# Ares I-X
# Flight Test Results

*April 2010*

# Ares I-X was extremely successful

- All objectives were met
- Data Analysis has shown excellent agreement with pre-flight predictions
- This presentation will review key findings by technical discipline

- Preliminary results as of March 30, 2010

# Agenda

- **Introduction**
- **Roll Control System**
- **First Stage**
- **Avionics**
- **Ground Systems**
- **Integrated Design and Analysis (ID&A)**
  - Operational/Development Flight Instrumentation (OFI/DFI)
  - Trajectory
  - Guidance Navigation and Control (GN&C)
  - Structural
  - Thermal
  - Aero
  - Vibro-acoustics
- **Summary**

# Public Ares I-X Objectives

- **Demonstrate Controllability of new launch vehicle**
- **Assemble and Recover new launch vehicle**
- **Characterize in-flight roll characteristics**
- **Perform staging of new launch vehicle**
- **Demonstrate parachute performance and booster entry sequence**
- **Gather data on liftoff/ascent environments during launch**

*I-X is a Development Flight Test*
*(Purpose is to learn information that can be used to improve analysis capability and design activities)*

# What is Success for a Development Test Flight

- **Purpose of a development test flight (unlike a prototype) is to learn**
  - Only true failure is failure to learn from this flight

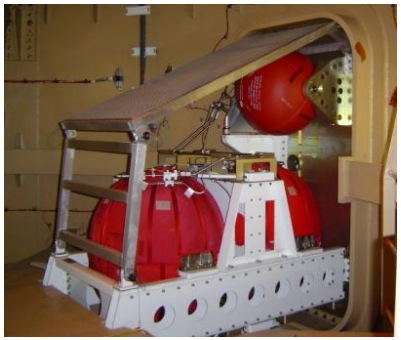
- **Success Criteria**
  - Rocket successfully rolls out
  - Rocket clears the pad without damage to rocket
  - Rocket stays within intended flight path
  - Flight data is collected that can be used to improve design of future launch vehicles.

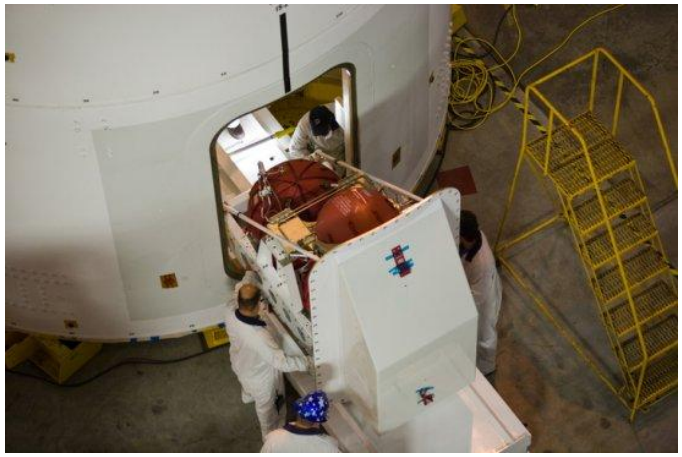
# Roll Control System

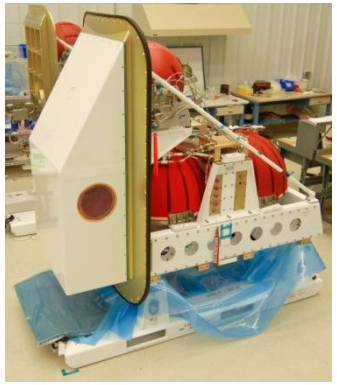
# Ares I-X Roll Control System Overview

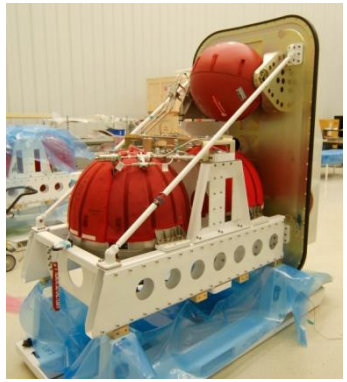
- **Description**
  - Roll Control System provides rotational azimuth control for:
    - mitigation against adverse vehicle roll torques (self- and aero-induced).
    - antenna and simulated crew launch positioning.

- **Salient Features**
  - The Roll Control System is an integral, modular, bi-propellant propulsion system installed in the Ares I-X Upper Stage Simulator Interstage.
  - RoCS utilized off-the-shelf and Government-furnished components that have been harvested from USAF Peacekeeper Stage IV, then re-integrated into a system.









Looking Forward

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# RoCS Performance
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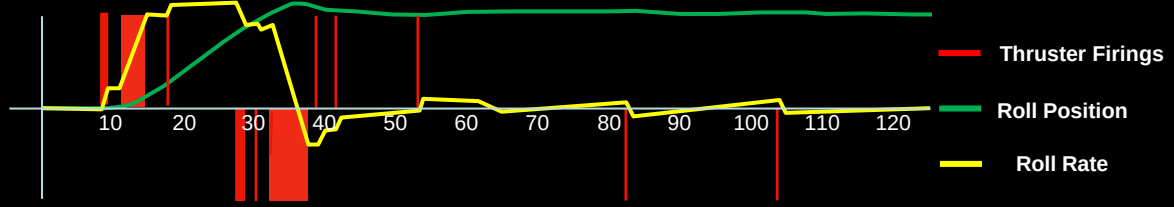
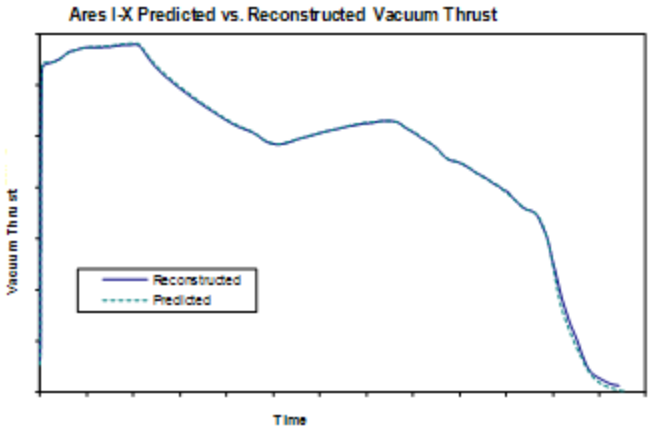


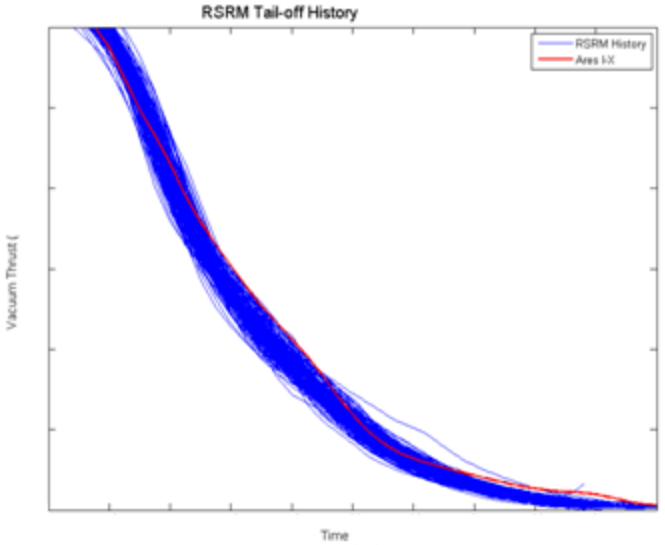

**Ares I-X Launch**
**October 28, 2009**
**11:30 am ET**

# First Stage

# First Stage Flight Highlights

- **Ares I-X Motor Performance**
  - All performance parameters within performance limits and RSRM history
  - Reconstructed performance compares well with prediction and with MSFC reconstruction
- **TVC system experienced commands generally within the RSRM experience base**




- **Thrust Oscillation Results Were Significantly Lower Than Predicted**
  - **1st mode results were one-third of pre-flight predictions**

# First Stage is still assembled and stored at Hangar AF

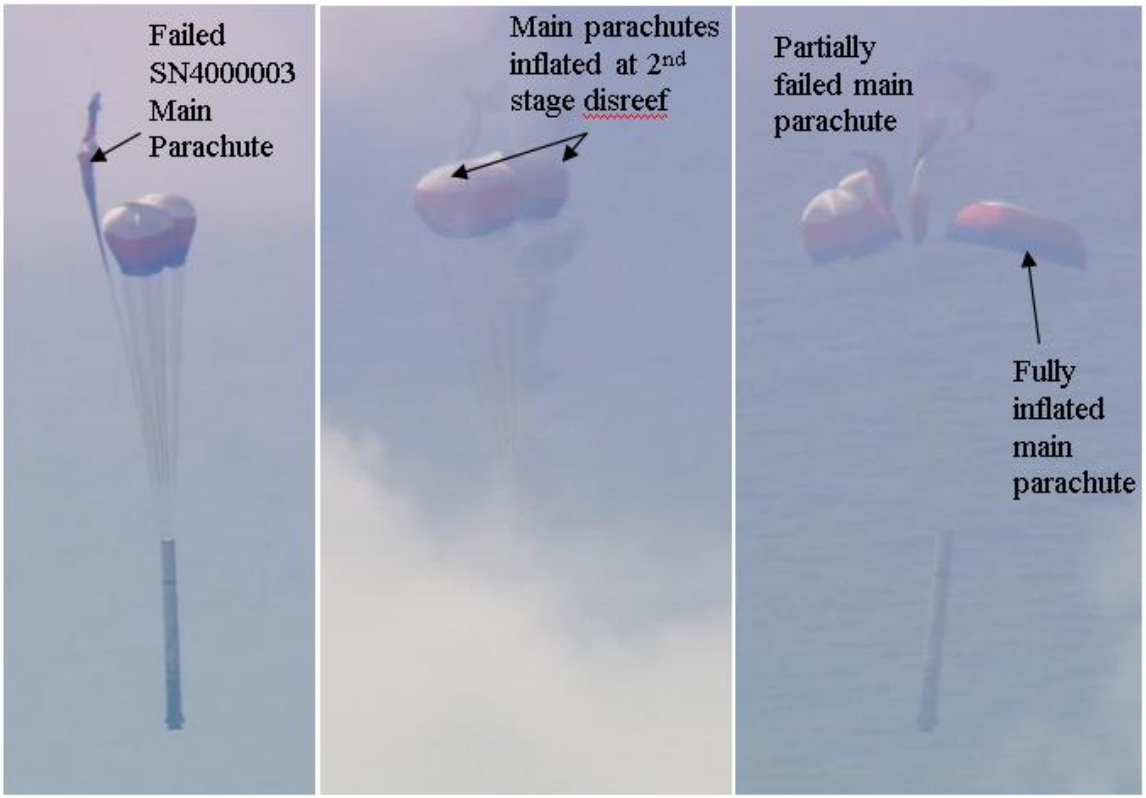
## Major Structural Hardware Condition

- **FSS/Forward Skirt is in good condition, however:**
  - **Aft XL cylinder clevis joint has most likely yielded or fractured**
- **Forward dome has fractured or severely yielded Y-joint**
- **All four cylinders associated with the Center segments are damaged (buckled and/or flattened) and most likely not usable**
- **Aft Segment**
  - **ETA and both stiffener cylinders have combinations of inboard and outboard stub cracks as well as "shape" issues**
- **Aft Skirt has significant cracking and "shape" issues**
- **TVC looks acceptable**
- **Hardware was not intended or needed for reuse**

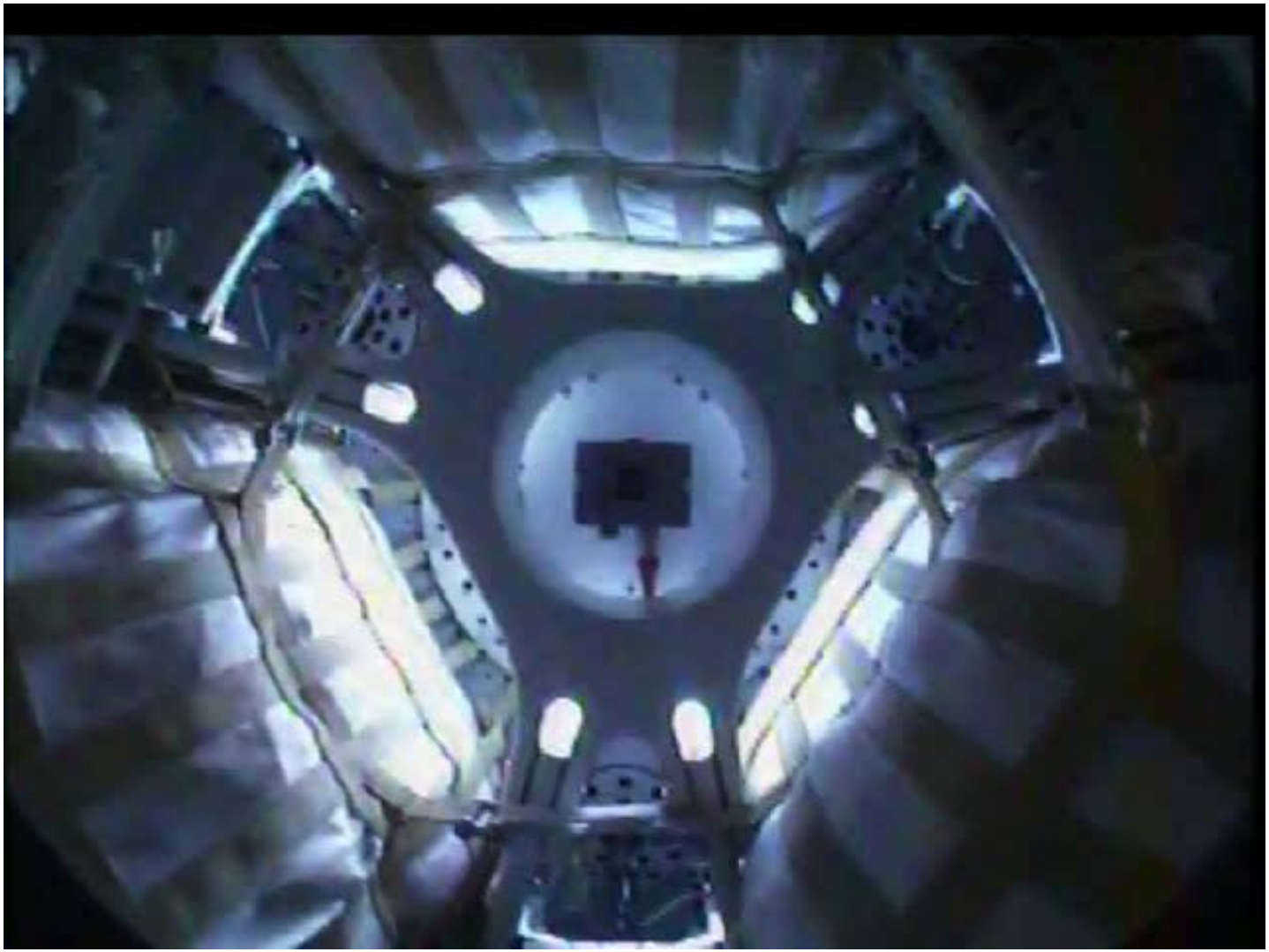

Aft Skirt Cracking

# Main Parachute Failure

- Most probable cause is pre-mature activation of a reefing line cutter
  - Reefing line cutter most likely actuated by errant pull of lanyard due to ascent vibrations of chute pack
  - Led to overload of a Salt Water Activated Release (SWAR) during deployment
- Design changes in work
  - Scheduled to be tested in drop test in mid-April



