Open-Loop Pitch Table Optimization for the Maximum Dynamic Pressure Orion Abort Flight Test

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ABSTRACT

NASA has scheduled the retirement of the space shuttle orbiter fleet at the end of 2010. The Constellation program was created to develop the next generation of human spaceflight vehicles and launch vehicles, known as Orion and Ares respectively. The Orion vehicle is a return to the capsule configuration that was used in the Mercury, Gemini, and Apollo programs. This configuration allows for the inclusion of an abort system that safely removes the capsule from the booster in the event of a failure on launch. The Flight Test Office at NASA's Dryden Flight Research Center has been tasked with the flight testing of the abort system to ensure proper functionality and safety. The abort system will be tested in various scenarios to approximate the conditions encountered during an actual Orion launch. Every abort will have a closed-loop controller with an open-loop backup that will direct the vehicle during the abort. In order to provide the best fit for the desired total angle of attack profile with the open-loop pitch table, the table is tuned using simulated abort trajectories. A pitch table optimization program was created to tune the trajectories in an automated fashion. The program development was divided into three phases. Phase 1 used only the simulated nominal run to tune the open-loop pitch table. Phase 2 used the simulated nominal and three simulated off nominal runs to tune the open-loop pitch table. Phase 3 used the simulated nominal and sixteen simulated off nominal runs to tune the open-loop pitch table. The optimization program allowed for a quicker and more accurate fit to the desired profile as well as allowing for expanded resolution of the pitch table.

NOMENCLATURE

α_t	Total Angle of Attack/Alpha Total
AA-1	Ascent Abort 1
AFT	Abort Flight Test
ACM	Attitude Control Motor
AM	Abort Motor
ANTARES	Advanced NASA Technology Architecture for Exploration Studies
ATB	Abort Test Booster
β	Angle of Sideslip
CM	Command Module
DoF	Degrees of Freedom
JM	Jettison Motor
LAS	Launch Abort System
LAV	Launch Abort Vehicle
p-β	Roll Rate-Angle of Sideslip
POST	Program to Optimize Simulated Trajectories

1 INTRODUCTION

The Constellation program was created by NASA to develop the next generation of manned space vehicles and launch vehicles. NASA's vision for the next manned spaceflight vehicle, known as Orion, involves a return to the capsule design of Mercury, Gemini, and Apollo. The Orion vehicle will be taken into orbit by a launch vehicle called the Ares I. The capsule design offers many advantages over the lifting body design of the space shuttle orbiters including: greater reentry velocities, higher altitude capability, extra-planetary capability, and an abort system that will protect the crew in the event of a launch failure. The primary disadvantages of the capsule design are a decreased crew capacity, less of the vehicle is reusable, and they cannot perform a controlled landing on a runway. Overall the capsule design should result in a safer and more versatile space vehicle.

The Orion vehicle will consist of four main sections: the spacecraft adaptor, the service module, Crew Module (CM), and the Launch Abort System (LAS). During an aborted launch the LAS and the CM, known as the Launch Abort Vehicle (LAV), separate from the malfunctioning Ares I. A visual representation of the Orion vehicle has been provided in Figure 1.

The LAS consists of a series of three solid rocket motors that work in tandem to ensure the Orion crew return safely to the ground. During an aborted launch the LAS initializes by igniting two of its three solid rocket motors: the Abort Motor (AM) and the Attitude Control Motor (ACM). The AM fires for approximately 5 seconds and provides the thrust necessary to create the separation distance between the CM and the Ares I. The ACM is used to keep the Launch Abort Vehicle (LAV) within the structural dynamic loads and to direct the CM away from the Ares I. Once the LAV has slowed sufficiently, the ACM reorients the LAV into a heat shield forward position. The ACM burns out at approximately 27 seconds, which signals ignition time for the third solid rocket motor called the Jettison Motor (JM). The JM separates the LAS from the CM and takes the LAS sufficiently far away so that the CM can begin its parachute deployment sequence without re-contact with the LAS. A visual representation of the sequence of events during an aborted launch has been provided in Figure 2.

1.1 FLIGHT TEST OVERVIEW

The Flight Test Office of the Constellation program has been tasked with the demonstration of the LAS capability in a series of Abort Flight Tests (AFT). The AFTs consist of two abort tests from the launch pad (Pad Aborts) and four abort tests at various stages along the Orion operational trajectory (Ascent Aborts). The first Ascent Abort (AA-1) is targeting the maximum dynamic pressure region of the Orion/Ares I operational trajectory. The second flight test is designed to test the minimum force at LAV separation and is targeting the transonic region of the Orion/Ares I operational trajectory. The third flight test is designed to be the maximum dynamic structural load test and simulates a nozzle hard-over failure scenario near the maximum dynamic pressure region of the Orion/Ares I operational trajectory. The last ascent abort test is targeting the Ares I stage 1 burnout/stage 2 ignition point of the Orion/Ares I operational trajectory. The first three ascent abort tests are scheduled to be conducted at White Sands Missile Range and use an Abort Test Booster (ATB) supplied by Orbital-Chandler to take the LAV to the desired test condition. The fourth ascent abort test is scheduled be conducted at Kennedy Space Center and use an operational Ares I launch vehicle to take the LAV to the desired test condition.

1.2 SIMULATION OVERVIEW

Prior to the launching of any flight test, the entire event is modeled in a simulated environment. There are two simulations that have been created for the Orion vehicle and each is used to verify the results of the other. The first simulation was developed by Lockheed Martin and was called Osiris. The second simulation was developed by NASA and was called the Advanced NASA Technology Architecture for Exploration Studies (ANTARES). Both simulations were developed using the Trick simulation toolkit. Trick provides a generic simulation environment that simulates and tracks multiple bodies in six Degrees of Freedom (DoF) or three DoF. Trick gives the programmer the ability to apply event based or timer based events in the simulation. The collection of common subsystem models and compilation of the ANTARES simulation is handled by Trick. The ANTARES simulation creates a specific simulated Orion mission after compilation through the use of input files. These input files can be used to modify mass properties, parachute timing, abort timing, atmospheric conditions, etc for an individual run or a set of trajectories like a dispersed Monte Carlo set. Trick also provides a set of plotting tools, in addition to the simulation modeling environment, which allows for quick analysis of the data after the simulation run.[2]

All of the analysis performed in this report uses simulated data from the ANTARES simulation. ANTARES provides simulated objects for the Ares Stage 1 booster, Ares Stage 2 booster, CM, LAS, service module, docking mechanism, International Space Station, as well as a few other assorted objects. The main body object, which varies from the full stack to just the CM, is tracked in 6 DoF and all objects jettisoned from the main body are tracked in 3 DoF. ANTARES includes a variety of subsystem models that can be changed out using the Trick compilation routine. The subsystem models include atmospheric models like Global Reference Atmospheric Model (GRAM) 1999 or GRAM 2007, the current and previous aerodynamic models, a variety of LAS controllers, etc. The variety of subsystem models, parameter modification and Monte Carlo capabilities, and data analysis tools give ANTARES the versatility to create specific simulations for many of the Orion missions.

2 PROBLEM STATEMENT

The LAS controller directs the forces from the ACM to maintain a pre-specified attitude, which is designed to direct the LAV away from the Ares I. The main-line LAS controller operates in a closed-loop configuration, but has an open-loop option should a failure occur in the closed loop configuration. Orbital-Chandler has provided a set of LAV separation points for each of the AFTs that were created from a simulated Monte Carlo set of ATB trajectories. The LAS controller uses the pitch and altitude at LAV separation to create an individualized pitch profile for the abort sequence. In the case of AA-1, the ATB is releasing the LAV at a wide range of altitudes and pitch angles as shown in Figure 3. The open loop pitch table needs to be developed to handle the wide variety of LAV separation points provided by the simulated ATB trajectories.

3 METHODOLOGY

The ANTARES simulation is initialized at the LAV separation point with position, velocity, attitude, attitude rate, atmosphere, and wind data provided by the ATB simulation. Once the LAV separation is initialized in ANTARES the LAS controller records the current pitch angle and altitude. The LAS controller uses this information to locate the four open-loop pitch table nodes closest to its recorded initial condition. This is accomplished by locating the two altitude nodes that the initial altitude is between and the two pitch nodes that the initial pitch is between. For example in Figure 3 the nominal point is between pitch nodes 1 and 2 and altitude nodes 1 and 2, so the four surrounding nodes are (1,1), (1,2), (2,1), and (2,2). The LAS controller uses the open-loop pitch profile of these four nodes and performs a two-dimensional interpolation to create an individualized open-loop pitch profile.

The baseline configuration consists of two open-loop pitch tables. The primary open-loop pitch table controls the LAV from abort initiation for 10 seconds. This table was designed to maneuver the LAV away from the Ares I. The primary open-loop pitch table is a series of 9 pitch profiles in a 3x3 initial altitude/initial pitch angle grid. Each pitch profile consists of 10 values, which are commands implemented at different time points. The secondary open-loop pitch table controls the LAV from 10 seconds until reorientation. This table was designed to reduce the total angle of attack (α_t) to zero in preparation for reorientation. The secondary open-loop pitch table has two pitch profiles corresponding to pitch angles and each of the secondary pitch profiles has three values associated with time points.

The AA-1 scenario is a maximum dynamic pressure scenario, so the dynamic pressure had to be reduced faster prior to reorientation than the other AFTs. In order to accomplish this reduction in dynamic pressure the desired α_t profile was created by Lockheed Martin using 3 DoF POST (Program to Optimize Simulated Trajectories) simulation. The desired α_t profile was set to a hold for 1 second, pitch up to a peak at 3 seconds, pitch down to a hold value at 6 seconds, and maintain the hold value until reorientation. The primary open-loop pitch table was manually adjusted to approximate the desired α_t profile at 1, 3, and 6 seconds in the simulated nominal run. The adjustments were accomplished by modifying the values of the open-loop pitch table, running the simulation, evaluating the fit to the desired α_t profile, and modifying the table again in a trial and error method. The secondary open-loop pitch table was also manually adjusted to hold a higher than zero α_t until reorientation in the simulated nominal run. Because of the tediousness involved in manually adjusting the primary open-loop pitch table, the grid was not refined beyond 3x3x10 and no off-nominal simulation runs were optimized.

In an effort to improve the results of the open-loop controller an optimization program was developed. In the optimization software, the simulation was run and the resulting α_t profile was compared at each of the specified time points to the desired α_t profile. Any deviations from the desired α_t profile were used to adjust the open-loop pitch table and then the process repeated. The secondary open-loop pitch table was not as effective in maintaining a non-zero α_t as it was in maintaining a zero α_t. Since the primary open-loop pitch table was more effective at maintaining a non-zero α_t the optimized versions were extended to cover from abort initiation until 0.5 seconds prior to reorientation. The secondary table was reduced to cover the remaining 0.5 seconds, and mainly handled the transition between primary open-loop pitch table phase and the reorientation phase. Since the optimization program could focus on all specified time points instead of just three, the number of specified time points was increased from 10 to 24 in the optimized open-loop pitch tables.

There was an additional controller that was activated at four seconds after abort initiation called the p-β controller. The p-β controller uses the offset in the LAV's center of gravity and a computed angle of sideslip to produce an aerodynamic roll moment and reduce the roll rate. This controller is necessary to reduce the roll rates, but affects the α_t profile which is expected to be higher when the p-β controller is active.

The development of the optimized open-loop pitch table was divided into three phases:

Phase 1: Generated an open-loop pitch table using the same 3x3 initial altitude/initial pitch grid as the baseline, see Figure 3. The deltas calculated from the simulated nominal run were applied to the open-loop pitch profiles at all nine of the nodes. The nominal trajectory was a no-winds scenario with the LAV rolled so that the theoretical astronauts were in a heads up position.

Phase 2: Generated an open-loop pitch table using a 5x5 initial altitude/initial pitch grid with the same altitude/pitch spread as the baseline, see Figure 4. Phase 2 started with the Phase 1 deltas applied to the open-loop pitch profile of all 25 nodes. Increasing the resolution of the altitude/pitch grid made it possible to include simulated off-nominal runs in the optimization software. As long as the open-loop pitch profiles at the four nodes surrounding the nominal were not modified, then the other open-loop pitch profiles could be modified to provide better off nominal results. Trajectories with similar altitude/pitch pairs have similar α_t trends, which means that higher initial pitch translates to higher initial α_t. The selected off-nominal trajectories were as centrally located inside of selected grid squares as possible so that the deltas could be applied evenly. Every other grid square was chosen so that each trajectory could have sole control over three of the nodes.

Since the simulated nominal run had to maintain the desired α_t profile it controlled all four of its surrounding nodes. The off-nominal trajectories only needed to be improved, so deltas for each simulated off-nominal trajectory were applied to three of the four surrounding nodes. For example in Figure 4 the optimized point annotated by the surrounding square had its deltas applied to nodes (4,3), (4,4), and (3,4) because node (3,3) was shared with the nominal trajectory. The open-loop pitch profile of any node shared with the nominal run was not altered. If a node didn't have a trajectory in its grid square, then the deltas from the closest trajectory were applied.

Three off-nominal trajectories were optimized in this method. Prior to being used by the optimizer the three off-nominal trajectories had two of their initial conditions modified. The wind profile strongly affects the α_t profile and trajectories with similar initial pitch and initial altitude can have vastly different wind profiles, so the winds were zeroed to be more like the nominal. The roll angle was also modified to the nominal value, so that a positive pitch always created a positive α_t change. All other initial conditions were identical to the LAV separation points of the Orbital-Chandler ATB simulation data.

