X-43A Flights 2 and 3 Guidance, Navigation, and Control Performance

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Presentation Topics

- **Overview of Hyper-X**
- **Overview of Separation & RV GNC**
- **Flight 2 GNC Performance**
- **Flight 3 GNC Updates**
- **Flight 3 GNC Performance**

X-43A Flight

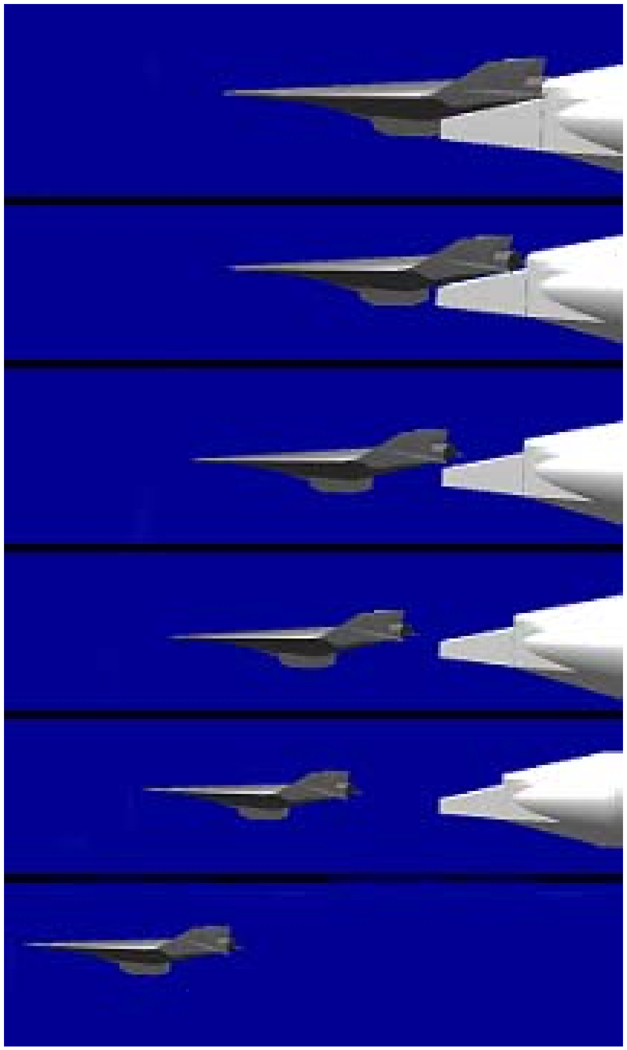
Captive Carry to Launch Condition
Boost to 100,000 feet
MACH 7 Separation
Free Flight & Scramjet Operation
HYPER X
U.S. AIR FORCE
HYPER-X
NASA

Mission Objectives

- Mission Objectives
  - Safely conduct ground operations, captive carry and flight experiment
  - Successfully launch booster stack and boost to stage separation point
  - Successfully perform stage separation resulting in controlled flight of the X-43A at the scramjet test point
  - Conduct the scramjet propulsion experiment and obtain data
- Additional Research Objectives
  - Vehicle acceleration during the scramjet propulsion experiment
  - Obtain data from all flight phases
    - Captive carry (Launch Vehicle (LV) and Research Vehicle (RV))
    - Boost (LV and RV)
    - Stage separation (LV and RV)
    - Stage separation video (LV)
    - Free flight (RV)
  - Obtain RV aero, structural, GNC, and other data to splash

Separation & RV GNC Overview

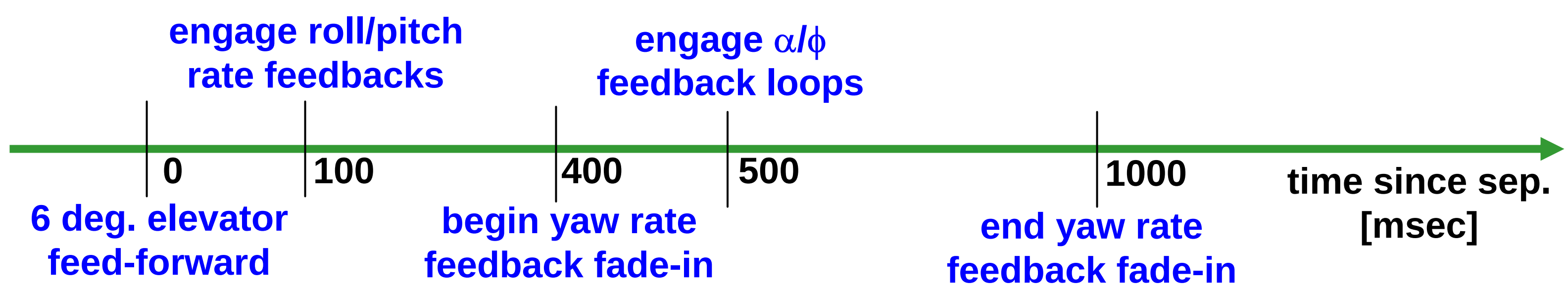
Nominal Separation Scenario



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

Separation Control Logic

Sep. control elements designed to initialize controller, minimize probability of re-contact, and ensure recovery from the separation upset



- Separation control design philosophy:
  - separation control is an initialization and sequencing task
  - state variables need to be initialized properly to eliminate dangerous startup transients
  - the control system should be engaged in stages to prevent maneuvering commands from disturbing the Hyper-X during the critical ejection/separation event

Guidance Overview

- Design/Implementation Description
  - Adaptation of Shuttle heritage code
  - Modifications included:
    - Constants designed for Hyper-X aerodynamics using POST
    - Added capability to perform POPU's and trigger PID's

- Engine Test
  - Altitude axis generates constant $\alpha = 2.5^{o}$ command
  - Azimuth axis generates constant $\phi = 0^{o}$ command
- Descent
  - Altitude axis controller generates normal acceleration command
    - commands generated by comparing vehicle state to predetermined descent profile
  - Azimuth axis controller generates bank angle command
    - commands determined by path steering to vehicle splash point

Flight Controls Overview

- Longitudinal Controller -

α controller

- Engine Test
  - Inertial angle-of-attack and body-axis pitch rate feedback arranged in a proportional-integral design, α regulated longitudinal controller
  - Feedforward elements incorporated to minimize effects of known disturbances
    - Inlet Open and Φ_{eng}
  - Feedforward on α_{cmd} provides estimated trim δ_e

n_z controller

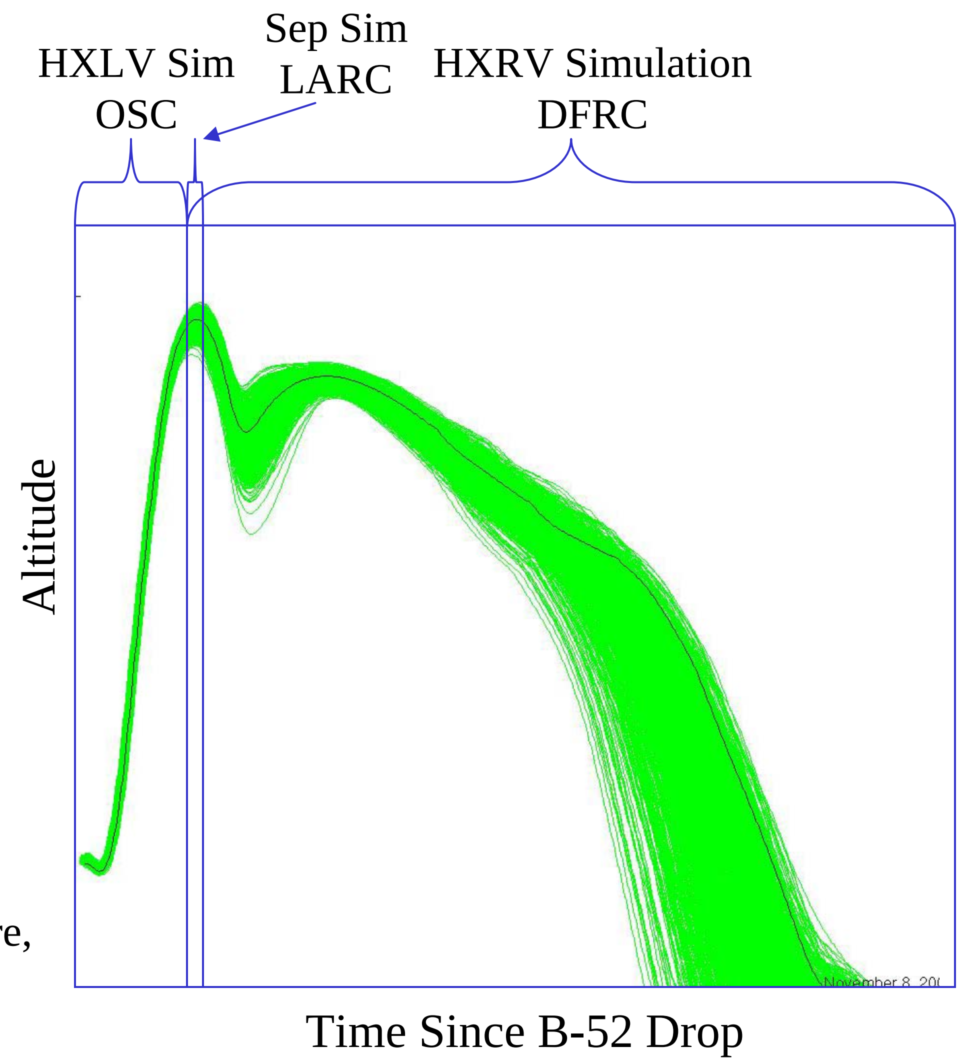
- Post-Test Descent
  - Desired and actual n_z used to generate a software limited, equivalent α_{cmd} passed to the alpha controller (at this point, α_{FADS} is used to augment $\alpha_{inertial}$)
  - estimated α_{trim} is the only feedforward element

- Lateral/Directional Controller -

- Engine Test and Descent
  - Bank angle and body-axis roll rate arranged in a proportional-integral design, ϕ regulated lateral controller
  - Stability-axis yaw rate feedback regulates directional motion
  - ARI utilized to provide coordinated maneuvers

Hyper-X Simulation Overview

- Primary simulation analysis of the Hyper-X mission is performed by flight phase
  - Boost (OSC, nrtsim)
    - Pegasus Heritage
    - Full-Stack Simulation up to Separation
  - Separation (LaRC, SepSim)
    - 6+6 DOF simulation of HXLV & HXRV using ADAMS
    - Used for Separation Analysis/Trade Studies
  - Experiment and Decent (DFRC, RVsim)
    - Used for RV Analysis and Monte-Carlo studies
    - Hardware-in-the-Loop (HIL) Capability



- Contain high-fidelity models (aerodynamics, propulsion, sensors, actuators, timing, software, atmosphere)
- Capable of running nominal and off-nominal trajectories
- Tools capable of running Monte Carlo analysis

Flight 2 – March 27, 2004

Mach 7 and Beyond
LaRC ★ DFRC ★
HYPER X
2004 World's Airbreathing Powered Vehicle Speed Record

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

Keeper of the Records
GUINNESS WORLD RECORDS LTD

Flight 2 GNC Mission Overview

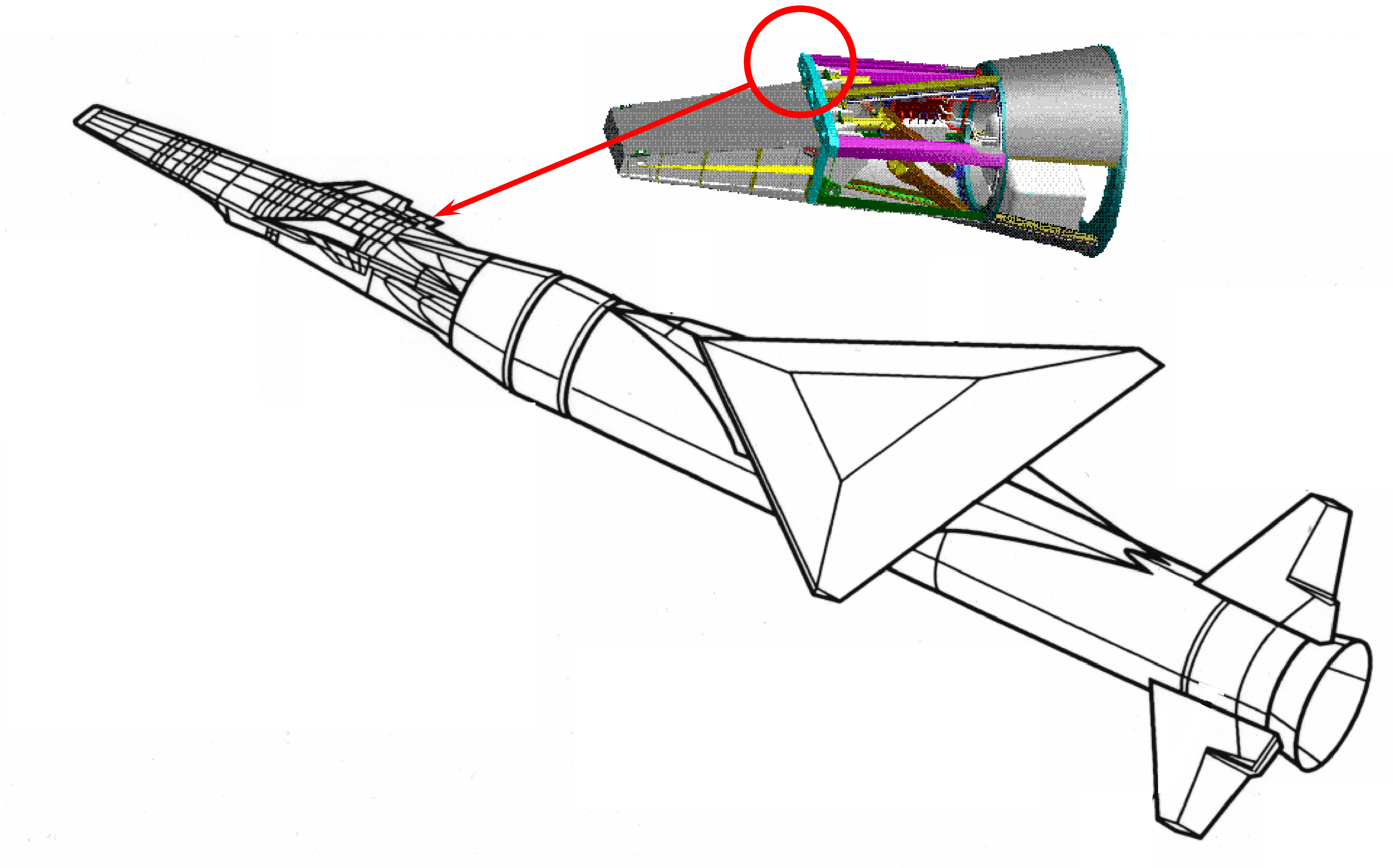
- Launch : Deliver RV to acceptable separation conditions
- Separation
  - Successfully separate the RV from the LV
  - Minimize the chance of re-contact with the LV
  - Minimize the upset imparted on the RV
  - Achieve the desired test conditions at the end of 2.5 seconds
- Engine Test
  - Maintain 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.
  - Demonstrate Flush Air Data System (FADS)

Separation Performance

- Separation Performance
  - No recontact of the RV with the LV
  - Pistons fired simultaneously and generated very little lateral/directional transient
  - Initial separation transient very close to nominal simulation
  - Following the initial separation transient, the RV took longer to reach the commanded angle-of-attack than predicted by pre-flight analysis
  - RV achieved the desired test conditions by the time the cowl opened