# Inside the Forward Skirt Extension (FSE) showing Parachutes prior to deployment



# Separation Connector Failure

- **Failure of the Forward Skirt-to-FSE separation connectors**
  - The most probable cause of this failure is that connectors were pulled at an angle higher than their rated cone angle
  - The cause of this higher angle is uncertain
    - Could have been a Pendulum Effect during the Drogue Chute phase

# Avionics

# Avionics System Performance

- **Avionics system performed as designed and without failure or anomaly through separation**
  - Flight control and software performance was nominal
  - GC3 system performance was nominal at all vehicle and external ground interfaces
- **Harnesses and avionics units in the aft skirt were damaged during re-entry and/or splashdown**
  - Harnesses were torn out of the harness connectors resulting in:
    - Auxiliary Power Unit Controller (APUC) lost at sea
    - Redundant Rate Gyro Unit (RRGU) P2 jam nut connector sheared off
    - Dead-face PYC harnesses torn out

# Data Recorder

- **Problem: Data corruption at end of flight**
  - Approximately 7% of the data is missing; all in the last 90 seconds
- **Background:**
  - The Multiplexer (MUX) data recorder stores data in temporary memory and writes it to permanent memory with a specified file structure
- **Suspected cause:**
  - When the MUX lost power as the vehicle impacted the water and switched to external power, the MUX was not able to properly commit data to permanent memory before the solid state device lost power resulting in holes in the data during the last 90 seconds
  - Post-flight testing in the SIL with the Flight and SIL MUX/Recorder determined that abrupt shut off of power can result in losing as much as 37% of the data in the last 100 seconds of the recording.
  - The manufacturer, Teletronics Corp. (TTC) has also reproduced the problem
- **Corrective Action:**
  - TTC will use another supplier for their solid state drive

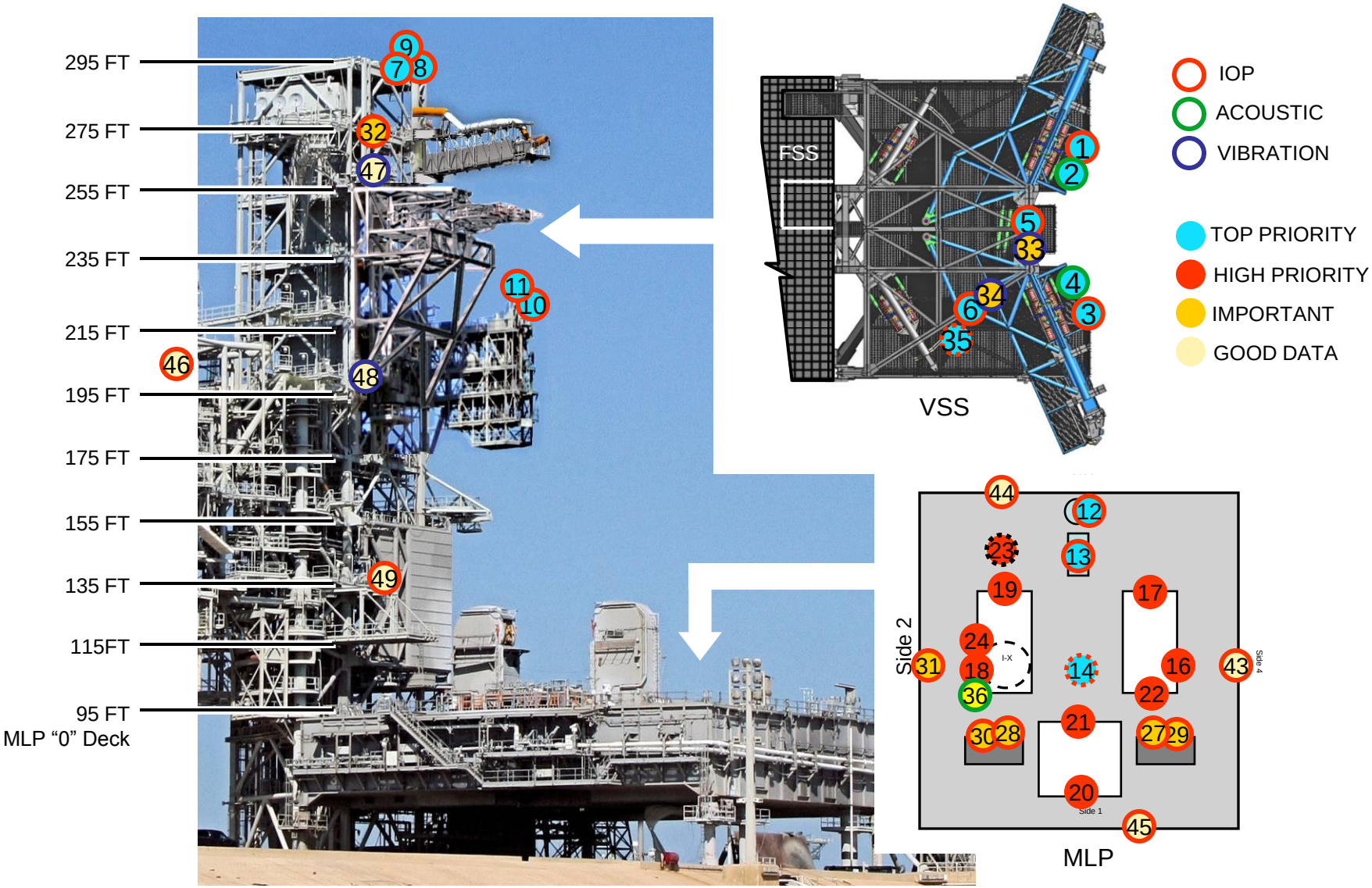
# Ground Systems

# Overview

- **Ares I-X launch damage greater than what has been seen on previous shuttle missions**
  - Launch pad was not hardened for Ares I-X plume impingement
  - More damage observed than Shuttle at 95’ Level
    - Due to drift/fly-away maneuver & lack of Sound Suppression water coverage
  - No major damage observed at 115’ Level
  - No damage at 135’ Level & above
- **Multiple pad area closures due to hypergol leaks following launch**
- **Data directly being used for design of new mobile launchers**

