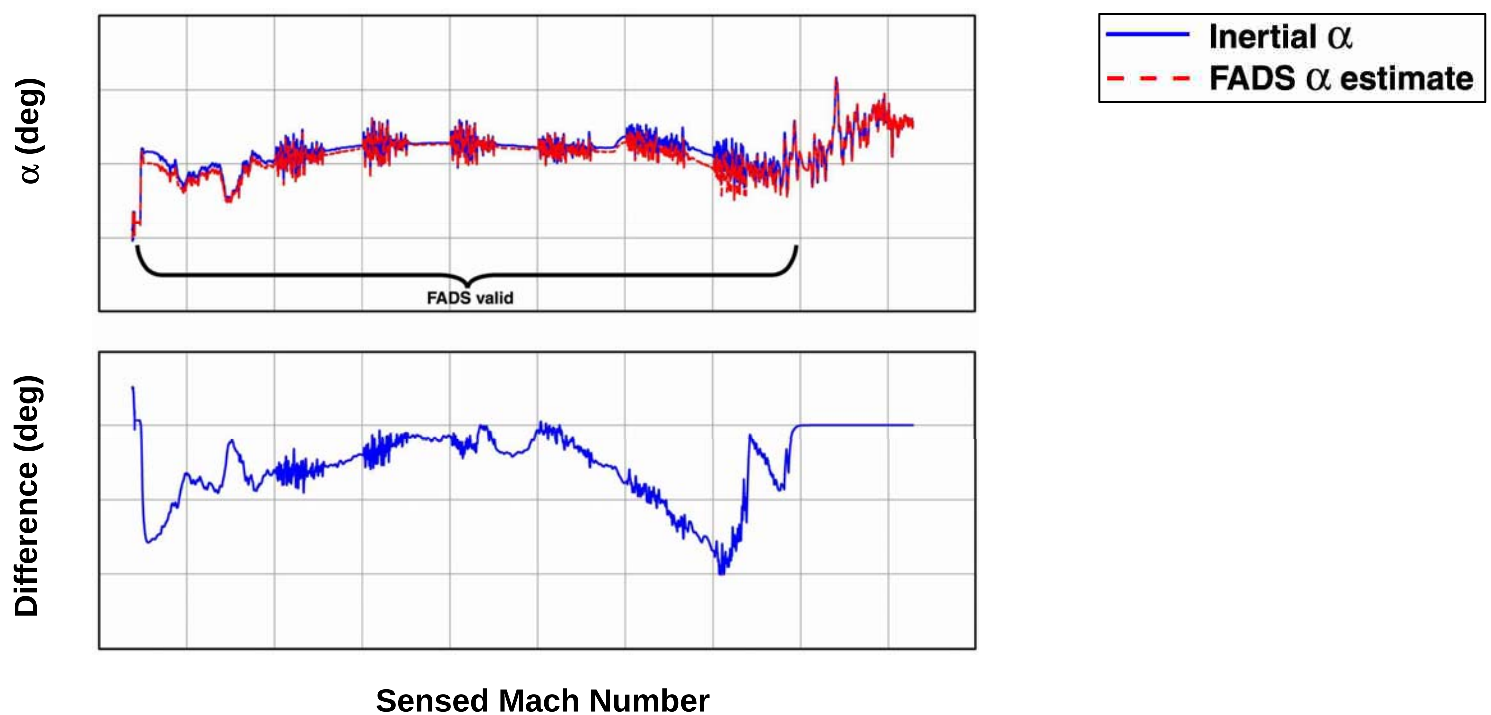


Mach 10 Mission Inertial Altitude Compared to Monte Carlo Predictions



Flush Air Data System (FADS)

- FADS
  - » A set of pressure ports on the nose of the HXRV were part of a FADS system.
  - » FADS algorithms onboard calculate α_{FADS} and dynamic pressure estimation.
- FADS algorithms not used to aid inertial system during the Mach 10 mission
  - » Algorithms not validated above Mach 8
  - » Preliminary results from the Mach 7 mission indicated areas for further study
  - » Data collected from the Mach 10 mission is currently being examined.