X-43A Flight 2 Right Adapter Camera Sequence

Right Adapter Camera Position



Frame Rate is Slowed Down to 1/30th of Real Time

Image 1

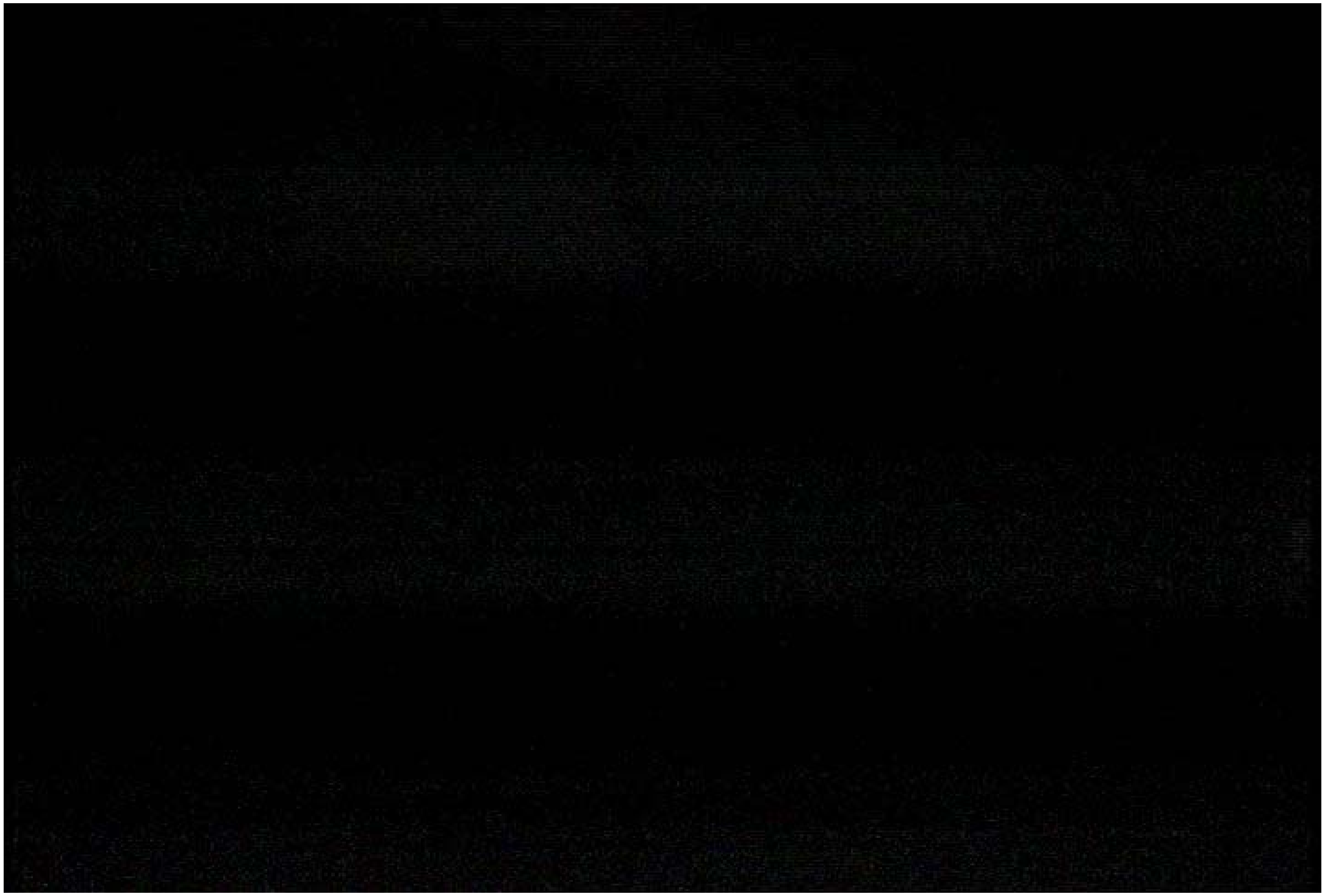


Image 2

Image 3

Image 4

Image 5

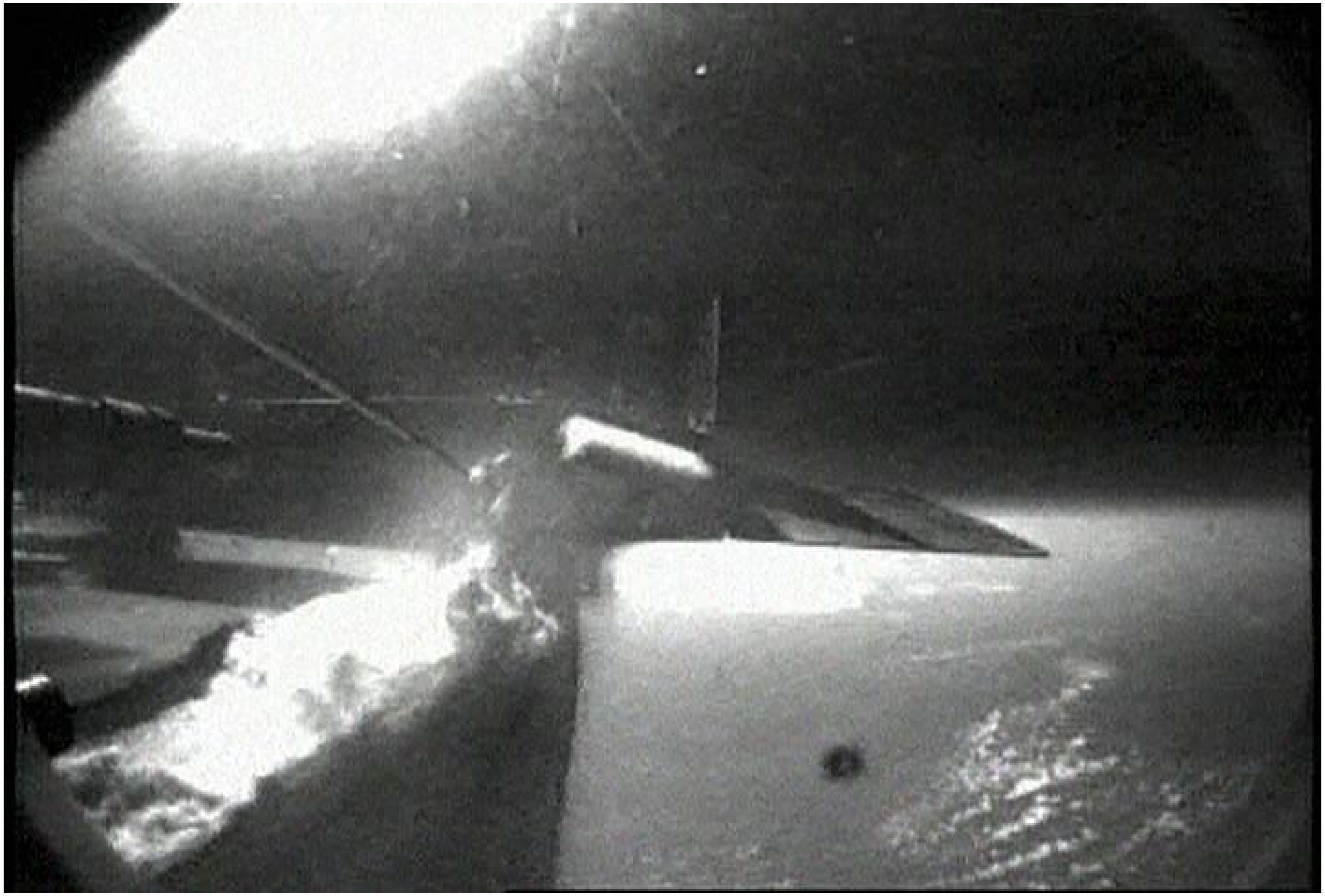


Image 6

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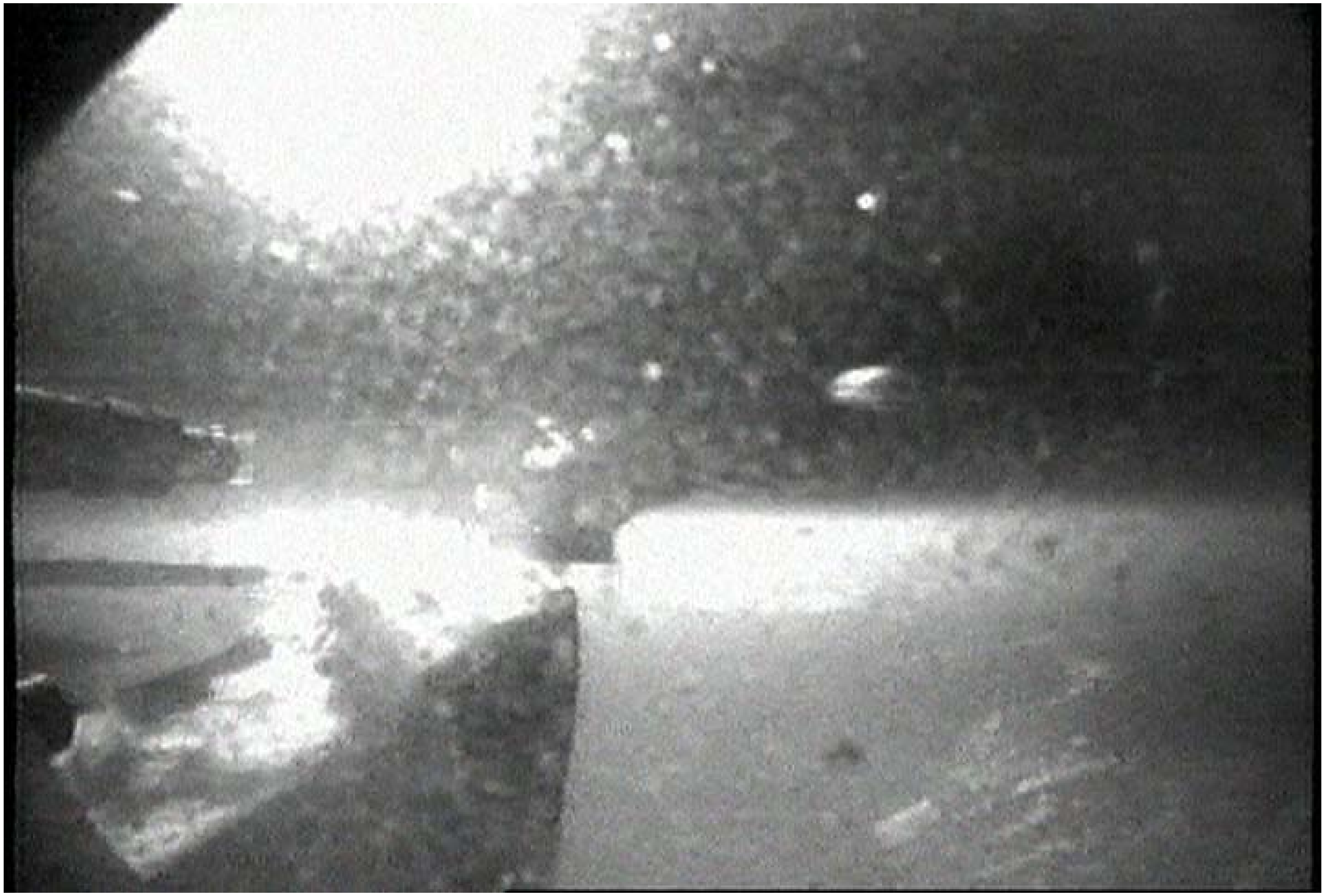
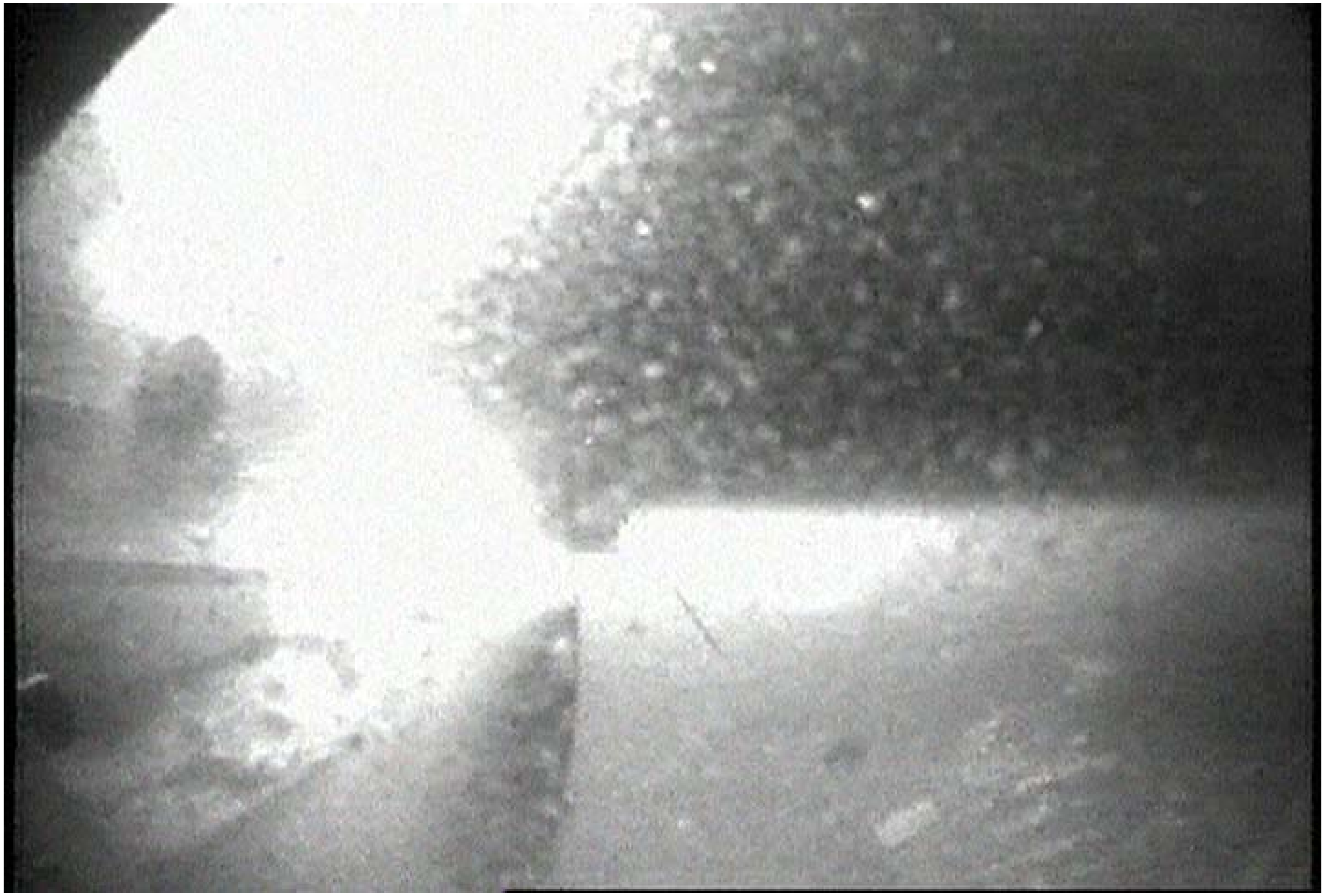
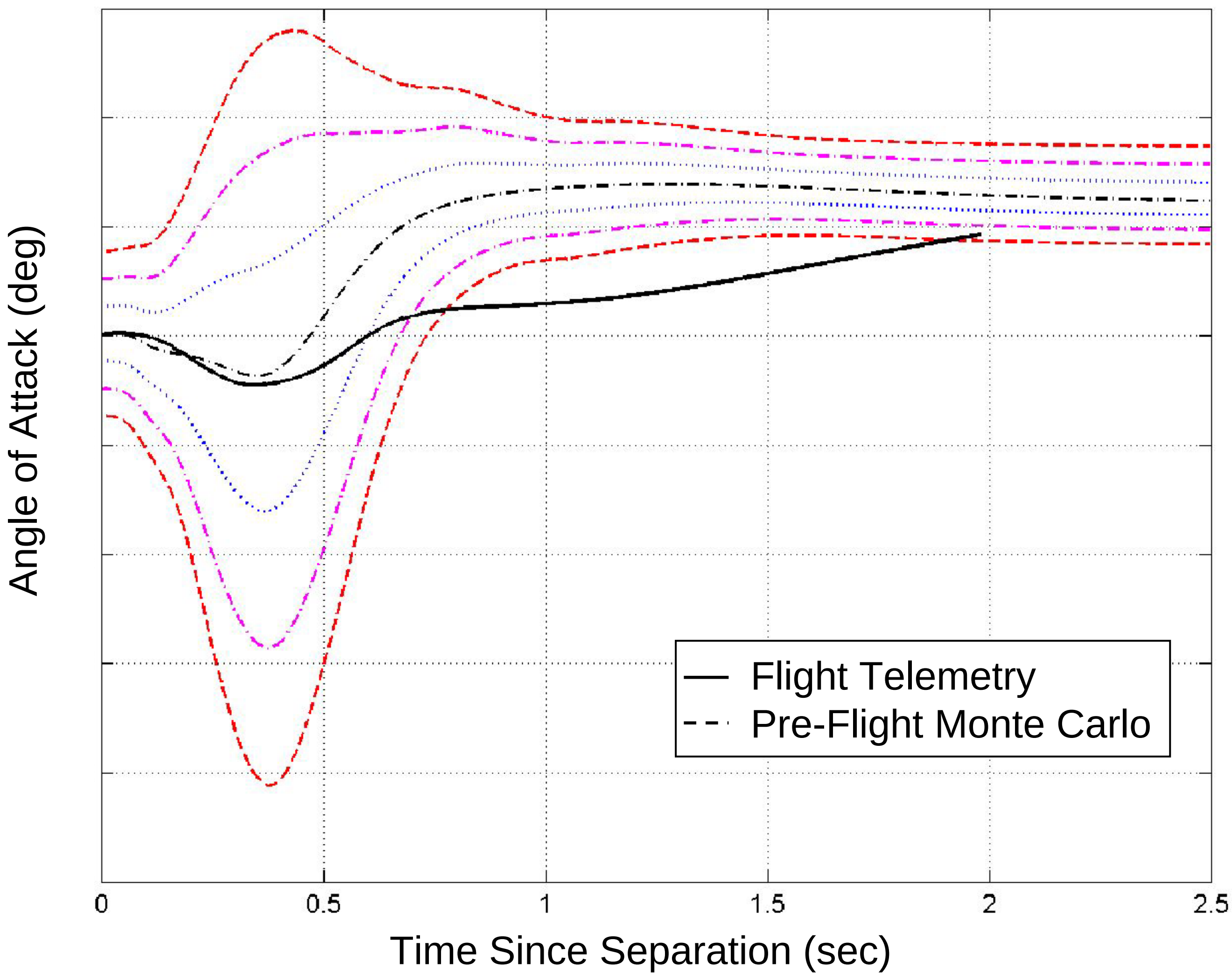


