ARES I-X TEST FLIGHT REFERENCE TRAJECTORY DEVELOPMENT

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ABSTRACT

Ares I-X was the first test flight of the Ares I crew launch vehicle, part of NASA's Constellation Program. One of the test flight's five primary objectives was to demonstrate controllability of an Ares I vehicle during first stage boost. In order to demonstrate controllability, the Ares I-X ascent control algorithms had to maintain stable flight throughout a flight environment similar to Ares I. The Ares I propulsion was under development at the time of the test flight; thus, Ares I-X made use of an existing Reusable Solid Rocket Motor from the Space Shuttle Program for its First Stage and had an inert Upper Stage. Because the Ares I First Stage propulsion would have a different thrust profile and higher total impulse, the goal of the test flight reference trajectory development was to design a boost trajectory with a dynamic pressure versus Mach number profile similar to Ares I. A trajectory similarity metric was defined as the integrated difference between the Ares I and Ares I-X dynamic pressure versus Mach number relationships. This metric was minimized over a range of launch months by adjusting the Ares I-X ascent steering profile and weight. The analyses determined the Ares I dynamic pressure versus Mach number relationship could be matched for launches throughout the year.

INTRODUCTION

One objective of NASA's Constellation Program (CxP) was to develop vehicles to meet the goals set forth in the US Space policy "Vision for Space Exploration." CxP initiated the development of the Ares I Crew Launch Vehicle (CLV) for transporting crews to low Earth orbit. Ares I was designed as a two stage to orbit vehicle that utilized heritage propulsion elements from the Space Shuttle Program (SSP) and Saturn V. The Ares I First Stage (FS) design consisted of a five-segment reusable solid rocket motor (RSRM) derived from the SSP four-segment RSRM. The Upper Stage (US) design consisted of a liquid propellant stage with a J2X engine derived from the J2 engine flown on the Saturn V. The Ares I FS was 167 feet in length with a diameter of 12 feet, while the US length was 154 feet with a nominal diameter of 18 feet. The rocket's long, slender geometry and center-of-gravity well aft of its center-of-pressure presented aerodynamic instability and structural flexibility problems that would require a robust control system to maintain stable flight.

CxP established a test and verification strategy in the development of its vehicles as outlined in the "*Constellation Program Integrated Flight Test Strategy Document*" [1] and created a Flight Test Program in support of that strategy. The Flight Test Program included a full-scale integrated flight test of the Ares I CLV to support its design analysis cycles (DACs). The flight test, named Ares I-X, was intended to mitigate technical risks such as controllability by providing a means to validate simulation models used in the Ares I DAC cycles and by determining how the hardware and software performed in an actual flight environment. The key operational systems, such as roll control and avionics, were integrated into the flight test vehicle (FTV). The Ares I propulsion systems were not available for integration into the FTV at the time of the test and as a result, a lower impulse SSP four-segment RSRM was used for the FS with an inert 5th segment simulator (5SS) added to maintain an OML similar to the operational vehicle. The US did not include propulsion and was an inert simulator. With only FS propulsion, the test flight was suborbital. The test focused on flight during the boost phase, stage separation, and FS reentry. There were no test objectives for the US following separation.

The primary test objectives were defined in the "*Constellation Program Ares I-X Flight Test Plan*"[2] as:

1. Demonstrate control of a vehicle dynamically similar to the Ares I/Orion vehicle using Ares I relevant flight control algorithms.

2. Perform an in-flight separation/staging event between Ares I similar First Stage and a representative Upper Stage.

3. Demonstrate assembly and recovery of a new Ares I like First Stage element at KSC.

4. Demonstrate First Stage separation sequencing and quantify First Stage atmospheric entry dynamics and parachute performance.

5. Characterize magnitude of the integrated vehicle roll torque throughout First Stage flight.

The FTV trajectory was instrumental in meeting test objectives 1, 2, 4, and 5, in that it defined the flight environment necessary to meet those goals. Since the flight test used a full-scale vehicle, the test flight environment had to be similar to that of the operational vehicle to provide equivalent aerodynamic, buffet, and thermal loads. Trajectory shaping techniques were used to develop a reference trajectory that provided an Ares I equivalent flight environment for as long as possible with the lower impulse FS. The available shaping parameters were optimized to minimize the difference between the FTV trajectory that results from using the four-segment FS rather than the Ares I five-segment FS.