Phase 3: Generated an open-loop pitch table using a 7x7 initial altitude/initial pitch grid with a reduced altitude/pitch spread, see Figure 5. Phase 3 started with the Phase 1 deltas applied to the open-loop pitch profile of all 49 nodes. The selected off-nominal trajectories were as centrally located inside of the grid squares as possible. Each trajectory had cognizance over the four surrounding nodes, unless a node was shared with the nominal trajectory. Since each node applied to multiple trajectories the deltas for a particular node were averaged prior to application. For example node (3,5) in Figure 5 has four trajectories trying to apply a delta so only ¼ of the delta from each trajectories was applied during each iteration. If a node didn't have a trajectory in its grid square, then the deltas from the closest trajectory were applied. This optimized more off-nominal trajectories, but since nodes were shared a compromised optimization was reached. The off-nominal trajectories were again modified as described in Phase 2.

Each phase of the optimizer is run until a convergence was reached: either the deltas applied were less than $1x10^{-6}$ degrees or the cumulative delta was no longer reducing in magnitude.

4 TRAJECTORY RESULTS

The performance of the open-loop pitch tables were evaluated using the ANTARES simulated environment through a 2000 run randomized dispersion set. The initial conditions of the simulated runs are based off of the 500 LAV separation points provided by the ATB simulation. Each of the 500 LAV separation points was used four times, but each of the four times used differing mass properties and aerodynamic coefficients. The dispersions were held constant between the baseline and each of the phases. The performance metric was the resulting alpha total profiles and was evaluated up through reorientation.

4.1 *BASELINE*

The results of the manual adjustment to the baseline open loop pitch table and the watch points have been provided in Figure 6. The nominal profile approximates the desired profile, but there is significant drift. The secondary table was able to hold a value in the nominal trajectory better than the primary pitch table. The α_t results of a simulated 2000 run dispersed set are provided in Figure 7. The nominal α_t matches the desired α_t at 1, 3, and 6 seconds after abort initiation, but the α_t wanders between these points. The α_t profiles show an increase between four and ten seconds while the p-β controller is active. The α_t steadily increases after the secondary pitch table activates at 10 seconds. The plus three sigma line in Figure 7 begins reorientation at an α_t that is 320% greater than the desired α_t at reorientation.

4.2 *PHASE 1*

The results of the optimized adjustment to the Phase 1 open loop pitch table and the watch points have been provided in Figure 8. The nominal profile provides a much closer fit to the desired profile than the baseline. The α_t results of a simulated 2000 run dispersed set are provided in Figure 9. The mean α_t profile followed the nominal α_t profile closer than the baseline up through 4.5 seconds. The α_t profiles show an increase between 4.5 and 8.5 seconds due to the p-β controller. The mean α_t steadily increases from the nominal α_t from 11 seconds through reorientation, but does not increase as much as the baseline. The plus three sigma line in Figure 9 peaks 0.5 seconds before reorientation at an α_t that is 281% greater than the desired alpha total at reorientation.

4.3 *PHASE 2*

The results of the optimized adjustment to the Phase 2 open loop pitch table and the watch points have been provided in Figure 10. The off-nominal profiles approximate the desired profile, but vary due to not controlling all four of their nodes or α_t being 100% β associated to the p-β controller. The α_t results of a simulated 2000 run dispersed set are provided in Figure 11. The mean α_t profile followed the nominal α_t profile closer than the baseline up through 4.5 seconds. The α_t profiles show an increase between 4.5 and 8.5 seconds due to the p-β controller. The mean α_t steadily increases from the nominal α_t from 11 seconds through reorientation, but not as much as the baseline. The plus three sigma line in Figure 11 peaks 0.5 seconds before reorientation at an α_t 277% greater than the desired alpha total at reorientation. The Phase 2 results showed a slight improvement over the Phase 1 results.

4.4 *PHASE 3*

The results of the optimized adjustment to the Phase 3 open loop pitch table and the watch points have been provided in Figure 12. The off-nominal profiles approximate the desired profile, but vary due to a compromise solution on all of their nodes or α_t being 100% β associated to the p-β controller. The α_t results of a simulated 2000 run dispersed set are provided in Figure 13. The mean α_t profile followed the nominal α_t profile closer than the baseline up through 4.5 seconds. The α_t profiles show an increase between 4.5 and 8.5 seconds due to the p-β controller and the increase is greater than any previous set. The mean α_t steadily increases from the nominal from 11 seconds through reorientation, but not as much as the baseline or the other phases. The plus three sigma peak just before reorientation in Figure 13 was at an α_t that is 234% greater than the desired alpha total at reorientation. The Phase 3 results showed an overall improvement over the Phase 1 and Phase 2 results.

4.5 OVERALL

The mean and mean+3σ plots have been combined for the baseline, phase 1, phase 2, and phase 3 simulated runs in Figure 14 for easier comparison. Summary statistics of the difference between the desired alpha total profile and the mean and mean + 3 σ profiles has been provided in Table 1.

Table 1 - Difference between the Desired Total Angle of Attack Profile and the Baseline, Phase 1, Phase 2, and Phase 3 Simulated Runs as Percentage of Desired Total Angle of Attack.

		Average	Range
Δ Mean	Baseline	+25.8%	-19.7% to +95.3%
	Phase 1	+17.7%	-28.0% to +67.2%
	Phase 2	+17.3%	-31.7% to +71.1%
	Phase 3	+12.9%	-35.6% to +61.3%
Δ Mean + 3σ	Baseline	+204.4%	+68.0% to +337.9%
	Phase 1	+187.4%	+50.9% to +281.2%
	Phase 2	+185.4%	+45.0% to +277.5%
	Phase 3	+176.4%	+42.8% to +288.1%

The average difference between the desired α_t profile and the mean and mean+3σ profiles improved with each of the phases. The average difference between the mean of the Phase 3 runs and the desired α_t profile was reduced by half compared to the mean of the baseline runs. The range of the difference between the desired α_t profile and the mean and mean+3σ profiles were all smaller than the baseline; however due to the increase in the Phase 3 α_t profile at 5.8 seconds, there was no trend.

5 CONCLUSION

The simulated nominal and dispersed runs of the optimized open-loop pitch tables provided a better fit to the desired alpha total profile than the simulated baseline runs. The phase 3 open-loop pitch table used inputs from the most off-nominal trajectories and provided the best overall fit to the desired α_t profile. The ideal situation would be to have a specified pitch profile for every possible scenario, but the variability in the scenarios makes this impossible. The reduction in time and effort required to generate an open-loop pitch table, the ability to easily expand the table in resolution and specified time points, and the improvement in the resulting simulated trajectories make the open loop pitch table optimizer the preferred generation method. However, even with these improvements, the open-loop pitch table cannot provide as accurate of an α_t profile fit as a closed-loop controller can.

REFERENCES

1. Davidson, John; et al., "Crew Exploration Vehicle Ascent Abort Overview", AIAA 2007-6590.
2. "Trick Simulation Environment User Training Materials Trick 2007.0 Release," Vetter, Keith and Chen, Hong, 5 December 2007.
3. "Orion Vehicle Simulation Data Book," NASA CEV Document Number: CEV-MA-08-046, 8 January 2008.

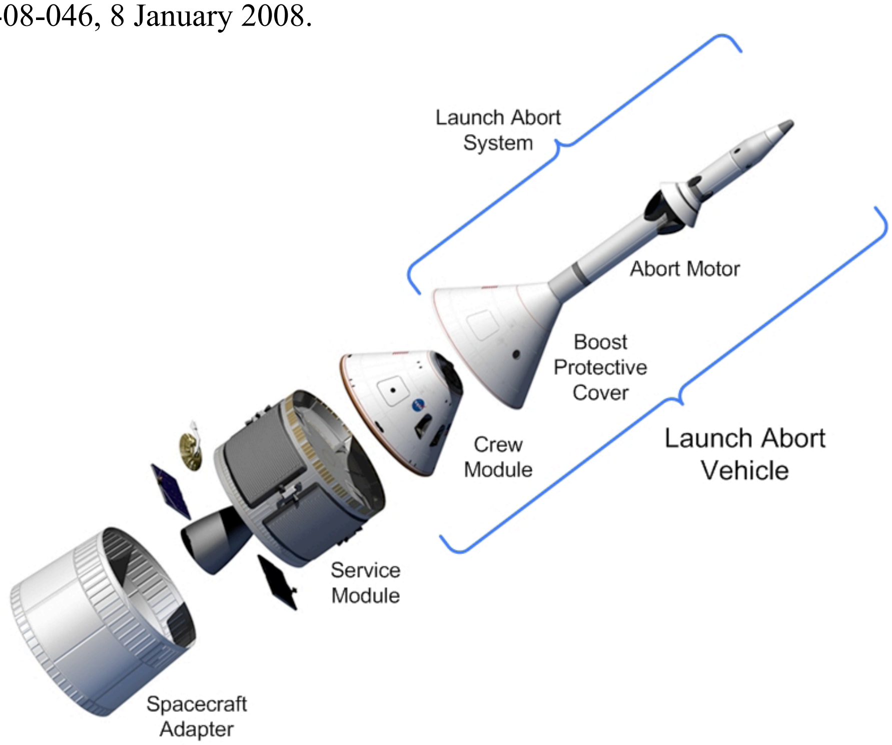

Figure 1 - Orion vehicle breakdown and naming convention[1]

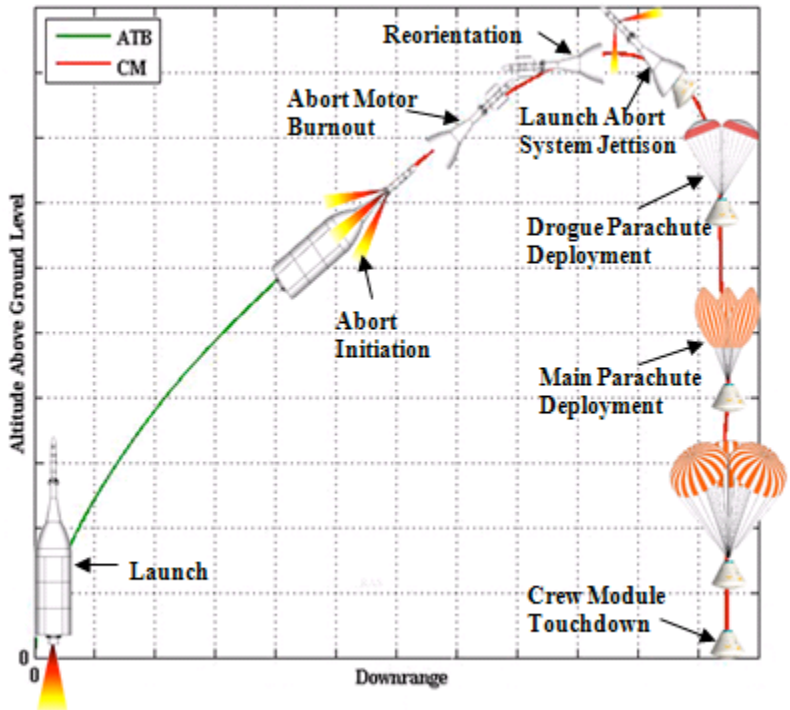

Figure 2 - Sequence of Events for an Aborted Orion Launch

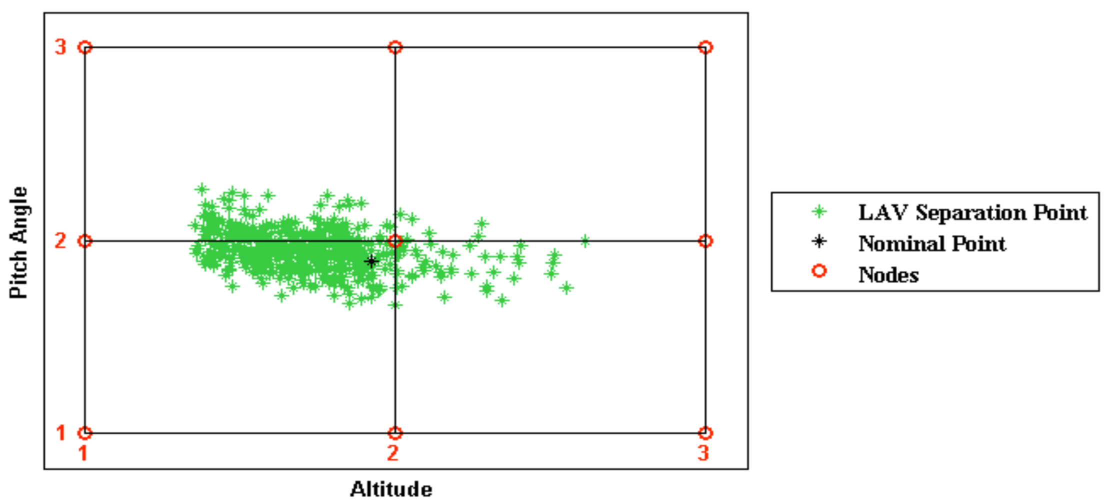

Figure 3 - Altitude and Pitch Launch Abort Vehicle Separation Points from the Ascent Abort 1 Flight Test with the Baseline/Phase 1 Grid Overlaid