Image 9

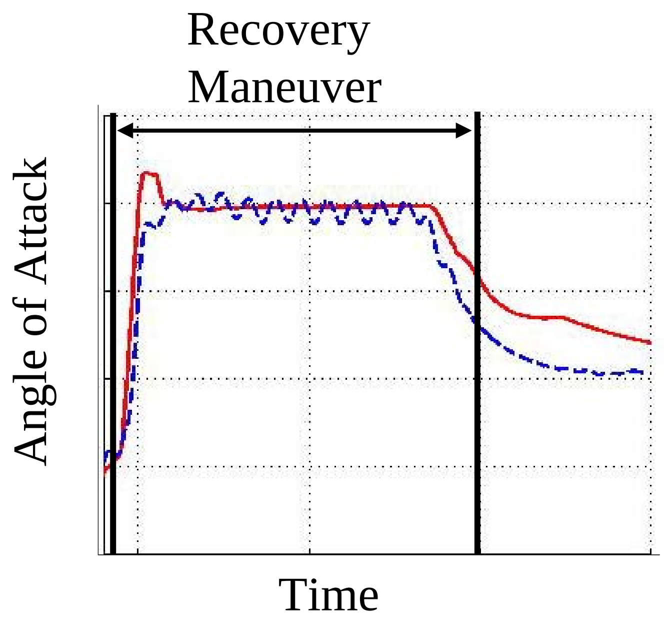


Separation Performance



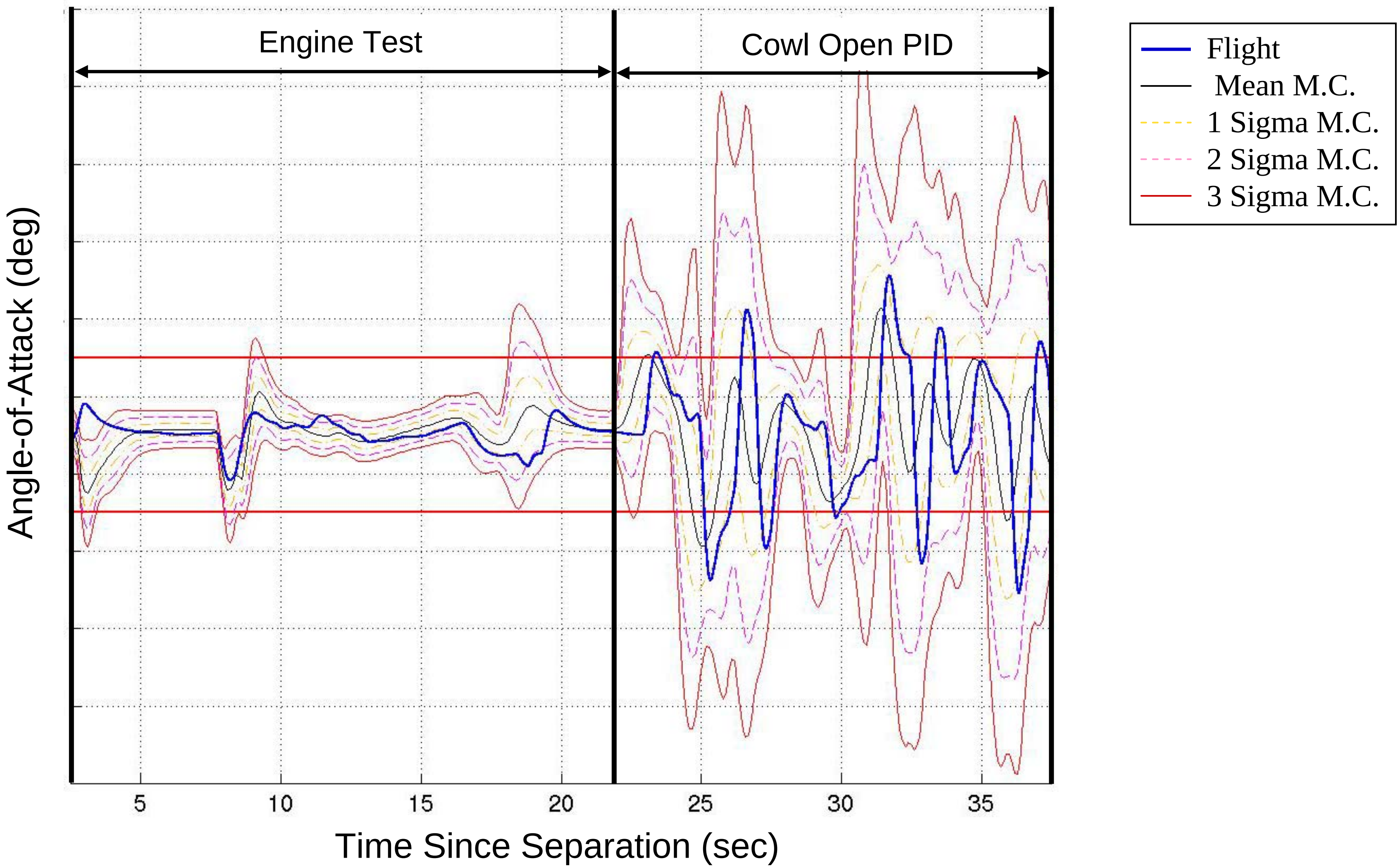
Engine Test & Descent Performance

- Engine Test Performance
  - RV maintained engine test conditions well within the requirements
  - Successfully completed pre- and post-engine test tare and cowl open PID
  - Cowl open transient was outside of the pre-flight predictions
  - Wing trim position offset during the engine test and throughout the descent
- Descent Performance
  - Alpha oscillations occurred during the recovery maneuver at 8° alpha
  - Post engine test performance was within Monte Carlo predictions and was very close to nominal
  - Performed all planned PID maneuvers
  - FADS performed well, with areas for improvement identified.
  - Flight derived frequency responses match the linear analysis predictions.

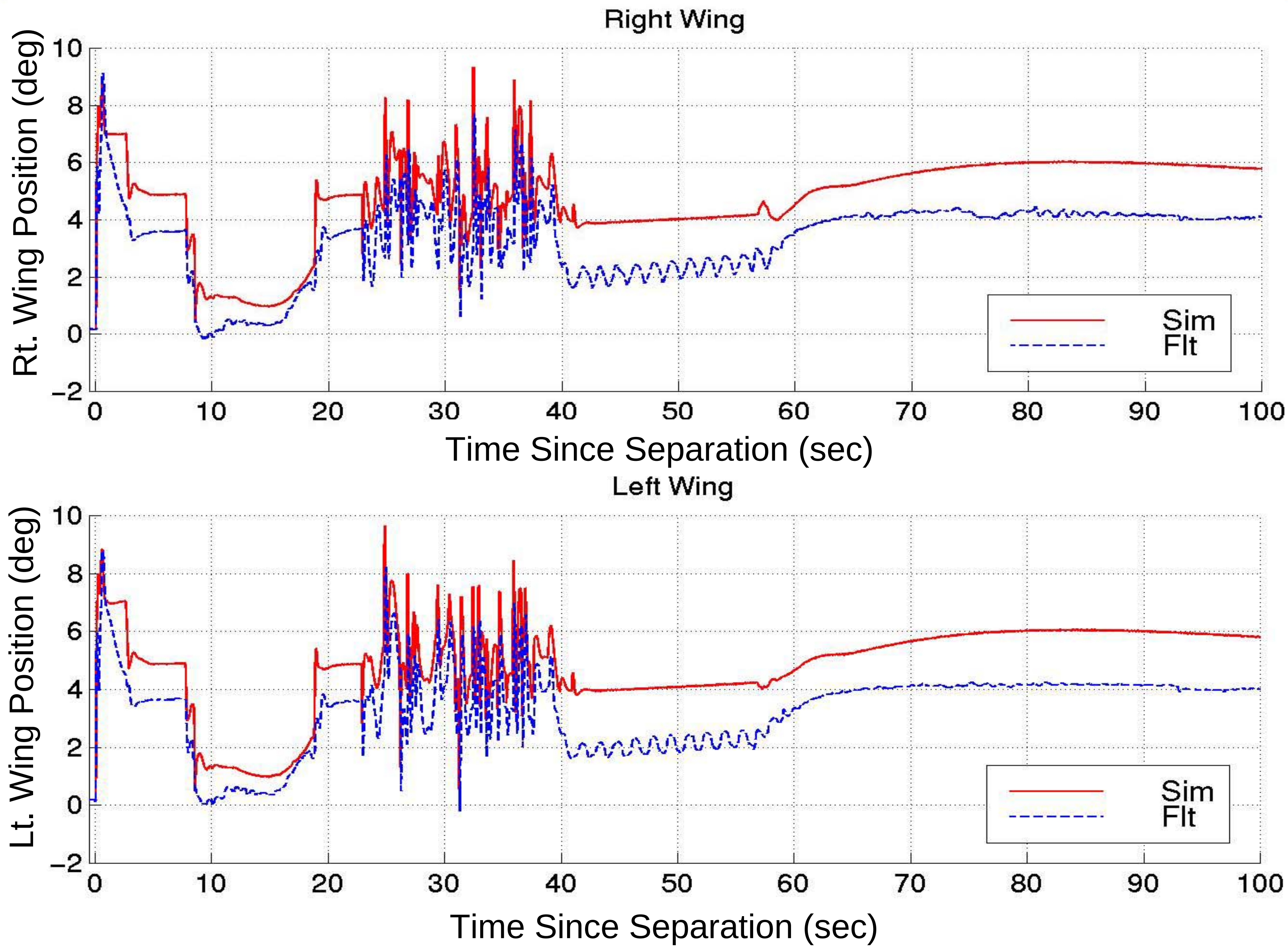


Engine Test Performance

Note – Angle-of-Attack is inertial



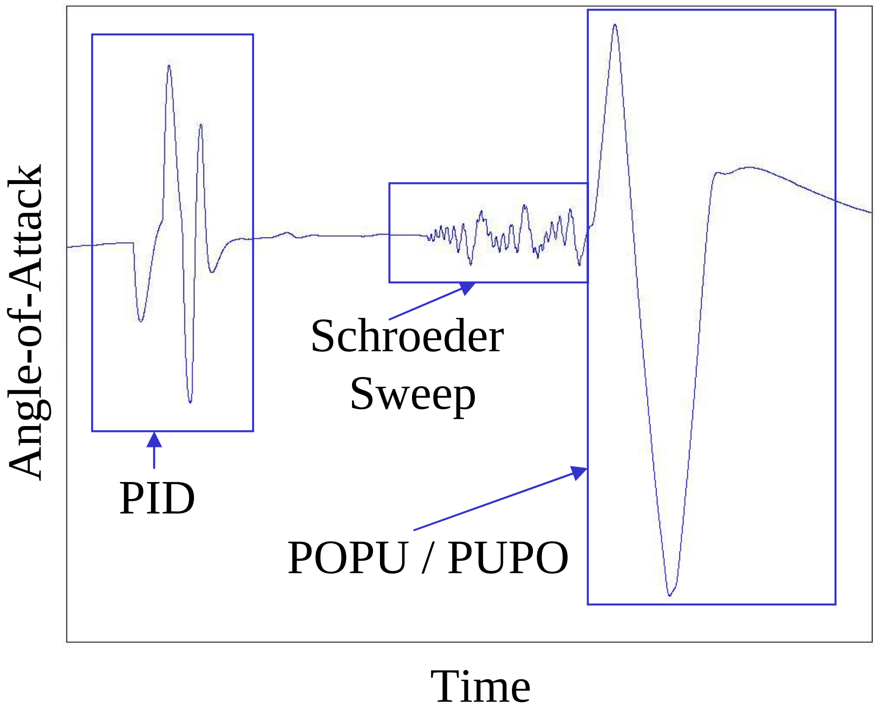
Engine Test Performance



Parameter Identification (PID) Maneuvers

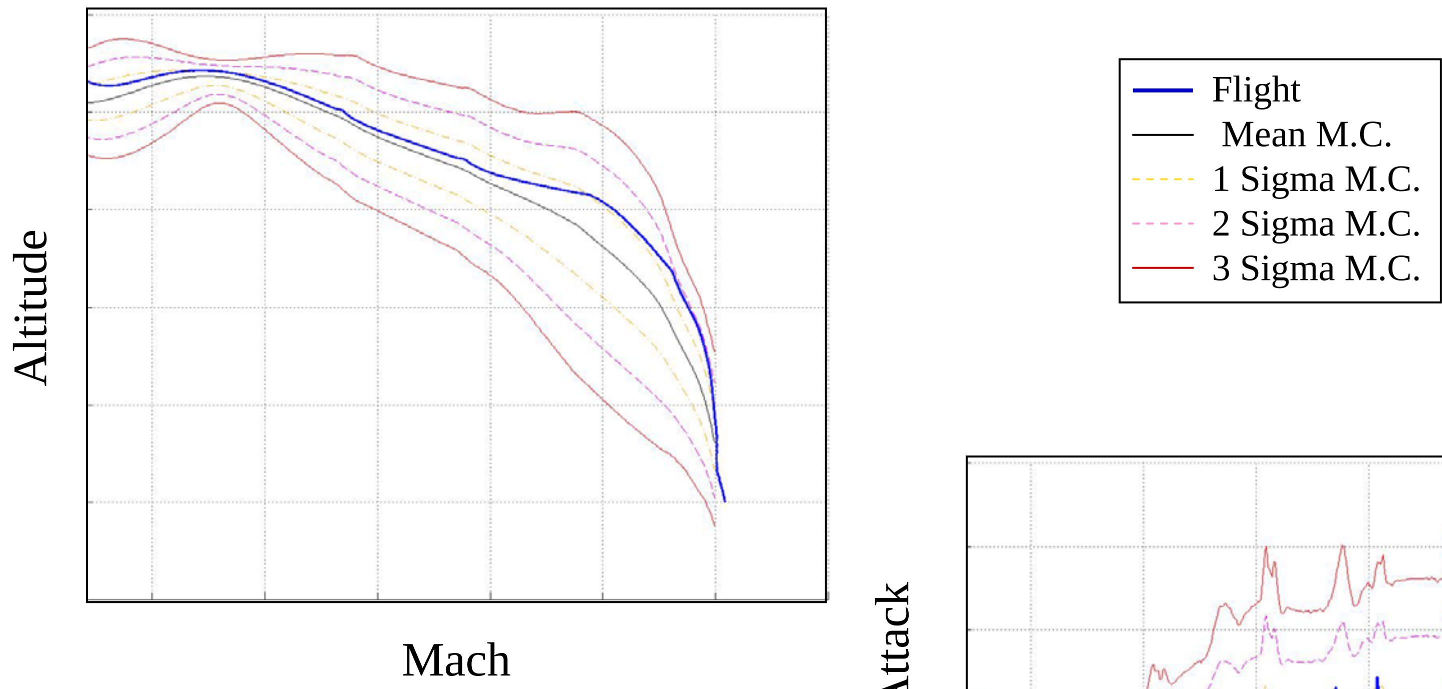
- Descent PID Maneuvers
  - At every Mach Number during Descent beginning at Mach 5
  - Allows for Identification of Aerodynamic Parameters
  - Frequency sweeps used to for flight frequency response estimation

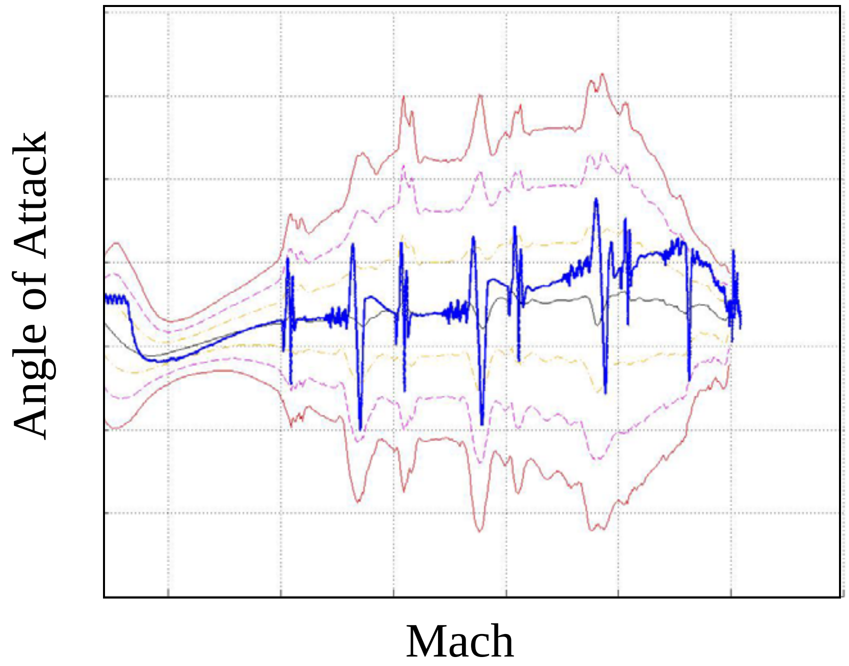
- Maneuvers Consist of
  - 3-2-11 Maneuver
  - Multi-axis Frequency /Schroeder Sweeps
  - Push Over Pull Up (POPU)



