Project Orion Abort Flight Test

Pitch Guidance Optimization for the Orion Ascent Abort Flight Tests

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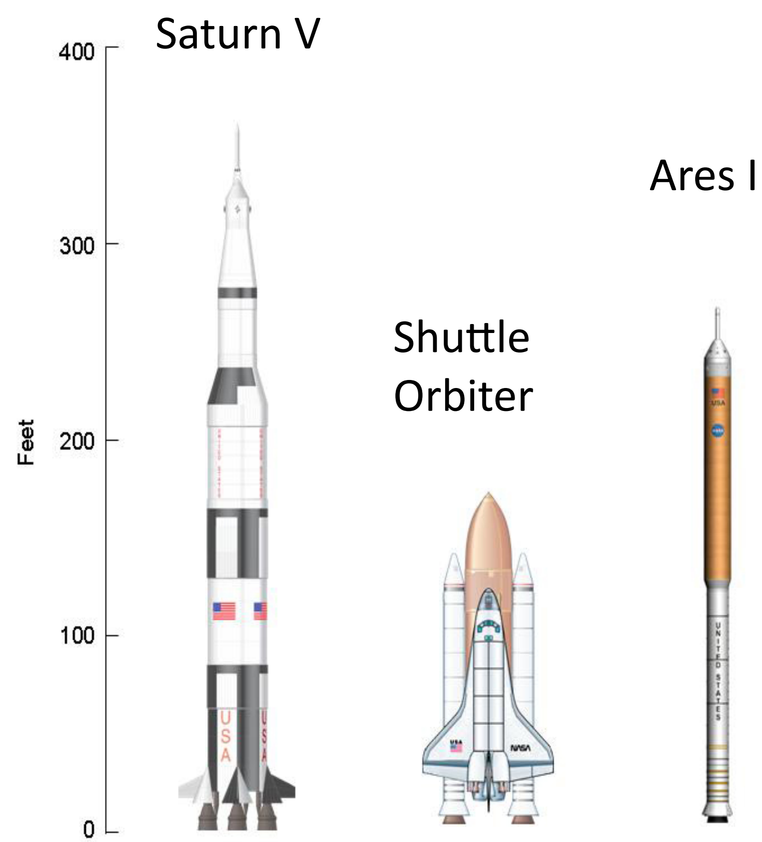
Introduction

- Orion vehicle overview
- Orion abort flight tests overview
- What is being optimized
- Method used for optimization
- Results from the optimization

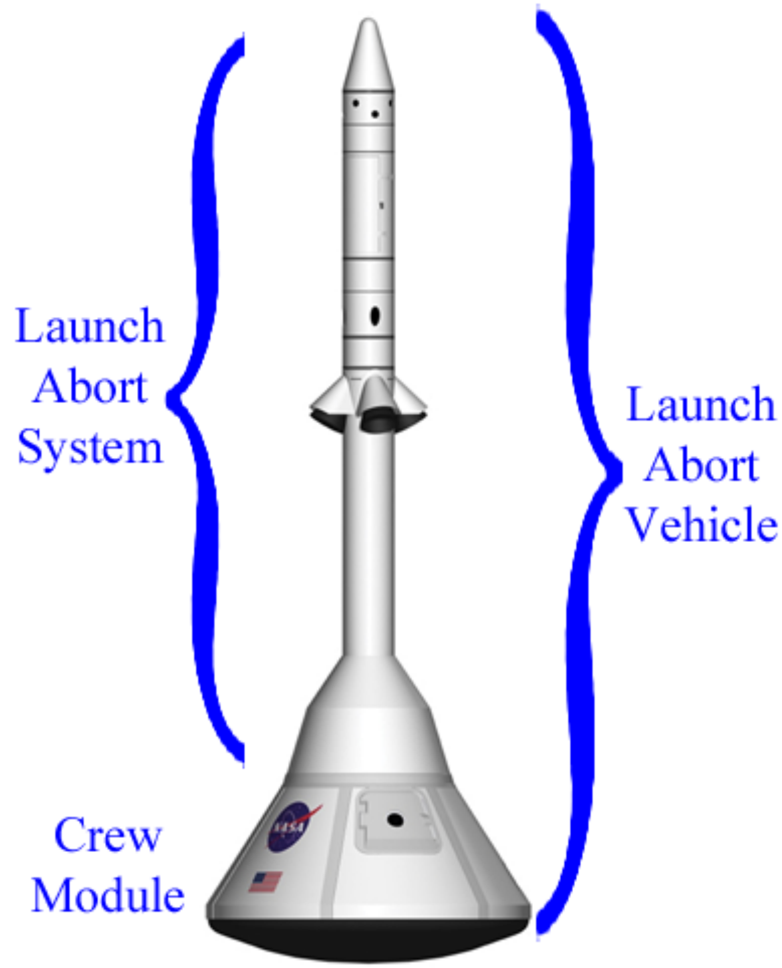
Constellation Overview

- Constellation program was initiated to create the next manned space vehicle
- Ares I launch vehicle
  - Launches Orion crew vehicle into orbit
- Orion crew vehicle
  - Carries astronauts to ISS or Moon