FLIGHT TEST VEHICLE OVERVIEW

The FTV, shown in Figure 1, was a full-scale representation of the Ares I CLV vehicle with an active FS but with inert simulators of the US and Crew Exploration Vehicle (CEV). The FTV outer mold line (OML) was similar to the Ares I DAC-2 design with only small differences between their protuberances and the spacecraft adapter (SA) transition. The overall length, individual stage lengths, and stage diameters were the same. The FTV OML is documented in "*The Ares I-X Flight Test Vehicle Outer Mold Line Definition.*"[3] The use of a SSP four-segment RSRM required an inert 5th segment simulator (FSS) to be added to the FS to maintain an OML similar to the operational vehicle. No propulsion was used in the US making it an inert Upper Stage Simulator (USS). The USS did not contain fuel tanks but instead had provisions to mount steel plates near its forward and aft ends to ballast it to the weight required to meet test objectives and to control the complete stack C.G. location. The FTV represented the Ares I Service Module (SM), Crew Module (CM), and Launch Abort System (LAS) components with a Crew Exploration Vehicle Simulator (CEVS) that had no propulsion, avionics, or Ares I flight systems. The CEVS had no operational joints between components, i.e. no provision for separation, and no attempt was made to match the mass properties of the individual CEVS components to those of the Ares I SM, CM, and LAS. The total weight of the FTV was not constrained to match Ares I, since it used a lower impulse FS. Instead, the total weight was defined by the trajectory optimization analysis discussed in the following sections. In the optimization analyses, the weight of all components not associated with the RSRM was considered to be a single design parameter that could be varied to define the ignition weight. Their combined weight is referred to as simulator weight in this paper, to distinguish it from the ballast placed inside the USS. The USS ballast was adjusted to match the center of gravity location and mass moments of inertia of the fully integrated Ares I vehicle to within values specified by the Ares I-X System Requirements Document.
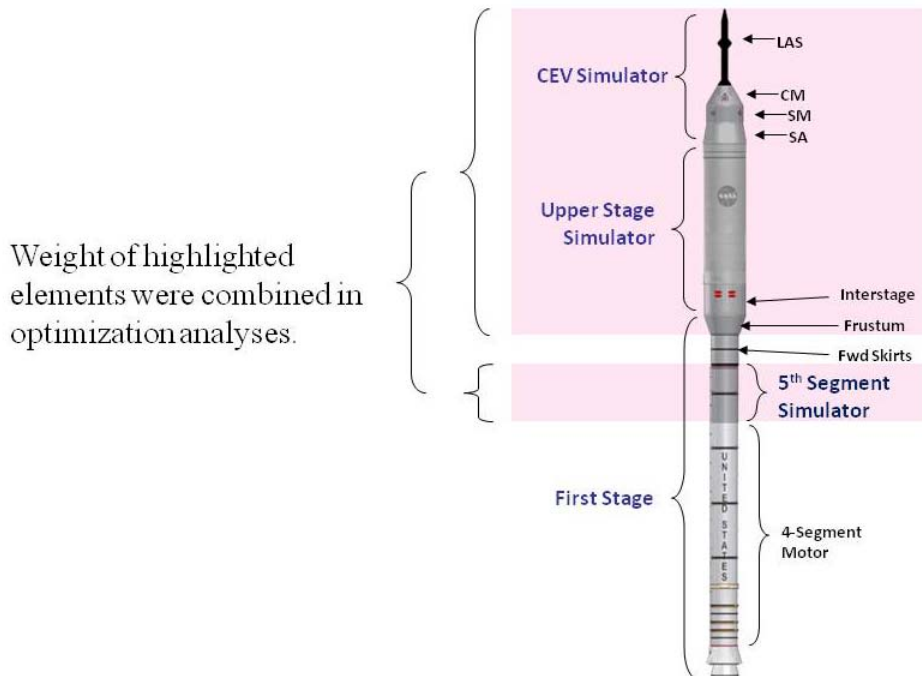
Figure 1 Ares I-X Flight Test Vehicle