Descent Performance

Note – Angle-of-Attack and Mach number are inertial

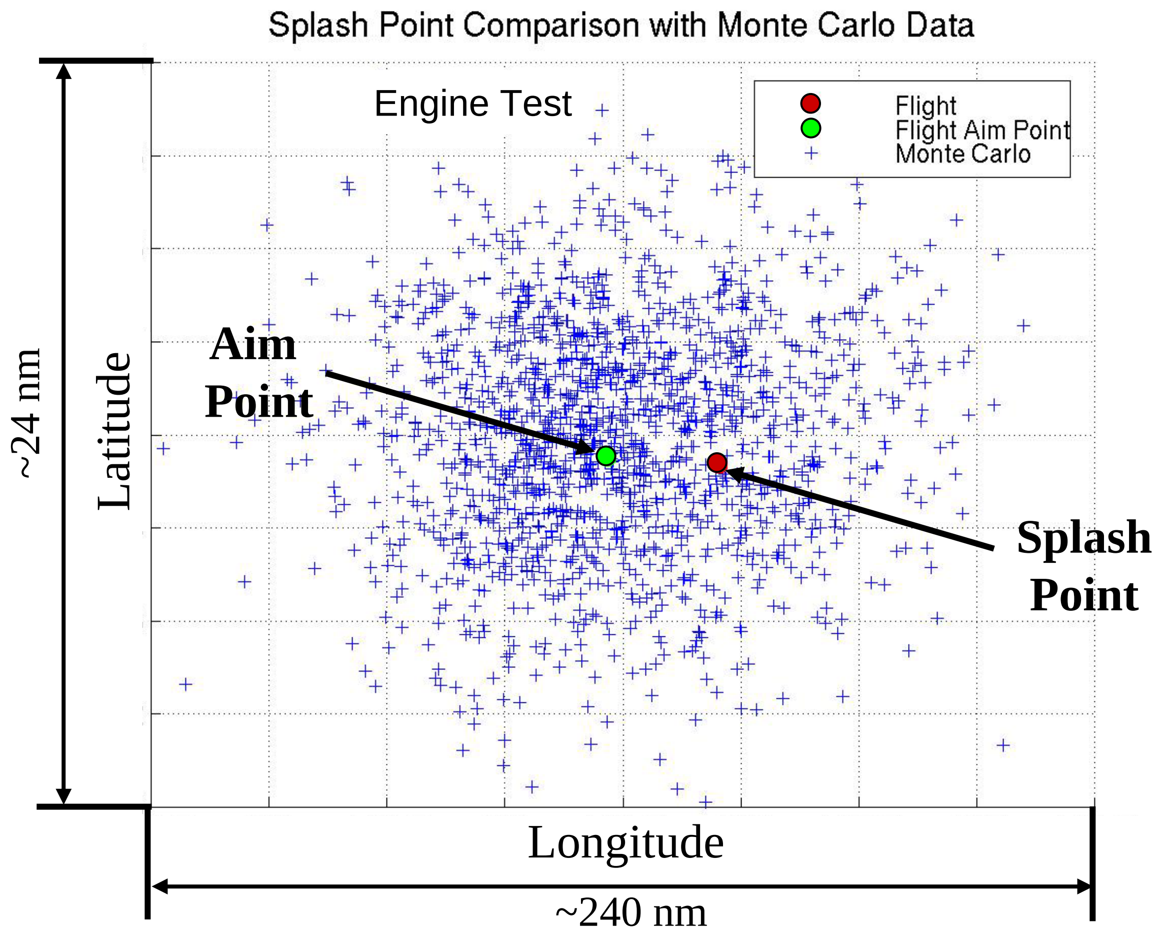




Descent Performance
Research Vehicle Splash Point

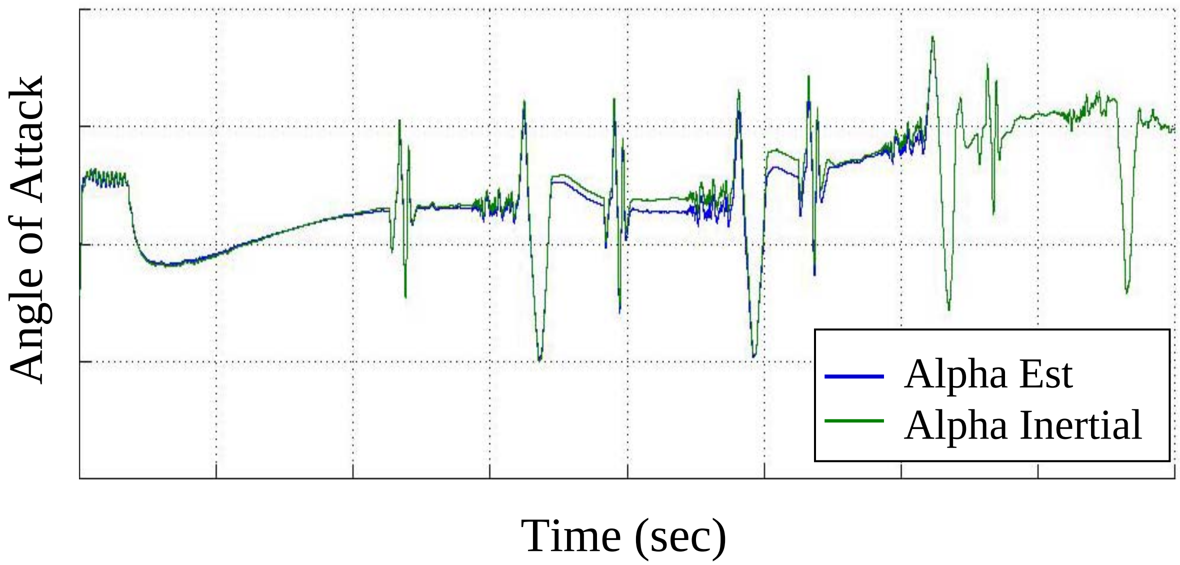
'Landing' Conditions

Altitude (ft)	Mach No. (-)	Altitude Rate (ft/s)	Alpha (deg)	Flight Path Angle (deg)	Bank Angle (deg)
41.86	0.92	-440.53	6.03	-25.67	1.29



Flush Air Data System (FADS)

- Intent
  - Collect pressure data and evaluate α_{FADS} estimate during the engine test
  - Exercise the estimation algorithm after the engine test and evaluate performance
- Approach & Implementation
  - Augment $\alpha_{inertial}$ with a pressure based estimate of angle-of-attack
  - α_{FADS} is used only after the engine test.
- Flight Results
  - FADS performed well, with areas for improvement identified.
  - Data was collected for Mach 10 flight, but FADS was not used during flight.

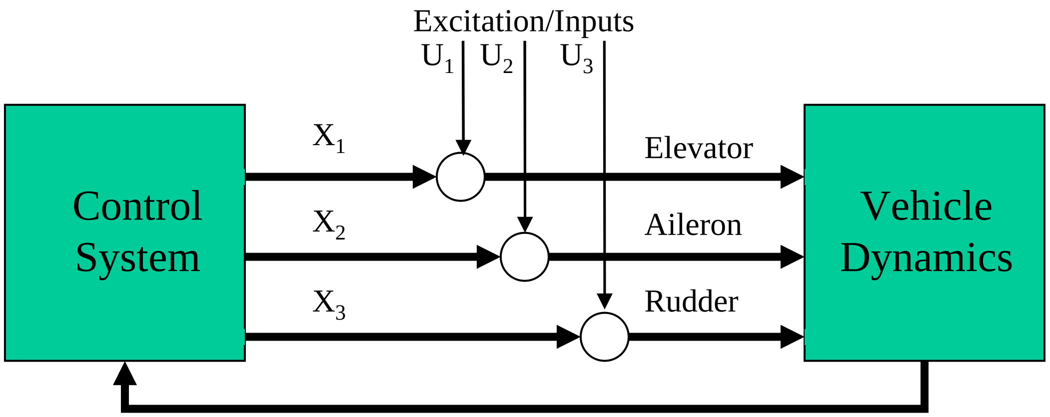


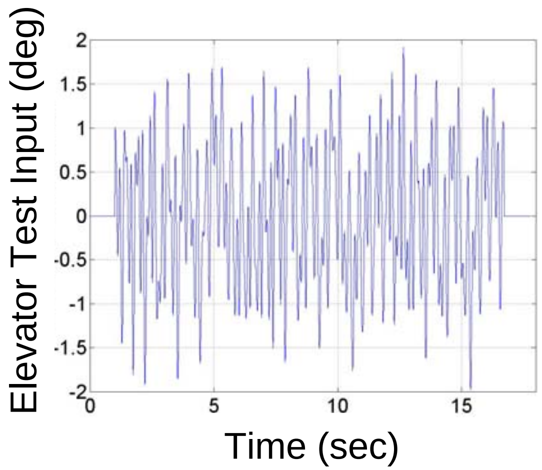
Flight Frequency Response Estimation

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

- Because this technique excites all of the control loops at the same time it allows for shorter overall excitation times required to accurately identify the frequency response characteristics versus traditional methods such as frequency sweeps.
  - This is particularly important to this vehicle because it has a very limited ability to maintain a given flight condition which is necessary for the analysis.

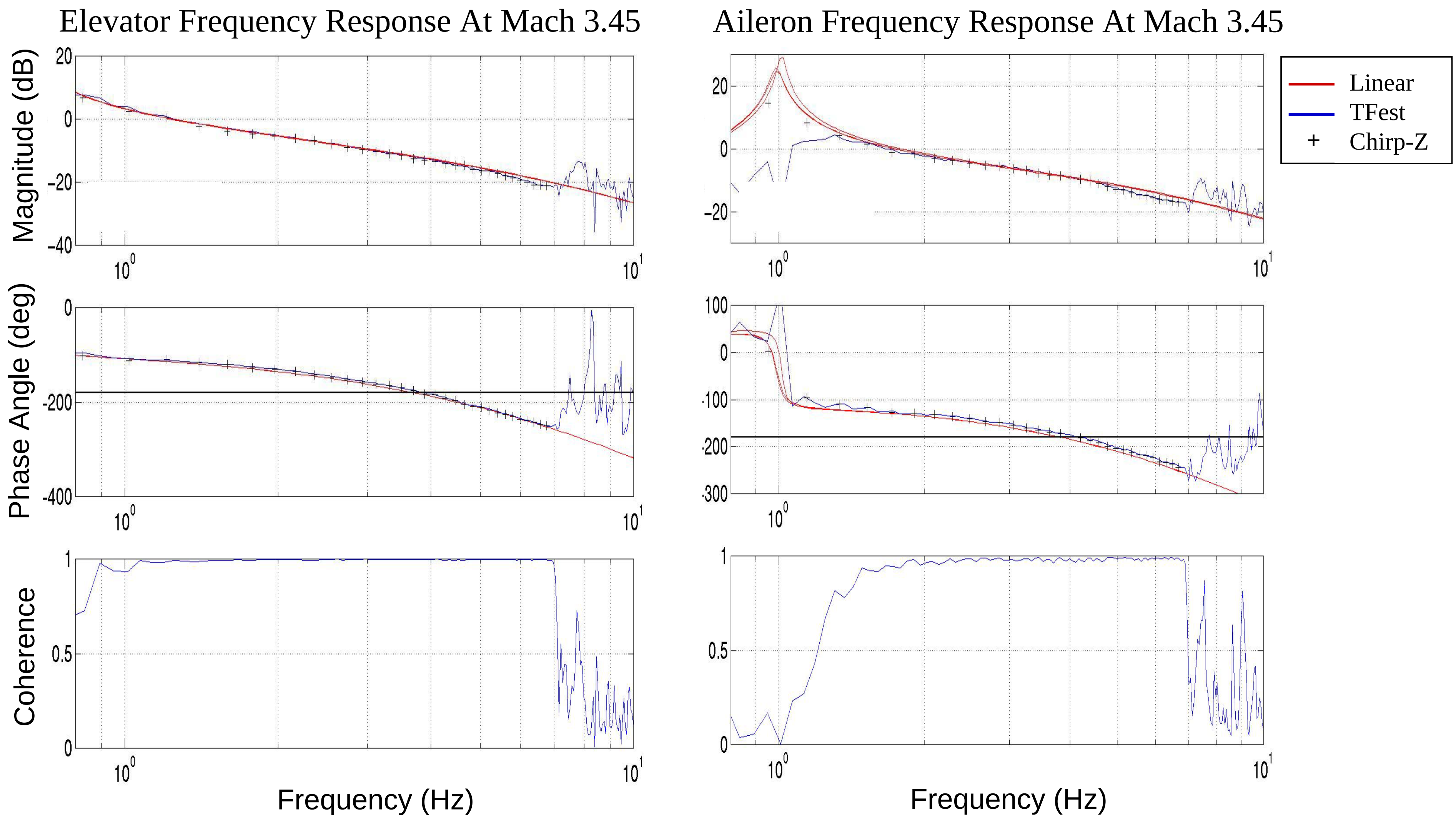
- Frequency responses were extracted from the test input and vehicle response using FFT and Chirp-Z techniques.





Flight Stability Margin 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.



Flight 3 GNC Updates

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.

Flight 2 Lessons Learned Applied to Flight 3

- RV slow to arrive on condition
  - Alpha error integrator gain increased
  - Cowl closed alpha error proportional gain significantly increased in this region of flight.
  - Stress cases developed to test the robustness of the design
- Pitch up at cowl open
  - Mach 10 model uncertainties reviewed and expanded to capture the possibility of a pitch up
- Alpha oscillations during the recovery maneuver
  - Descent reference trajectory shaped to avoid flying at 8° alpha during flight at high Mach numbers. The Mach 10 flight flies the recovery maneuver at 6° angle of attack
  - Post engine test post flight analysis were of secondary importance, received significantly less attention and were worked as time permits.
  - The cause of the oscillation is still under investigation.
    - Initial causes identified were used as stress cases for the Mach 10 analysis

Separation Control Logic Updates

- Six new inputs were added to the Mach 10 MDL for the Separation Control Logic
  - In addition to existing feed-forward elevator command and slope
  - Longitudinal inner (q) and outer (α) loops
  - Lateral/Directional inner (ϕ) and outer (p) loops
  - Yaw rate-to-rudder feedback loop closure times (start & end for fade)
- Nominal slope and α-loop closure selected from parametric analyses
- Monte Carlo comparisons used to select bias, phi-loop and yaw fade times
  - 44 Monte Carlo analyses, each using same 100 dispersed cases
  - Statistical results combined in a cost function to determine which set of parameters performed best. Cost function weighted to account for different objectives
  - Failure rate & target box accuracy weighted 5x more than surface rate and deflection limiting

Variable	Number	Values										
Bias	11	1.0	1.5	2.0	2.5	3.0	**3.5**	4.0	4.5	5.0	5.5	**6.0**
slope	4	-2	-1	**0**	1							
q-loop closure	1	**100**										
aoa-loop closure	4	100	300	**500**	700							
p-loop closure	1	**100**										
phi-loop closure	4	100	300	**500**	700							
yaw-loop start	5	**100**	200	**400**	500	600						
yaw-loop end	10	500	600	700	800	**900**	**1000**	1300	1400	1500	1600	

Flight 3 Baseline values are highlighted, Flight 2 values are in blue

Summary of Changes to Guidance

- Guidance modifications consisted of the following:
  - Addition of PIDs at Mach 8, 7, and 6
  - Removal of cowl open PID and descent POPU maneuvers
  - Modification of engine test alpha command
  - Modification of reference trajectory and aimpoint latitude
  - Modification of alpha and qbar limits
  - Updated weights, INS-to-CG corrections, and CN tables.

Summary of Changes to Flight Control Laws

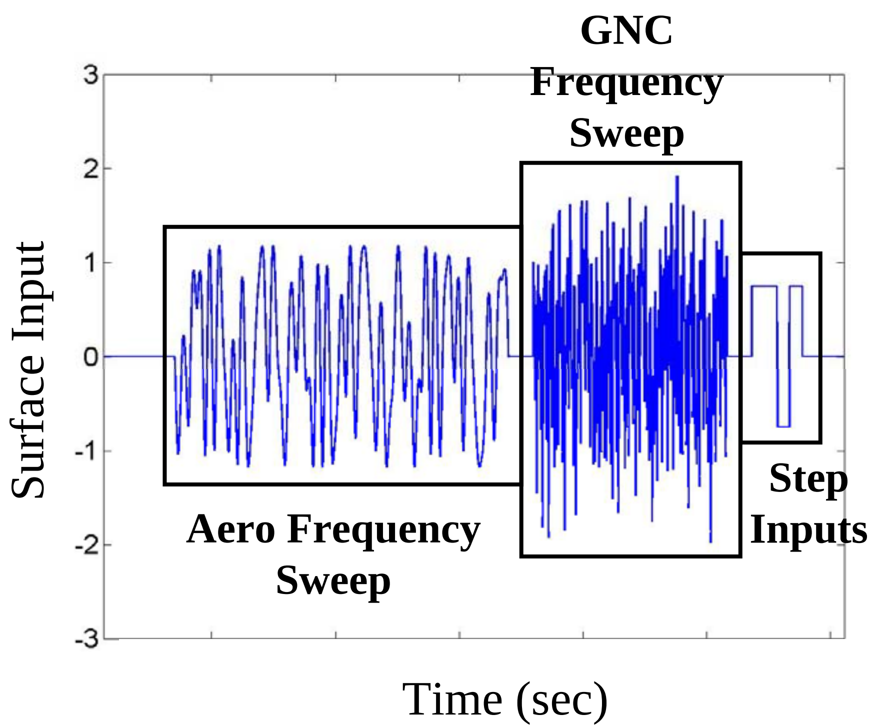
- Longitudinal
  - Updated gain tables, alpha limits, elevator trim tables, and alpha feed forward tables
  - Modified Cowl Open and Ephi feedforwards
  - Made small modifications to pitch rate lead/lag filter

- Lateral-Directional
  - Updated gain tables
  - Updated Aileron-Rudder Interconnet (ARI) table
    - Removed ARI from separation through cowl closed
    - Faded ARI in over 1 second when the longitudinal controller transitions to the nz control mode (post cowl closed).

- FADS no longer aids the inertial alpha solution in descent.
- Aero PID maneuvers and GNC frequency sweeps modified and added for higher Mach no.