# New Ares I-X Pad Instrumentation

- Total Measurements: 49




*Ares I-X Flight Test Results April, 2010*

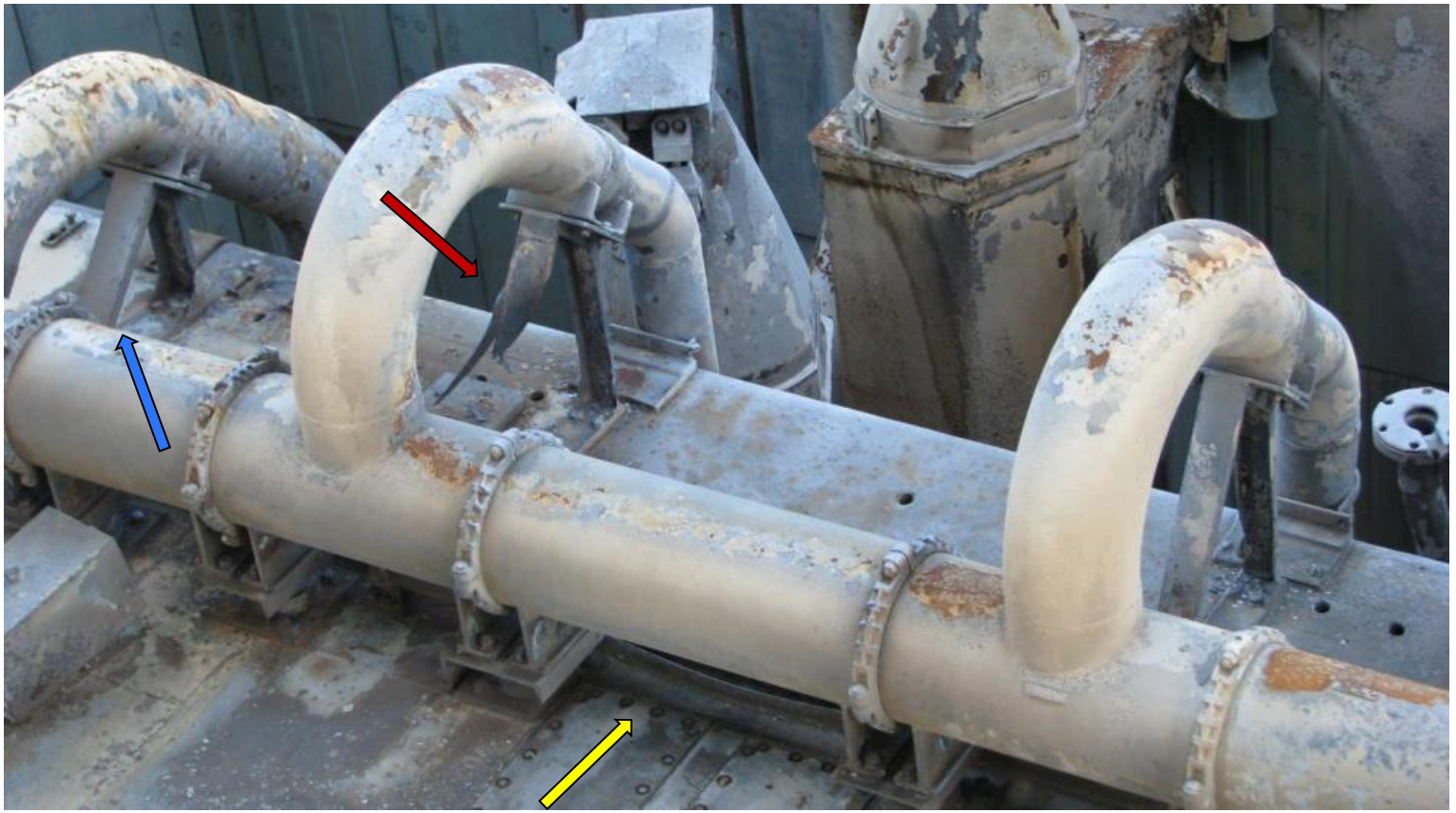
# MLP “0” Deck: Birdseye View

I-X causes more damage than Shuttle

# Ares I-X Exhaust Hole Holddown Posts & GN2



# MLP “0” Deck: Water System Damage




# Fixed Service Structure (FSS)

## FSS 95 Level


Color Key: Hand Rails; Tubing; Gridding; Sensors; Cables

# FSS 95’ Level: Handrail Damage


# FSS 95’ Level : Grating Damage

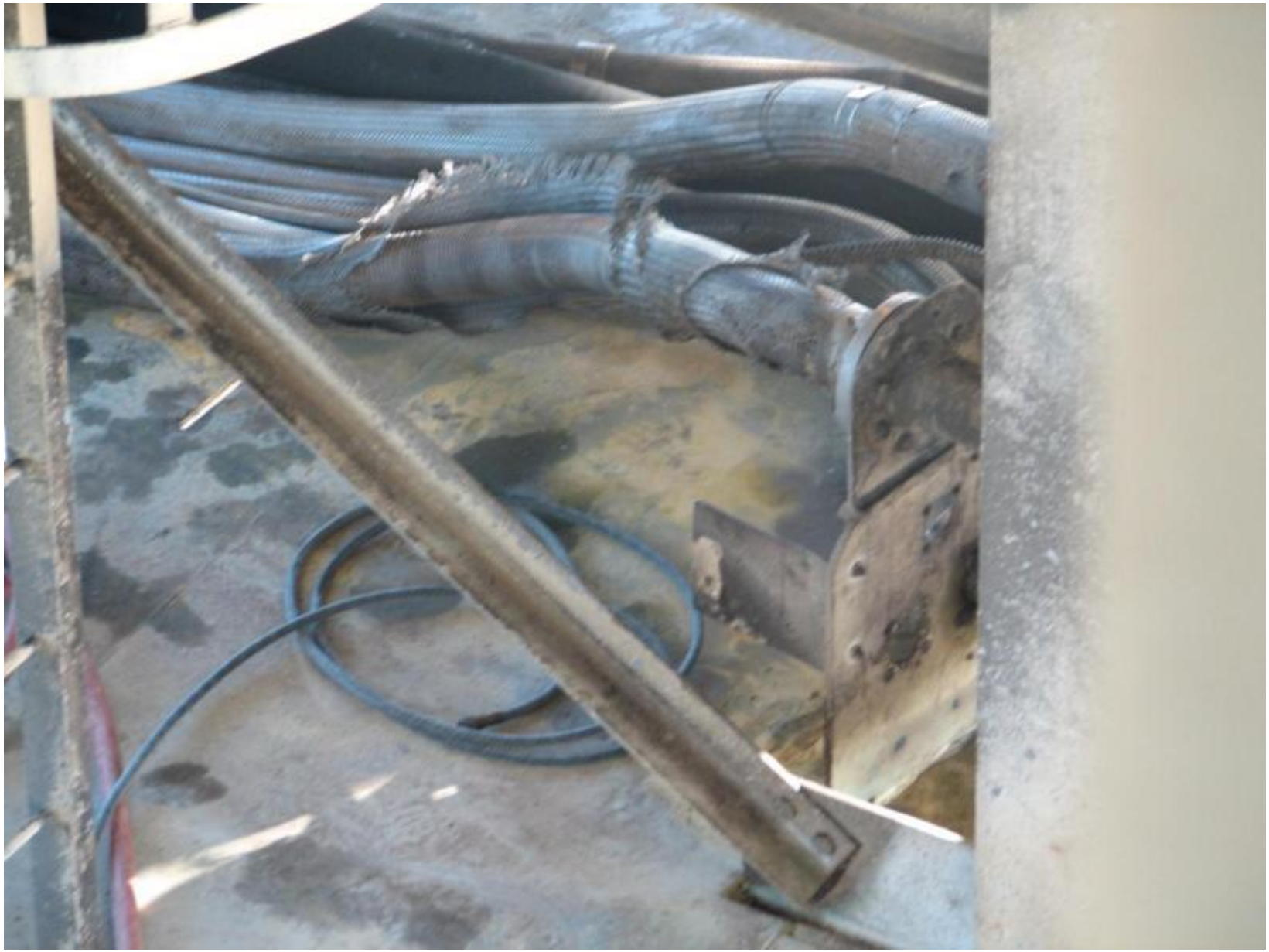
95’ Level

115’ Level

135’ Level

# FSS 95’ Level : Elevator Door Damage

# RSS 95ft Level: Hypergol Flex Hose Damage

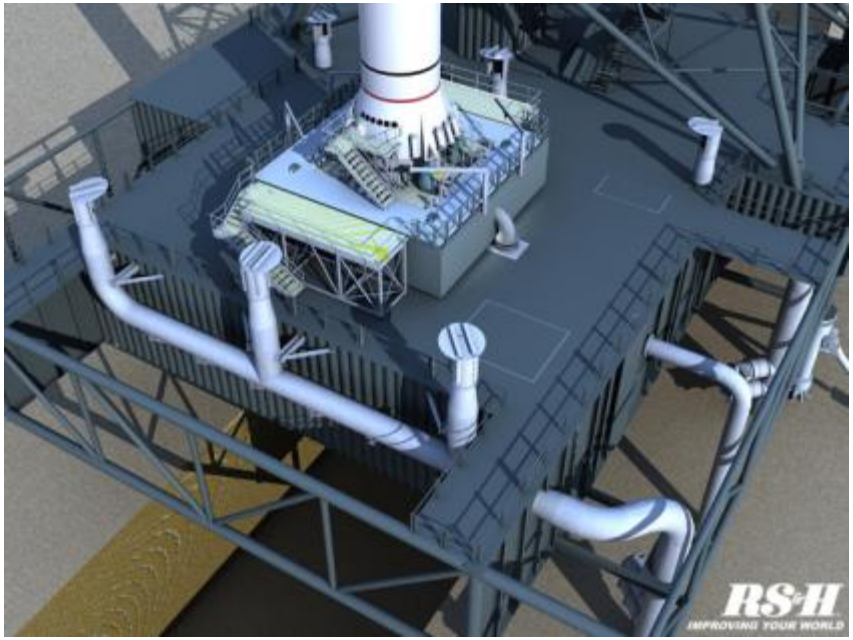


# FSS 115’ Level: Electrical Box & ECS Duct



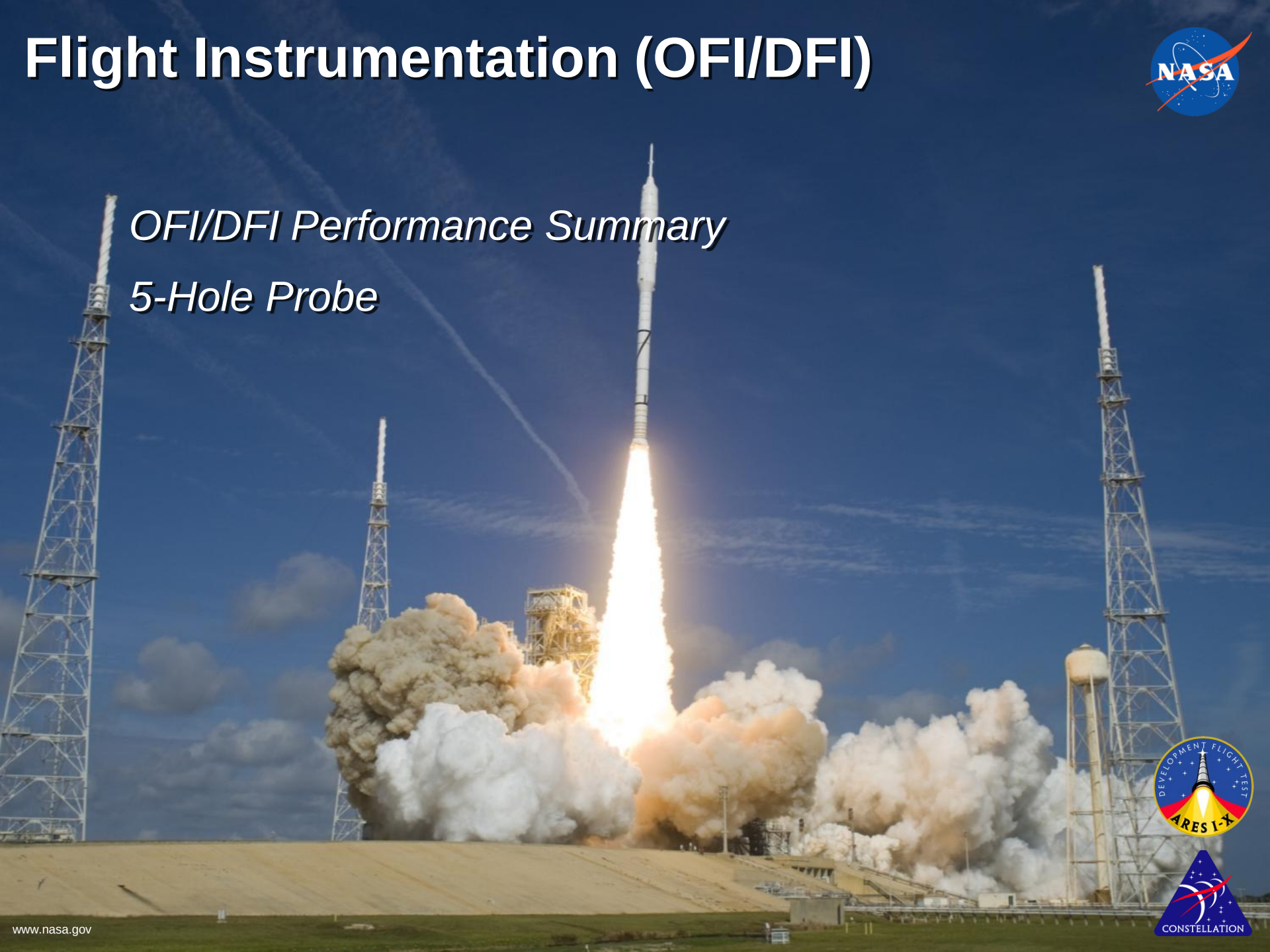
# Sound Suppression System Comparison

- **I-X Sound Suppression System**
  - Not effective
    - 3-sides of deck surface uncovered
  - Vulnerable to plume damage
    - Piping exterior to MLP deck
- **Orion-I Sound Suppression System**
  - 60ft diameter coverage in all directions
  - Piping interior to LM




# Integrated Design and Analysis

# Flight Instrumentation (OFI/DFI)



*OFI/DFI Performance Summary*

*5-Hole Probe*

# OFI/DFI Performance Summary

- **Operational Flight Instrumentation (OFI)**
  - 292 measurements; 285 Nominal, 7 Defective
- **Development Flight Instrumentation (DFI)**
  - 901 Measurements provided by 716 Sensors
  - 98% of DFI measurements functioned during the flight
    - ***Only*** 13 DFI measurements did not provide data

**5HP Cover**

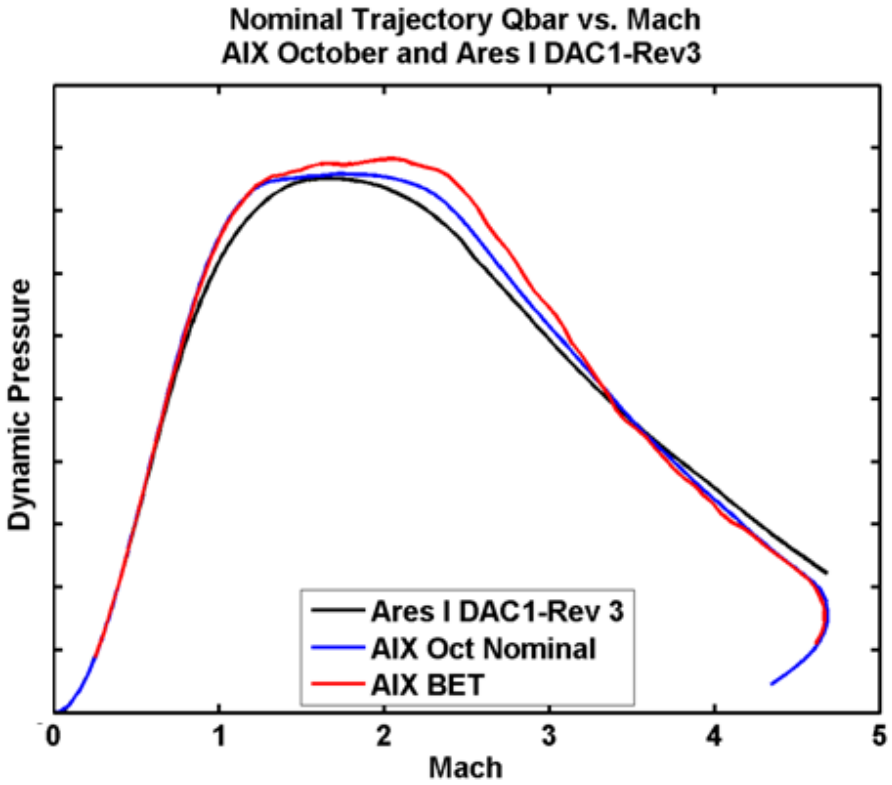
**TAT Cover**

- **5HP and TAT covers were removed for 1st flight attempt**
  - Heavy Thunderstorms overnight
  - Probe data flawed
    - Water Intrusion (probable cause)
    - Oil Canning Effect of Sensor

Overall, less than 3% of sensors did not perform as expected during the mission
All mandatory measurements were within LCC's/Limits throughout the countdown and flight

# Successful Ascent Trajectory

- **Ares I-X ascent trajectory matched the Ares I dynamic pressure vs. Mach number relationship to within 10%**
  - Provided aerodynamic, thermal, and acoustic loads sufficient to demonstrate controllability of a dynamically similar vehicle
- **Ares I-X separation occurred at the targeted state**



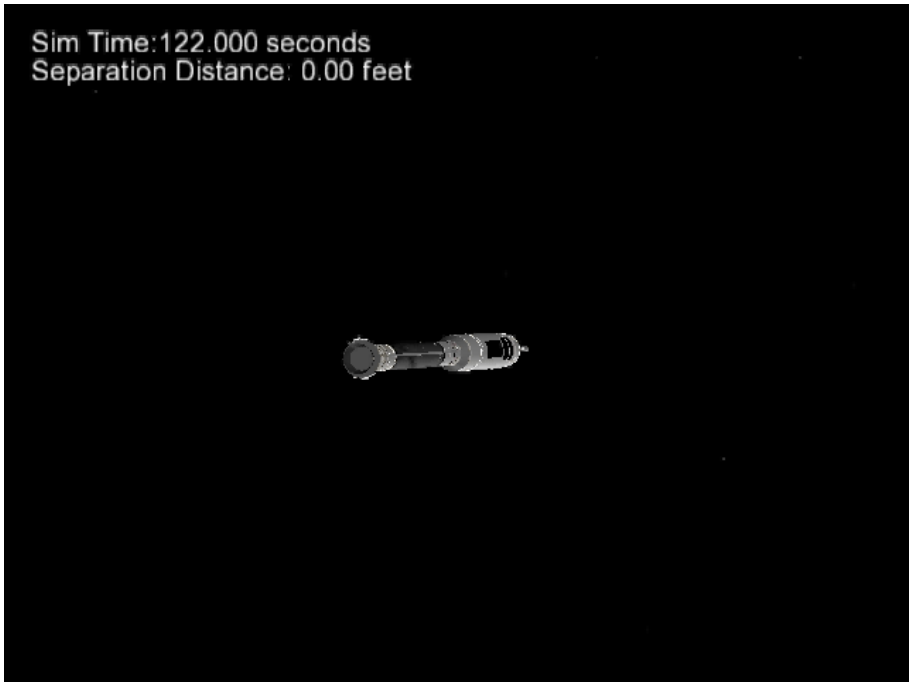

| State and tolerance | Difference from sim with launch conditions |
|---|---|
| Time (sec), 0.5 seconds | -0.12 (-0.1%) |
| Altitude (nmi), 0.75% | 0.057 (0.3%) |
| Latitude (deg), none | -0.0001 (40 ft) |
| Longitude (deg), none | -0.0079 (2500 ft) |
| Velocity Magnitude (ft/s), 1% | 6.75 (0.1%) |
| Velocity Elevation (deg), 0.75 degrees | 0.195 |
| Velocity Azimuth (deg), 0.375 degrees | -0.234 |
| Roll (deg), 3 degrees | 1.046 |
| Pitch (deg), 3 degrees | 0.181 |
| Yaw (deg), 3 degrees | 0.455 |