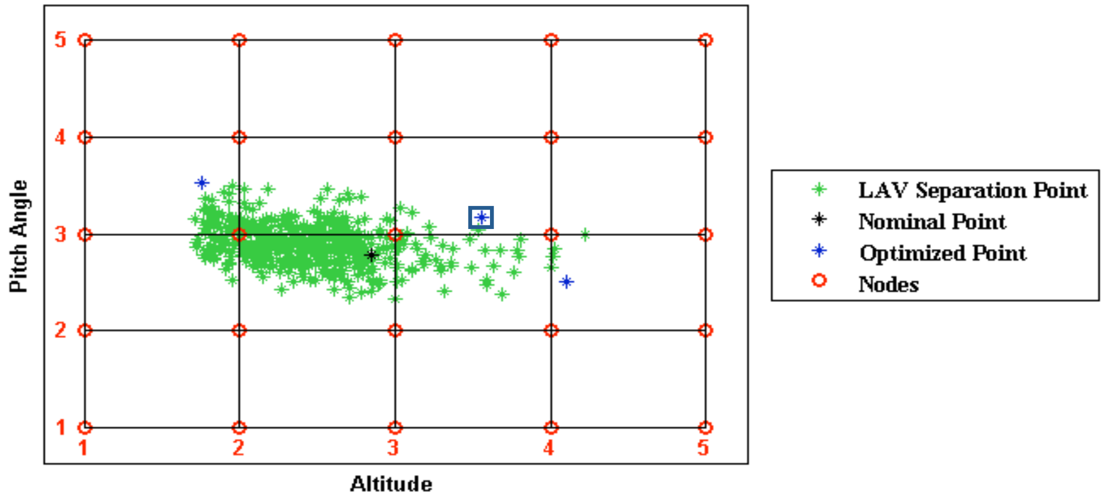

Figure 4 - Altitude and Pitch Launch Abort Vehicle Separation Points from the Ascent Abort 1 Flight Test with the Phase 2 Grid Overlaid

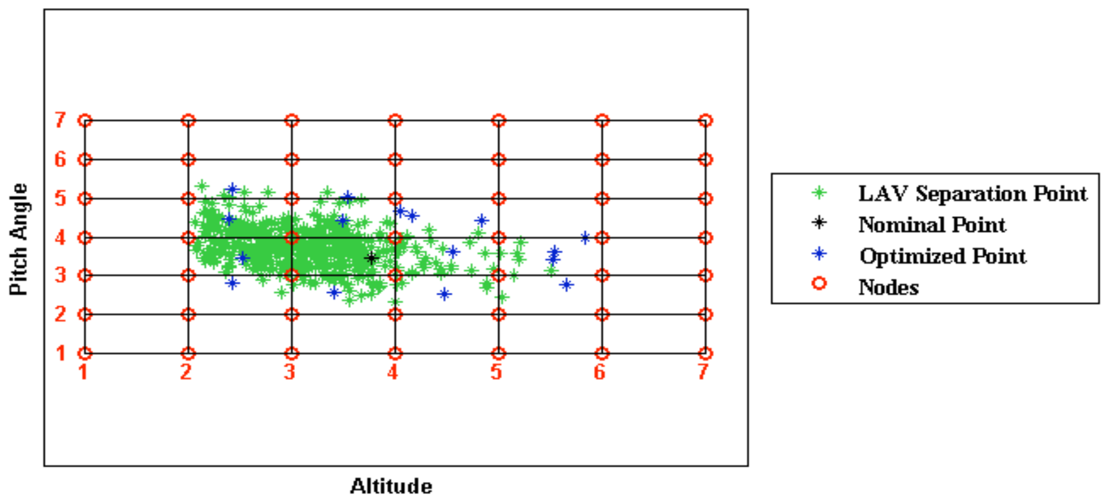

Figure 5 - Altitude and Pitch Launch Abort Vehicle Separation Points from the Ascent Abort 1 Flight Test with the Phase 3 Grid Overlaid

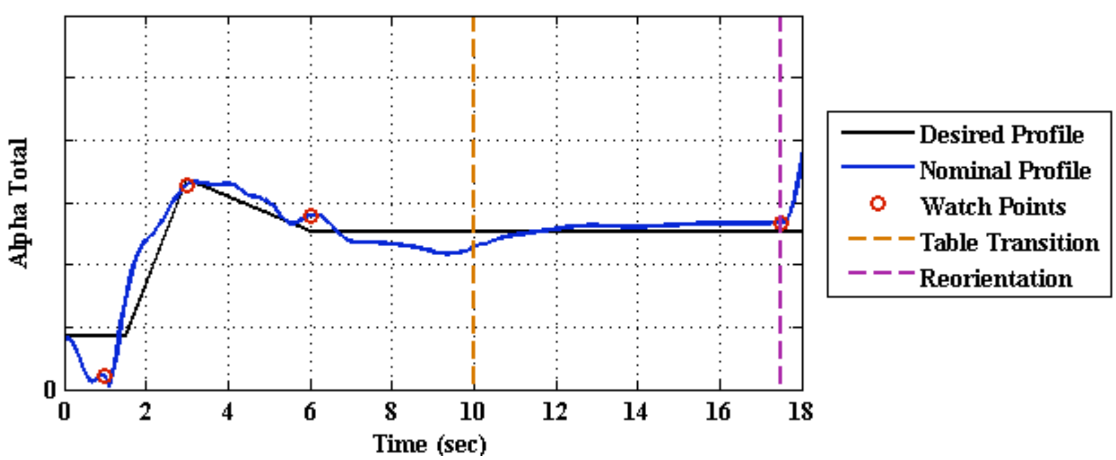

Figure 6 - Nominal Profile and the Watch Points for the Baseline Open-Loop Pitch Table

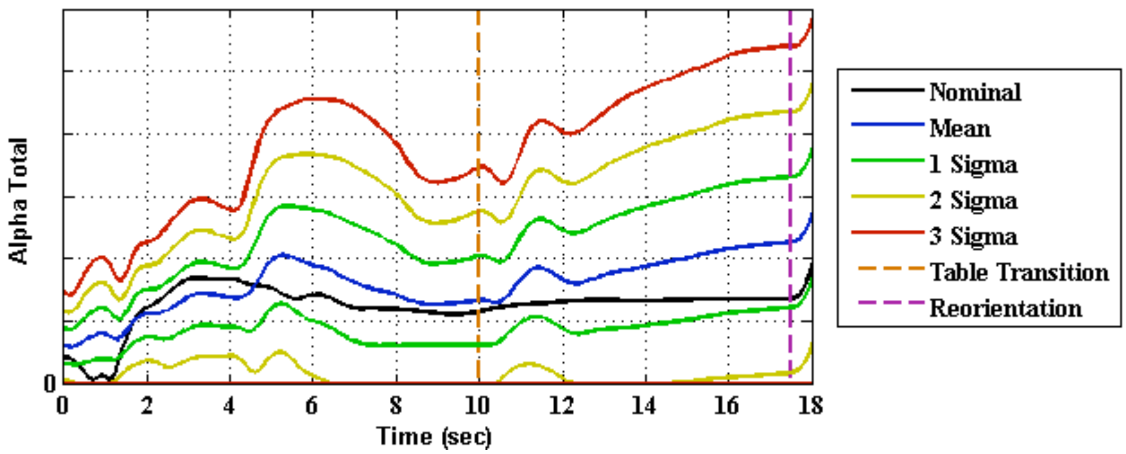

Figure 7 - Alpha Total Results from the Simulated Ascent Abort 1 Runs with the Baseline Open-Loop Pitch Table

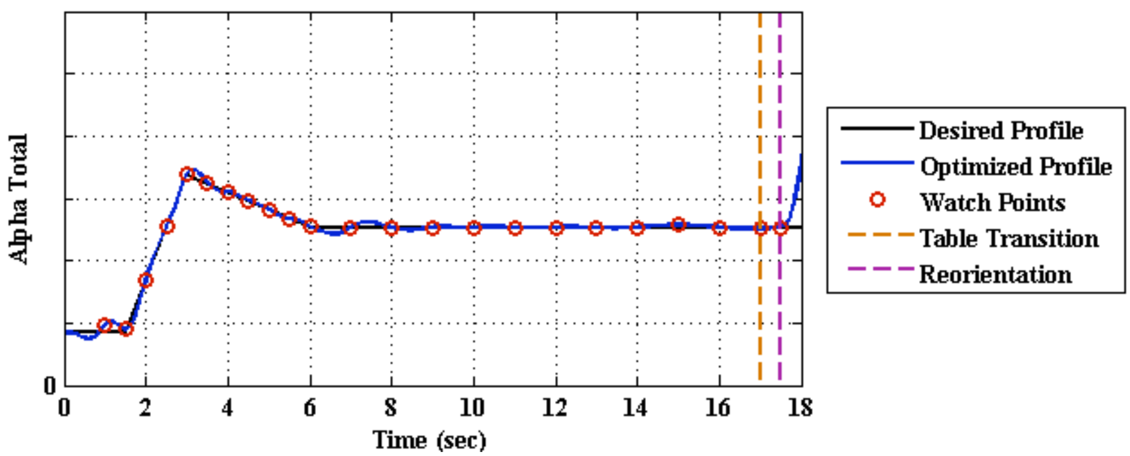

Figure 8- Nominal Optimized Profile and the Watch Points for the Phase 1 Open-Loop Pitch Table

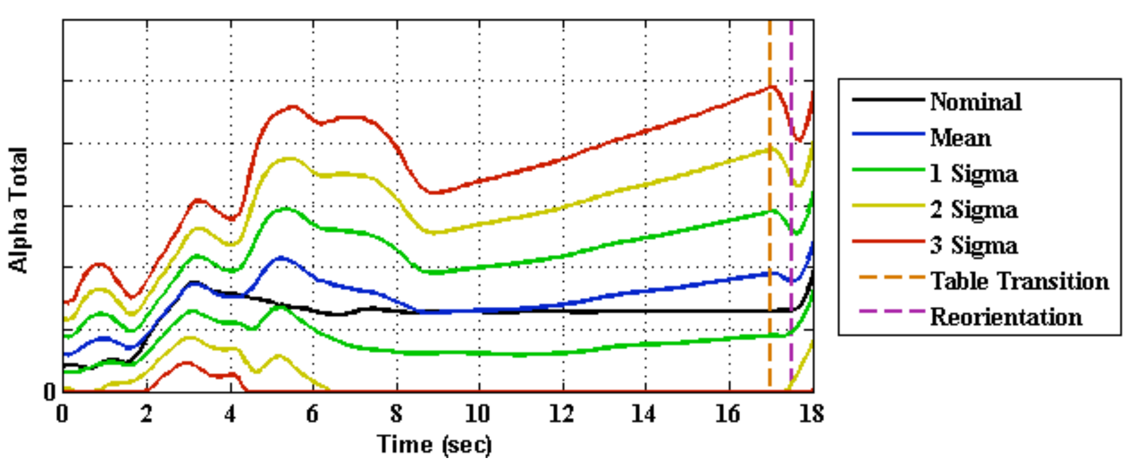

Figure 9 - Alpha Total Results from the Simulated Ascent Abort 1 Runs with the Phase 1 Open-Loop Pitch Table

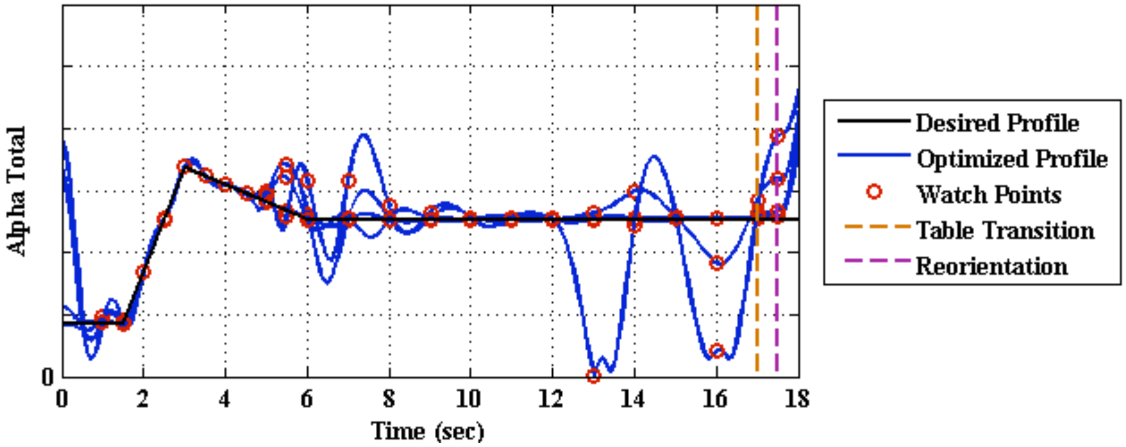

Figure 10- Nominal/Off nominal Optimized Profiles and the Watch Points for the Phase 2 Open-Loop Pitch Table

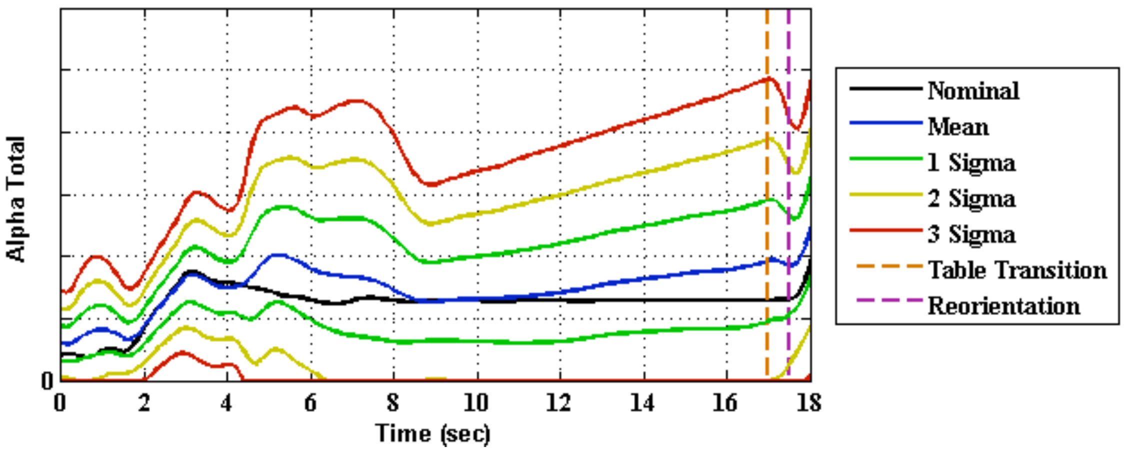

Figure 11 - Alpha Total Results from the Simulated Ascent Abort 1 Runs with the Phase 2 Open-Loop Pitch Table