Parameter Identification (PID) Maneuvers

- Descent PID Maneuvers
  - PID maneuvers initiated at every Mach Number during the descent beginning at Mach 8
  - Step inputs are only active from Mach 5 and below
  - Maneuvers modified based on lessons learned from Flight 2
    - Aero PID maneuver replaced by a frequency sweep
    - Rudder and aileron excitation is alternated during the descent
    - POPU maneuvers replaced by step inputs



GNC Mission Overview

- Launch : Deliver RV to acceptable separation conditions
- Separation
  - Successfully separate the RV from the LV
  - Minimize the chance of re-contact with the LV
  - Minimize the upset imparted on the RV
  - Achieve the desired test conditions at the end of 2.5 seconds
- Engine Test
  - Maintain RV attitude & control
  - Conduct the pre-experiment tare
  - Maintain test conditions
  - Conduct the post-experiment tare
  - Controlled flight following engine operation
- Descent - Post Cowl Closed
  - Post engine test pull-up to 6 degrees angle-of-attack (arrest dynamic pressure build up and heating)
  - Descend along a predetermined descent profile and impact location
  - Perform parameter identification maneuvers and frequency sweeps along the descent at starting at Mach 8
  - Collect Flush Air Data System (FADS) data

Flight 3 – November 16, 2004



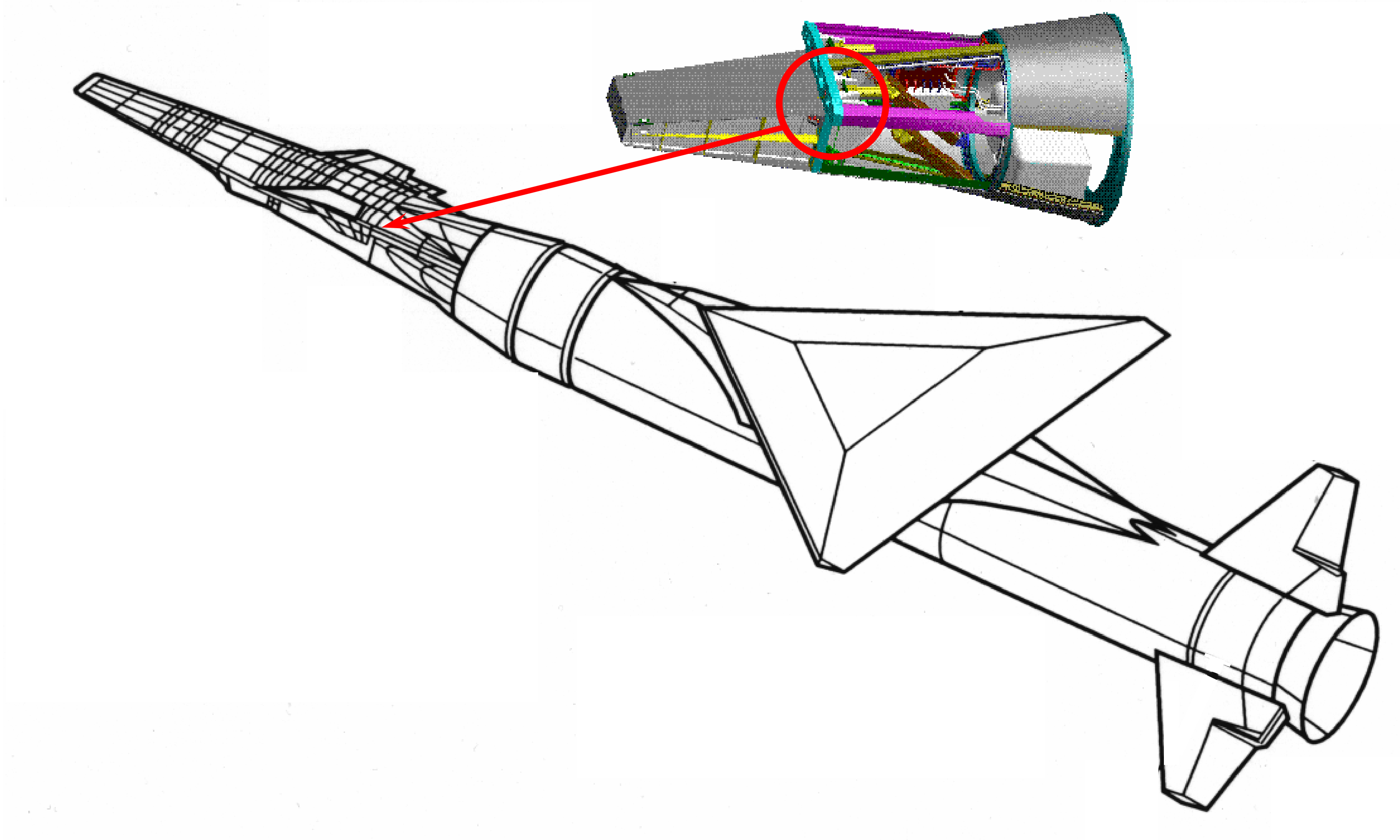


Separation Performance

- Separation Performance
  - No recontact of the RV with the LV
  - Pistons fired simultaneously and generated very little lateral/directional transient
  - Initial separation transient close to nominal pre-flight prediction
  - Following the initial separation transient, the RV took longer to reach the commanded angle-of-attack than predicted by pre-flight analysis
  - RV achieved the desired test conditions by the time the cowl opened