# Separation Data and Video – No Recontact

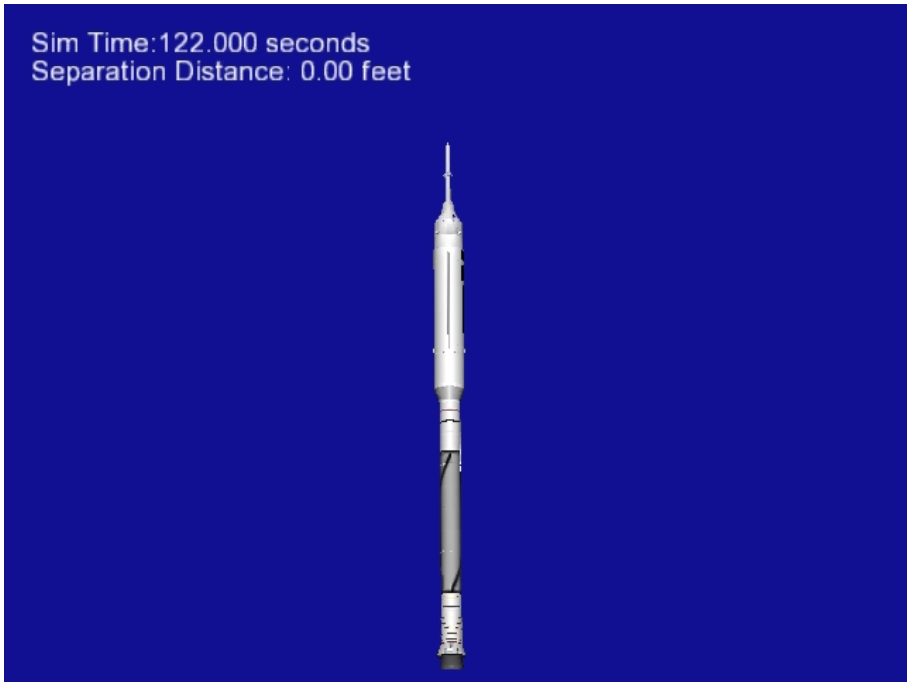

| Time Stamp | Observation |
|---|---|
| 3:37 | Start of Separation with BDM Burn |
| 3:38-3:39 | FS Moves axially away from the US with little or no relative yaw between stages |
| 3:40 | BTMs fire and FS begins yaw tumble. No discontinuous change in US yaw is observed |
| 3:43 | Little US yaw rotation is detected, suggesting that the US yaw and yaw rate was not affected by the initiation of the FS tumble |
| 3:44 | US yaw begins to be noticeable, FS is well out of range |
| 4:07 | Next time US is seen in video, when it is much further away |

# Separation Animation

- **Post-flight simulation, using flight data, demonstrates USS behavior**
- **Simulation predicts a successful separation.**
- **Simulation is consistent with ground video of flight.**



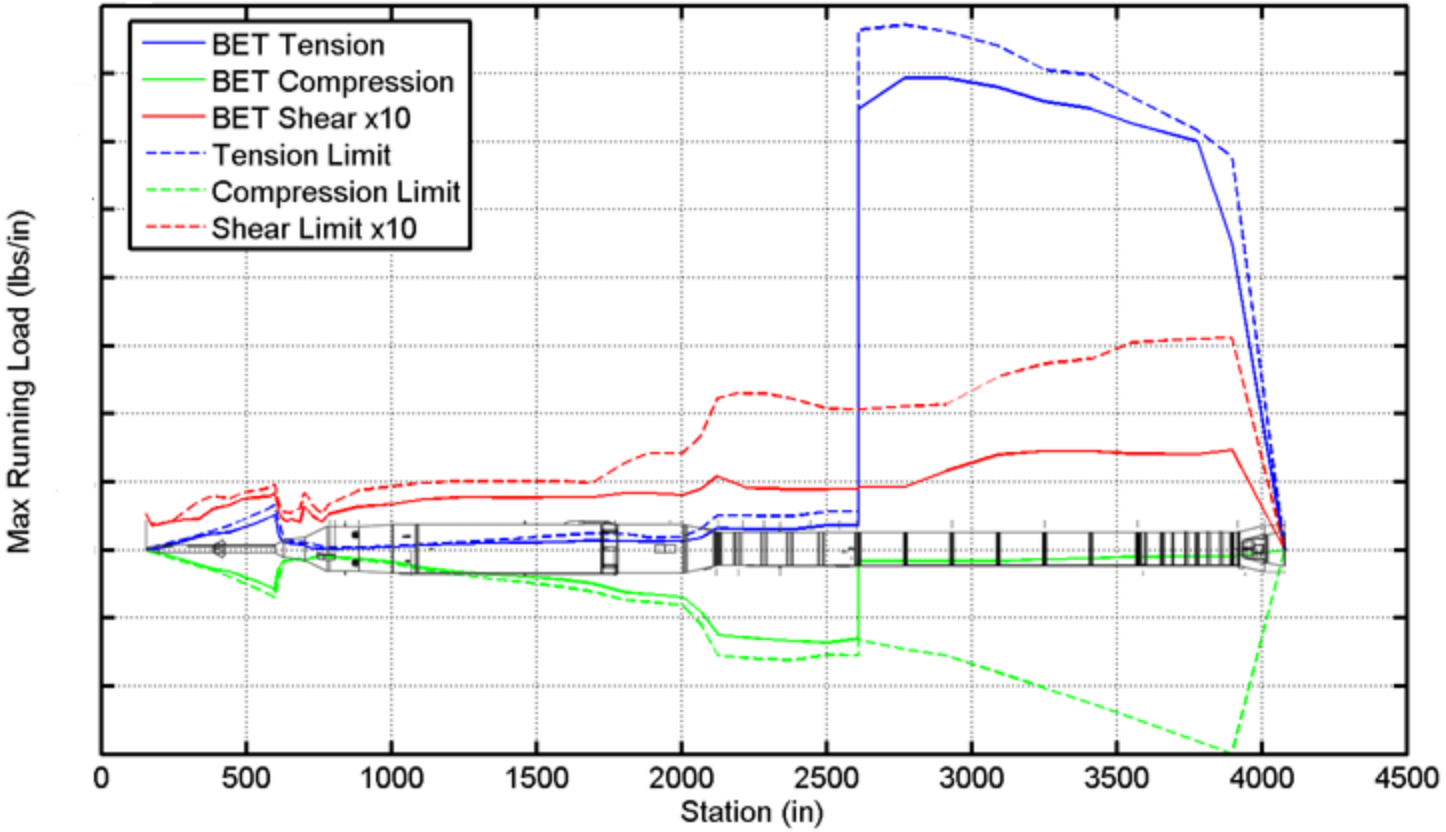

Simulated Ground View




View from Top

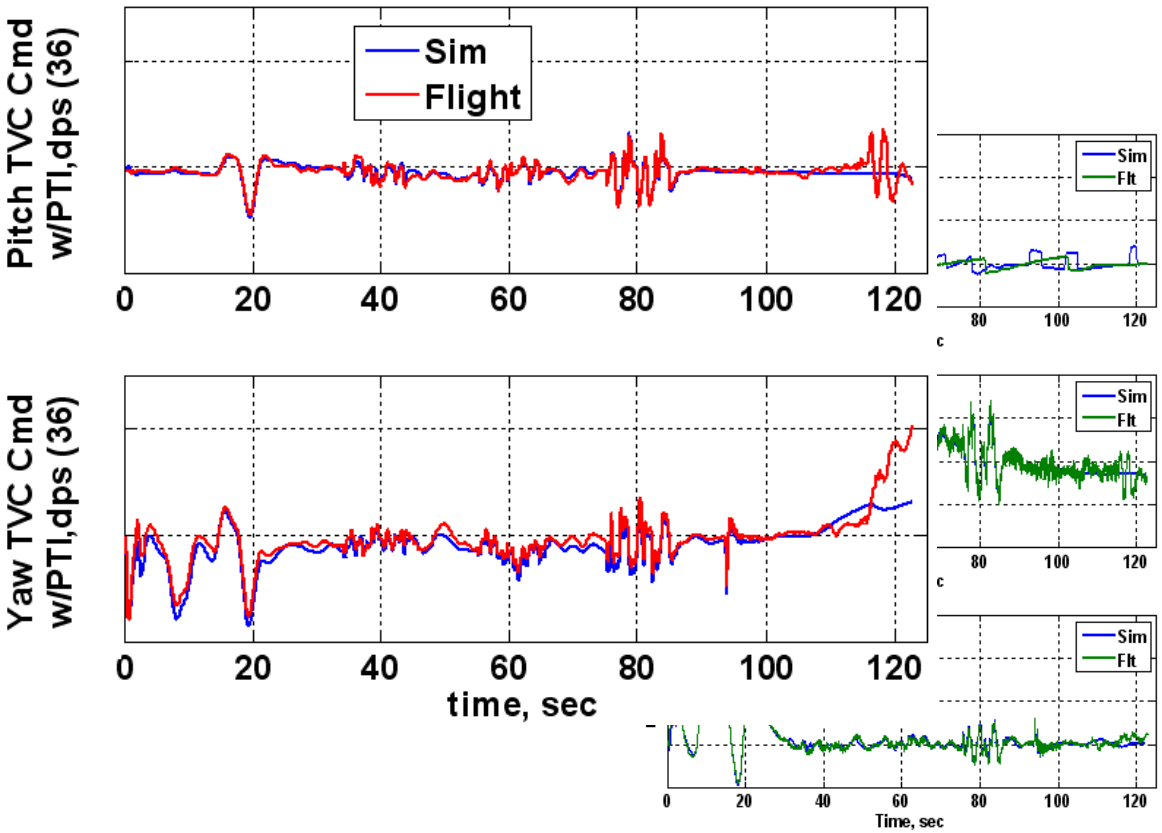
# Successful Day of Launch (DOL) Loads Assessment

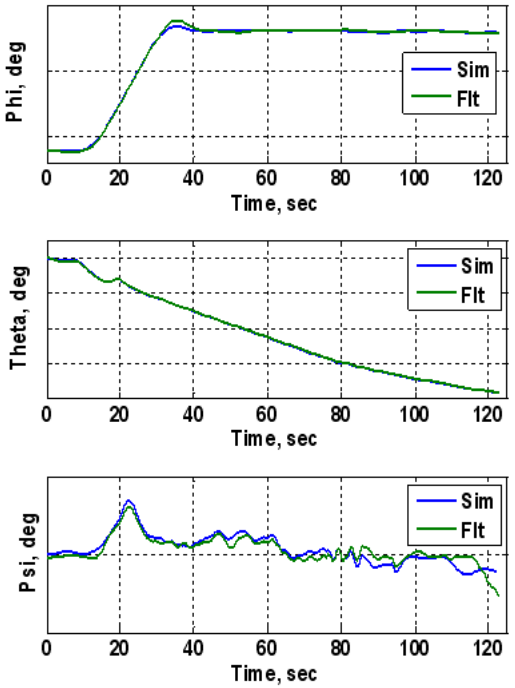
- **Ares I-X used high fidelity coupled loads analysis with DOL balloon data to generate comprehensive DOL loads.**
  - New approach uses DOL methods (previous used a Q*ALPHA indicator only)
  - New approach gives much more detail in the event of an exceedance



# Guidance Navigation and Control

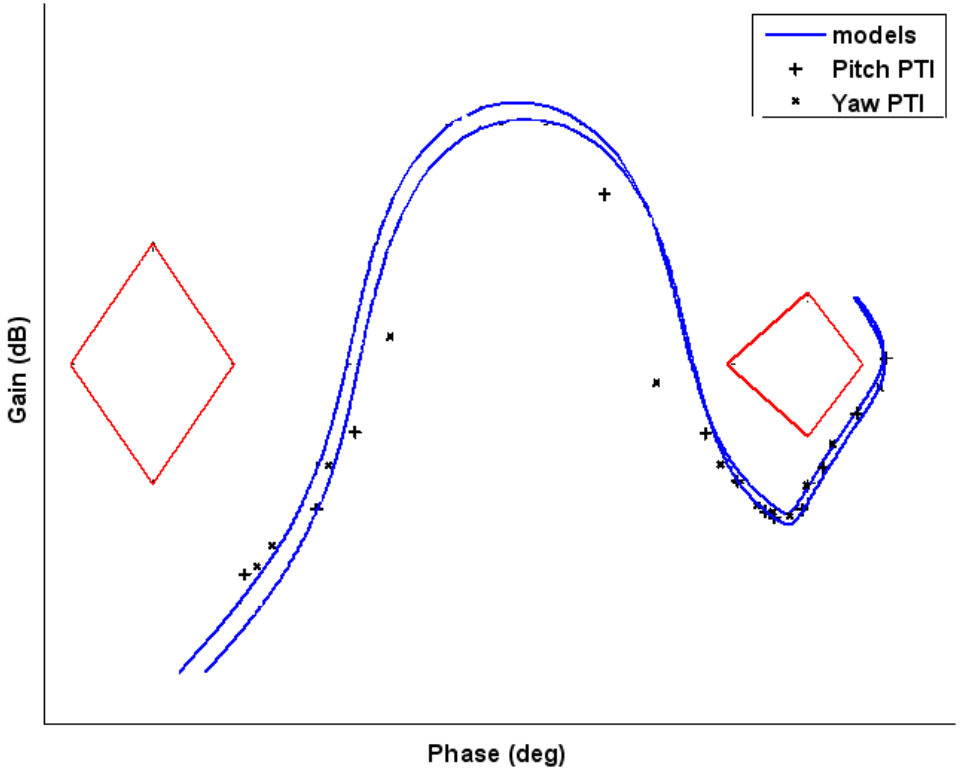
- **Demonstrated excellent control**
  - Long/slender and aerodynamically unstable
  - Ares I relevant control approach
  - Very close matches of predictions and flight performance