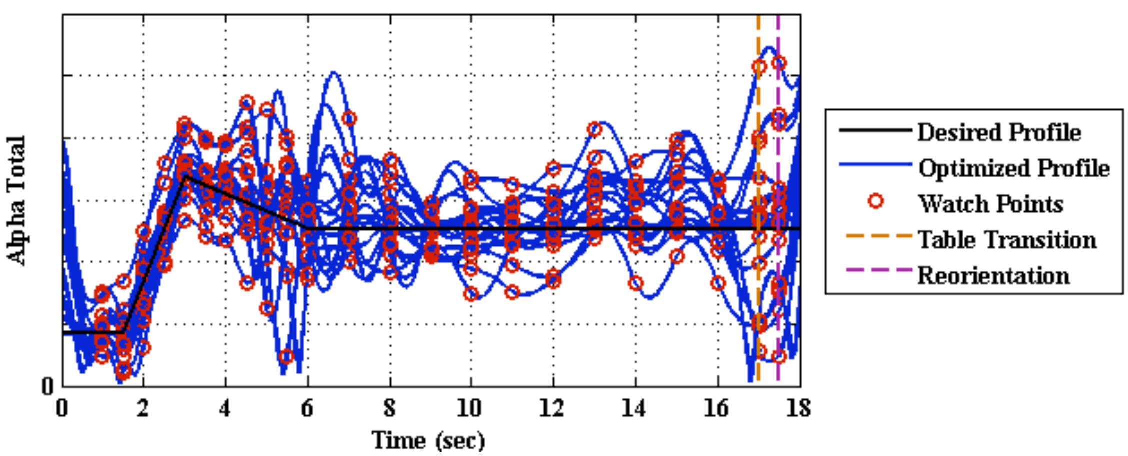

Figure 12- Nominal/Off nominal Optimized Profiles and the Watch Points for the Phase 3 Open-Loop Pitch Table

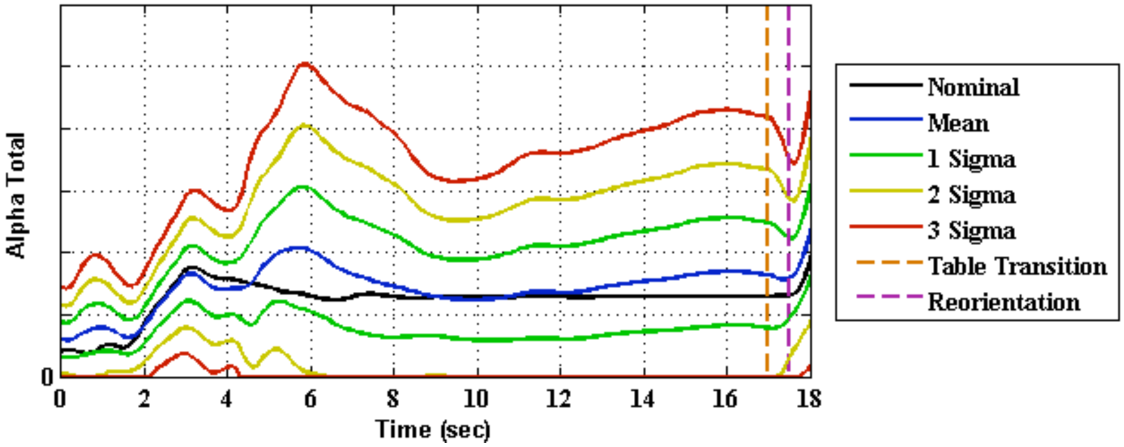

Figure 13 - Alpha Total Results from the Simulated Ascent Abort 1 Runs with the Phase 3 Open-Loop Pitch Table

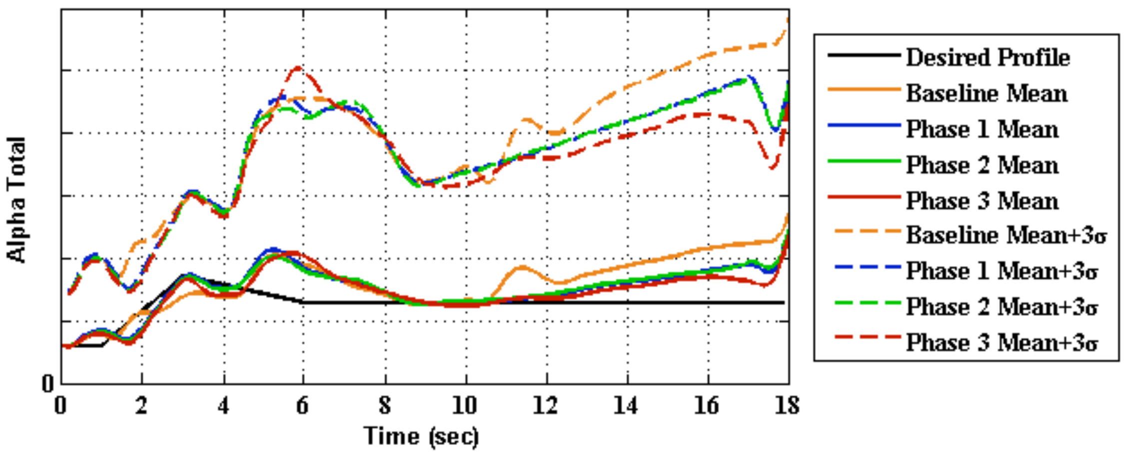

Figure 14 - Alpha Total Results from the Simulated Ascent Abort 1 Runs

Open-Loop Pitch Table Optimization for the Maximum Dynamic Pressure Orion Abort Flight Test

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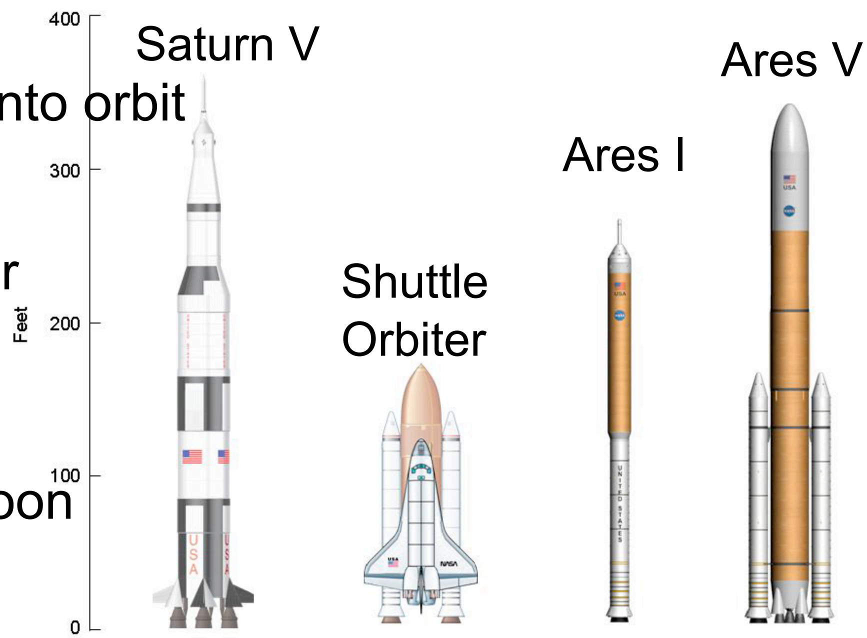
Introduction

- Orion/Abort Flight Test Overview
- Problem Definition
- Methodology
- Baseline Results
- Phase 1 Optimization Results
- Phase 2 Optimization Results
- Phase 3 Optimization Results
- Summary

Project Orion Abort Flight Test

Constellation Overview

- Retirement of the Space Shuttle Orbiters scheduled for 2010
- Constellation program was initiated to create the next manned space vehicle and consisting of four sub-programs
- Ares I launch vehicle
  - Launches Orion crew vehicle into orbit
- Ares V launch vehicle
  - Launches cargo and Altair lunar lander into orbit
- Orion crew vehicle
  - Carries astronauts to ISS or Moon
- Altair lunar lander
  - Facilitates the landing of the Orion crew vehicle on the Moon



Ares I

- Ares I launch vehicle will carry Orion crew vehicle into Orbit
- Two stage rocket
  - Stage 1: 5-Segment Reusable Solid Rocket Booster
    - Shuttle heritage (4-segment)
    - Burns out at ~189,000 ft
  - Stage 2: J2-X engine that uses liquid hydrogen/oxygen as fuel
    - Apollo heritage (Saturn V's J-2)
    - Burns out at ~425,000 ft

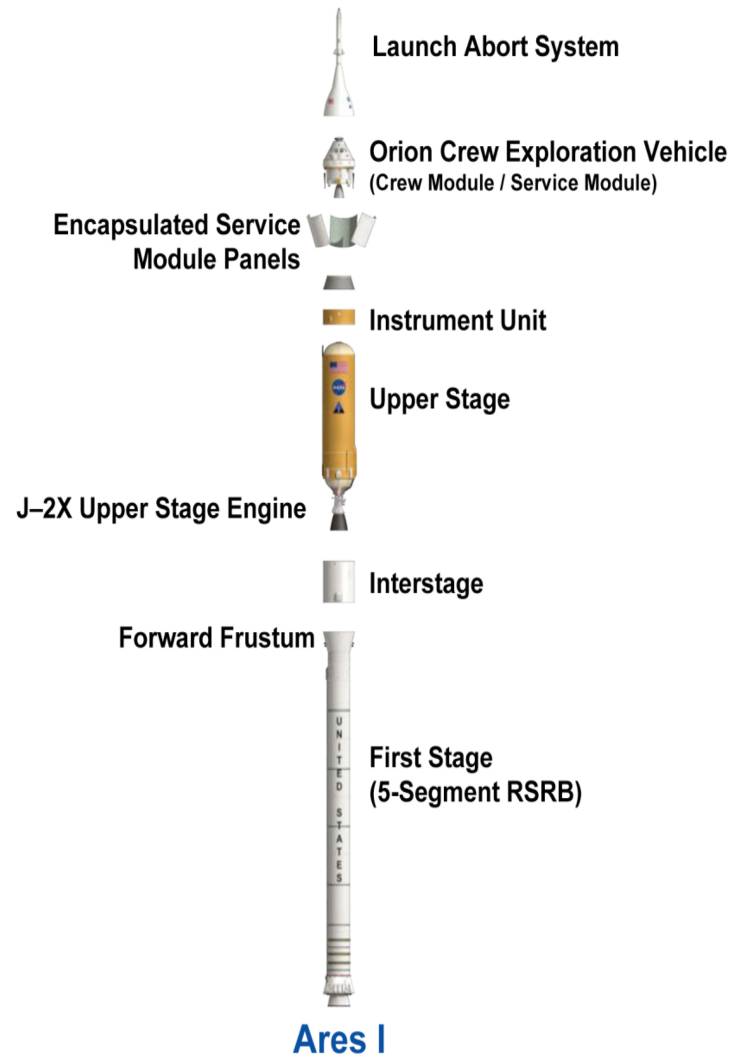


Image from: NASAFacts Constellation Program: America's Fleet of Next Generation Launch Vehicles The Ares I Launch Vehicle

Orion

- Next generation of manned space vehicles is a return to the capsule design of Mercury, Gemini, and Apollo
- Advantages
  - Higher reentry velocities
  - Higher altitude capability
  - Interplanetary capability
  - Launch abort capability
- Disadvantages
  - Cannot perform a controlle runway landing
  - Reduced crew capacity
  - Less reusable parts

Image from: NASAFacts Constellation Program: America's Spacecraft for a Next Generation of Explorers The Orion Crew Exploration Vehicle

Orion Vehicle Overview

- Consists of four main components
- 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) is the combined CM and LAS
- Service Module
  - On-orbit maneuvering and Lunar orbit escape section
- Spacecraft Adapter
  - Interface between Orion crew vehicle and Ares I

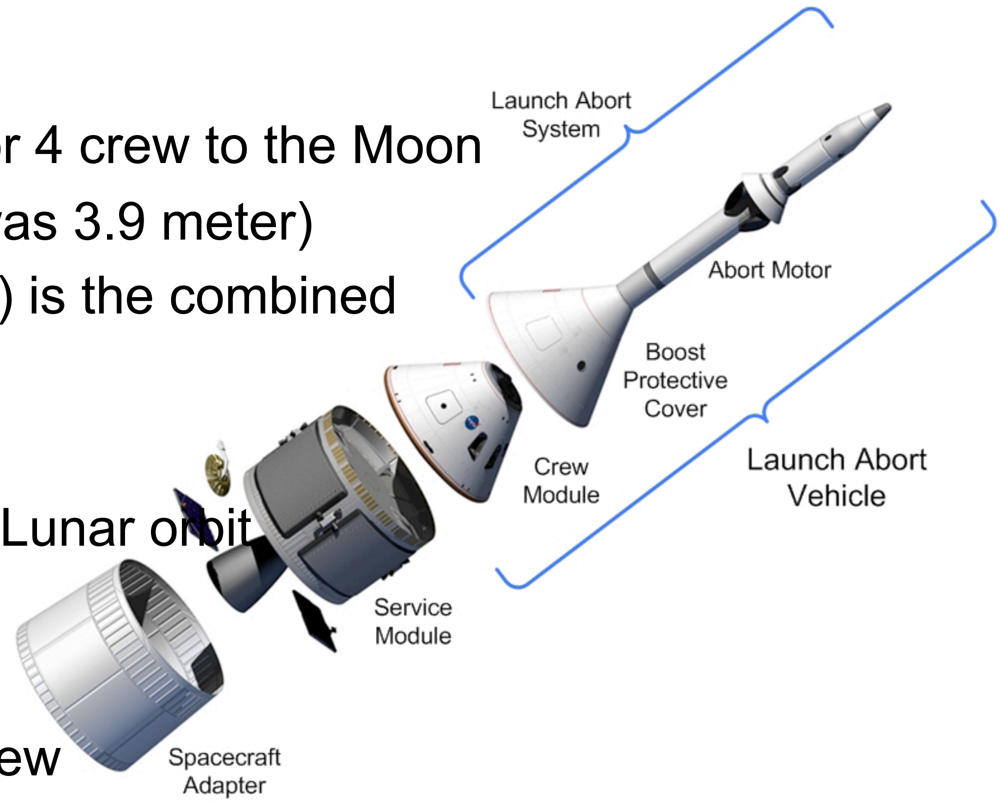


Image from: Davidson, John; et al., "Crew Exploration Vehicle Ascent Abort Overview", AIAA 2007-6590.