X-43A Flight 3 Left Adapter Camera Sequence

Left Adapter Camera Position



Frame Rate is Slowed Down to 1/30th of Real Time

Image 1

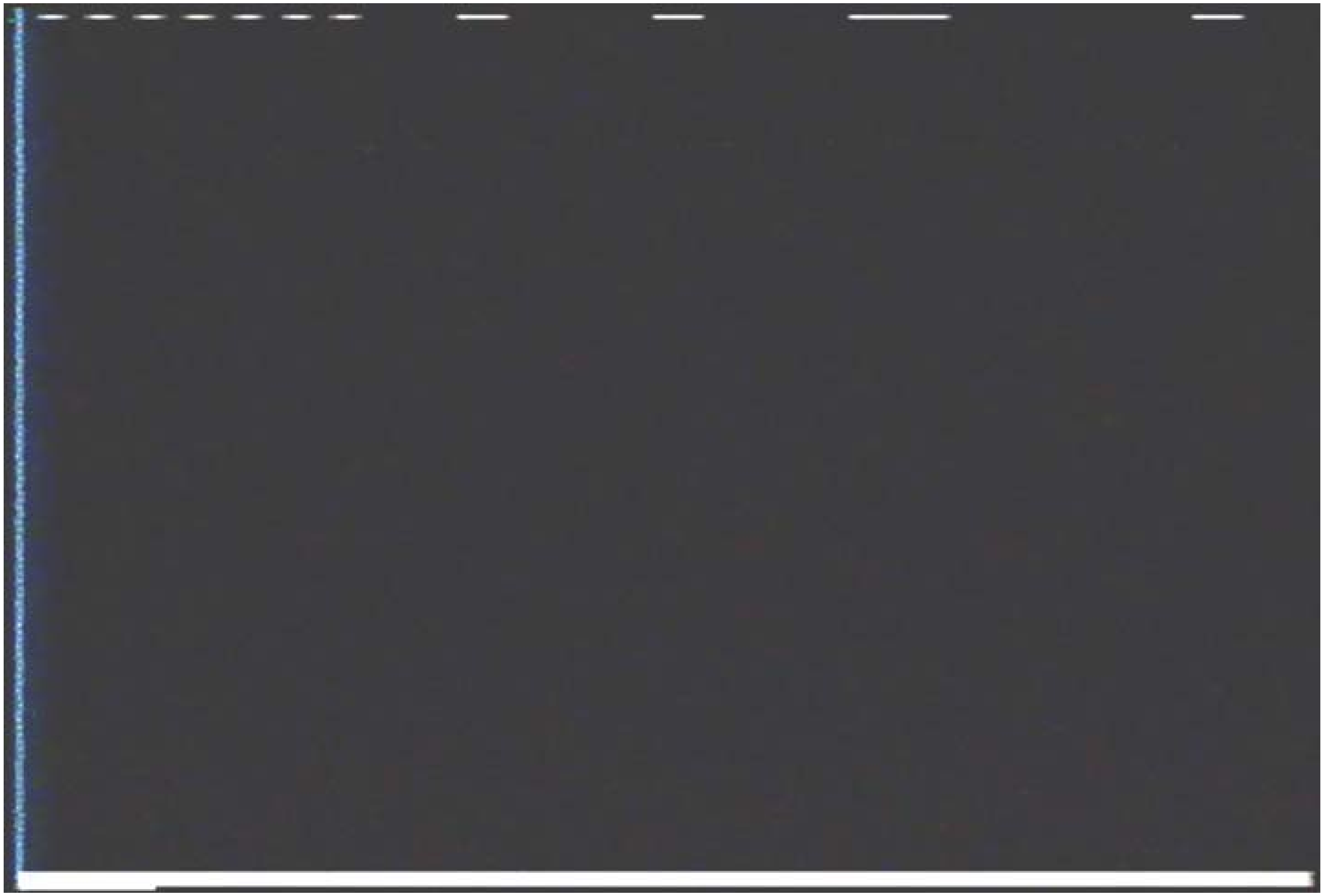


Image 2

Image 3

Image 4

Image 5

Image 6

Image 7

Image 8

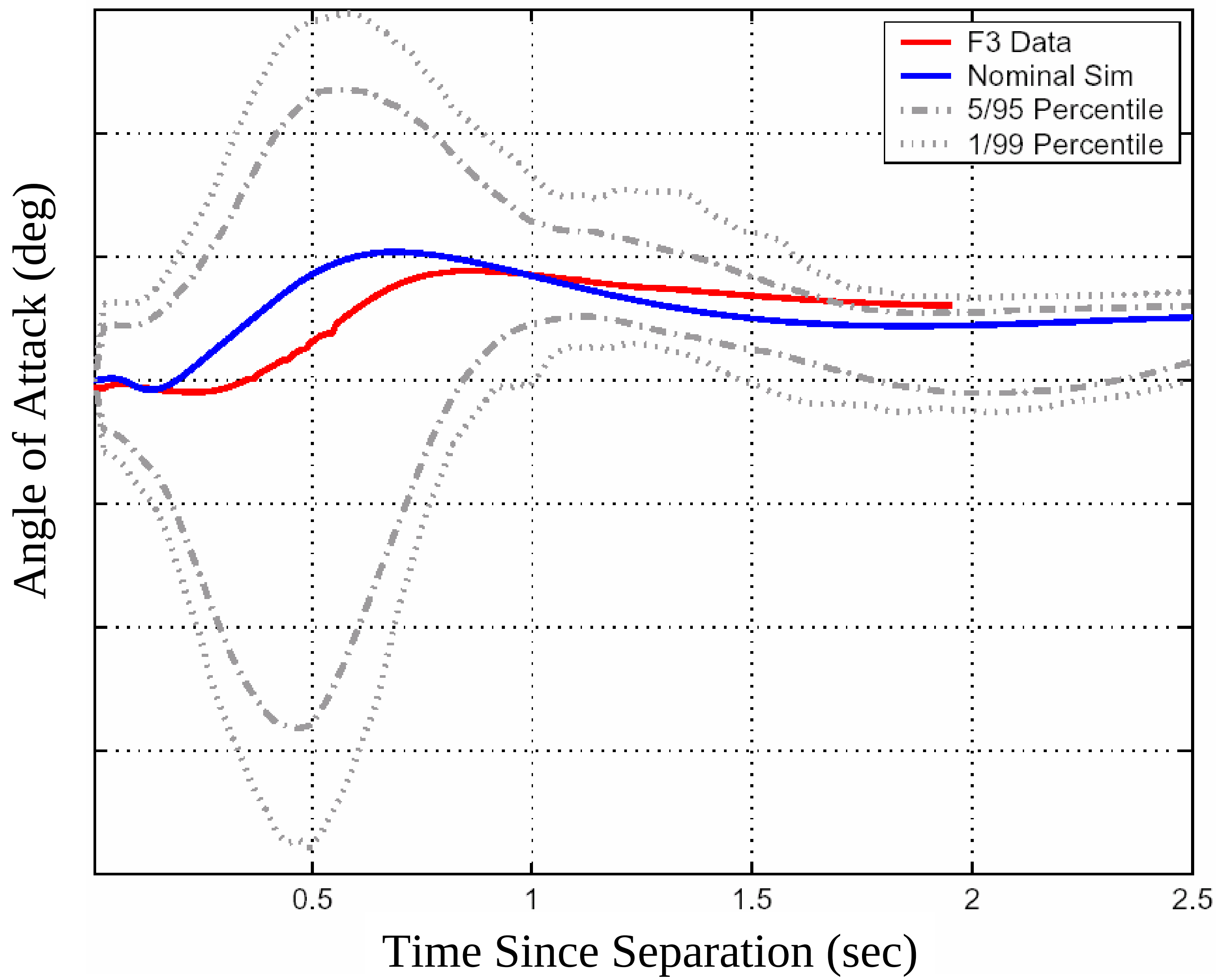
Image 9

Image 10

Image 11

Image 12

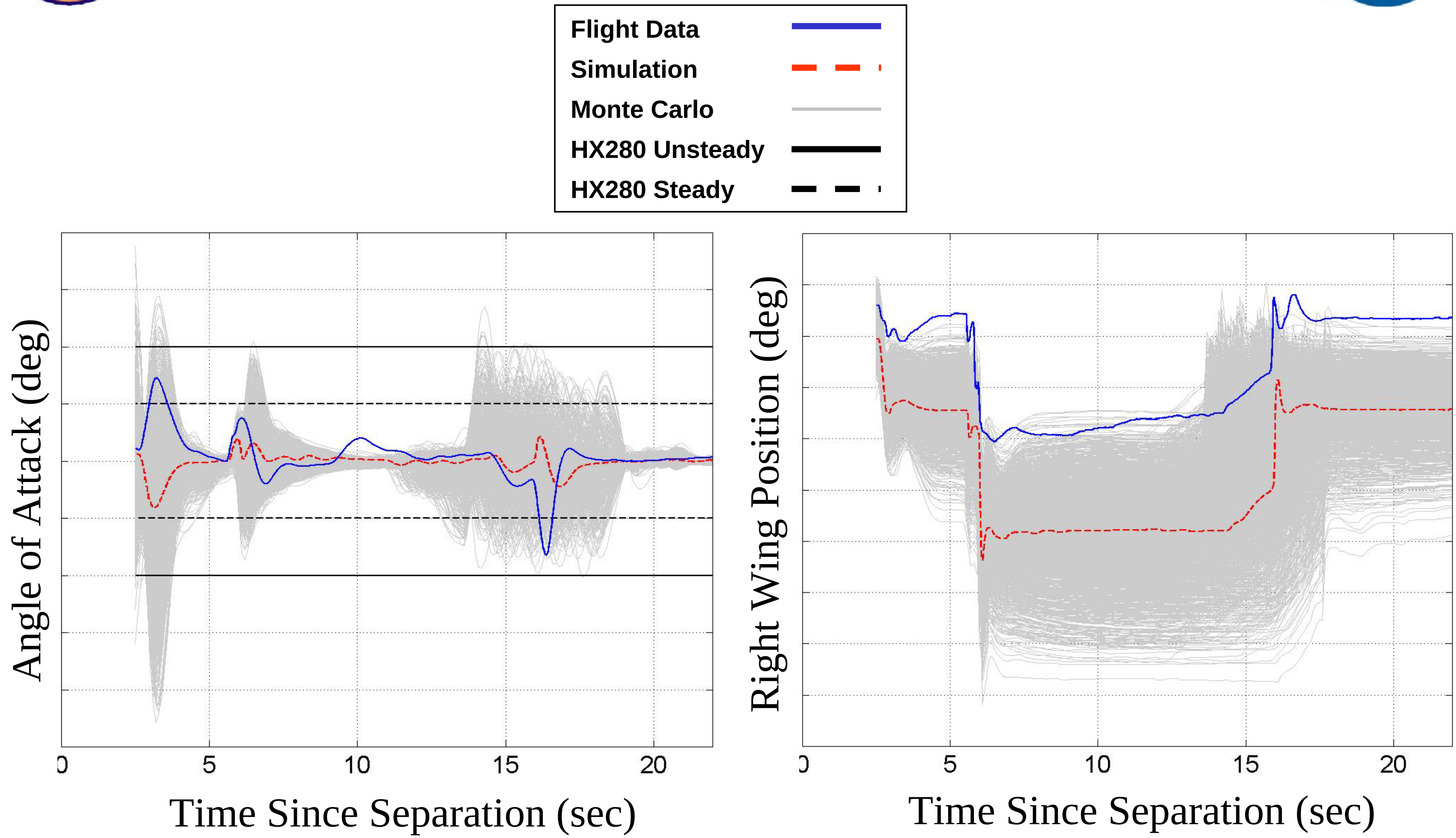
Separation Performance



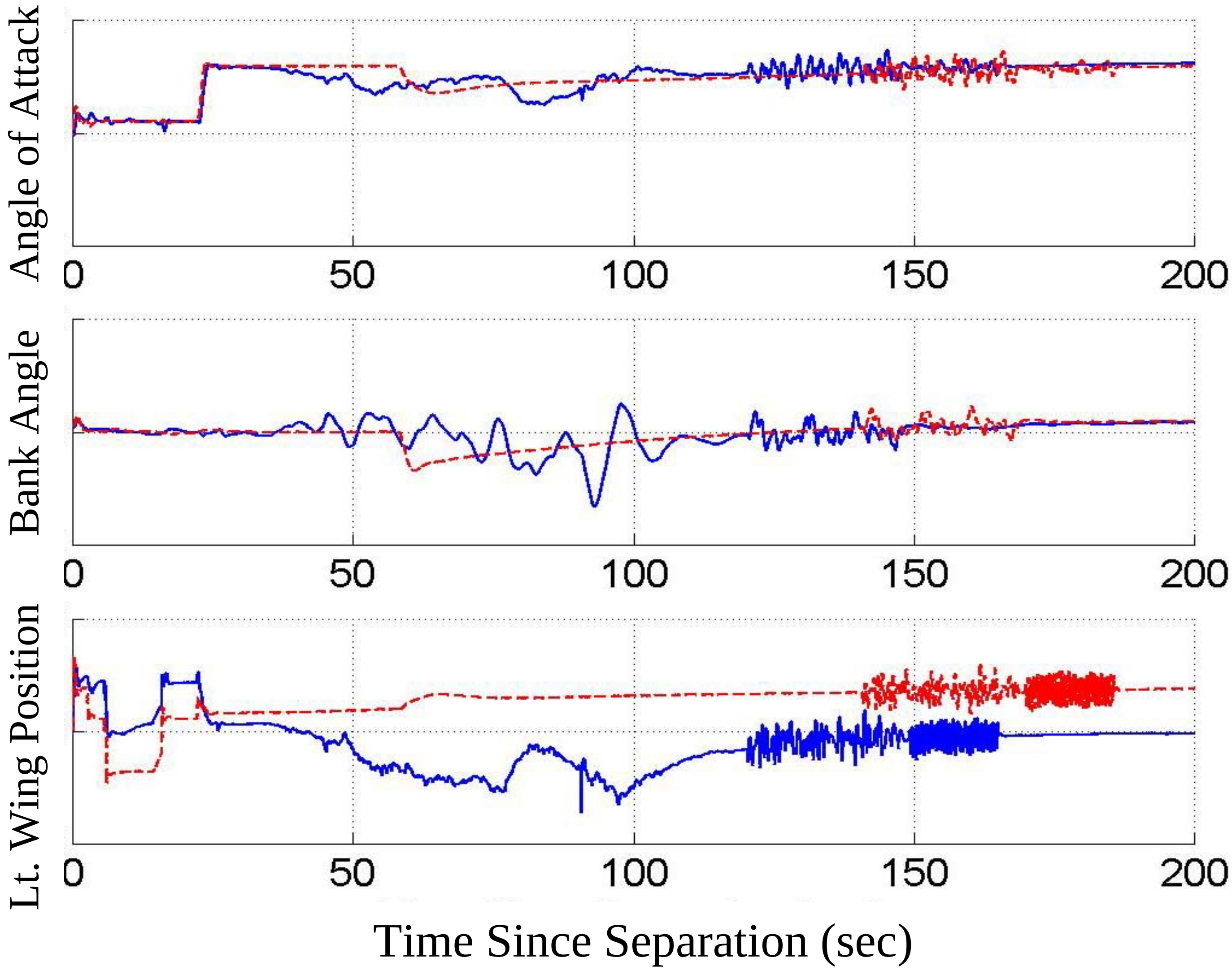
Engine Test & Descent Performance

- Engine Test Performance
  - RV maintained engine test conditions well within the requirements
  - Successfully completed pre- and post-engine test tare
  - Cowl open transient was different than the nominal pre-flight prediction but well within pre-flight Monte Carlo predictions
  - Small pitch up occurred during the engine test at 10 seconds
  - Wing trim position offset during the engine test and throughout the descent
- Descent Performance
  - RV roll oscillations and large trim required during the recovery maneuver.
    - Preliminary analysis indicates that this was most likely caused by airflow through the engine post cowl closed and the vehicle flying in a non-standard configuration.
  - Spike in wing position, accelerations and alpha at 90.7 sec possibly due to venting.
  - With the exception of the recovery maneuver anomaly, the post engine test performance was within Monte Carlo predictions and was very close to nominal
  - FADS data was collected along the descent and preliminary post-flight comparisons show good agreement with inertial angle-of-attack
  - All planned PID maneuvers were performed. The results from the Mach 2 & 3 PIDs are questionable since the flight conditions were rapidly changing.
  - Flight derived frequency responses match the linear analysis predictions.

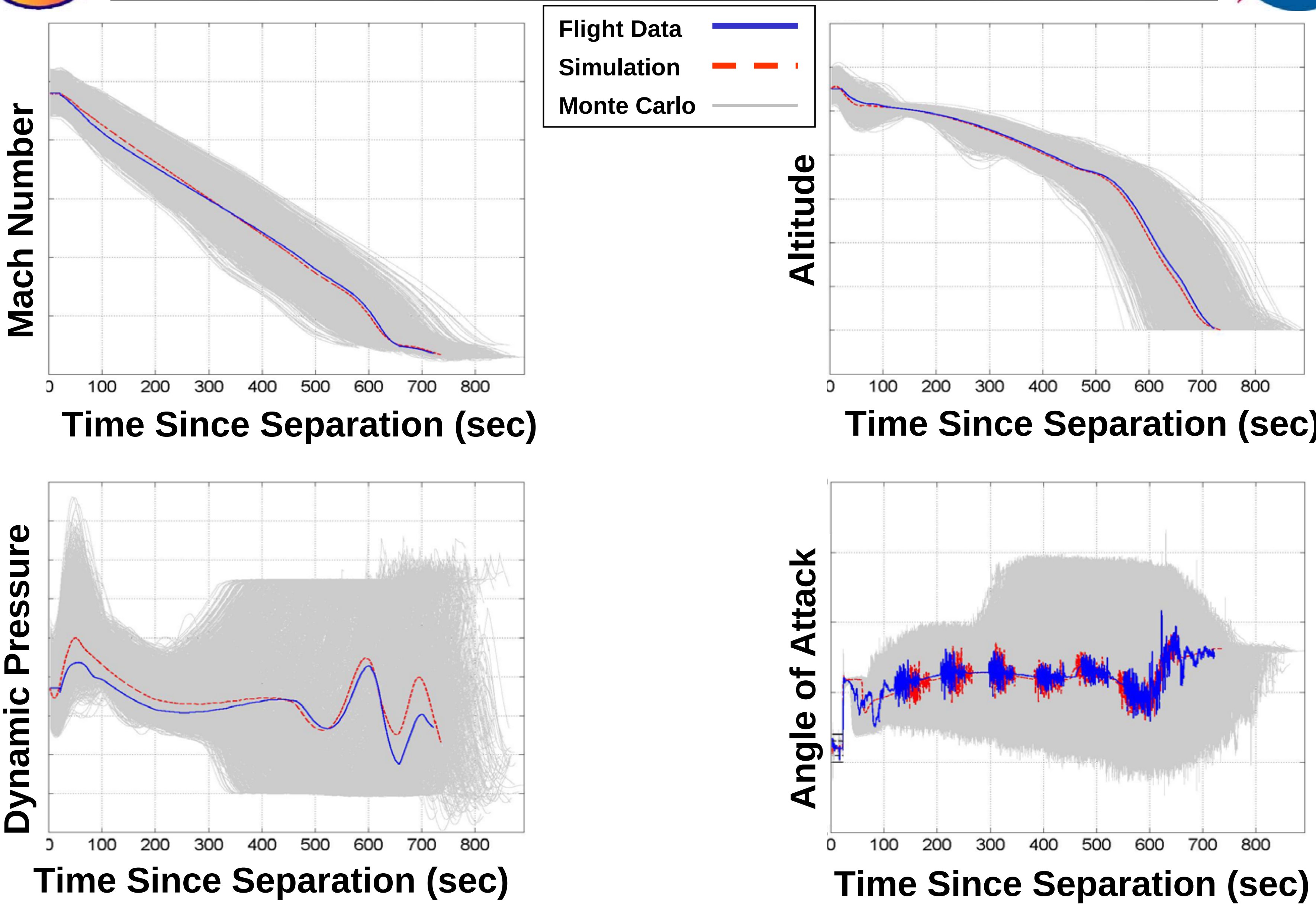
Engine Test Performance



Recovery Maneuver Performance



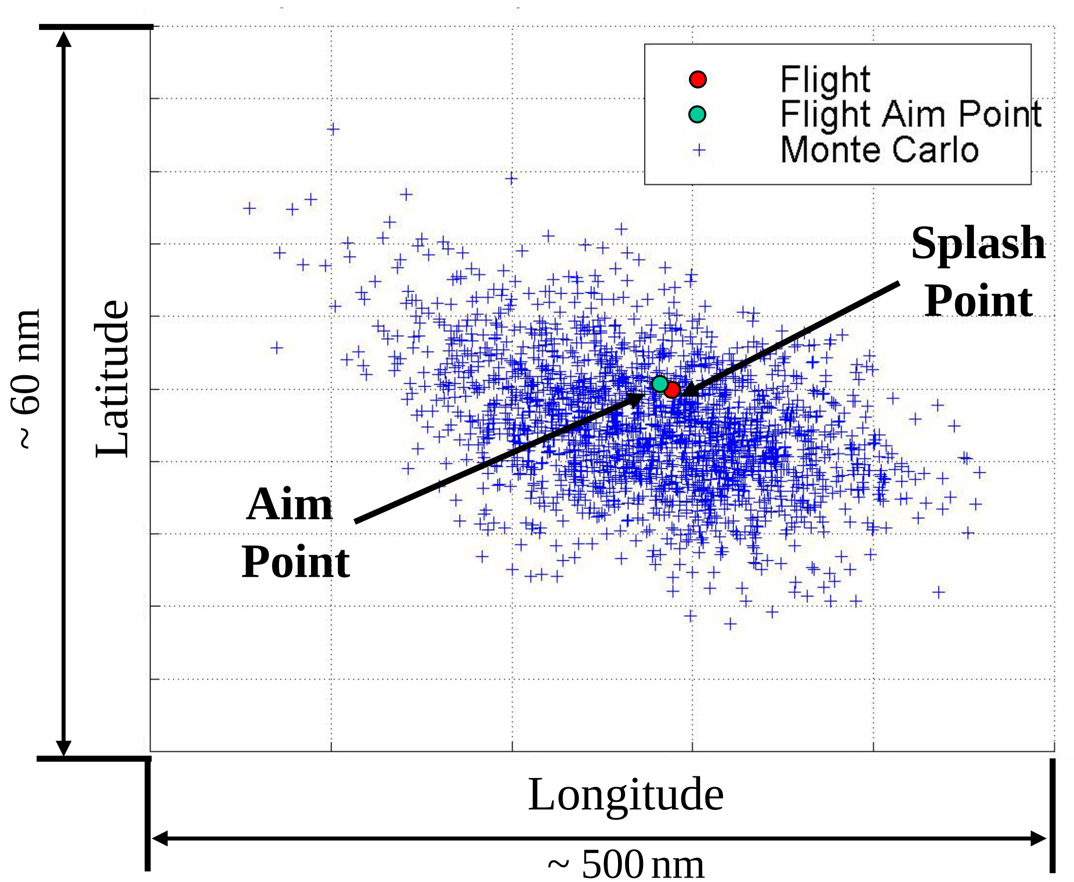
Descent Performance



Descent Performance
Research Vehicle Splash Point or LOS

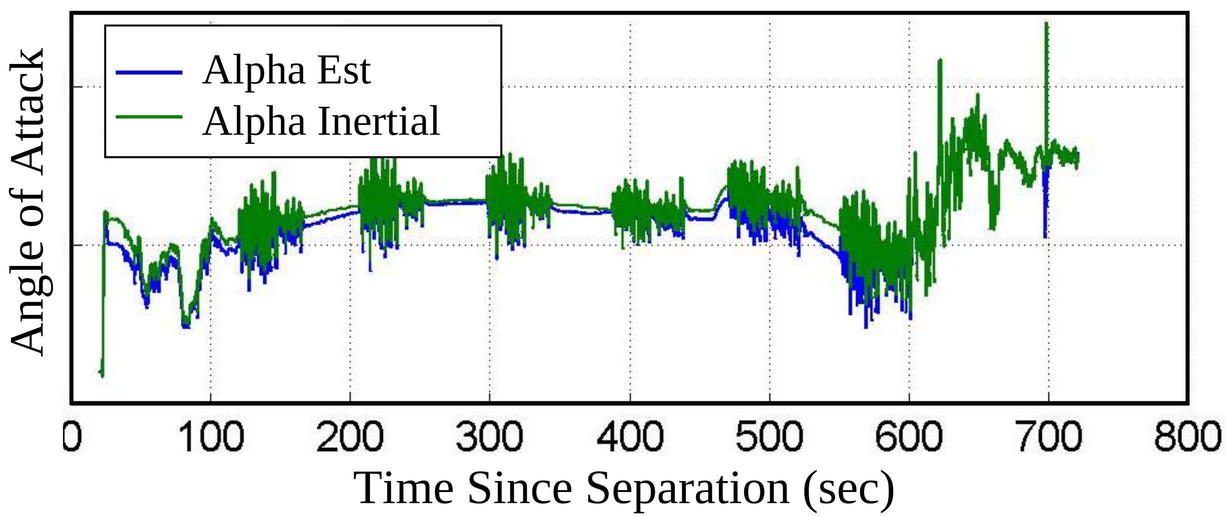
Last Valid Data Point

Altitude (ft)	Mach No. (-)	Altitude Rate (ft/s)	Alpha (deg)	Flight Path Angle (deg)	Bank Angle (deg)
918.49	0.72	-228.43	7.71	-16.60	1.6



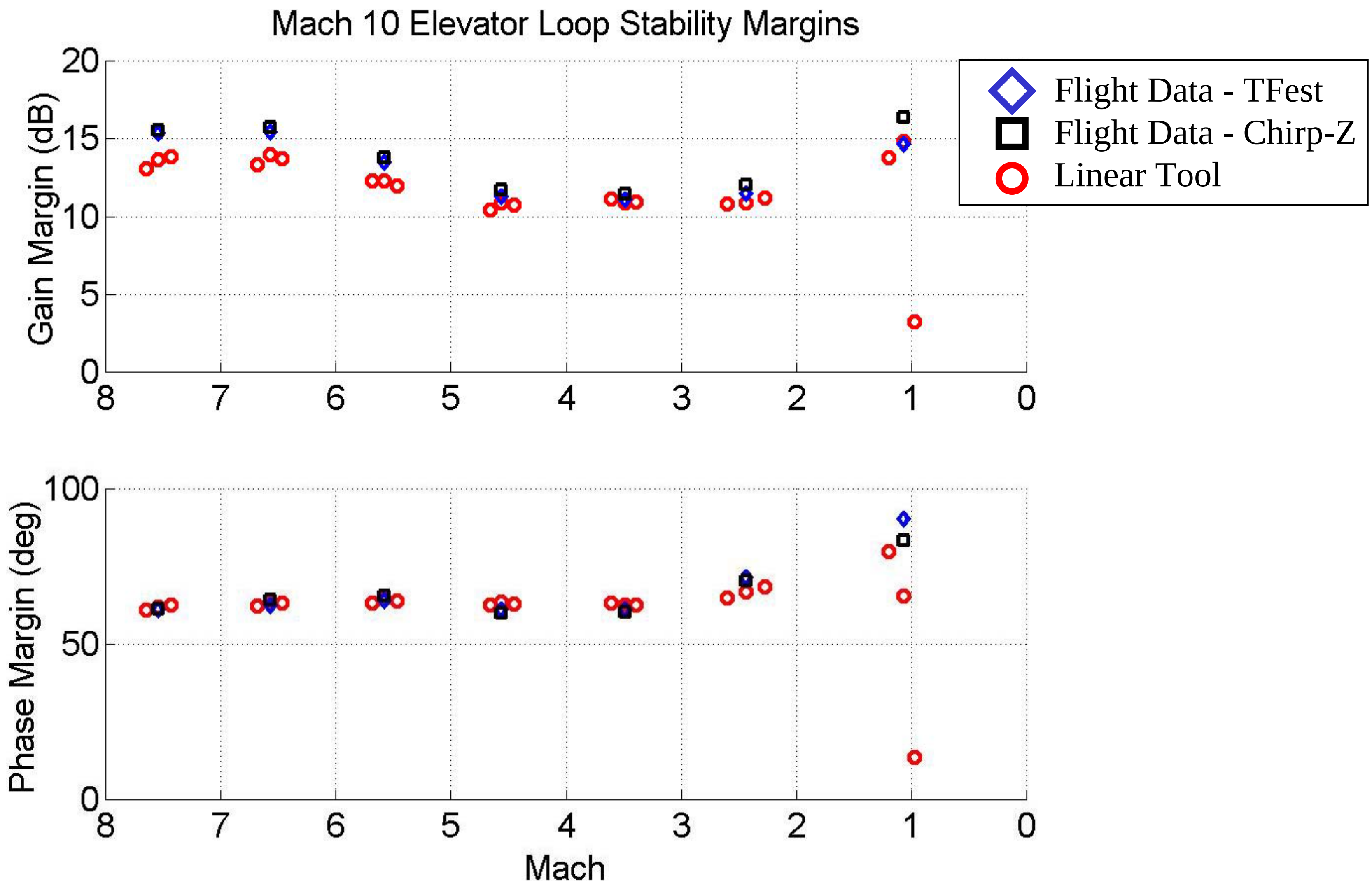
Flush Air Data System (FADS)

- Intent
  - For Flight 3, FADS alpha was not used to aid the inertial solution in flight.
  - The pressure data was collected and the FADS algorithms were running so that the in-flight α_{FADS} estimate could be evaluated post-flight
- Flight Results
  - Initial Post-flight analysis indicates that the FADS estimated angle-of-attack compares well with the inertial angle-of-attack, especially below Mach 8 where wind tunnel data was used to create the model



Flight Stability Margin 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.