Frequency Response Estimation

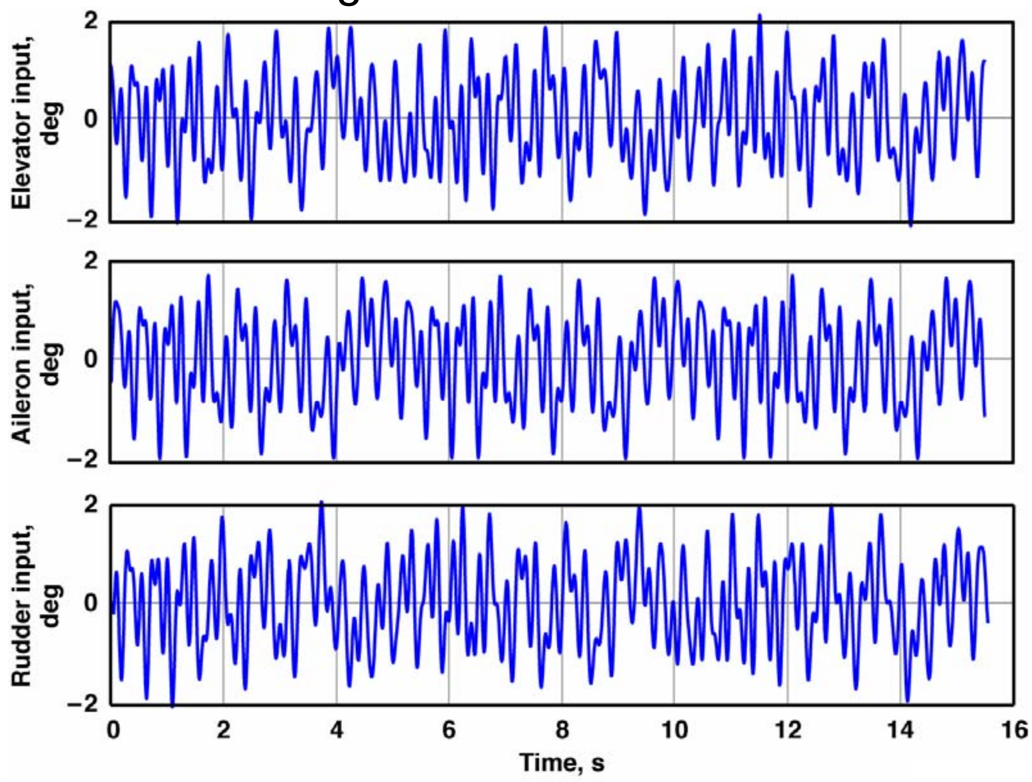
- During the descent phase, a set of input signals were simultaneously applied to the elevator and either the aileron or rudder command paths. The input signals were tailored to excite each of the three paths at different frequencies making it possible to extract the frequency responses for each axis.

- This technique allows for shorter overall excitation times required to accurately identify the frequency response characteristics versus traditional methods such as frequency sweeps.
  - Short duration inputs are particularly important for this vehicle since it is constantly changing flight condition.

- Frequency responses were extracted from the test input and vehicle response using FFT and Chirp-Z techniques.