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
  - Burns for ~5 seconds
  - Provides the separation distance between the Launch Abort Vehicle and the Ares I
- Attitude Control Motor (ACM)
  - Ignites on abort
  - Burns for ~27 seconds
  - Directs the attitude of the LAV during the abort
- Jettison motor
  - Ignites after AM and ACM burnout
  - Separates the LAS from the CM
  - Only motor that will ignite on every Orion launch

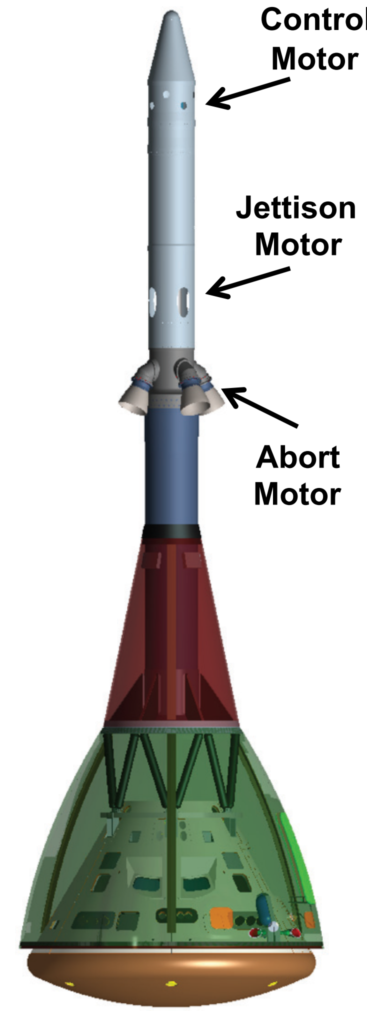


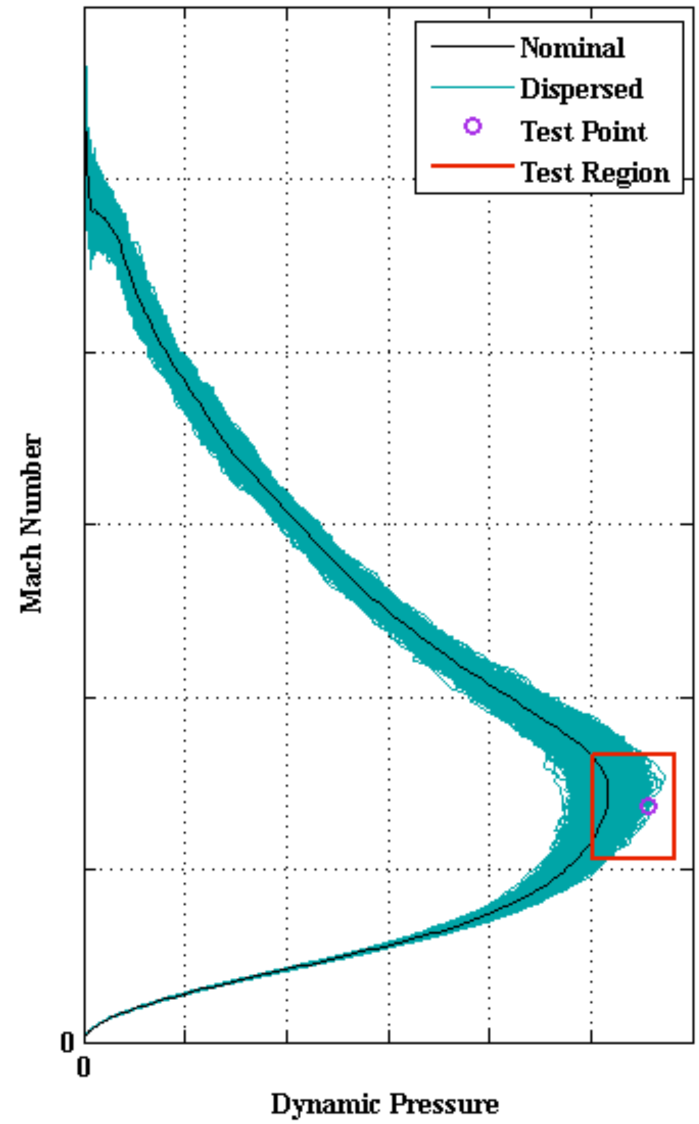
Image from: NASAFacts Constellation Program: Astronaut Safety in a Launch Emergency The Orion Launch Abort System

Orion Abort Flight Tests

- Five flight tests are currently scheduled to verify the functionality of the LAS
- Two aborts from the launch pad
- Three aborts along the ascending trajectory
  - Nominal maximum dynamic load abort
    - Maximum dynamic pressure region
  - Minimum separation force
    - Transonic region
  - High Altitude Abort
    - Stage 1 burnout/Stage 2 ignition point

Ascent Abort 1 Overview

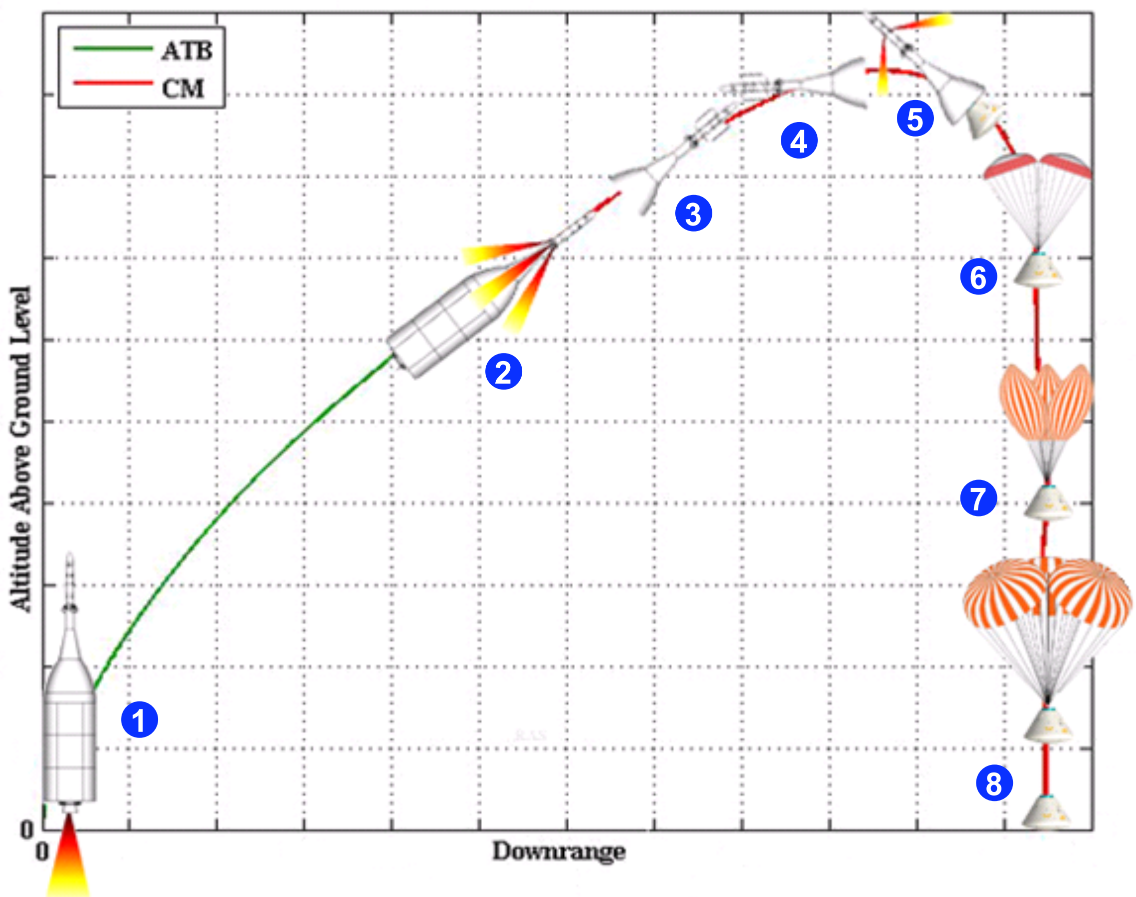
- Nominal maximum dynamic load scenario
- Targeting the maximum dynamic pressure region of the simulated Ares 1 trajectory
- An Abort Test Booster (ATB) will take the AA-1 LAV to the test conditions
- The ATB can release the LAV at any point within the test region
- Wide variety of initial conditions at LAV separation
- LAV must separate from ATB while staying within dynamic load limits



Ascent Abort 1 Timeline

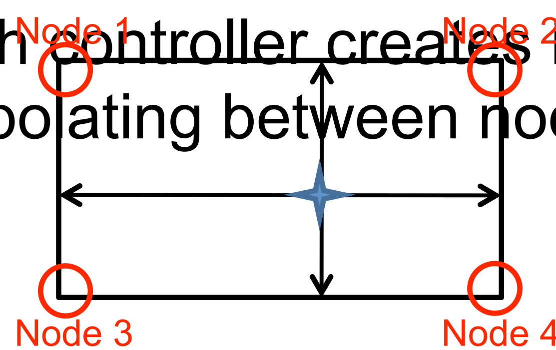
Project Orion Abort Flight Test

Event	Time Since Ignition (sec)	Event
1	0.000	ATB Liftoff
2	48.495	LAV Separation
3	63.495	Begin reorientation
4	69.159	End reorientation
5	75.495	Jettison tower
6	78.995	Deploy drogues
7	205.060	Deploy mains
8	486.888	CM touchdown



Problem Definition

- Tune open-loop pitch table to produce the best match to the designed total angle of attack profile
  - Profile designed to create separation distance between the LAV and ATB while staying within structural dynamics limits
  - Open-loop pitch controller is used for trajectory development and as backup to the closed-loop controller
  - Open-loop pitch controller one table to separate and another to transition into reorientation
  - Open-loop pitch controller creates individualized pitch profile by interpolating between nodes with defined pitch profiles



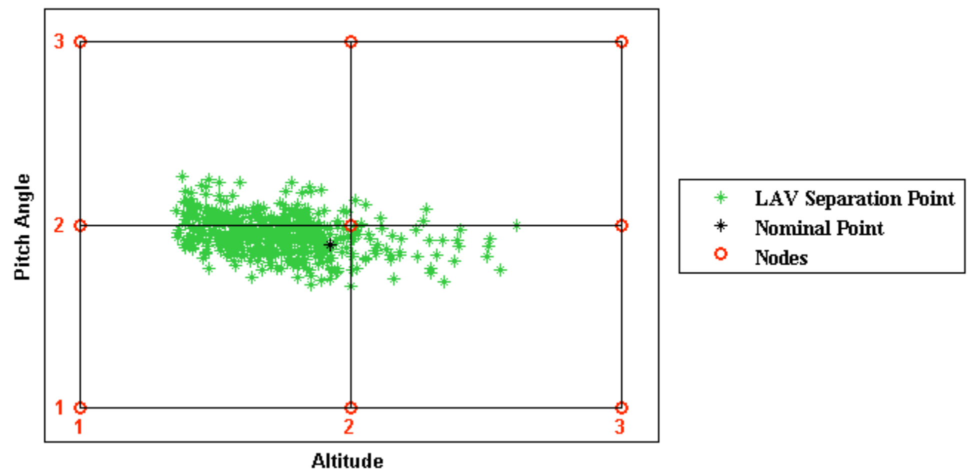
ANTARES

- Advanced NASA Technology Architecture for Exploration Studies (ANTARES)
  - NASA developed
  - Uses shuttle and Apollo heritage models
  - Created using the Trick simulation toolkit
  - Mission specific Orion simulations
  - Tracks objects in 3 or 6 degrees of freedom
  - Generated all trajectories that were analyzed
  - Simulation initialized at LAV separation point from ATB simulation