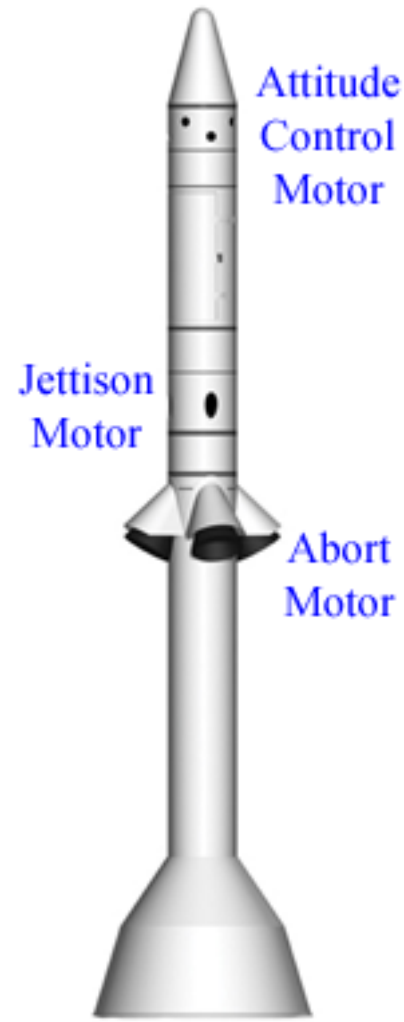
Orion Vehicle Overview

- Launch Abort System (LAS)
  - Will remove the CM from the Ares I in the event of a launch failure
- Crew Module (CM)
  - Carries 6 crew to the ISS or 4 crew to the Moon
  - 5 meter diameter (Apollo was 3.9 meter)
- Launch Abort Vehicle (LAV)
  - Combined CM and LAS



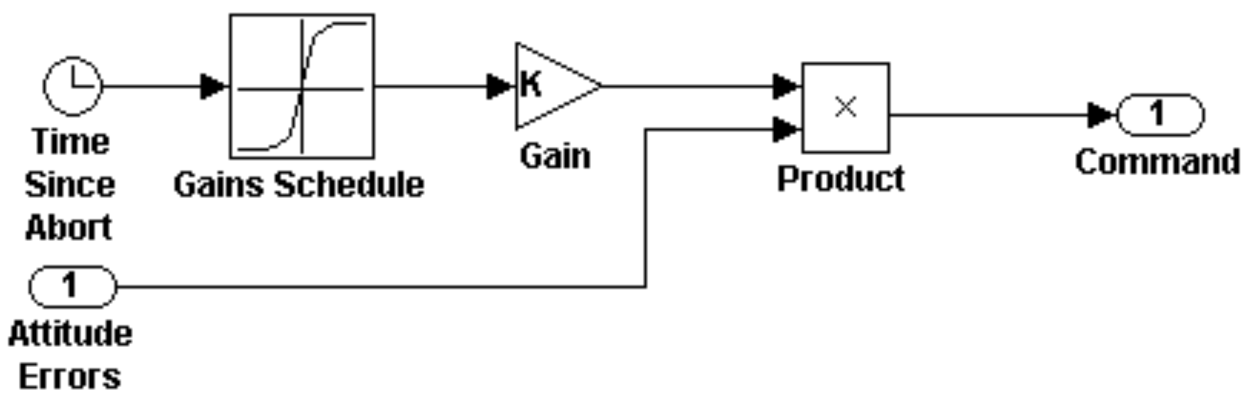
LAS Overview

- The Launch Abort System (LAS) will rescue the crew in the event of a launch vehicle failure
- Consists of three solid rocket motors
- Abort Motor (AM)
  - Ignites on abort
  - Provides thrust to separate the Launch Abort Vehicle and the Ares I
- Attitude Control Motor (ACM)
  - Ignites on abort
  - Directs the attitude of the LAV during the abort
- Jettison motor
  - Ignites after AM and ACM burnout
  - Separates the LAS from the CM



LAS Controller

- PID controller with channels for the pitch and yaw axes
- Uses time-based gain schedules
- Pitch channel
  - Uses angle of attack (α), integral α, pitch angle (θ), pitch rate (q), and flight path angle (γ)
  - Used for optimization
- Yaw channel
  - Uses sideslip angle (β), integral β, yaw angle (ψ), yaw rate (r), roll angle (ϕ), roll rate (p), and heading
  - Also commands β to damp out initial roll rate using an aerodynamic roll moment
  - Not used for optimization