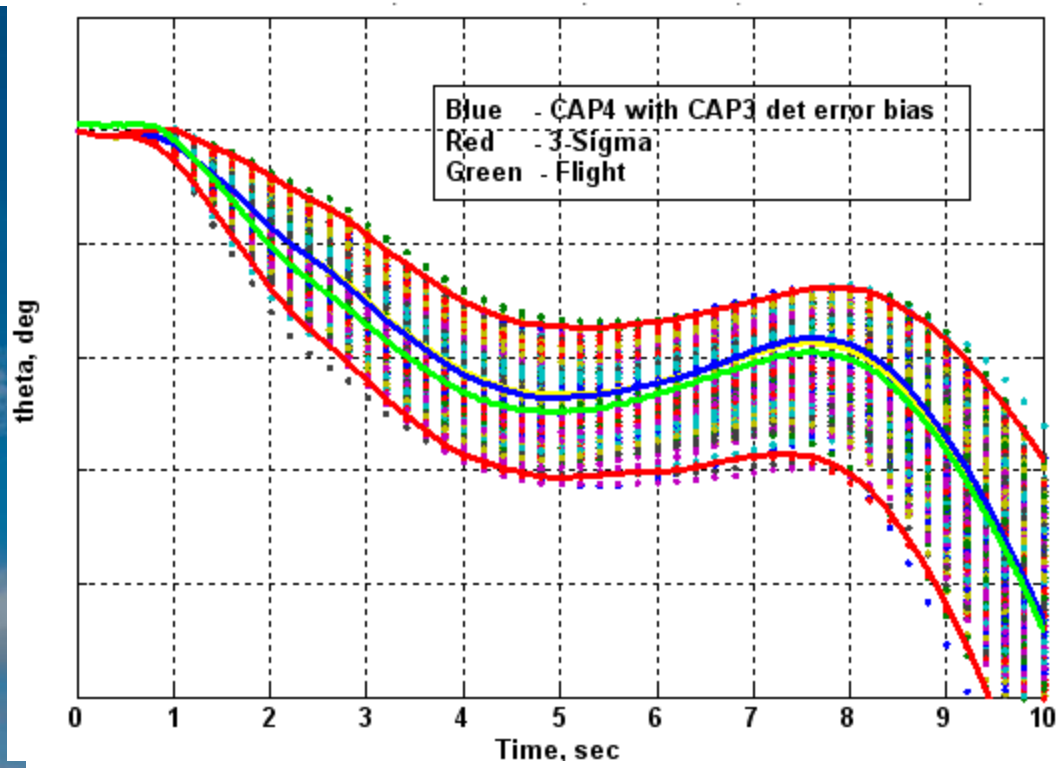



# Flight Control System Performance

- **Control system performance as predicted**
  - Shows robust control
- **Gain and phase margin results closely match predictions**
- **First time System Identification maneuvers were used in ascent flight**
  - Included to generate data for model validation
  - System worked flawlessly – good data analysis results as result
- **Demonstrated Ares I control algorithms relevancy and provided design/analysis tool validation**

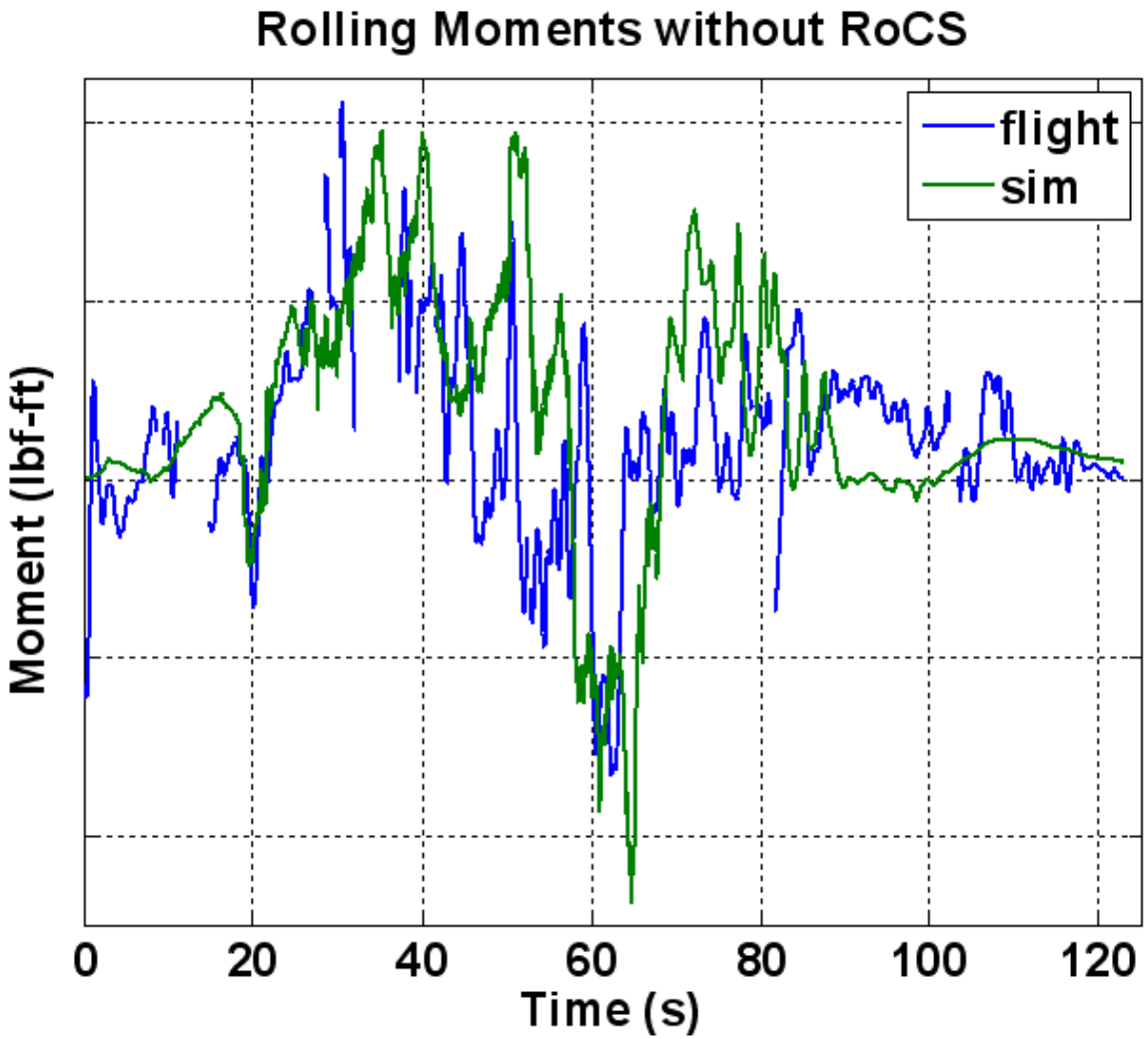


# Fly-Away Maneuver (FAM) Performance



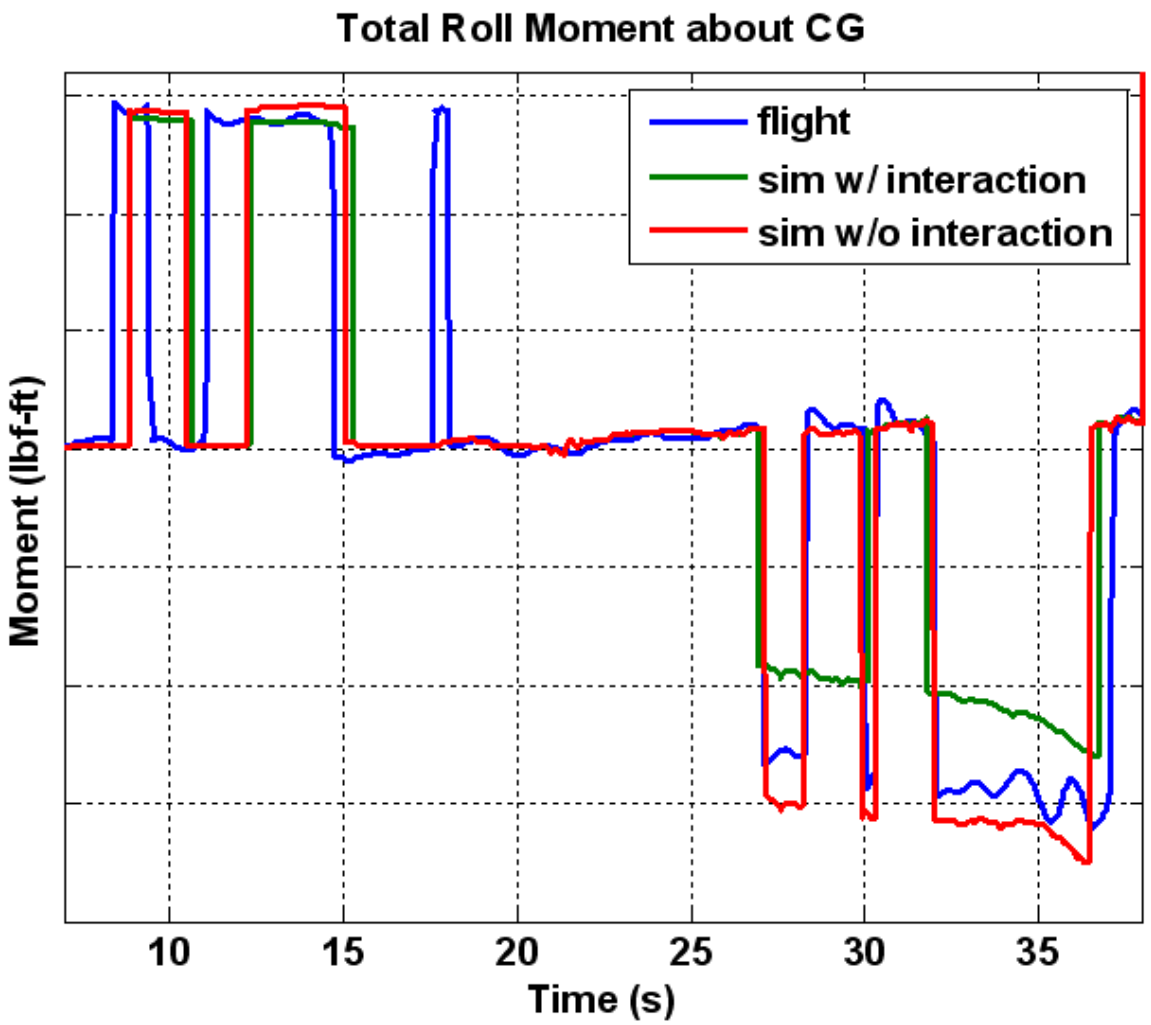

- **Liftoff clearance as predicted**
  - Aggressive fly-away maneuver demonstrated
    - Protected the FSS from any major structural damage – no damage above 135 Level
    - "Plumed" lower levels to protect upper levels
  - Data for design of pad for similar rockets obtained

# Roll Torque

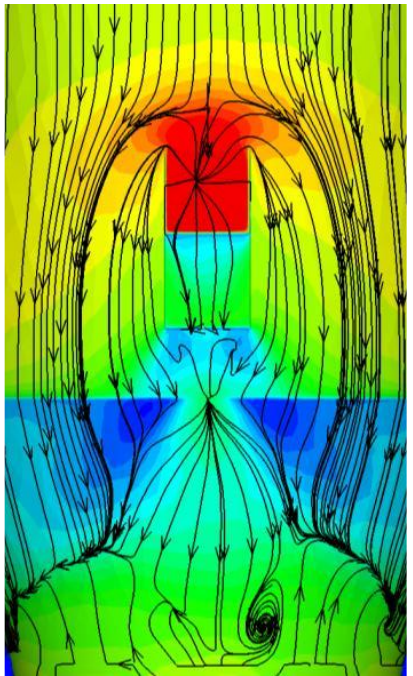



- **Successfully estimated roll torques acting on vehicle**
  - Much lower than the dispersed values used in Ares I-X design
- **Had to repeat simulation with motor-induced roll removed**
- **Simulation indicates most torque is aerodynamic**
  - Small magnitudes

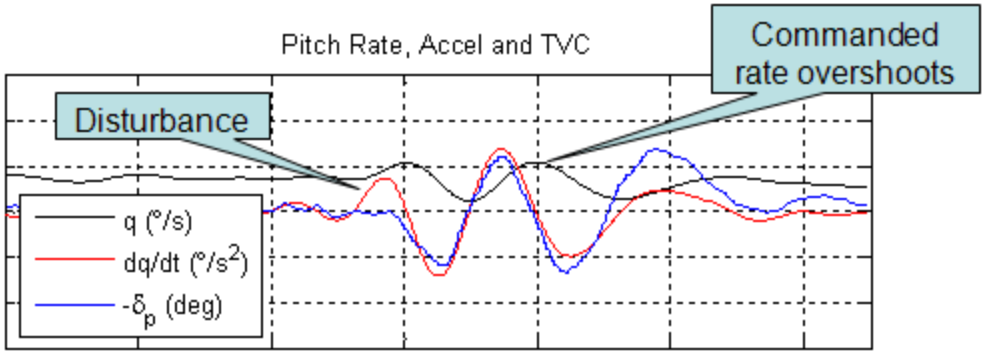
# Aero/Jet Interference Effects




- **Unanticipated data collected on RoCS aero jet interactions**
  - No test data available
  - Model constructed with CFD
  - Flight data shows that there appears to be much less interaction effects
- **Data will be useful for future jet effect databases**