Project Orion Abort Flight Test

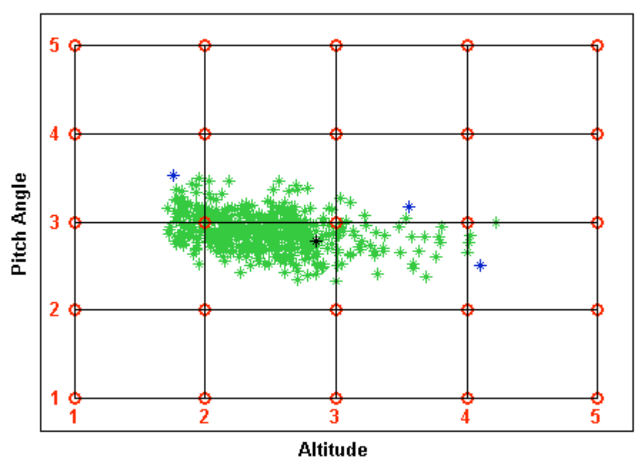
Methodology

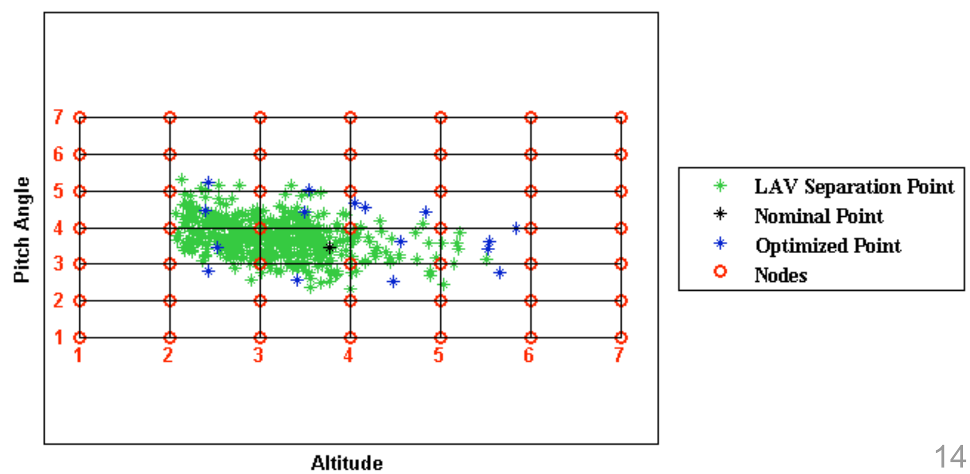
- Baseline
  - 3x3 pitch/altitude grid
  - Open-loop pitch table modified by hand using trial and error
  - Approximated designed total angle of attack profile in nominal trajectory
- Phase 1
  - Same 3x3 pitch/altitude grid
  - Open-loop pitch table modified iteratively by program
  - Only optimized nominal trajectory



Methodology cont.

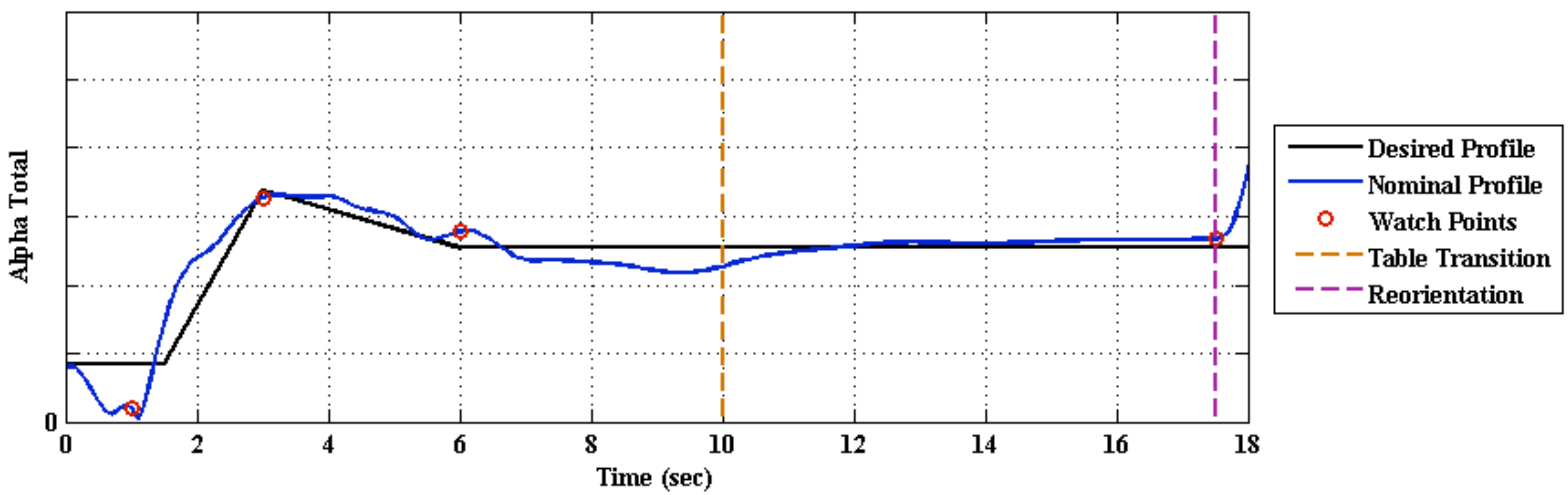
- Phase 2
  - 5x5 pitch/altitude grid
  - Open-loop pitch table modified iteratively by program
  - Optimized nominal trajectory and three off nominal trajectories
- Phase 3
  - 7x7 pitch/altitude grid with reduced spread
  - Open-loop pitch table modified iteratively by program
  - Optimized nominal trajectory and 16 off nominal trajectories





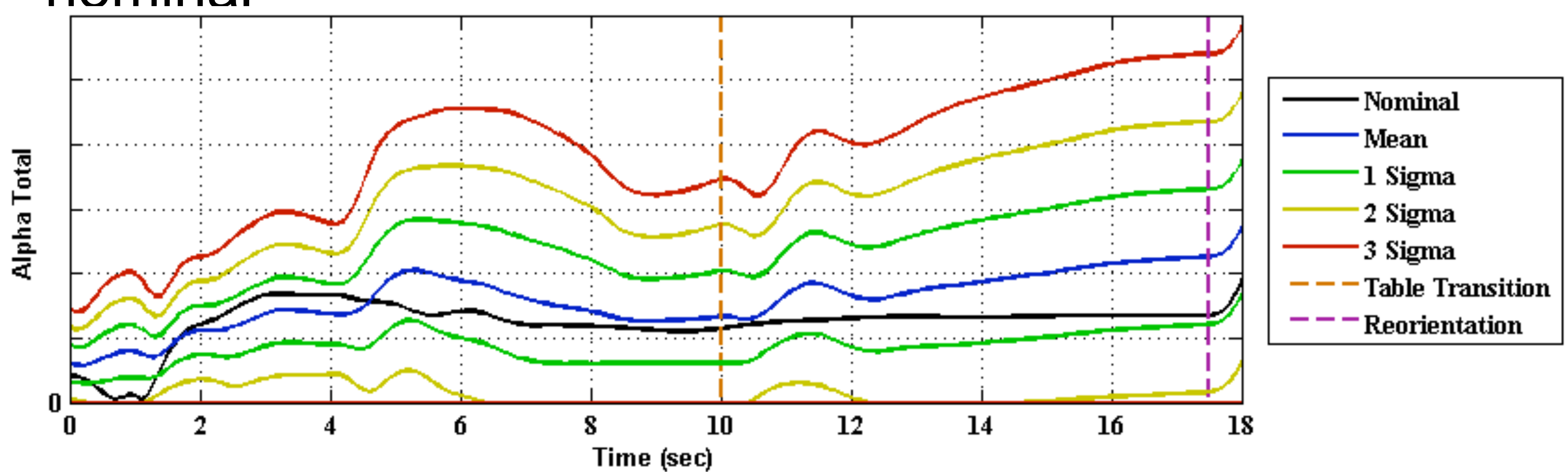
Baseline Results

- Manual table manipulation to obtain a smooth profile
- Alpha total profile monitored at 4 points
- Nominal profile roughly follows desired profile
- Secondary table follows better than primary table



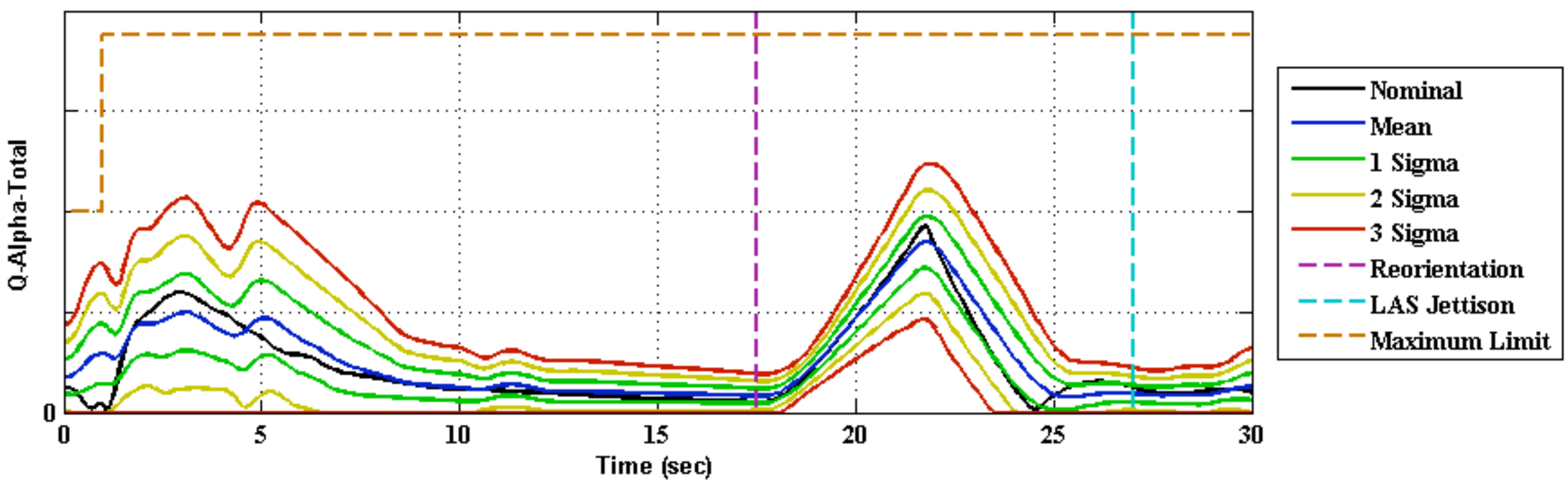
Baseline Results cont.

- Shows a large increase in alpha total when p-β controller is initialized
- Secondary table worked well for nominal, but not off-nominal
- Average difference between mean and designed profile is 26%
- Mean+3σ begins reorientation 320% greater than nominal



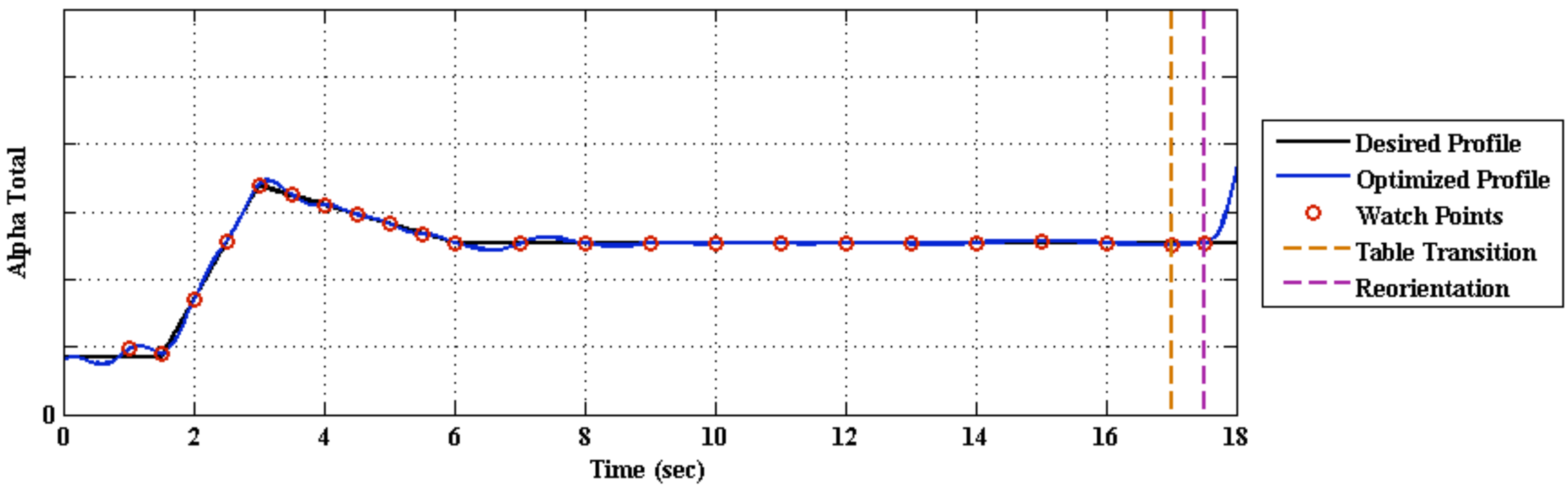
Baseline Results cont.