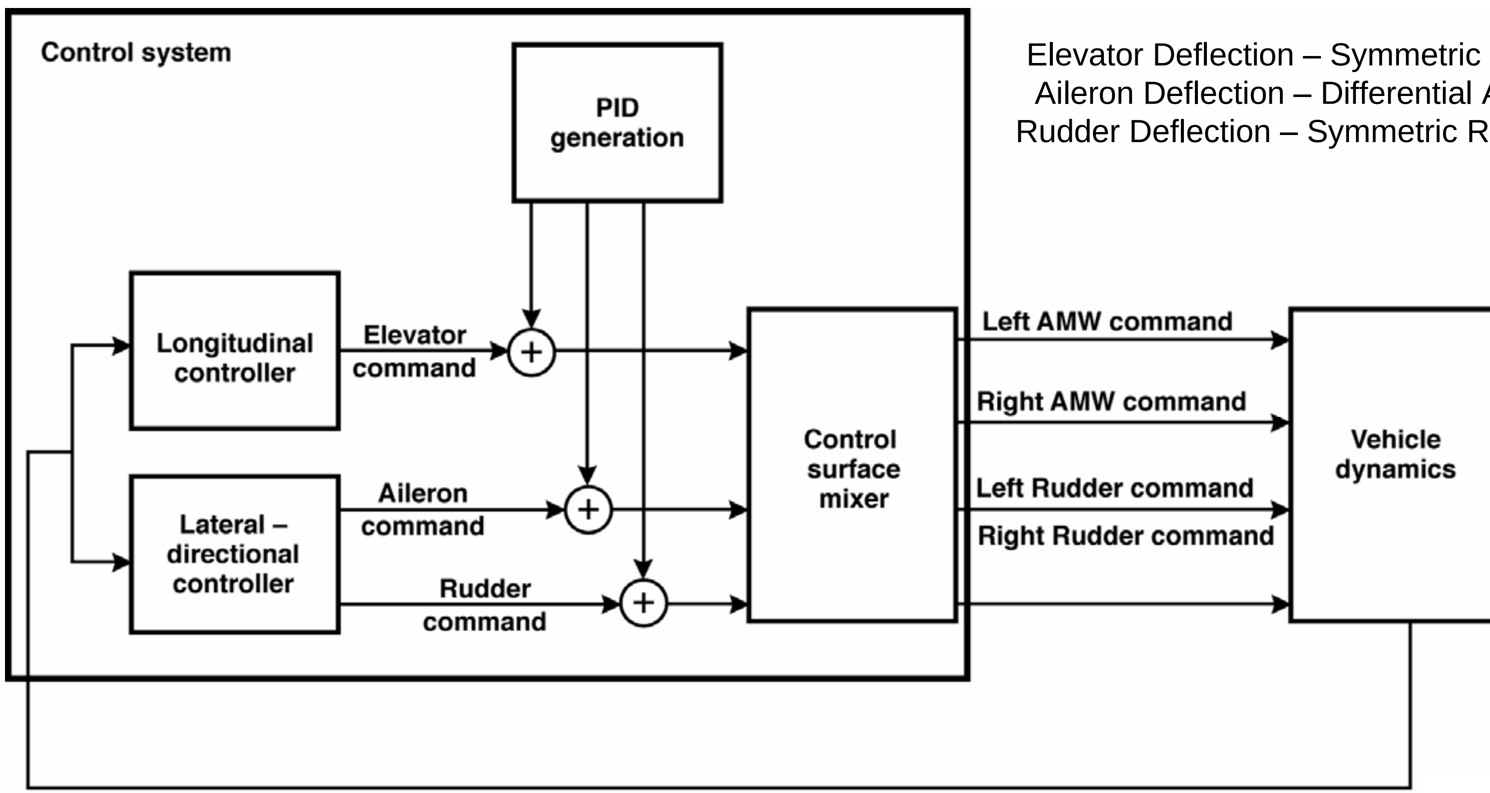
HXRV Tailored Excitation Signal Time Histories

- A unique input signal was used for the elevator, aileron, and rudder control loops.
  - 3 signals total
  - The same input signals were used during Flights 2 & 3
- Corresponding excitation signal was applied to appropriate control loop for every PID maneuver.
  - During the Mach 10 flight the rudder and aileron loops were excited at alternating Mach numbers



Block Diagram Detailing The Application of the Tailored Excitation Input Signals to the HXRV

- The Input Excitation signals were a part of the PID maneuver set.
- The PID maneuver set was contained in the flight control software.
- When triggered, the flight control system applied the PID maneuvers to each control loop command.
- Frequency response calculated between tailored excitation signal and the output of the longitudinal & lateral-directional controllers