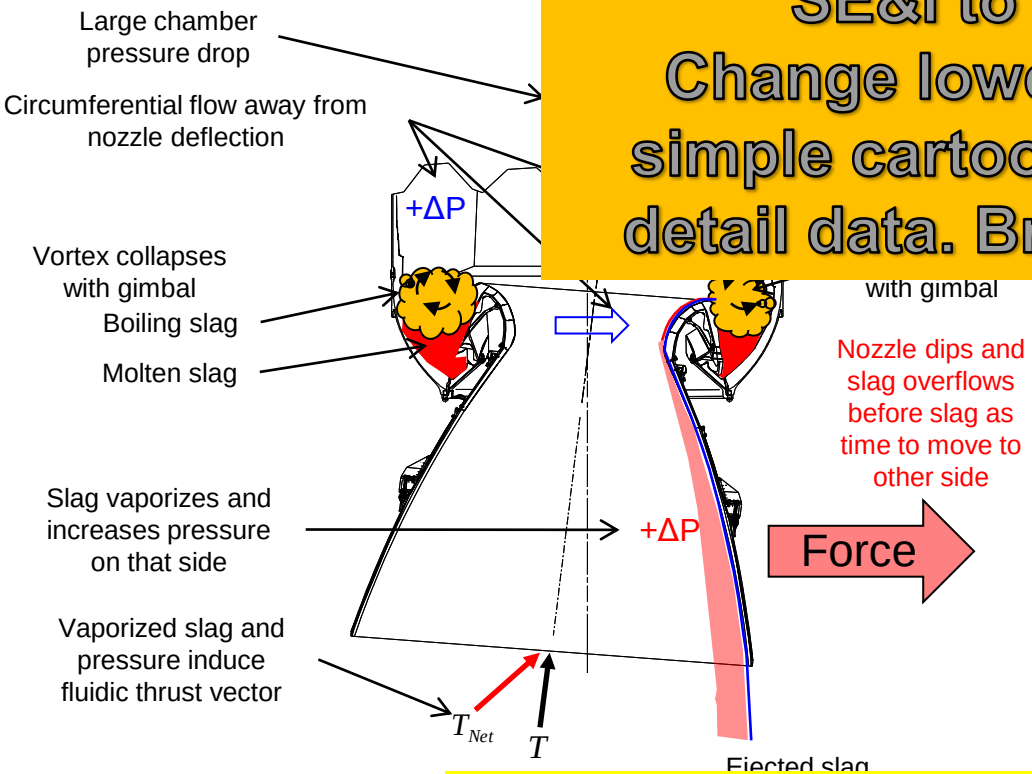


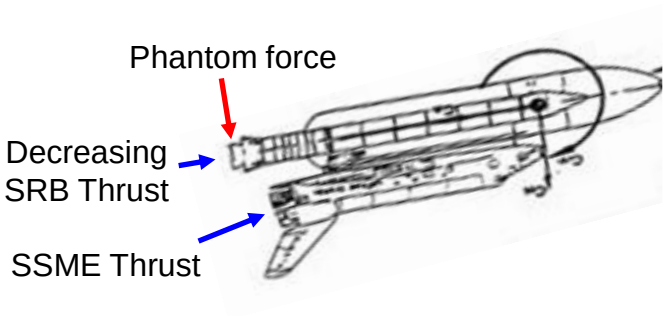
# Slag-Induced Dynamics and Control Effects




- **Hypothesis based on flight data**
  - Consistent with unexplained moments seen in Shuttle Flights
- **Slag ejection**
  - Causes initial upsets
  - wer
  - ring tail-off
  - t factor for
  - h vehicles
  - with submerged nozzle

**SE&I to update - Change lower figure to a simple cartoon without the detail data. Bruce to review**

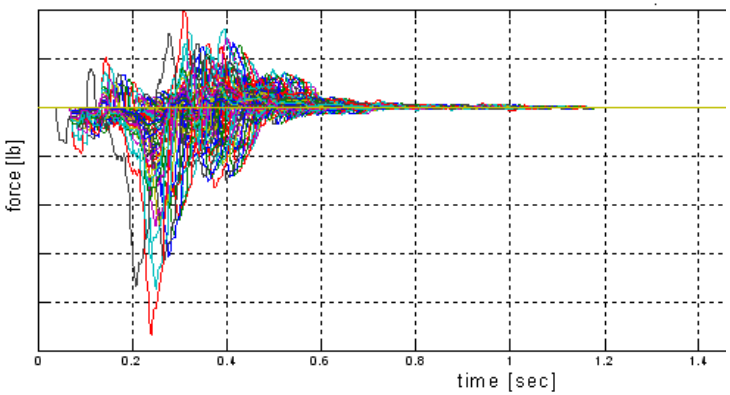


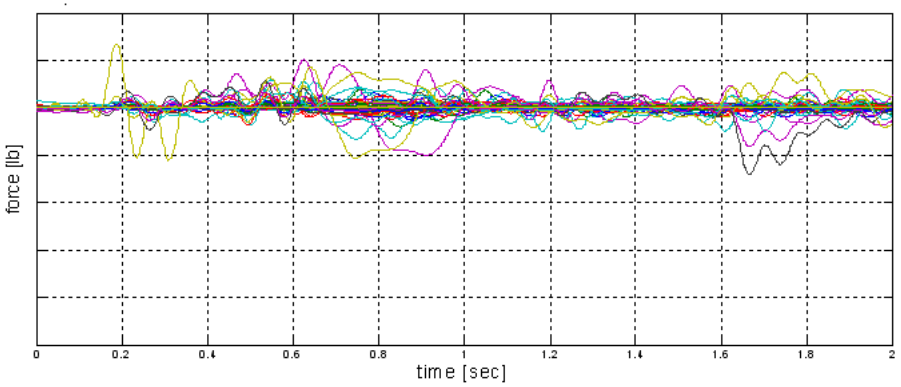
# Structural Loads

- **Prelaunch Loads (Rollout and On-pad)**
  - Measured loads during prelaunch were well below the design loads
    - Based on worst on worst given maximum winds, WIO and structural tuning
  - Recommendations for future prelaunch loads predictions developed
    - Use statistical methods for load combinations
- **Liftoff Loads**
  - Measured ignition overpressure (IOP) had a significantly lower amplitude than the predicted IOP
  - Measured forces and moments were much less than design values (3 sigma)
  - Reconstructed liftoff loads were significantly less than liftoff design loads (worst on worst cases)

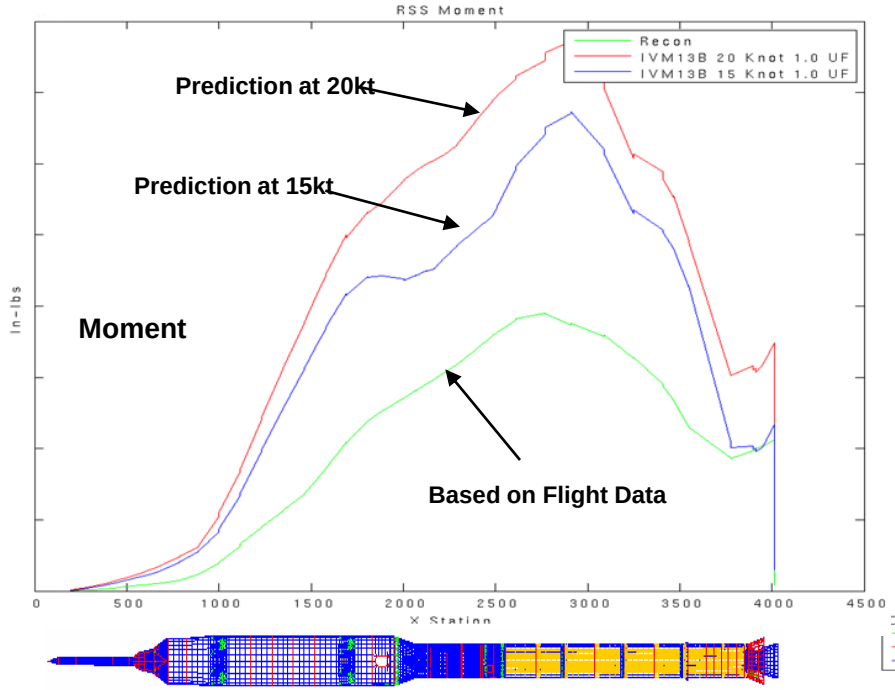
**Ares I-X Predicted Liftoff IOP**

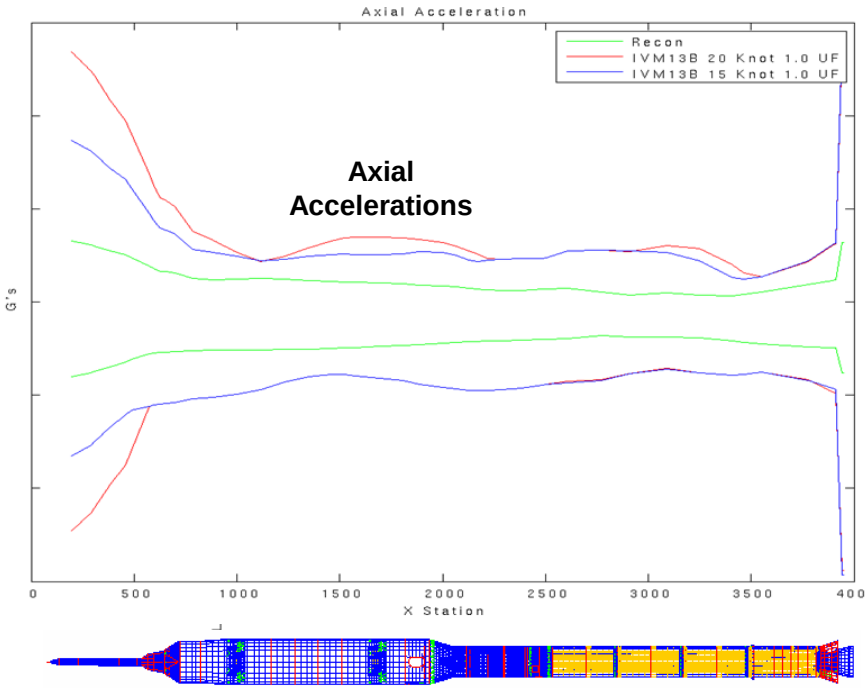


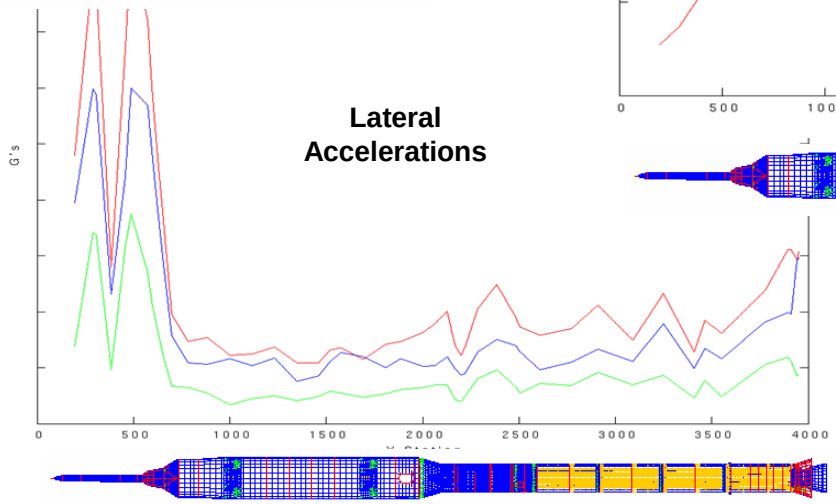

**Ares I-X Liftoff Reconstructed IOP**



# Liftoff Loads Comparisons



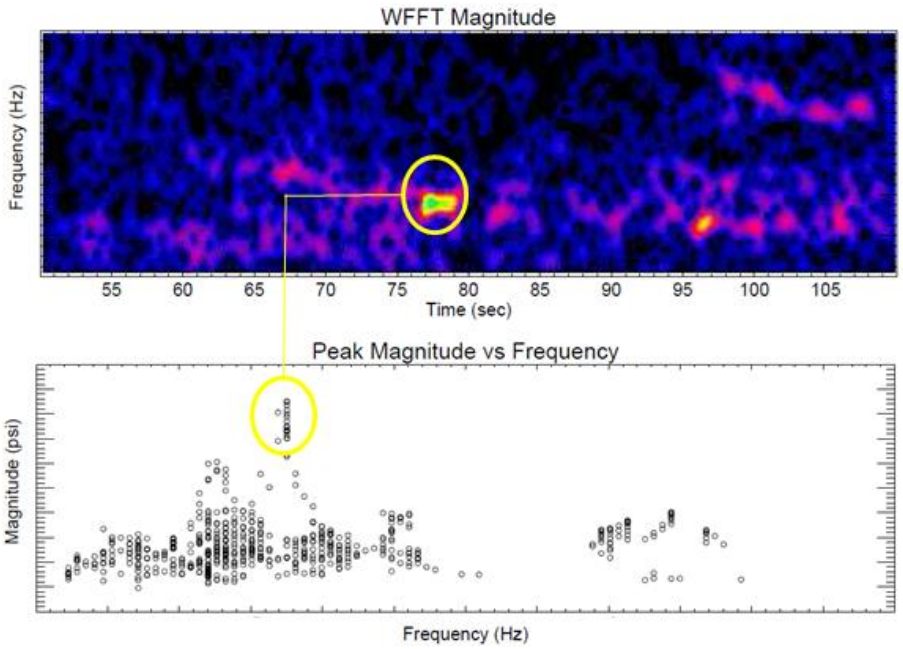



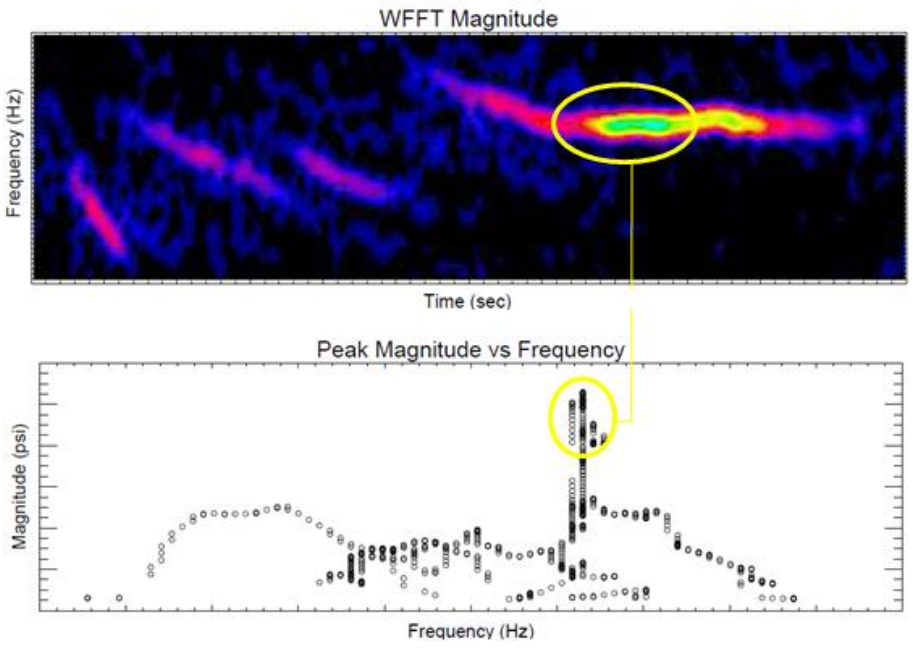
# Thrust Oscillation

- **Thrust Oscillation pressures were much less than predicted**
  - 1L thrust oscillation peaked between T+77 and T+79 seconds
    - Peak pressure approx. 1/3 of prediction
  - 2L thrust oscillation peaked between T+75 and T+85 seconds
    - Peak pressure approx. 1/2 of prediction