- 3σ line always stays within dynamic load limits
- < 26% margin in first second
- < 43% margin first second to reorientation
- < 34% margin during reorientation



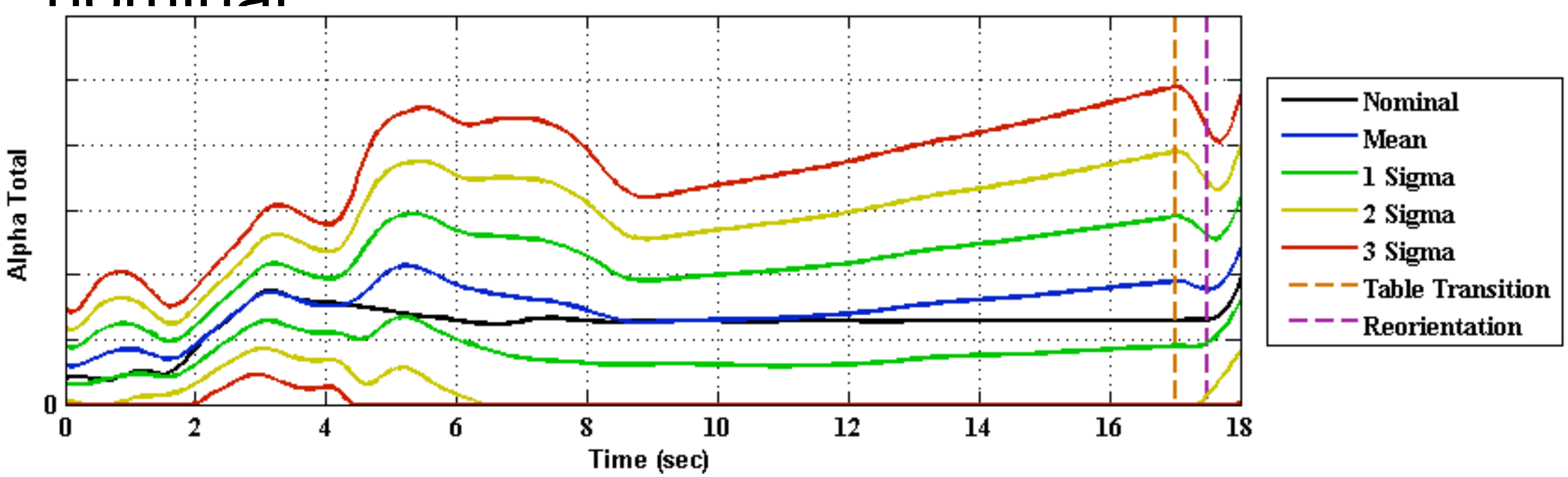
Phase 1 Results

- Program manipulated table
- Alpha total profile monitored at 24 points
- Nominal profile follows desired profile much better
- Secondary table reduced to last 0.5 seconds



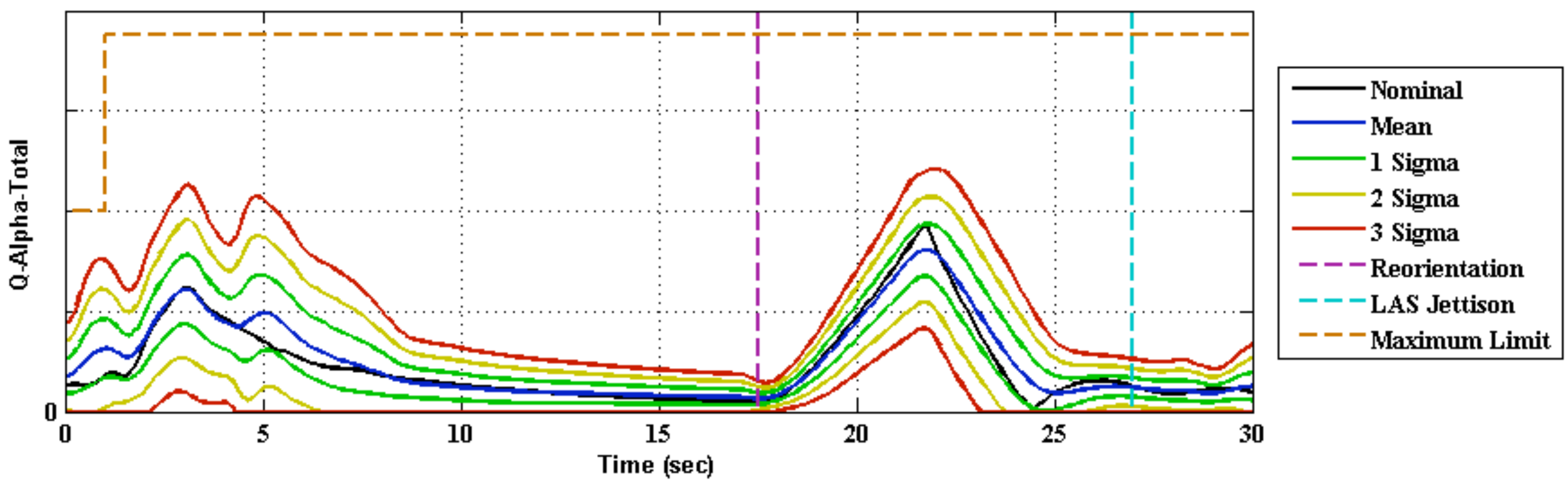
Phase 1 Results cont.

- Shows a large increase in alpha total when p-β controller is initialized
- Extension to optimized primary table worked better than baseline secondary table
- Average difference between mean and designed profile is 18%
- Mean+3σ pre-reorientation peak is 281% greater than nominal



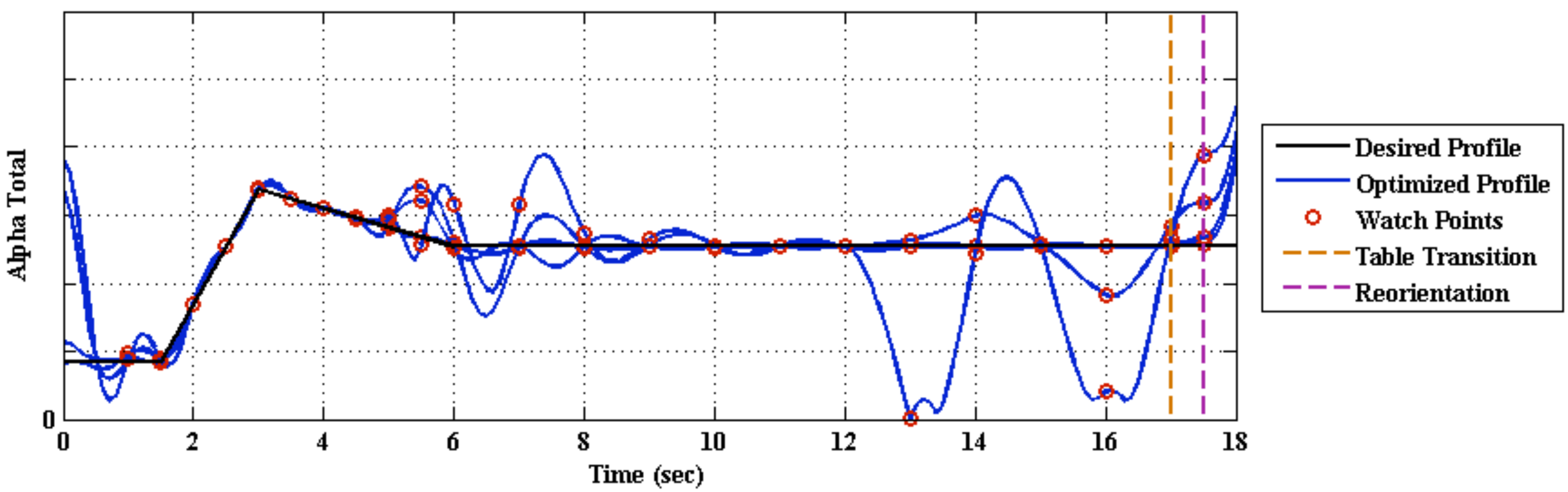
Phase 1 Results cont.

- 3σ line always stays within dynamic load limits
- < 24% margin in first second
- < 40% margin first second to reorientation
- < 35% margin during reorientation
- Slightly less margin than baseline



Phase 2 Results

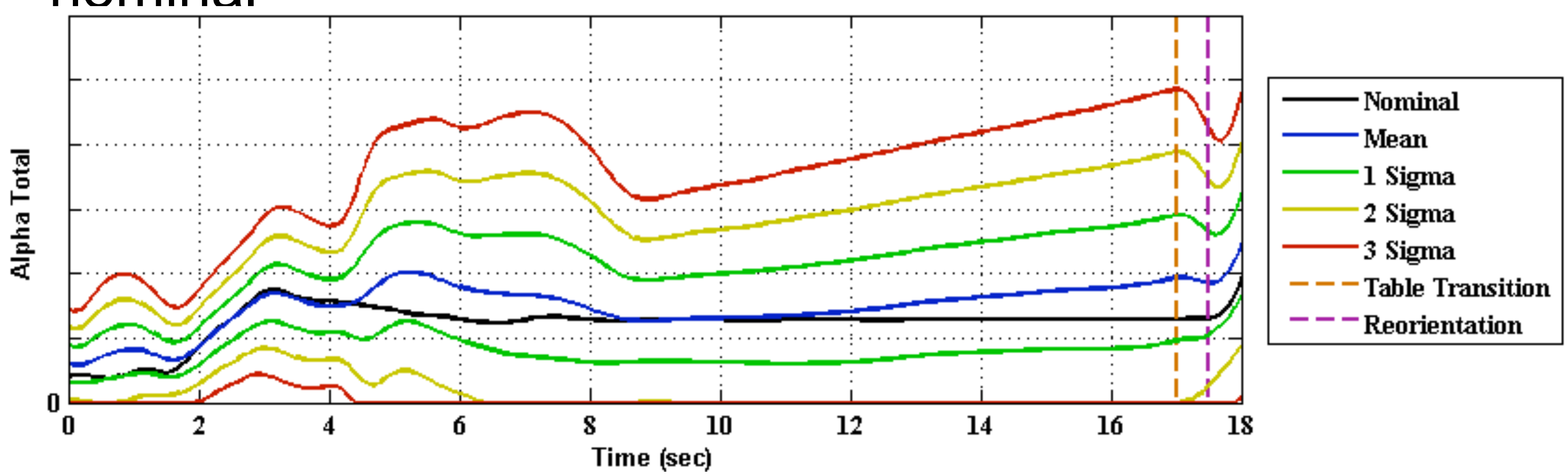
- Program manipulated table
- Alpha total profile monitored at 24 points
- Secondary table reduced to last 0.5 seconds
- Three off-nominal trajectories included
- Off-nominal controlled 3 surrounding nodes



Project Orion Abort Flight Test

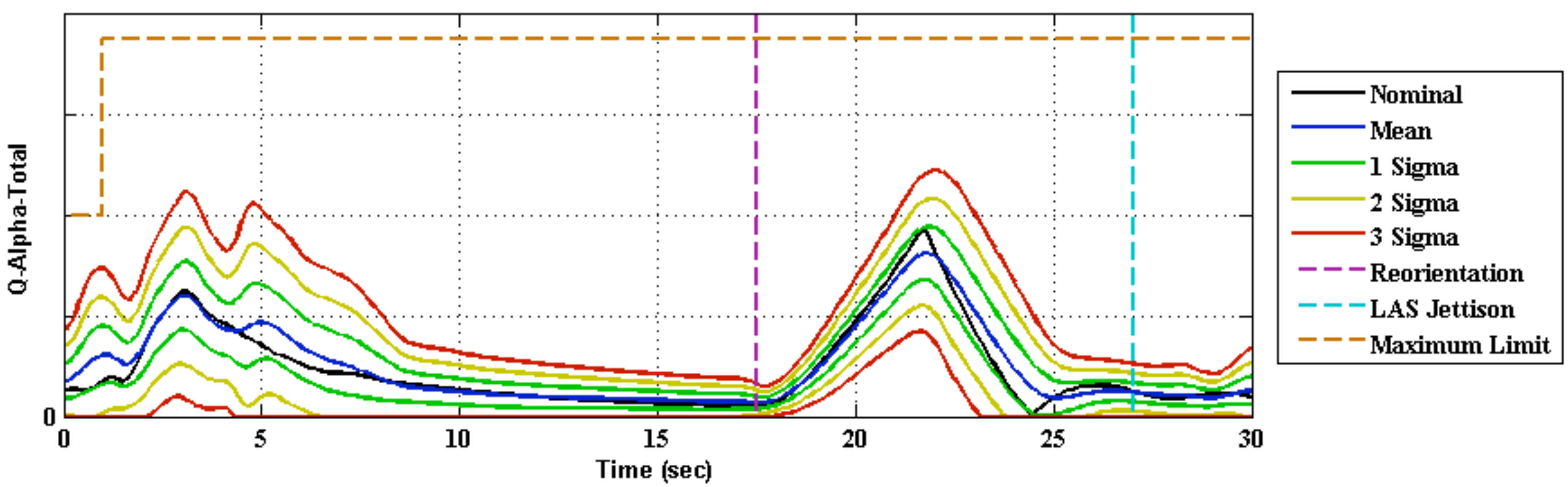
Phase 2 Results cont.