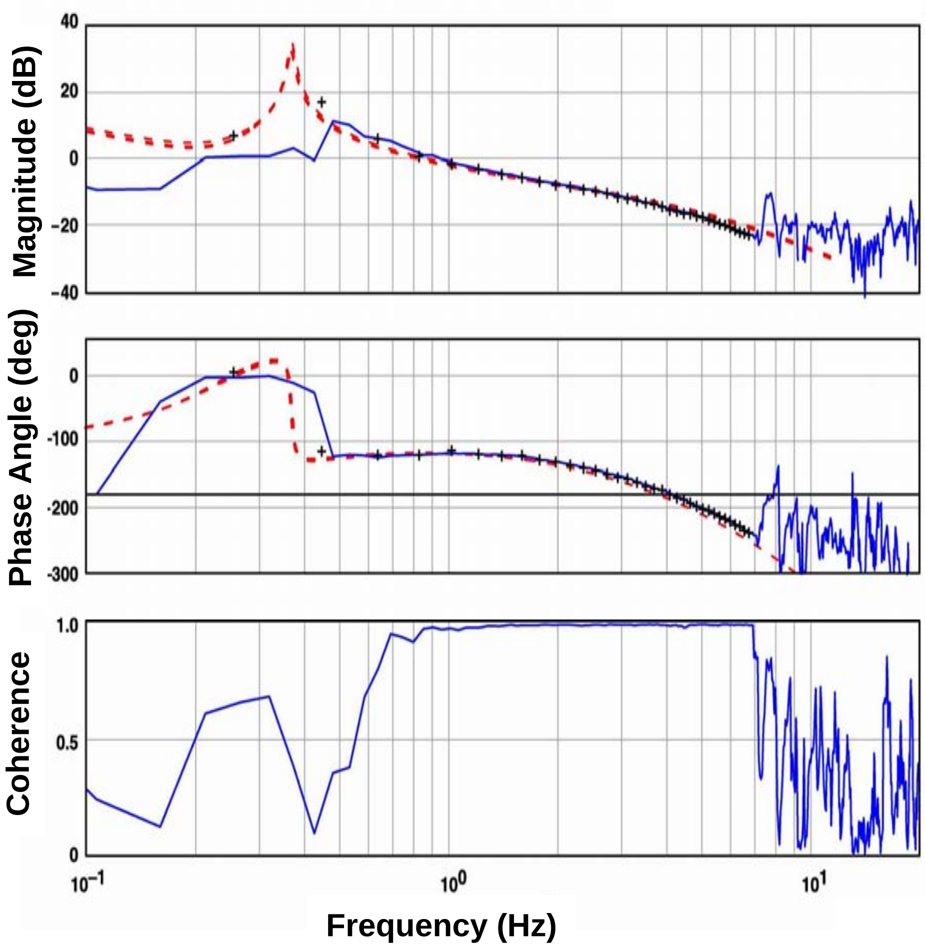


Elevator Deflection – Symmetric AMW Deflection
Aileron Deflection – Differential AMW Deflection
Rudder Deflection – Symmetric Rudder Deflection