**1L SRM Thrust Oscillation Pressures**

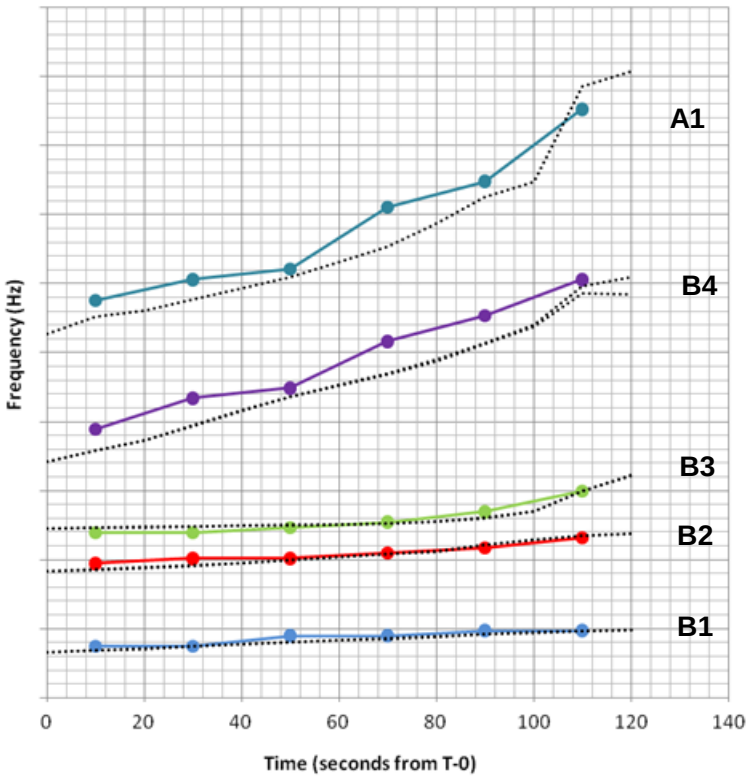


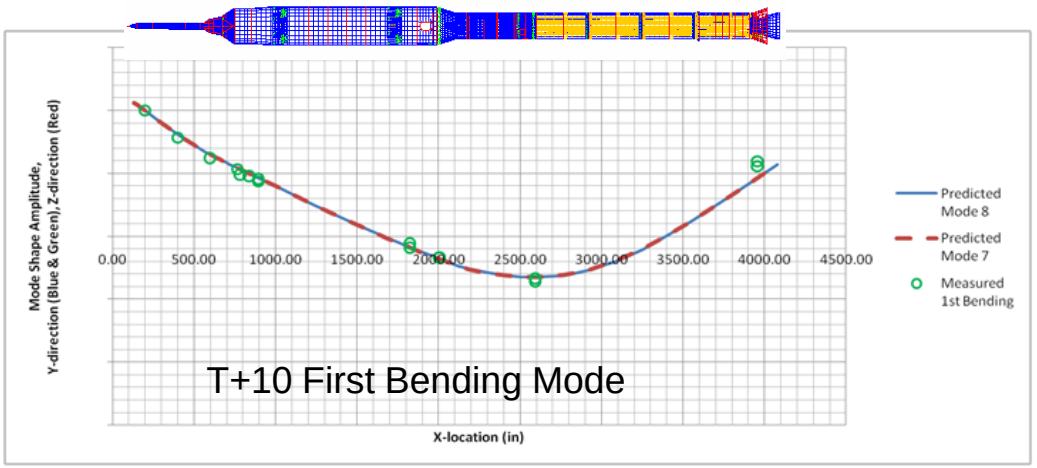

**2L SRM Thrust Oscillation Pressures**

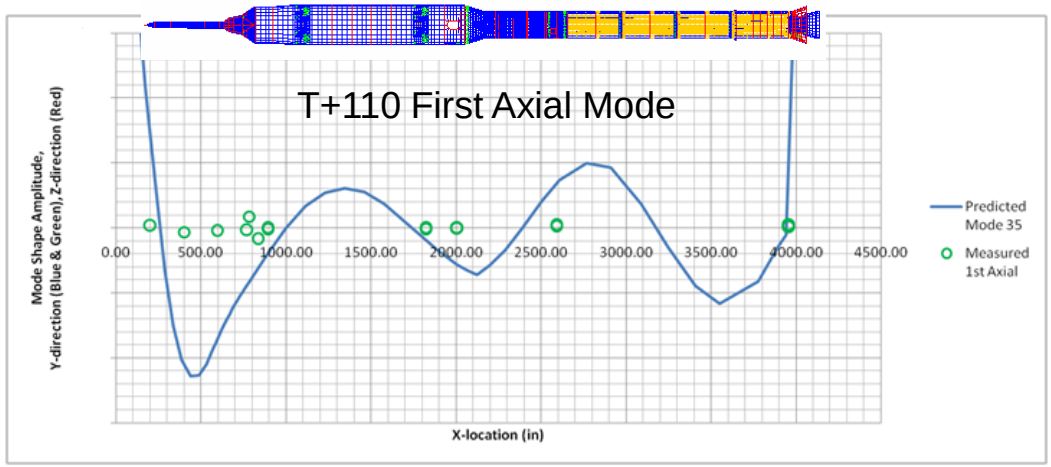


# Comparison Frequencies and Mode Shapes

- Good agreement for mode shapes and frequencies

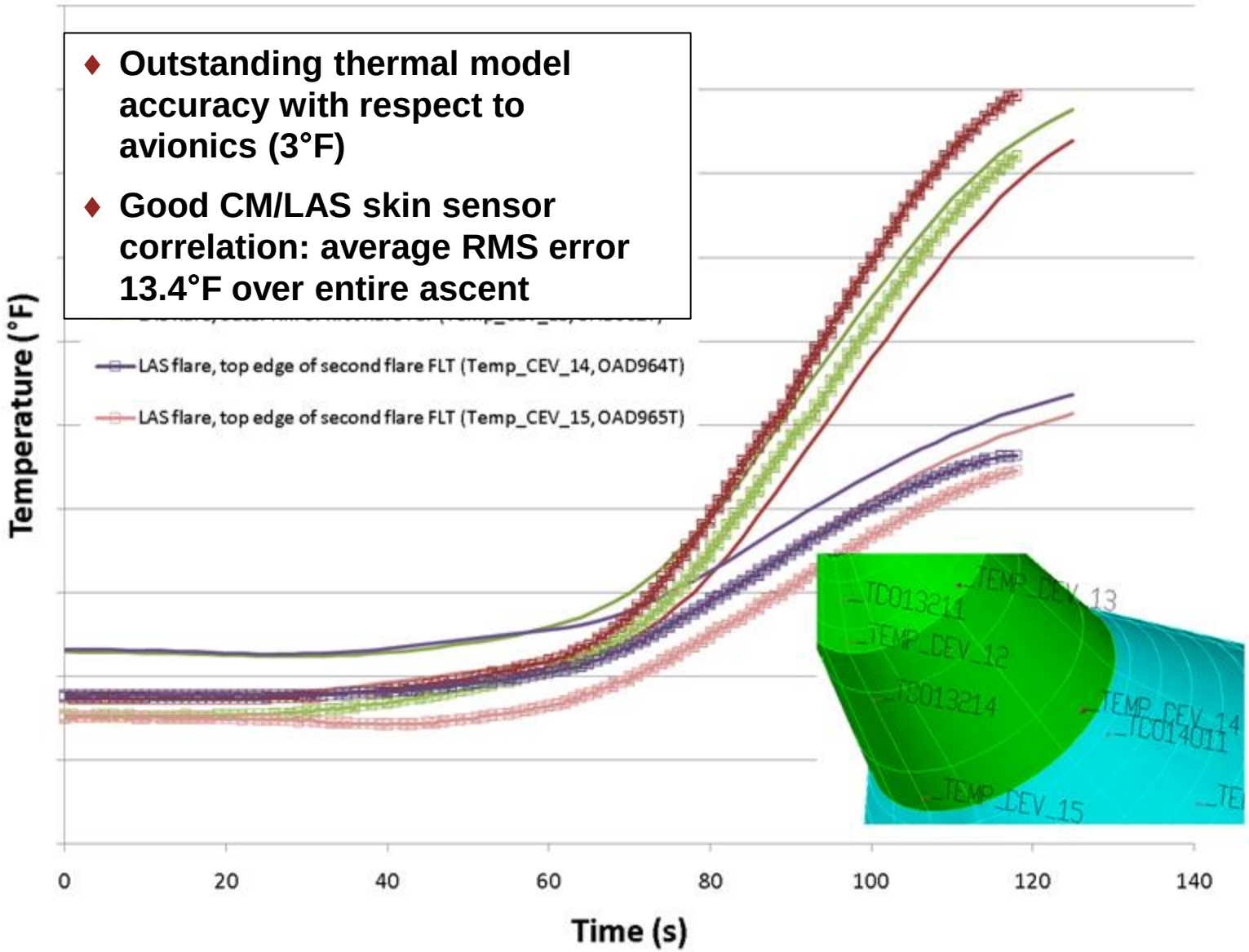


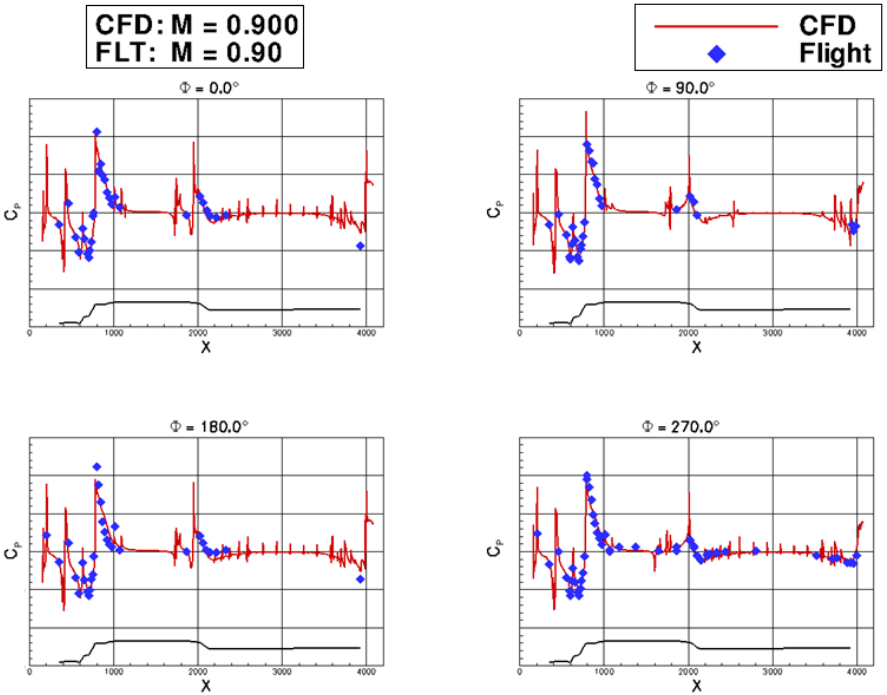
# Thermal Results

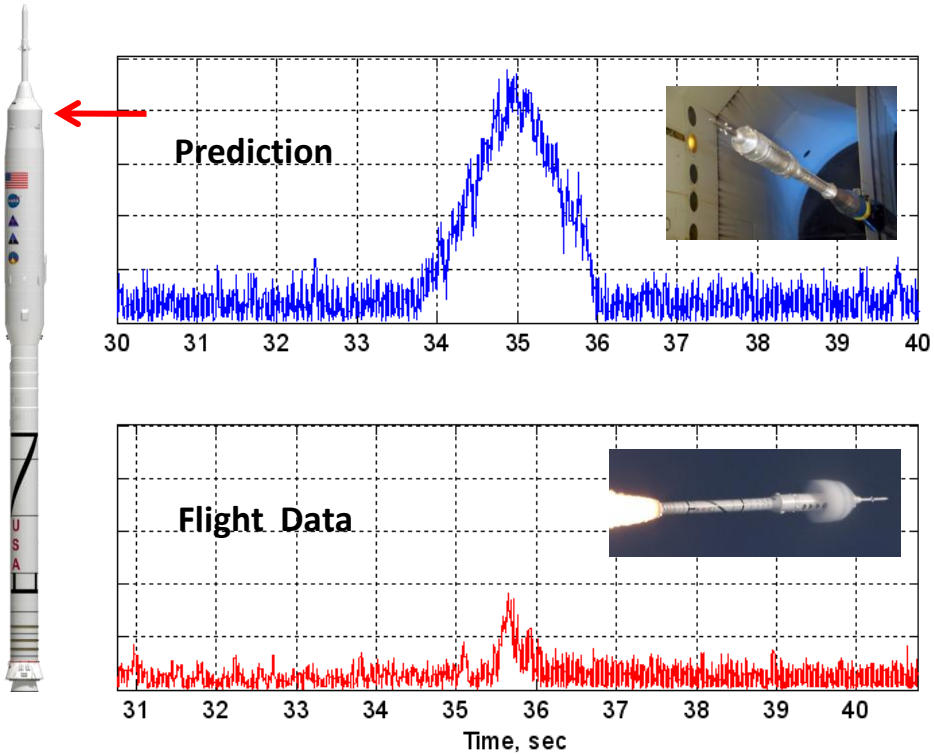
- **Outstanding thermal model accuracy with respect to avionics (3°F)**
- **Good CM/LAS skin sensor correlation: average RMS error 13.4°F over entire ascent**