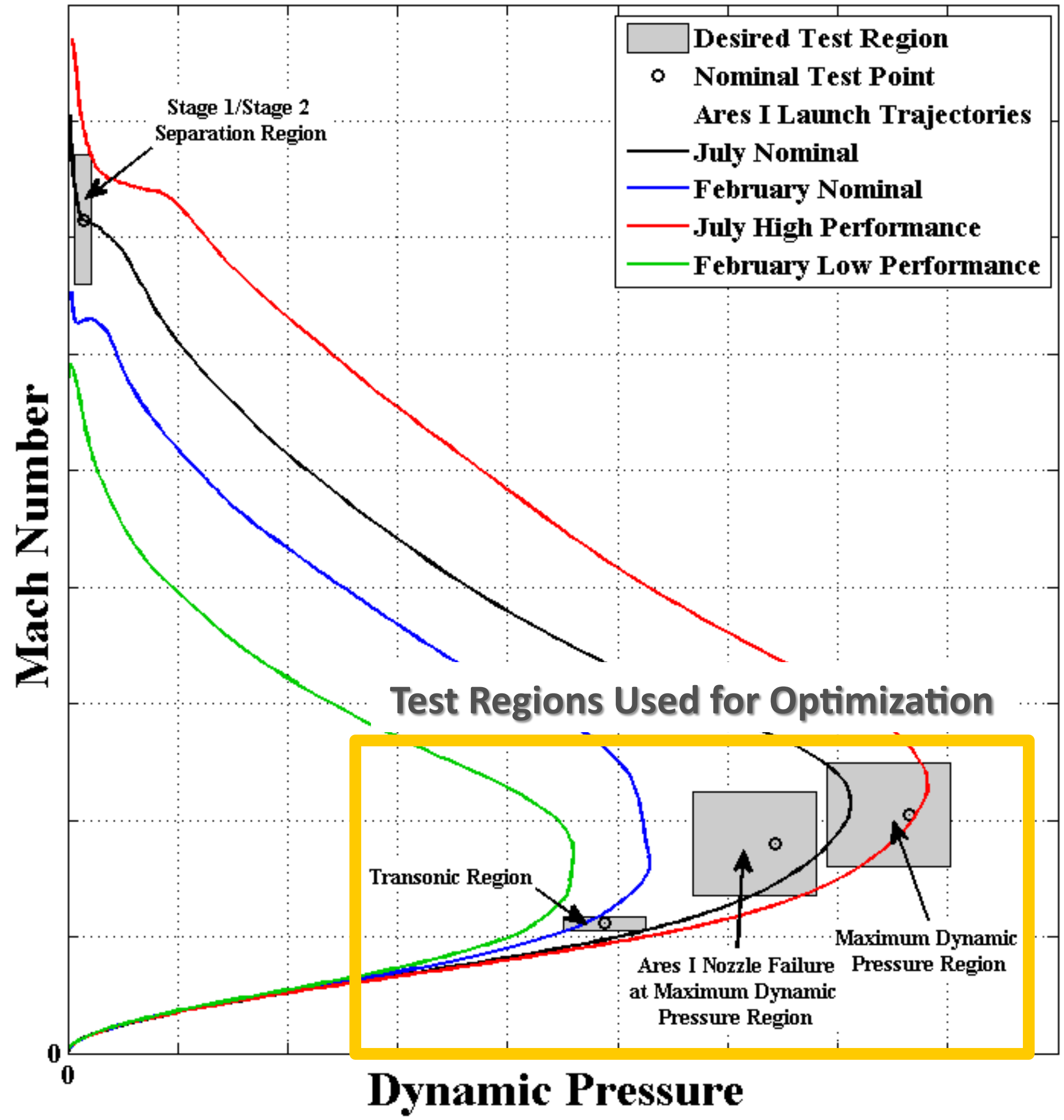


Orion Abort Flight Tests

- Six flight tests were originally scheduled to verify the functionality of the LAS
- Two aborts from the launch pad
- Four aborts along the ascending trajectory
  - Uses an Abort Test Booster (ATB) to reach test condition
  - Minimum separation force
    - Transonic region
  - Nominal maximum dynamic pressure
    - Maximum dynamic pressure region
  - Failure scenario: Ares I nozzle actuators stick hard-over
    - High dynamic pressure region
  - High altitude
    - Stage 1 burnout/Stage 2 ignition point

Test Regions

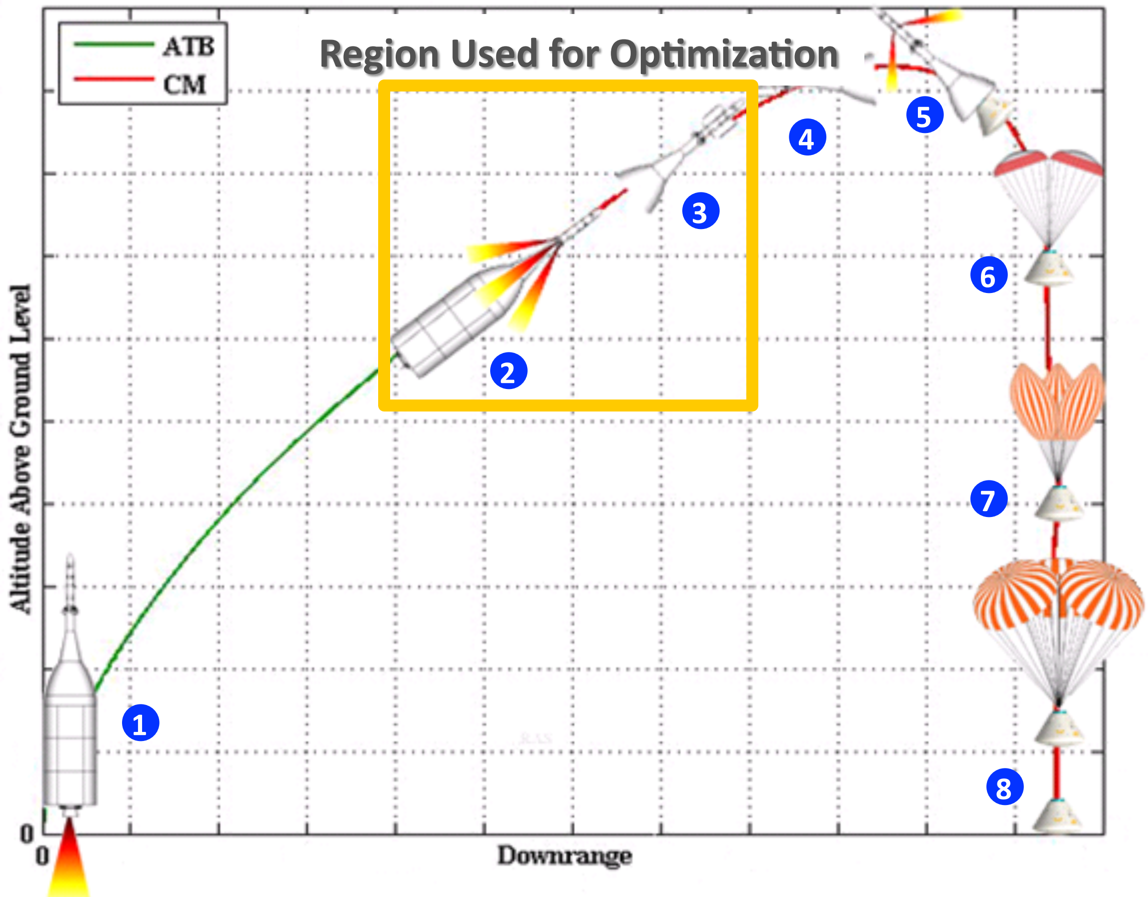
- Three ascent abort test regions used for optimization
  - Transonic
  - Maximum dynamic pressure
  - Ares I nozzle failure at high dynamic pressure
- Stage 1/Stage 2 separation was not included