- Shows a large increase in alpha total when p-β controller is initialized
- Including three off-nominal trajectories slightly improved the off-nominal distribution
- Average difference between mean and designed profile is 17%
- Mean+3σ pre-reorientation peak is 277% greater than nominal



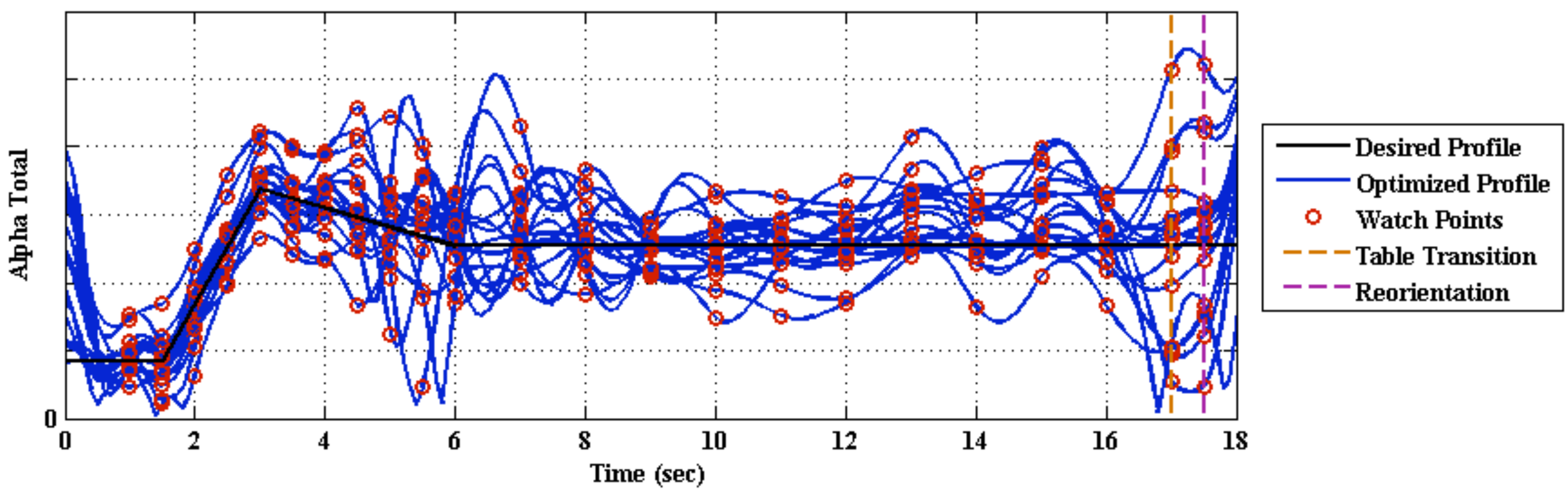
Phase 2 Results cont.

- 3σ line always stays within dynamic load limits
- < 26% margin in first second
- < 41% margin first second to reorientation
- < 35% margin during reorientation
- Approximately the same margin as baseline



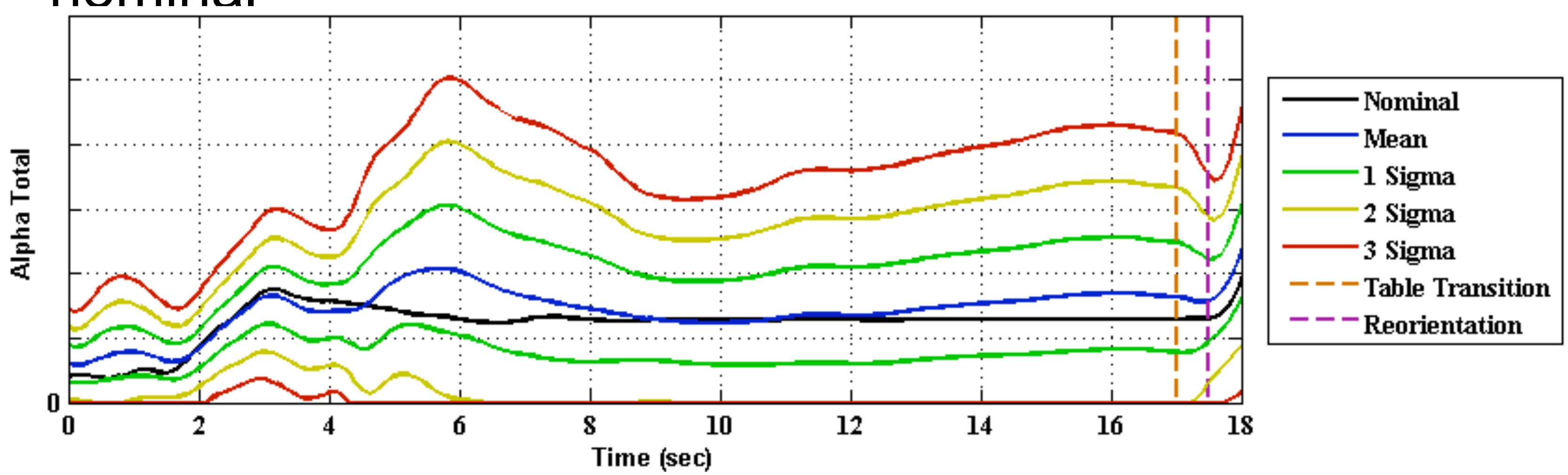
Phase 3 Results

- Program manipulated table
- Alpha total profile monitored at 24 points
- Secondary table reduced to last 0.5 seconds
- 16 off-nominal trajectories included
- Average deltas from off-nominal applied to nodes



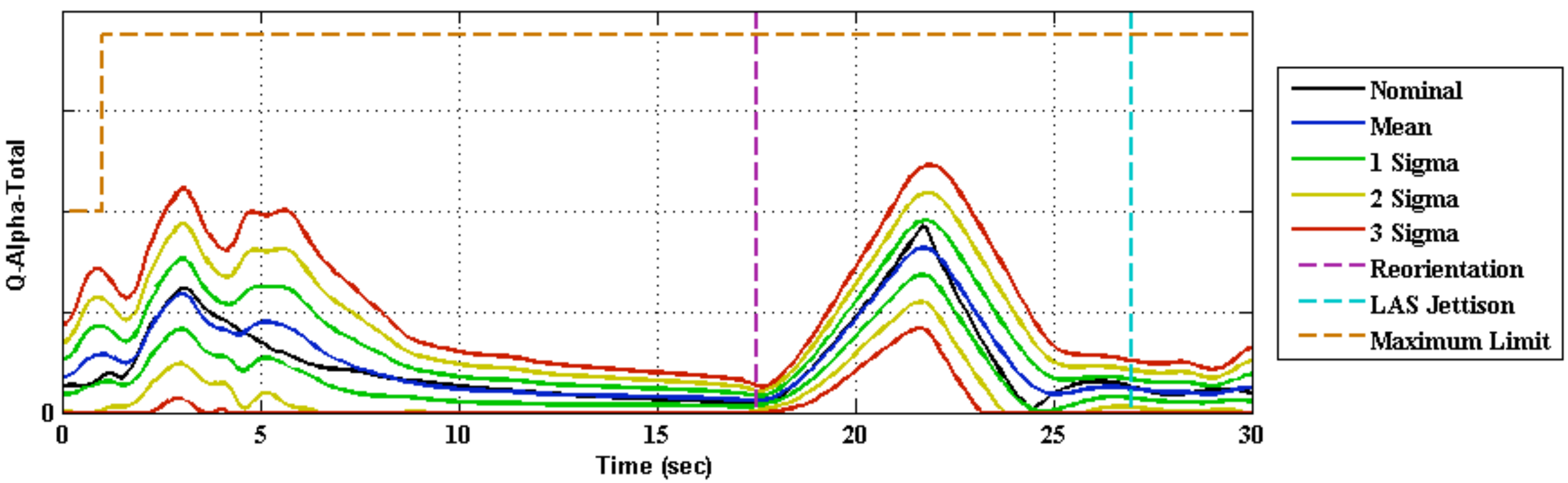
Phase 3 Results cont.

- Shows largest increase in alpha total when p-β controller is initialized of all phases
- Including sixteen off-nominal trajectories provided more improvement in off-nominal distribution
- Average difference between mean and designed profile is 13%
- Mean+3σ pre-reorientation peak is 234% greater than nominal



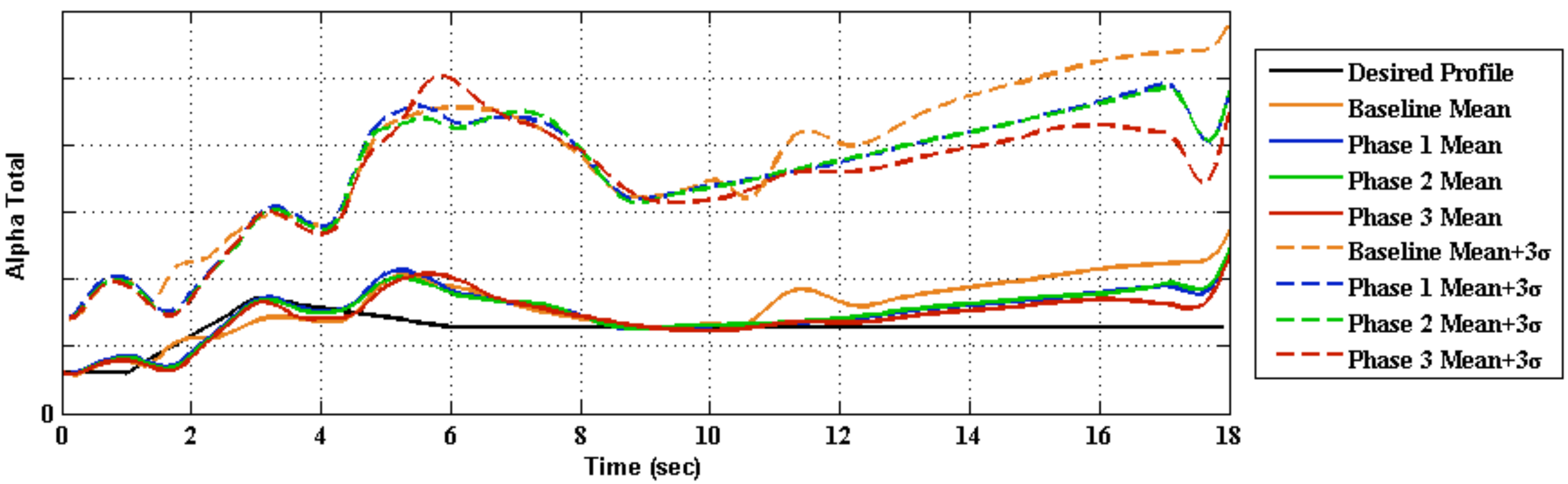
Phase 3 Results cont.

- 3σ line always stays within dynamic load limits
- < 29% margin in first second
- < 41% margin first second to reorientation
- < 34% margin during reorientation
- Slightly better margin than baseline



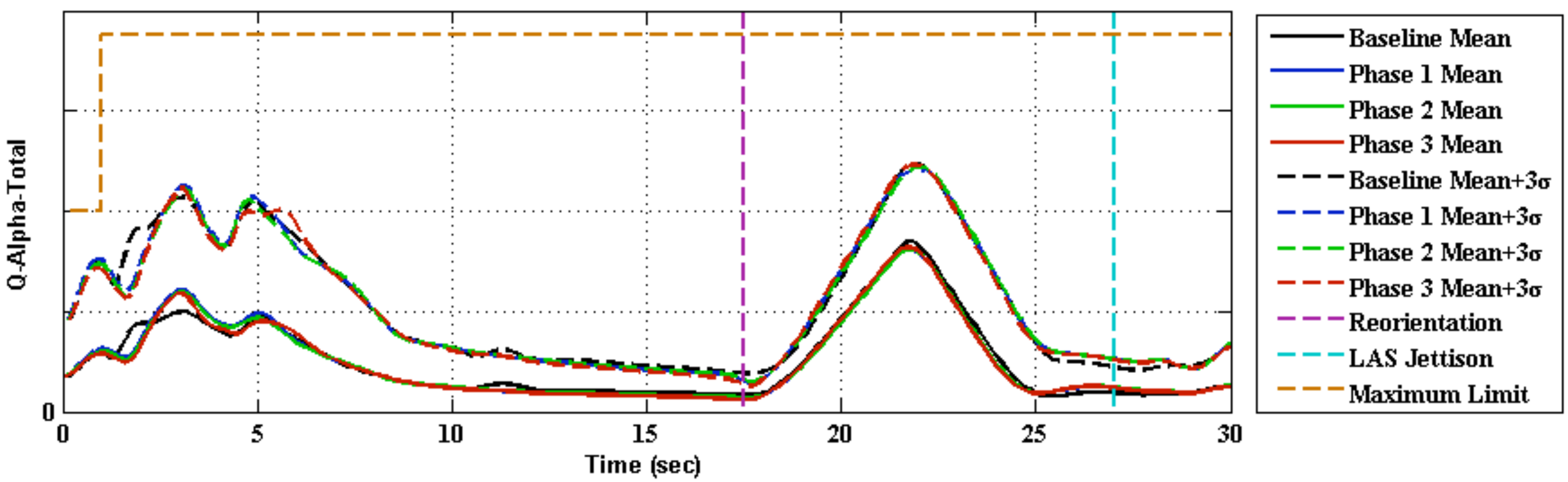
Overview Results

- Considerable improvement between baseline and phase 1
- Minimal improvement between phase 1 and phase 2
- Some improvement between phase 2 and phase 3



Overview Results cont.

- Mean dynamic load margin
  - Decreased in optimized profile at ~3 seconds
  - Generally unchanged elsewhere
- +3σ dynamic load margin slightly improved or unchanged in optimized profile



Summary

- Phase 1
  - Provide a better, faster fit to the desired alpha total profile
- Phase 2
  - Optimized 3 off-nominal trajectories, but provided little overall improvement
- Phase 3
  - Optimized 16 off-nominal trajectories and provided overall improvement
- Dynamic loads margins remained nearly constant through all phases

Questions

Questions?