# Aero

- **Good comparison of flight data to CFD predictions and wind tunnel test data**

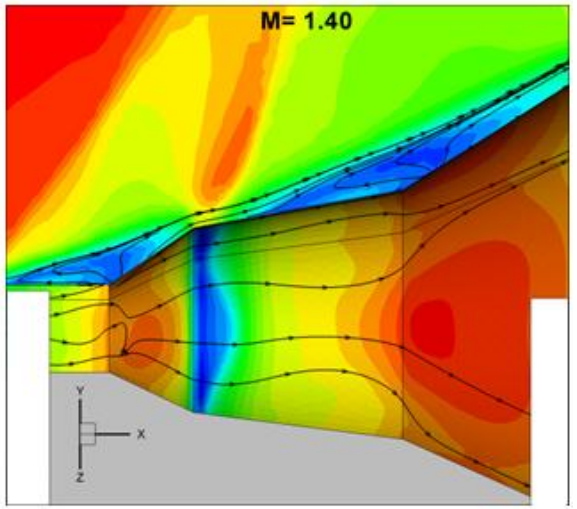


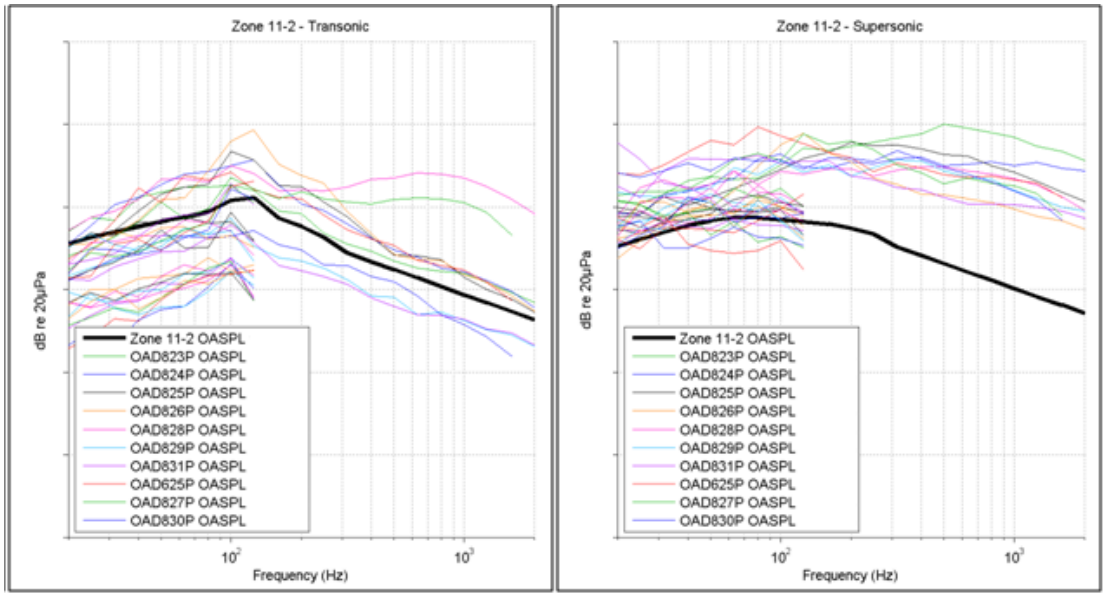




- **Good prediction of transonic buffet**
  - Prediction is a worst case estimate
  - Actual data was approx. 1/3 of predicted

# Vibro-acoustics Exceedances

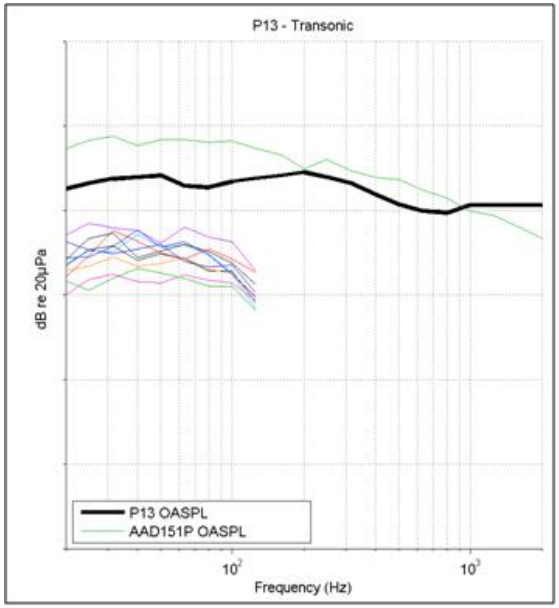
- **Exceedances identified throughout CM/LAS and SM for transonic and supersonic portions of ascent**
  - Up to 11dB exceedance at supersonic for crew module not identified in wind tunnel testing
  - Under prediction may be related to shock-shock interaction at the vehicle surface
    - WT testing does not capture well due to scale and less realistic conditions than can be obtained in flight

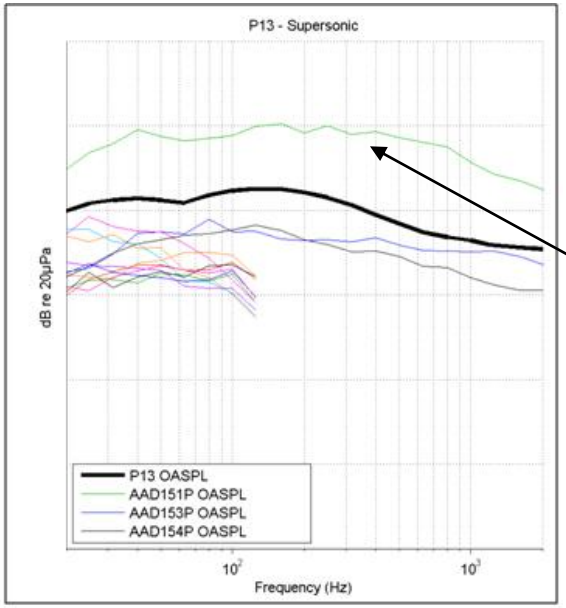


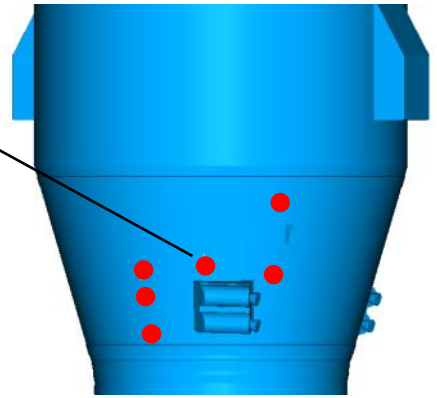



# Vibro-acoustics Exceedances

- **Protuberance exceedance also identified**
  - 8dB exceedance at BTM simulator not identified in wind tunnel testing

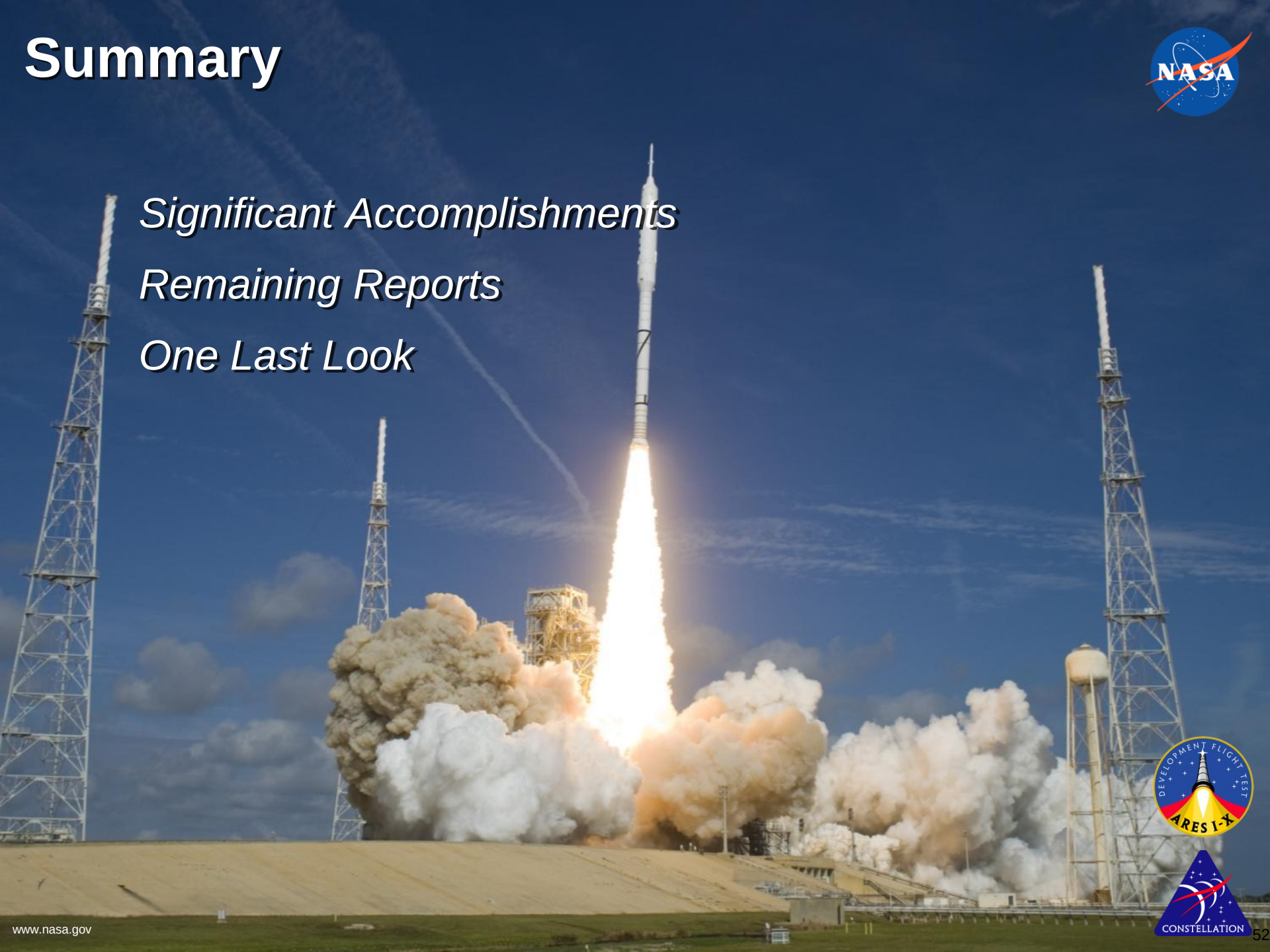


- **Good agreement on predicted random vibration environments except in CM/LAS area**
- **Good agreement in separation shock environments**

# Summary



*Significant Accomplishments*

*Remaining Reports*

*One Last Look*

# Significant Results (1/3)

## 1. Demonstrated Controllability

- Developed and successfully demonstrated control of very long, slender vehicle with a low fundamental frequency
- Flight data was very close to the predictions
- Off-nominal ascent maneuvers were flown to better understand controllability

## 2. Performed an in-flight separation/staging

- Separation dynamics and rates consistent with predictions
- Booster separation and tumble motors performed as predicted
- Single solid rocket booster allowed for assessment of unique forces on vehicle during tailoff

## 3. Demonstrated assembly and recovery

- First new vehicle processed at KSC in 28 years
- Successfully recovered a 5 segment booster

# Significant Results (2/3)

## 4. Demonstrated First Stage separation sequencing

- Booster separation sequence performed as predicted
- Successful deployment of parachutes –largest cluster
- Premature reefing under investigation

## 5. Characterized magnitude of integrated vehicle roll torque

- Roll Control System performed flawlessly
- Roll torque was measured and significantly below predictions

# Significant Results (3/3)

## Secondary: Characterized induced environments and loads

- Thermal flight data very close to predictions
- Aerodynamic flight data being used to anchor CFD predictions & wind tunnel data
  - Jet interaction effects were smaller than CFD and ground test data
  - Overall body pressures correlate well with predictions
- Significant data collected on vibro-acoustics
  - Point for point comparison to predictions/tests in work
  - Flight data was higher in magnitude for large geometry variations than predictions
- Structural modeling overall compared well with flight data models
  - Lift off loads were over-predicted. Assessing model updates for ignition pressure
- Measured thrust oscillation effects were below predictions
  - Pressure oscillation was consistent with nominal Shuttle boosters
  - Demonstrated no structural/acoustic interaction between motor and vehicle
  - Low levels of acceleration were measured at crew location
    - 25% of Ares I crew performance requirement


DEVELOPMENT FLIGHT TEST
ARES I-X