Project Orion Abort Flight Test

Ascent Abort ConOps

Event	Event
1	ATB Liftoff
2	LAV Separation
3	Begin Reorientation
4	End Reorientation
5	Jettison Tower
6	Deploy Drogues
7	Deploy Mains
8	CM Touchdown



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Simulation Overview

- ATB/LAV Simulation
  - Created by Orbital Sciences Corporation (Chandler, AZ)
  - Simulations developed for the three test regions used
  - Simulates ATB/LAV vehicle dynamics up thru ATB/LAV separation
  - Provides initial conditions for LAV simulation
- LAV Simulation
  - Created by NASA
  - Initialized at ATB/LAV separation point
  - Generates the state data used in optimization program
  - Used to simulate vehicle dynamics until LAS/CM separation

Problem Statement

- Problem Statement
  - Tune the Orion pitch gains schedule to reduce the error between the simulated α and the desired α
- Cost Function
  - Running the LAV simulation with a different gains schedule results in different α errors (α_e)

$$\alpha_e = f(K_\alpha, K_{integral\ \alpha}, K_\theta, K_q, K_\gamma)$$

  - The optimization program seeks where the gradient of α_e is zero (minima)

Optimization Algorithm

- Uses the method of steepest descent
- Outer loop
  - Approximate Jacobian

$$\bar{J}(\overline{K_{n,1}}) = \begin{bmatrix} \dfrac{\delta f}{\delta K_{\alpha_{n,1}}} \\ \dfrac{\delta f}{\delta K_{i\alpha_{n,1}}} \\ \dfrac{\delta f}{\delta K_{q_{n,1}}} \\ \dfrac{\delta f}{\delta K_{\theta_{n,1}}} \\ \dfrac{\delta f}{\delta K_{\gamma_{n,1}}} \end{bmatrix}$$

$$\overline{K_{n,1}} + \Delta K_\alpha = \begin{bmatrix} K_{\alpha_{n,1}} \\ K_{i\alpha_{n,1}} \\ K_{q_{n,1}} \\ K_{\theta_{n,1}} \\ K_{\gamma_{n,1}} \end{bmatrix} + \begin{bmatrix} \Delta K_\alpha \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad \overline{K_{n,1}} - \Delta K_\alpha = \begin{bmatrix} K_{\alpha_{n,1}} \\ K_{i\alpha_{n,1}} \\ K_{q_{n,1}} \\ K_{\theta_{n,1}} \\ K_{\gamma_{n,1}} \end{bmatrix} - \begin{bmatrix} \Delta K_\alpha \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\frac{\delta f}{\delta K_{\alpha_{n,1}}} \approx \frac{f\left(\overline{K_{n,1}} + \Delta K_\alpha\right) - f\left(\overline{K_{n,1}} - \Delta K_\alpha\right)}{2\Delta K_\alpha}$$

Optimization Algorithm

- Inner loop
  - Each time point in gains schedule

Step 1: $c_0 = 0$ $\quad \alpha_{e_0} = f(\overline{K_{n,J}})$ $\quad g_0 = \sum_{m=1}^{m=31} [\alpha_{e_0}]^2$

Step 2: $\nabla g_0 = 2 * \bar{J}(\overline{K_{n,1}}) * \alpha_{e_0}$ $\quad \bar{z} = \frac{\nabla g_0}{\|\nabla g_0\|}$

Step 3: $c_2 = 1$ $\quad \alpha_{e_2} = f(\overline{K_{n,J}} - c_2 * \bar{z})$ $\quad g_2 = \sum_{m=1}^{m=31} [\alpha_{e_2}]^2$

Step 4: if $g2 > g0$, then rerun Step 3 with $c_2 = c_2/2$ until $g2 < g0$

Optimization Algorithm

Step 5: $c_1 = c_2/2$ $\quad \alpha_{e_1} = f(\overline{K_{n,J}} - c_1 * \bar{z})$ $\quad g_1 = \sum_{m=1}^{m=31} [\alpha_{e_1}]^2$

Step 6: $h_0 = \dfrac{g_1 - g_0}{c_1 - c_0}$ $\quad h_1 = \dfrac{g_2 - g_1}{c_2 - c_1}$ $\quad h_2 = \dfrac{h_1 - h_0}{c_2 - c_0}$

Step 7:

$$P(c_3) = g_0 + h_0 * c_3 + h_2 * c_3 * (c_3 - c_1)$$
$$P'(c_3) = h_0 + 2 * h_2 * c_3 - c_1 * h_2$$

Step 8: $c_3 = \dfrac{c_1 * h_2 - h_0}{2 * h_2}$ $\quad \overline{K_{n,J+1}} = \overline{K_{n,J}} - c_3 * \bar{z}$