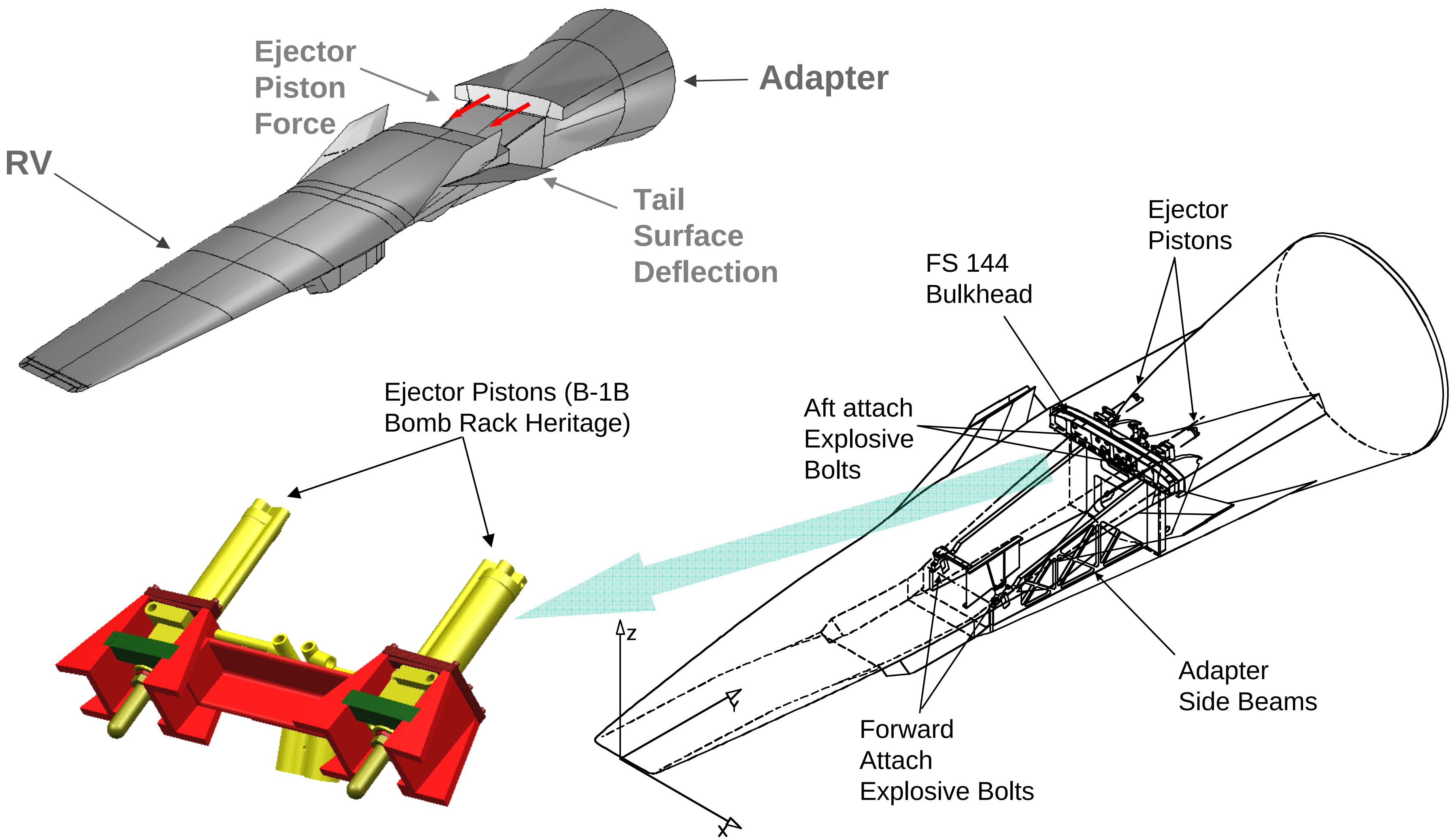
Final Thoughts

- The X-43A successfully separated at Mach 7 and Mach 10 from the launch vehicle and achieved stable free flight throughout the engine test.
- The RV maintained engine test conditions well within the requirements for both the Mach 7 and the Mach 10 flights
- Following the scramjet experiment, the vehicle remained controlled during the descent and successfully completed a series of descent maneuvers.
- For both flights, the impact point was well within pre-flight predictions.
- The FADS algorithms performed well for flights 2 and 3
- Frequency responses generated from the Mach 7 and Mach 10 flight data match the linear analysis predictions very well.

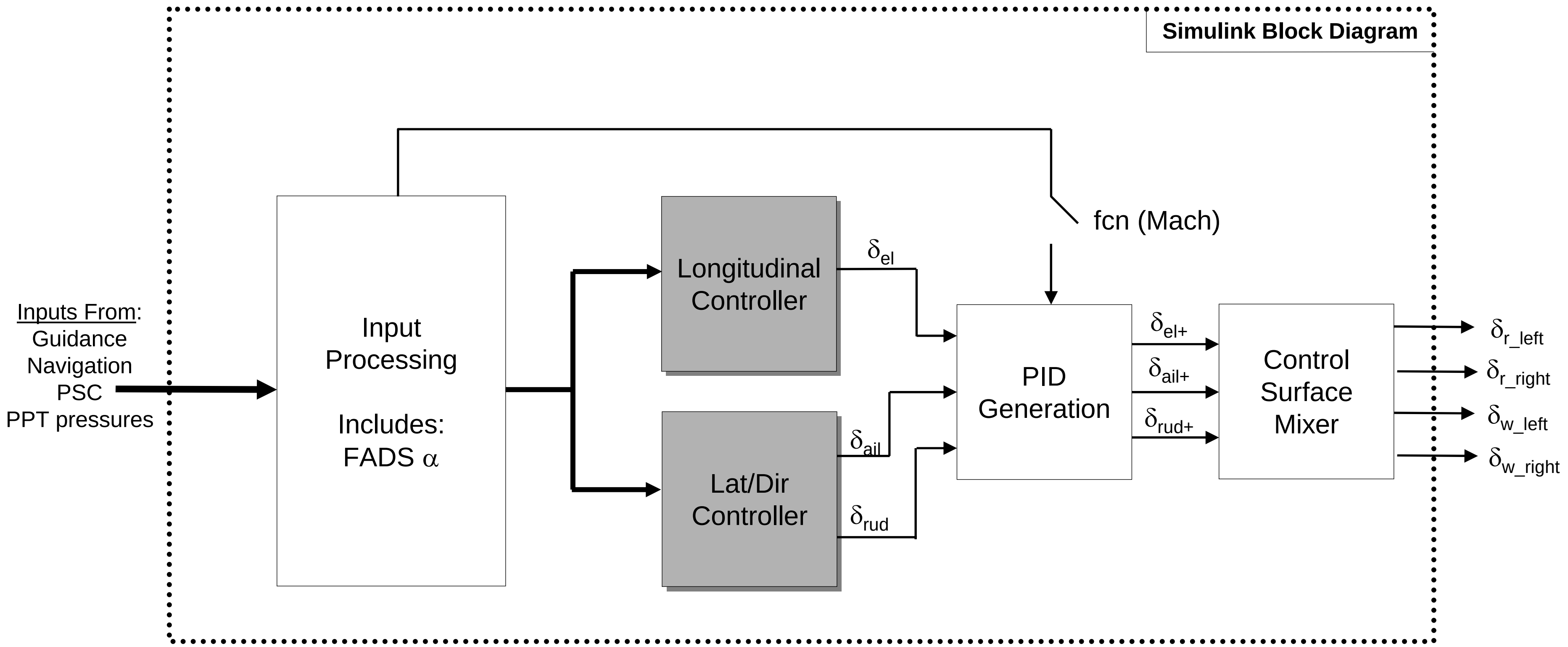

Questions ???

Backup Charts

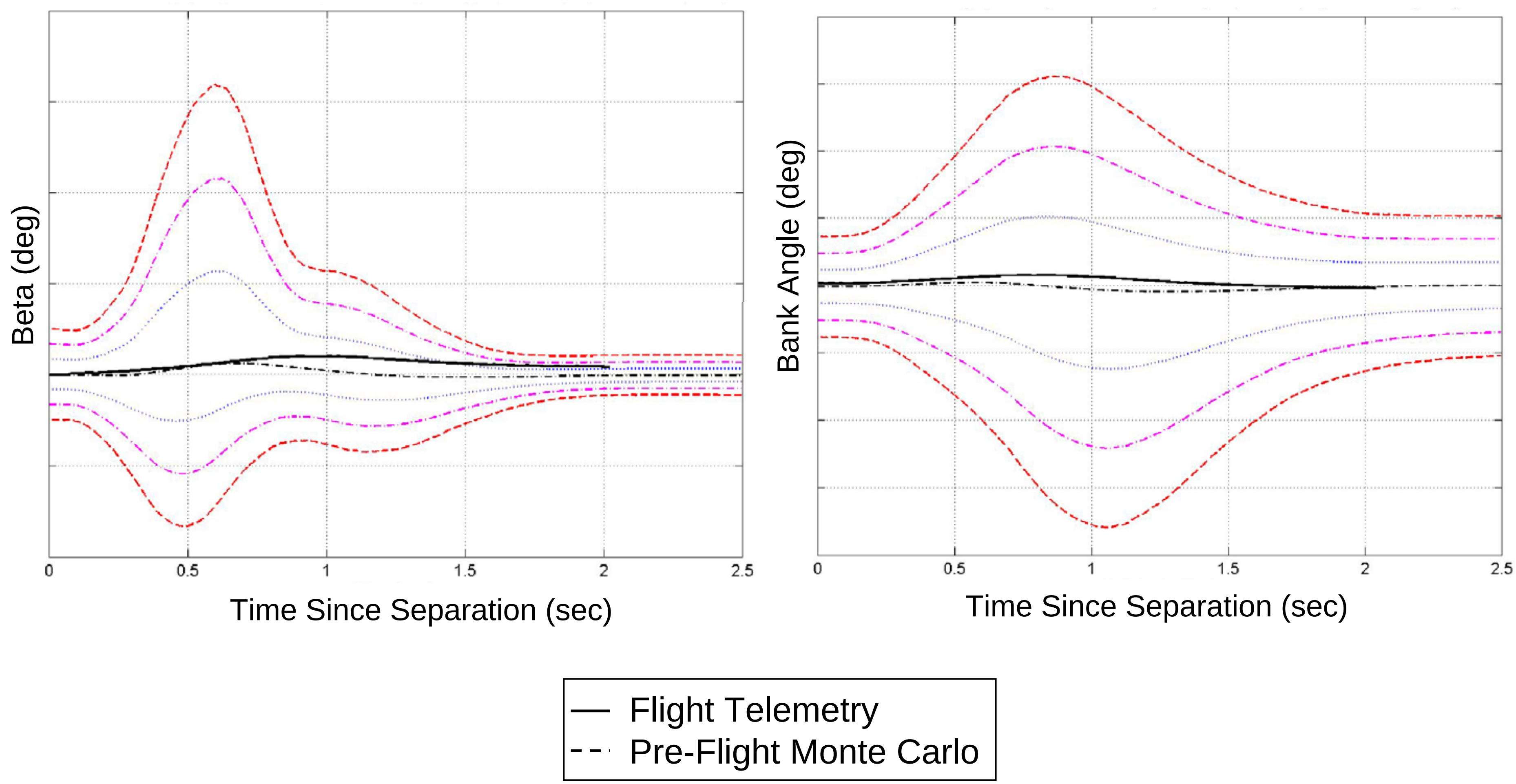
Separation Systems



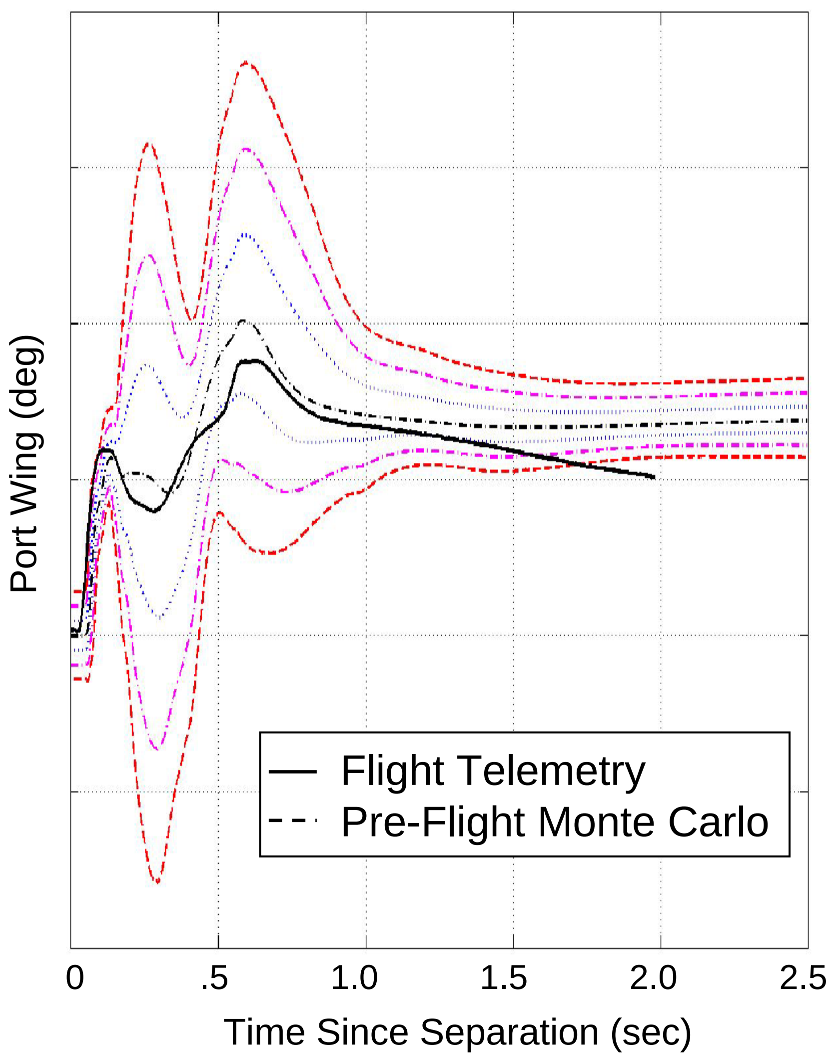
Flight Controls Block Diagrams

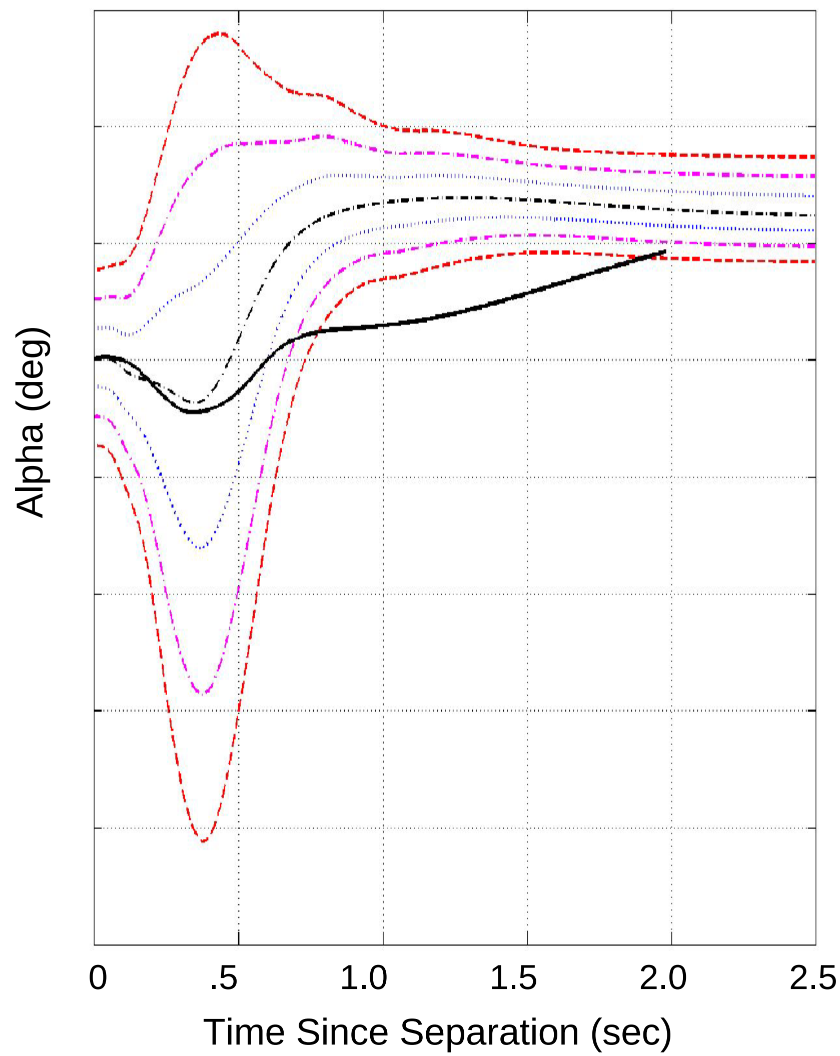


Flight 2 Separation Sideslip Angle & Bank Angle



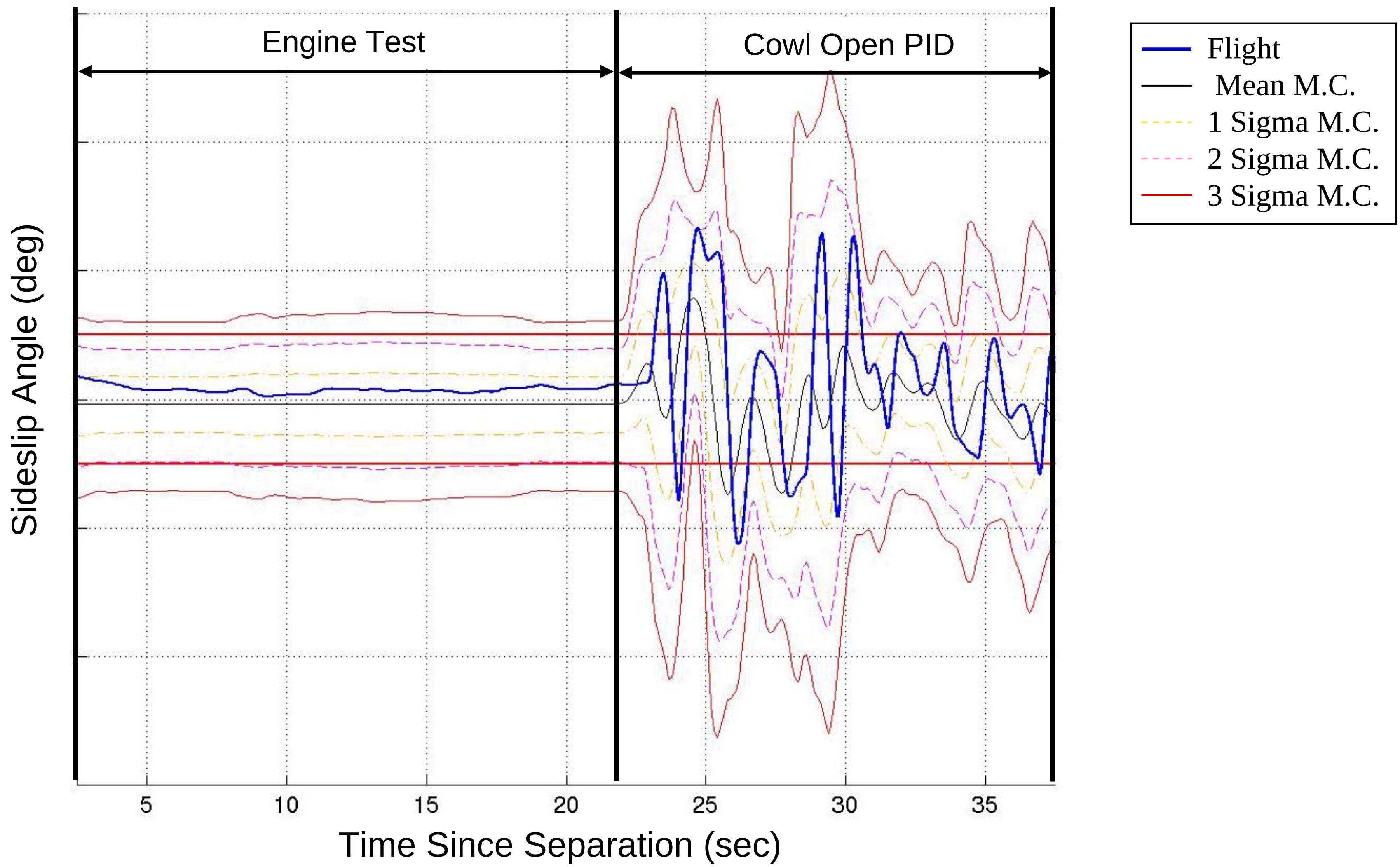
Flight 2 Separation Angle of Attack & Elevon