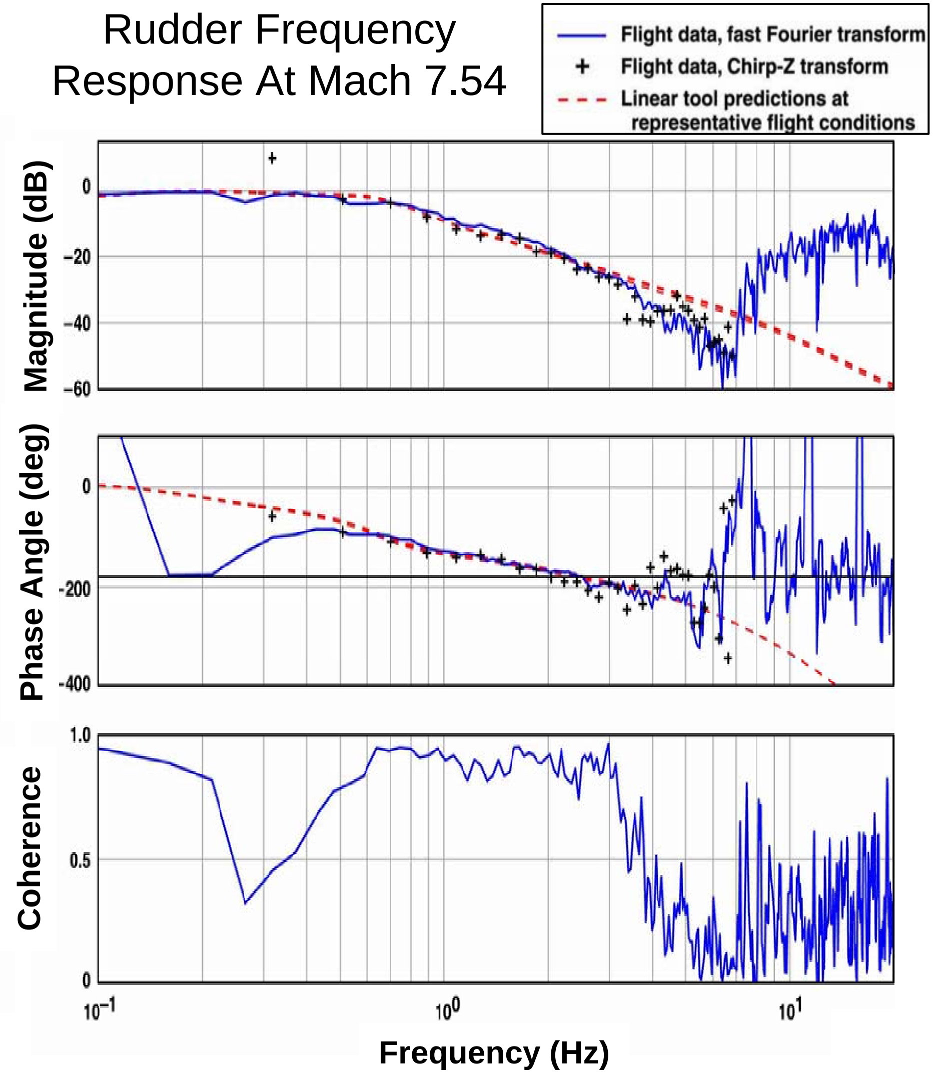
Frequency Response Estimation

- Frequency responses generated with both FFT and Chirp-Z methods from flight data match the linear analysis predictions at the same flight conditions very well.