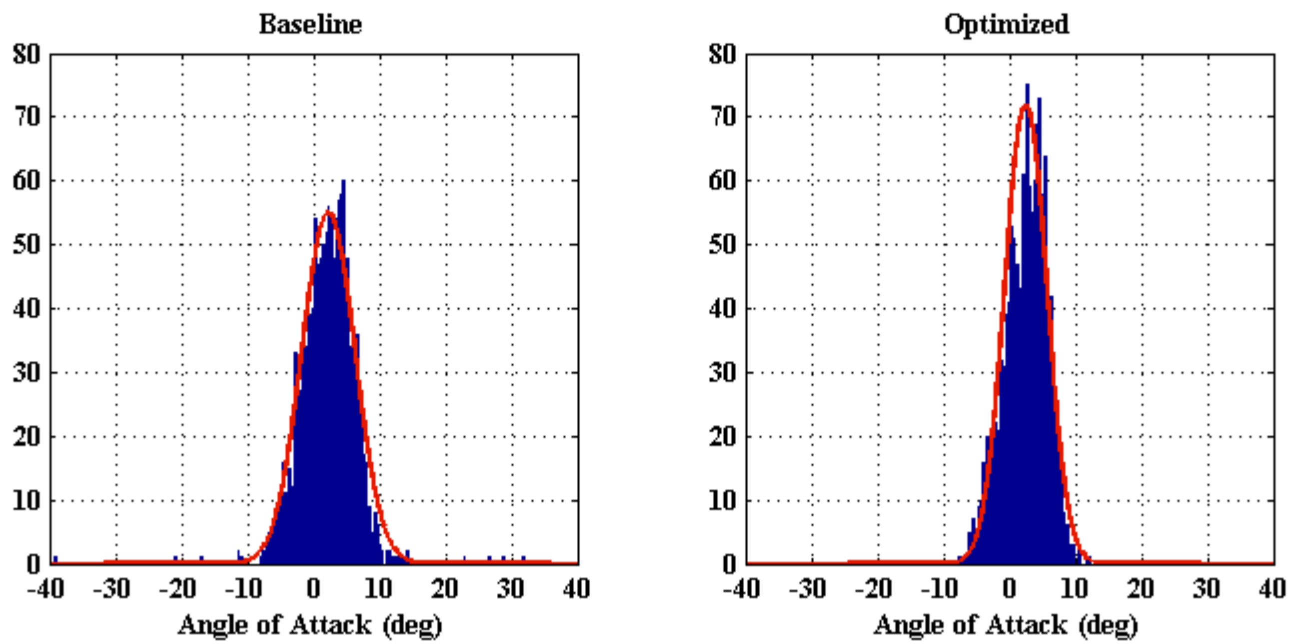
Next inner loop iteration (next gains schedule point)