Flight 2 Engine Test Performance

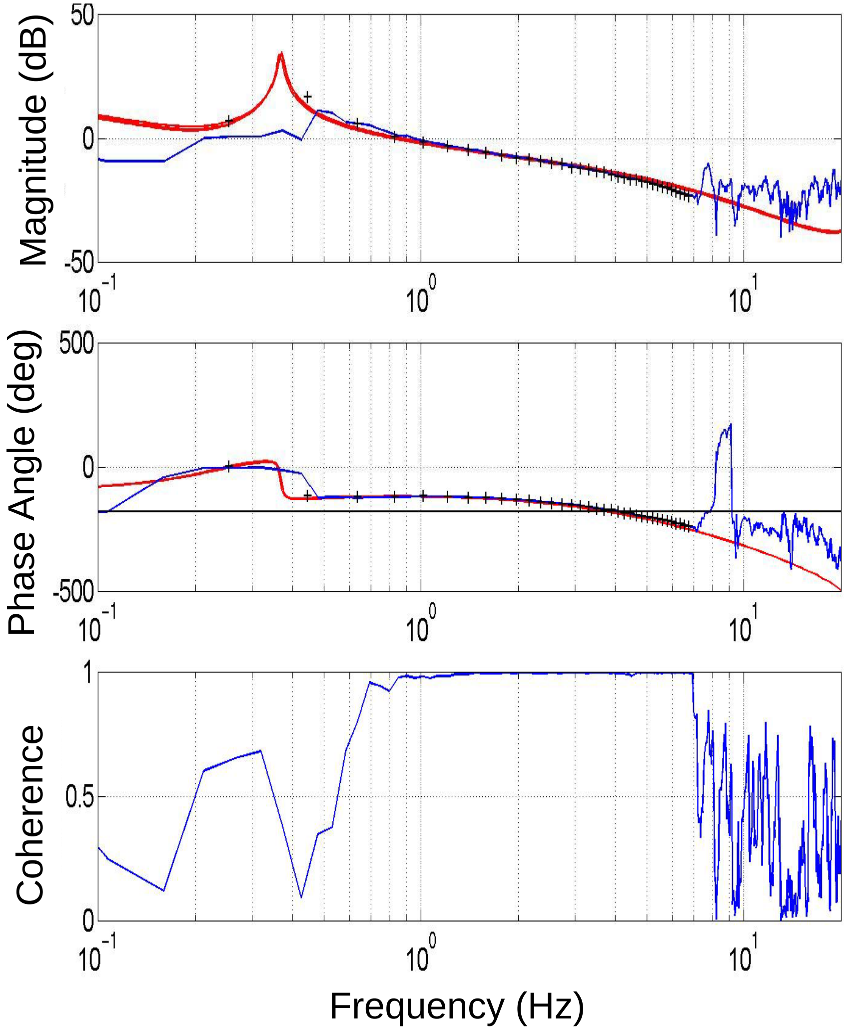
Note – Sideslip Angle is inertial



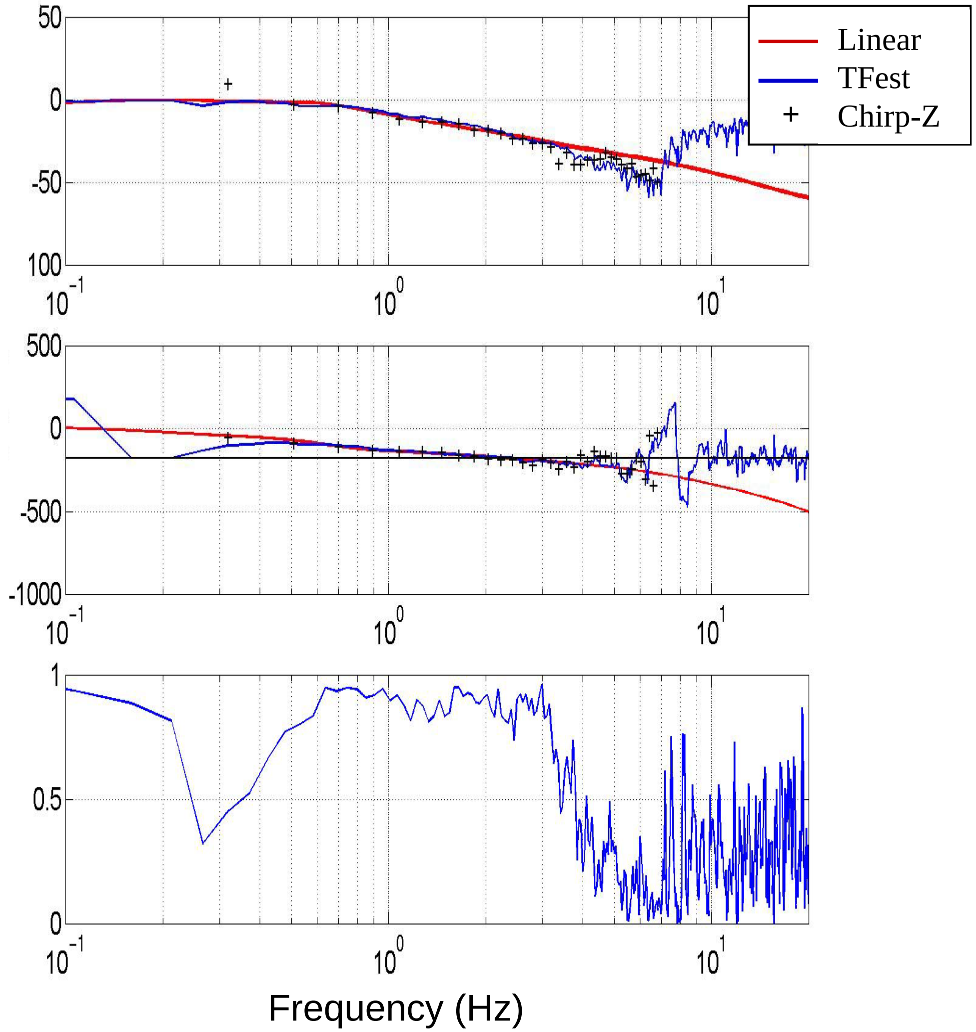
Flight 3 Flight Stability Margin Estimation

- 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.

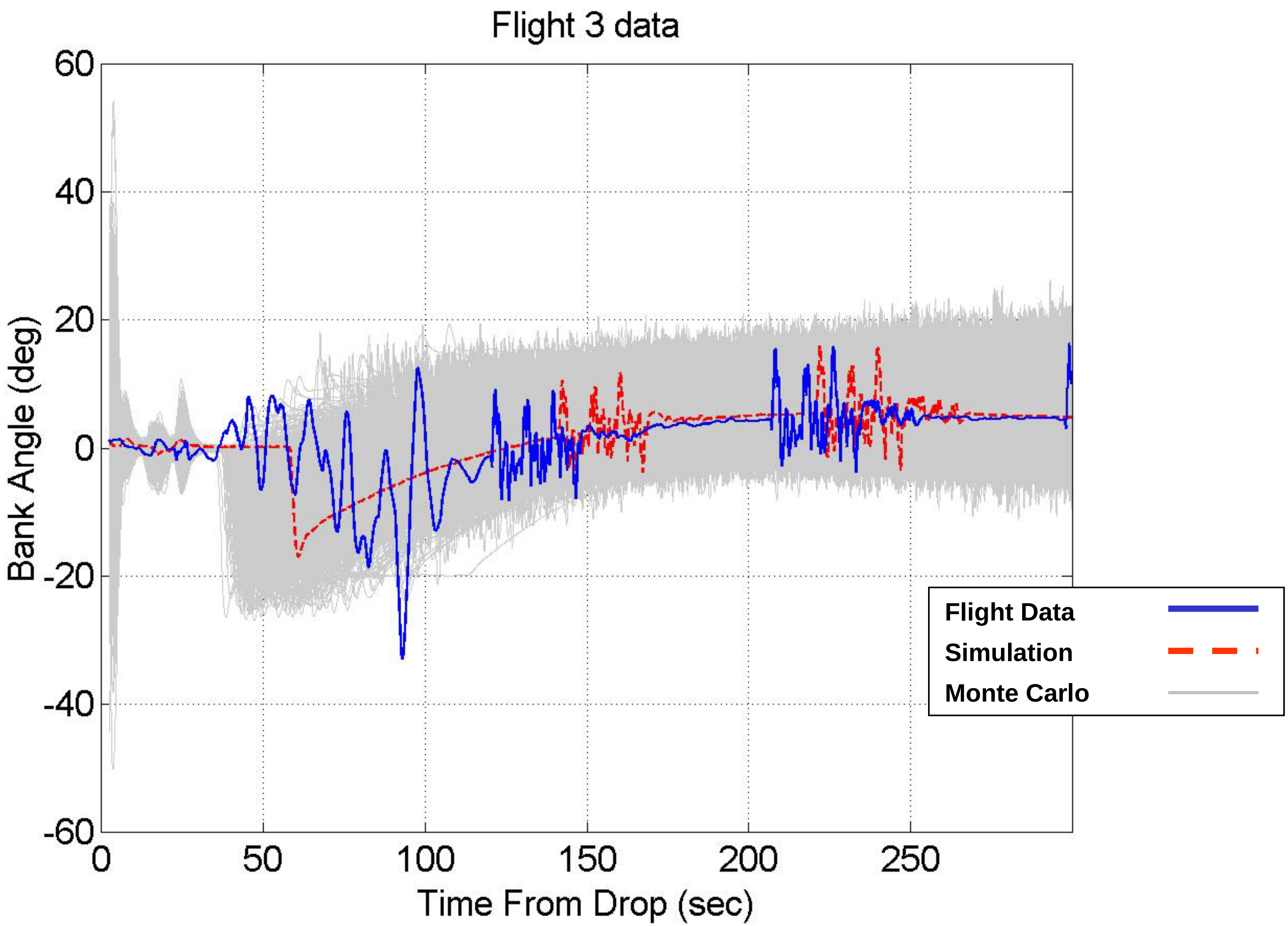
Elevator Frequency Response At Mach 7.54



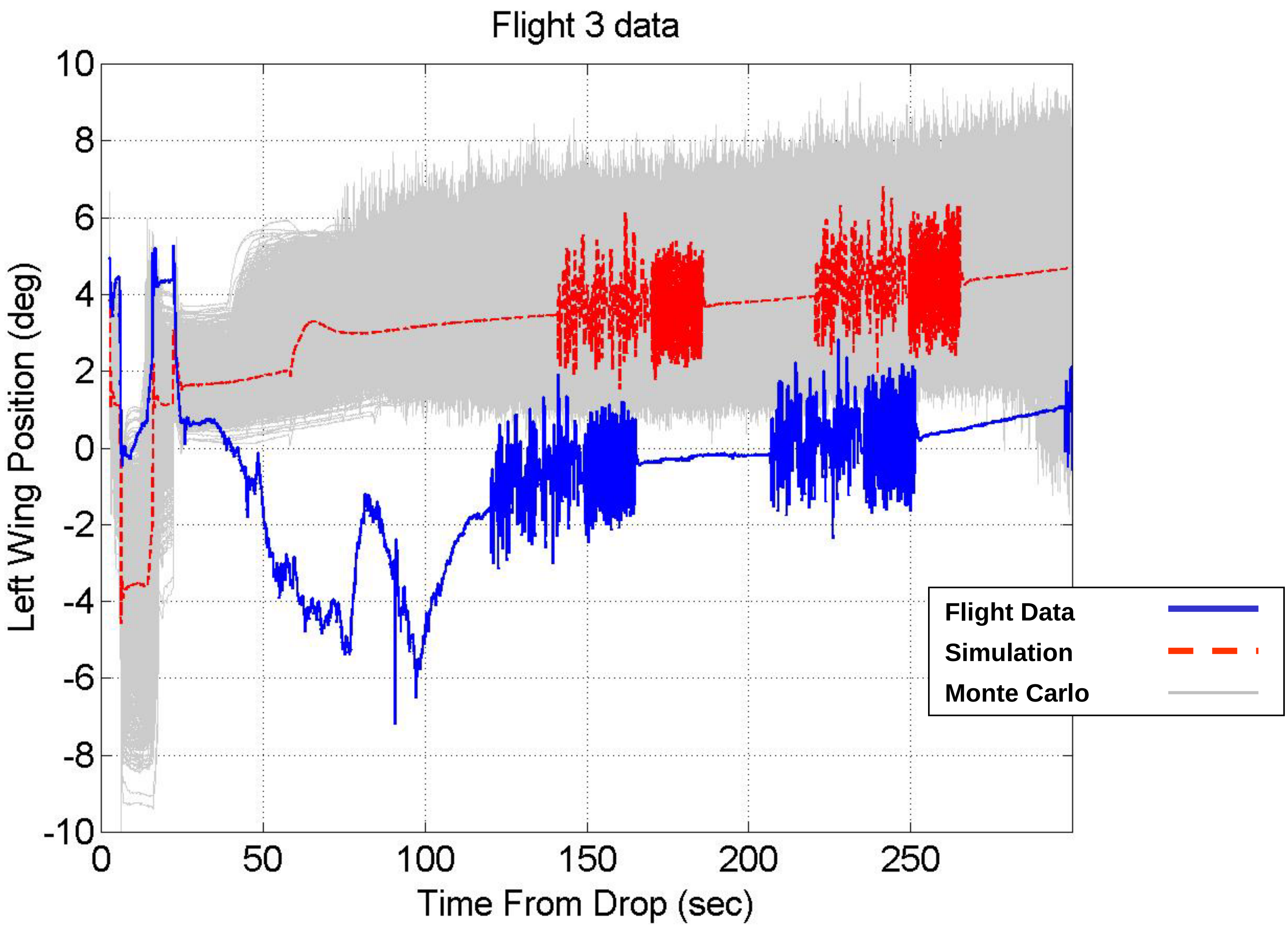
Rudder Frequency Response At Mach 7.54



Flight 3 Bank Angle versus Time



Flight 3 Left Wing Position versus Time



M10 Unpleasantness Story

- Angle of Attack dynamics are caused by oscillations in roll.
  - Could also be caused by vehicle/engine deforming or material melting off vehicle.
- The lateral axis is lightly damped with the elevators being at negative deflection. The vehicle becomes very sloppy in roll.
  - Some lateral-directional parameters (Clb, Cnda, Cyda) switch sign at negative elevator deflection so the ARI hurts performance instead of helping.
    - This was seen during the Mach 10 design during the engine test.
    - Need to do some more work to confirm this theory
  - Could also be caused by vehicle deformation or material melting off.
- Negative elevator deflection likely caused by air flowing through the engine.
  - Pressures in the engine drop when the cowl closes, but rise again at the same time as the roll oscillations.
    - See work by Tom Jones for details.
  - Aft portion of the vehicle is pressurized forcing the nose down which pushes the elevators to negative deflection to bring the nose up.
- RV does not track Nzcmd because of low setting of integrator gain.
  - This was set intentionally low.
  - Higher integrator gain would not have helped since integrator output was near limit.
- RV flew nominally from about Mach 8 down and matches predictions well. Possible explanations are:
  - The vehicle/engine continued to deform thereby cutting off the flow through the engine.
  - The engine unstarted thereby being essentially closed.