Elevator Frequency Response At Mach 7.54



Rudder Frequency Response At Mach 7.54

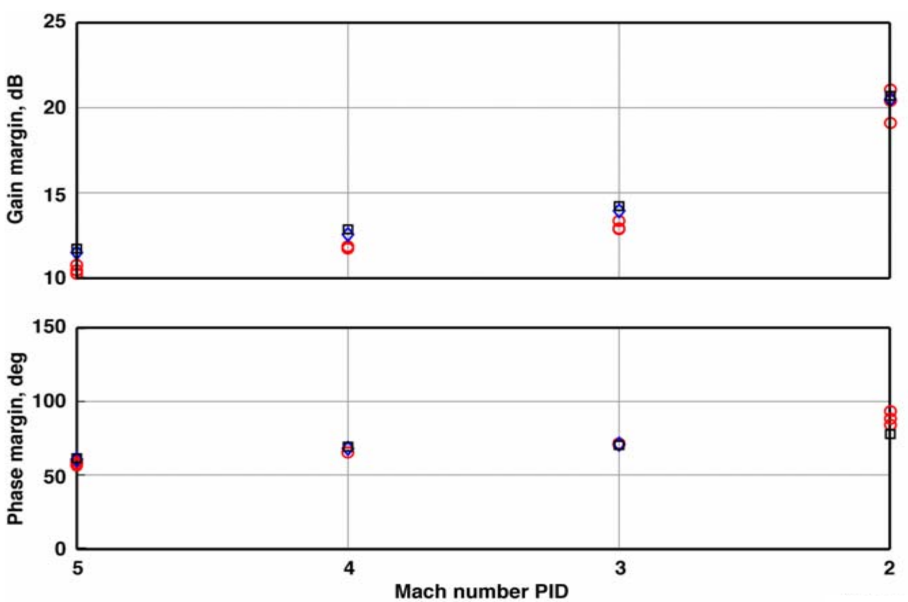


Elevator Loop Stability Margin Estimates for Flights 2 & 3

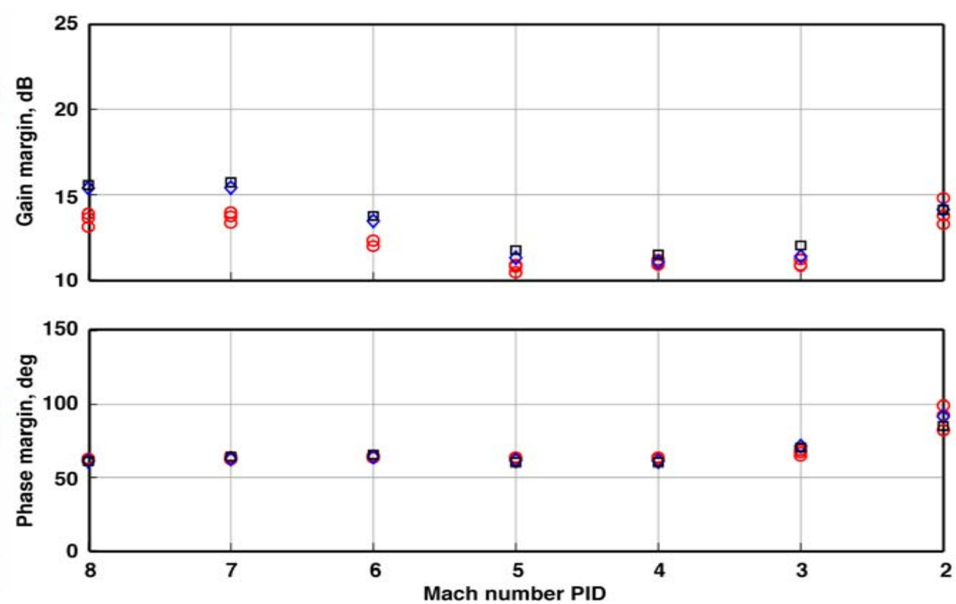
- Gain and Phase Margins were extracted for Flights 2 & 3 from the flight data.
- Post-flight linear analysis tool margin estimates compare well with those derived from the flight data.
- A slightly greater difference is seen in the gain margin comparisons for Mach 5-8 from Flight 3.
  - Un-modeled and unexpected airflow through the scramjet engine in this region possibly explains this greater difference.

◇ Flight data, fast Fourier transform
□ Flight data, Chirp-Z transform
○ Linear tool predictions

Flight 2

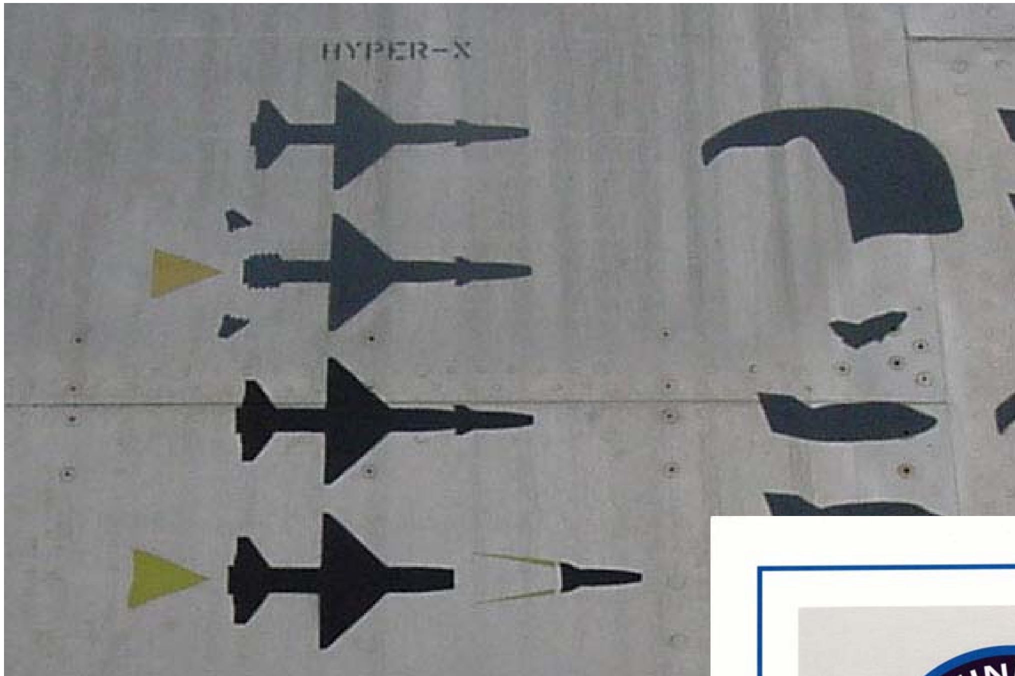


Flight 3



The Results

Best Possible Outcome: Scramjets Work & Flight Test Is Still Necessary


HYPER-X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On 16 November 2004, NASA's unmanned Hyper-X (X-43A) aircraft reached Mach 9.68. The X-43A was boosted to an altitude of 33,223 m (109,000 ft) by a Pegasus rocket launched from beneath a B52-B aircraft. The revolutionary 'scramjet' aircraft then burned its engine for around 10 seconds during its flight over the Pacific Ocean
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CERTIFICATE
The fastest air-breathing aircraft is NASA's X-43A, which achieved Mach 6.8316 on 27 March 2004 in a flight lasting 11 seconds over the Pacific Ocean
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Questions ?