Convergence check

Next outer loop iteration

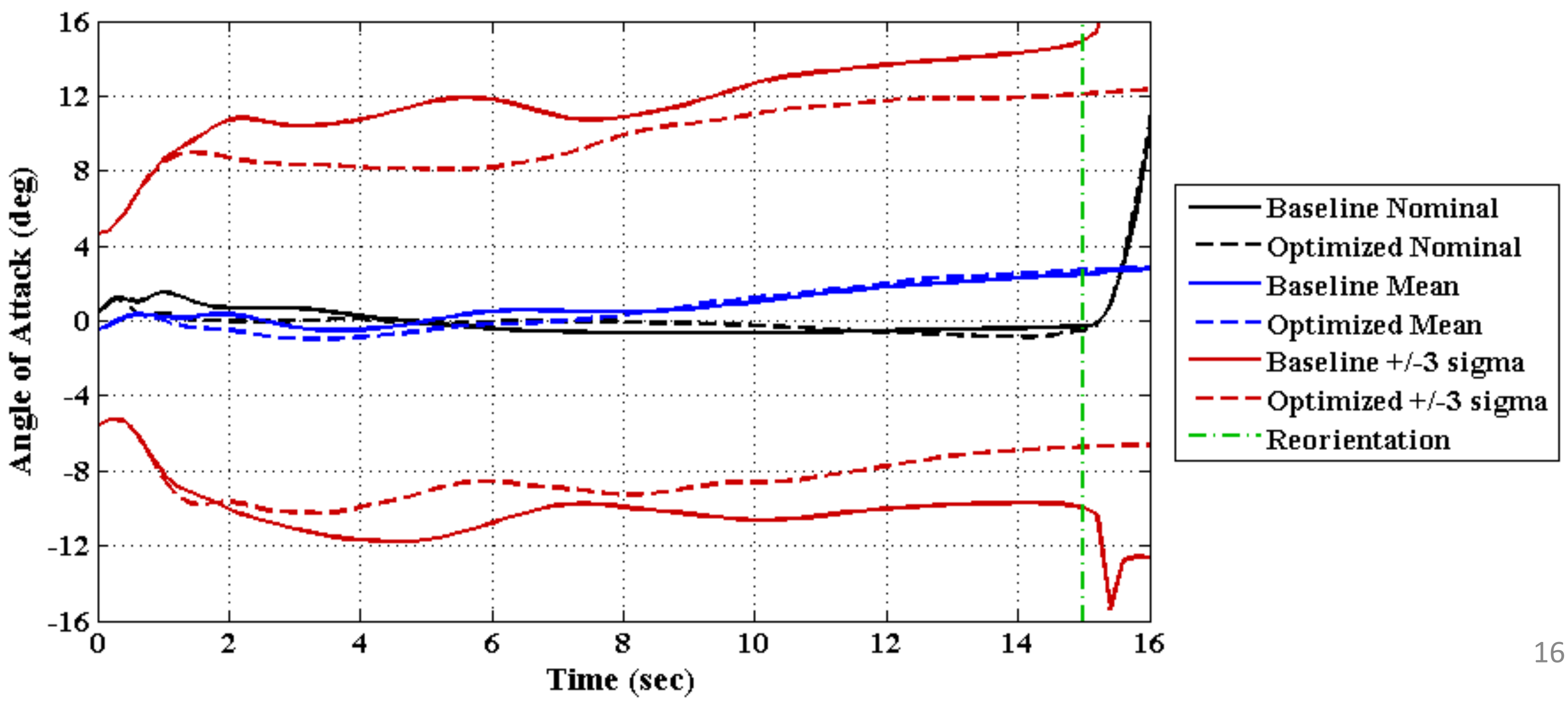
Results

- Desired α profile for all scenarios was zero α from LAV separation until reorientation
- Assessing the improvement (if any) was performed by:
  - Creating a mean and mean+3σ profiles
    - Gaussian mean and σ are calculated at each discrete point
  - Differencing the optimized and baseline profiles
  - Summing the α_e along the profiles for overall change



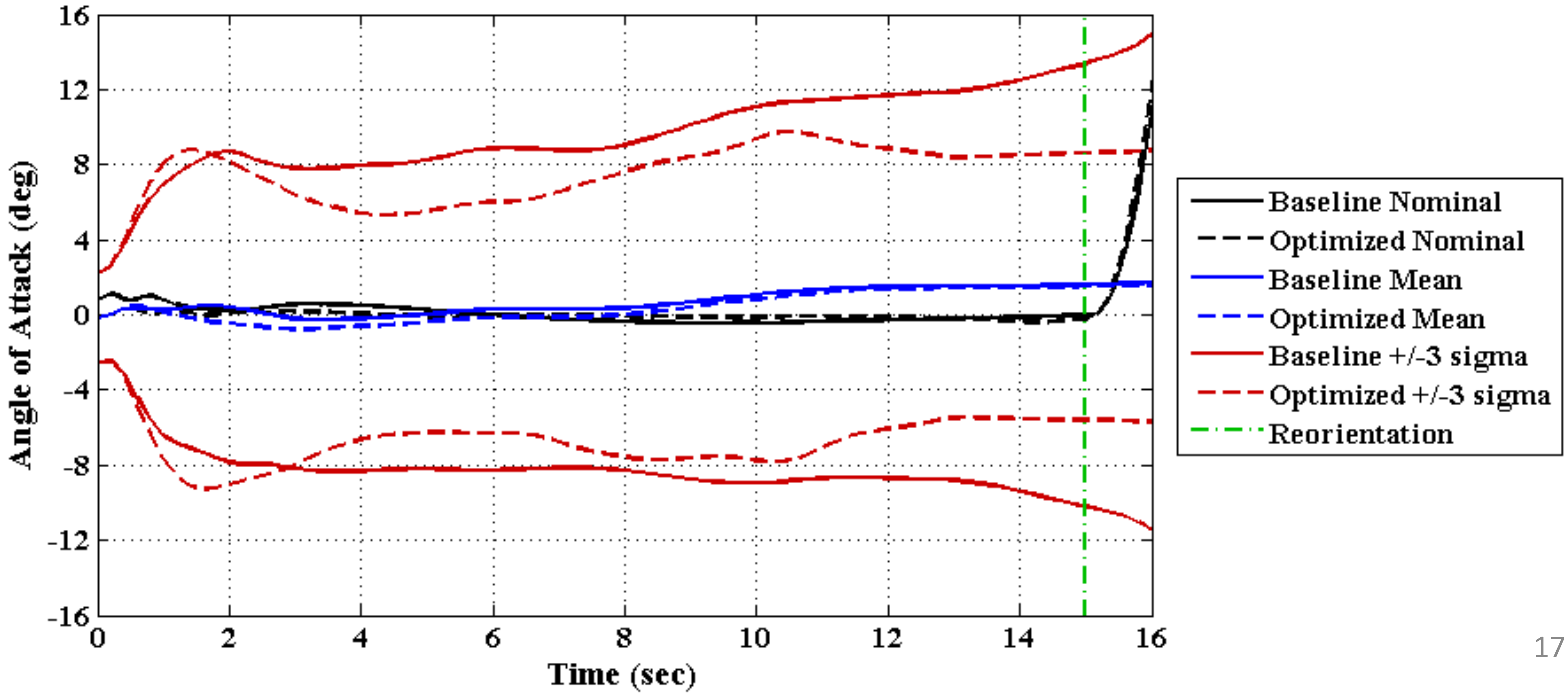
Results

- Transonic scenario
  - Reduced tumbling cases by 24%
  - Reduced nominal profile α_e by 49%
  - Reduced mean profile α_e by 5%
  - Reduced mean+3σ profile α_e by 45%



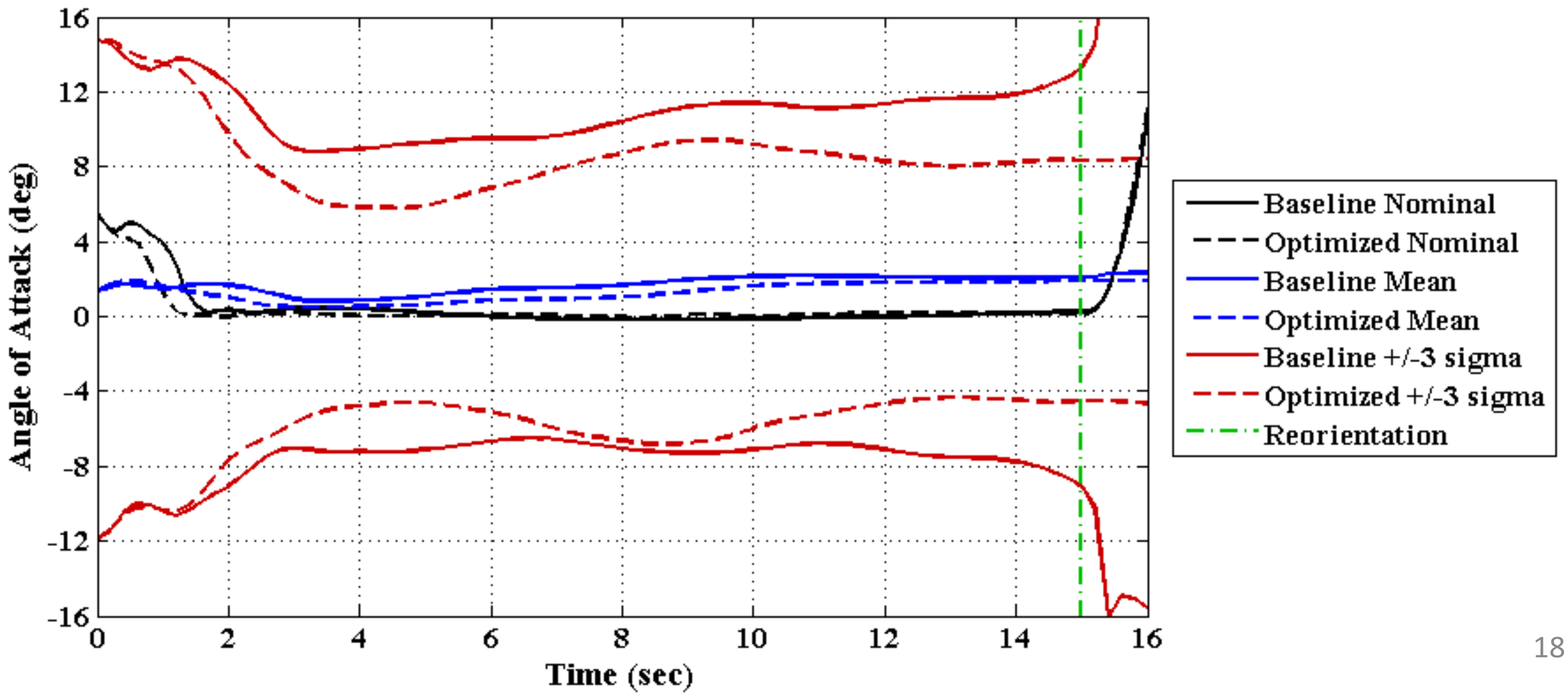
Results

- Maximum dynamic pressure scenario
  - Reduced tumbling cases by 3%
  - Reduced nominal profile α_e by 57%
  - Reduced mean profile α_e by 28%
  - Reduced mean+3σ profile α_e by 61%



Results

- Ares I nozzle failure scenario
  - Reduced tumbling cases by 47%
  - Reduced nominal profile α_e by 35%
  - Reduced mean profile α_e by 37%
  - Reduced mean+3σ profile α_e by 60%



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Summary

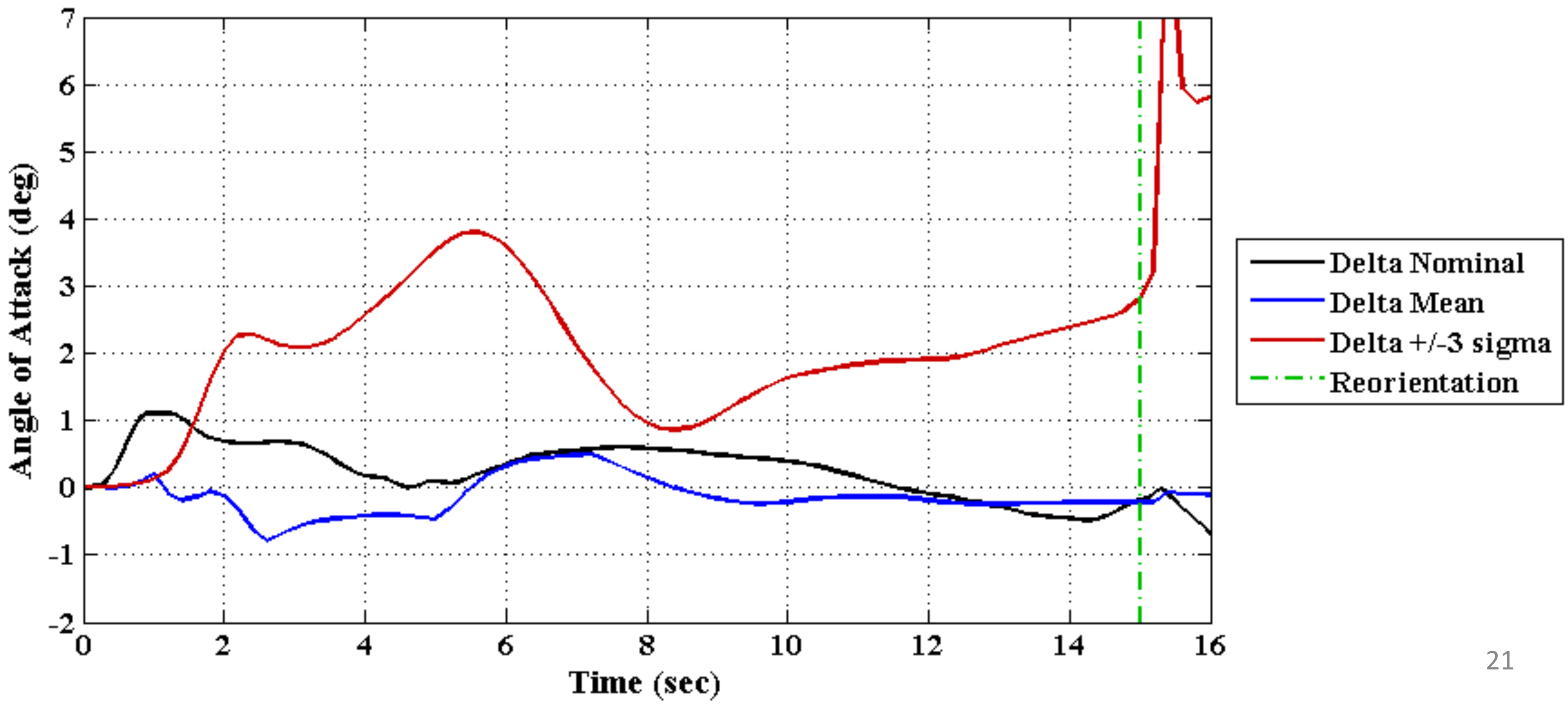
- All three scenarios showed overall reduction in the α errors
- The method of steepest descent is effective in tuning the gains schedule
- All Orion ascent abort flight tests should benefit from tuning the gains schedule

- Questions?

Backup

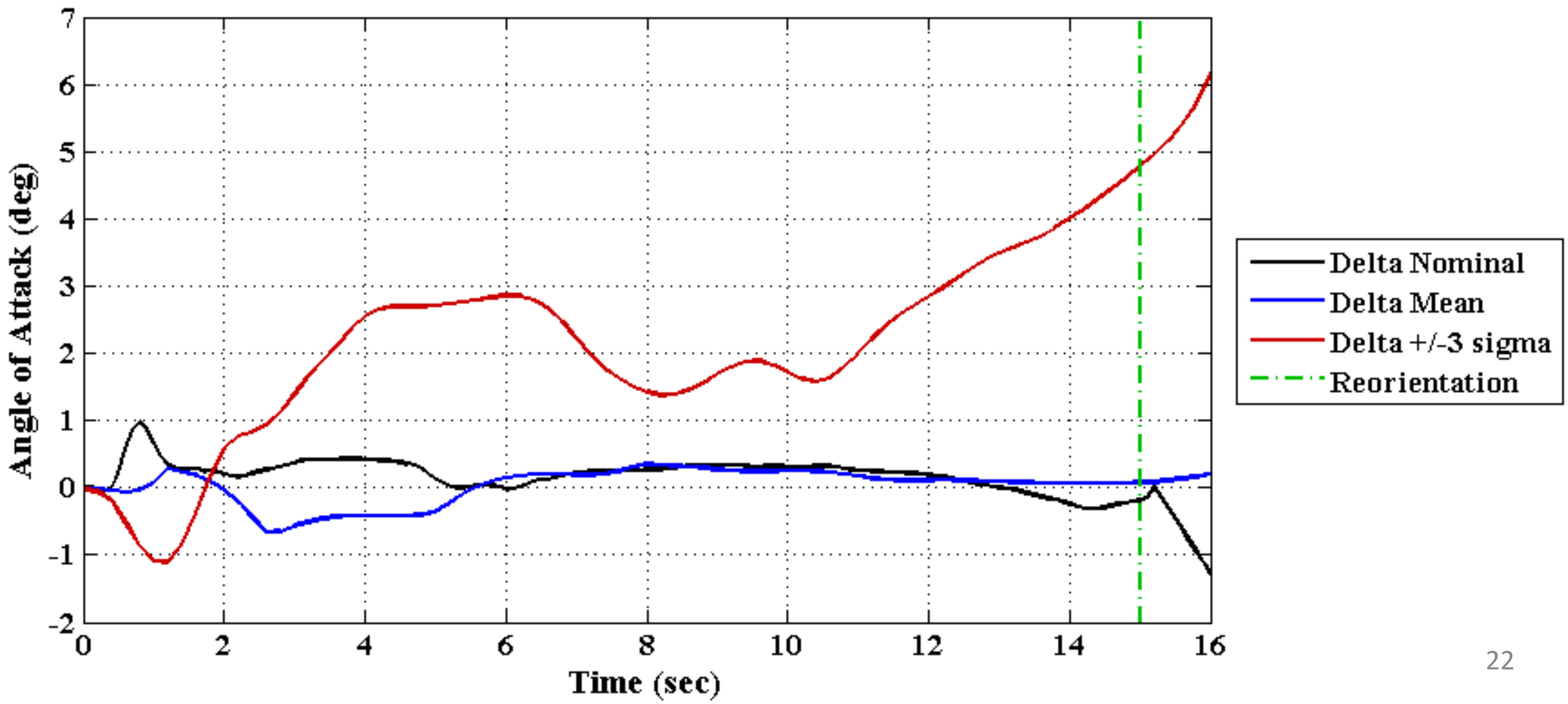
Results

- Transonic scenario
  - Nominal profile improved from 0-12 sec
  - Mean profile improved mainly from 5-8 sec
  - Mean+3σ profile improved throughout



Results

- Maximum dynamic pressure scenario
  – Nominal profile improved from 0-13 sec
  – Mean profile improved from 0-2 sec and 5-15 sec
  – Mean+3σ profile improved from 1.5-15 sec



Results

- Ares I nozzle failure scenario
  - Nominal profile improved from 0-11 sec
  - Mean profile improved from 1-15 sec
  - Mean+3σ profile improved from 1-15 sec