FLIGHT LOAD SIMILARITY

To meet the primary test objective of demonstrating controllability of the Ares I design, the FTV's flight control system had to control both rigid body and flexible body dynamics similar to the operational vehicle and maintain stable flight. The control system was required to maintain a prescribed vehicle attitude as a function of altitude without large overshoots or oscillations, while damping the vehicle's first bending mode to prevent adverse interactions between its flexible structure and thrust vector control. The FTV control system is documented in "*Control Algorithm and Parameters for the Ares I-X Flight Test Vehicle.*"[4] The dynamics are a function of the vehicle's response to flight loads, and since the FTV was a full-scale representation of Ares I, its flight loads had to be similar to those of Ares I to produce similar dynamics. The dynamics due to aerodynamic flight loads affected controllability. The axial acceleration produced by the thrust does not affect the flight control system's ability to maintain stable flight. Similar aerodynamic loads are required to demonstrate controllability but similar acceleration loads are not required. The aerodynamic loads are a function of dynamic pressure and Mach number; thus, the FTV must fly a trajectory with a dynamic pressure vs. Mach number (Mach-q) relationship similar to that of Ares I to be subjected to similar aerodynamic loads.

The aerodynamic loads are influenced to a lesser extent by the vehicle's flight orientation and flight heading. The orientation influenced aerodynamic loads due to slight OML asymmetries arising from its protuberances. The flight heading. relative to the predominant wind direction at Kennedy Space Center (KSC), affected aerodynamic loads due to the headings effect on atmospheric relative velocity and angle of attack. To account for those influences and to maintain similarity with Ares I, the FTV vehicle orientation during ascent and trajectory heading would need to be matched to the operational vehicle. With equivalent loads and a dynamically similar vehicle (inertia and modal characteristics), the FTV dynamic response would be similar to Ares I and would provide a relevant test environment for demonstration of the adequacy of the flight control algorithms.

RESULTS AND DISCUSSION

The FTV trajectory was designed to match the boost segment of the Ares-I Exploration Mission that inserts the CM into a -30X100 nmi, 28.5° inclination orbit. A three-degree-of-freedom FTV trajectory simulation was developed with the Program to Optimize Simulated Trajectories (POST II)[5] and was used to define FTV ignition weight and pitch attitude steering commands that would provide the best possible match of the Ares I trajectory given its lower impulse FS. Matching the Ares I heading, vehicle orientation, and ascent sequence was trivial in that they were prescribed in the simulation by constraining the FTV to fly in the Ares I ascent plane in a heads down orientation with the same sequence of events. The FTV's launch azimuth was made an independent control variable that was adjusted to satisfy the ascent plane constraint. A launch azimuth of approximately 88.2 degrees was required to ascend in the Ares I plane. In the test flight, the FTV would be mounted on the mobile launch platform (MLP) using the SSP FS hold down posts, which results in a heads pointing South orientation. The MLP was to be modified to accommodate the Ares I heads pointing East mounting, but was not done for the test flight, since the MLP was still in use for Shuttle launches. The FTV would roll approximately 91.8 degrees after clearing the tower to put it in the Ares I ascent plane with a heads down orientation. In the optimization simulation, the FTV mounting on the hold down posts and subsequent roll maneuver was not modeled. Instead, the FTV was aligned with heads pointing along the launch azimuth at ignition to put it in the Ares I ascent plane in a heads down orientation on the pad. This was done so that the zero angle of attack constraint could be enforced in the simulation. The 90-degree roll required more time to complete than the pitch-over maneuver, resulting in roll continuing into the period of zero angle of attack flight. The simulation could not enforce zero angle of attack flight relative to the pitch plane in the presence of roll, since the body XZ plane did not coincide with the pitch plane. The roll did not affect the pitch maneuver; thus, for optimization purposes, the FTV was simulated being in the pitch plane from liftoff. Once the optimal pitch attitude was determined, the FTV roll was superimposed onto it. The FTV ascent sequence was defined to follow the Ares I 3-DOF reference trajectory sequence up to FS separation. The ascent sequence was as follows: after ignition, the FTV performed a 350 feet vertical rise with fixed inertial attitude to clear the tower. After tower clear, a pitch-over maneuver was performed to start down range flight in the Ares I orbital plane in a heads down orientation. The pitch-over maneuver ended with a transition to zero angle of attack flight when dynamic pressure reached 150 psf. Zero angle of attack flight was maintained until FS burn out at approximately 125 seconds. The ascent simulation was terminated at FS burnout, since its burnout ended controlled flight.

A match of the Ares I ascent trajectory's Mach-q relationship could not be obtained using the Ares I pitch attitude steering commands due to the FTV's four-segment RSRM providing 18% less impulse than the Ares I five-segment RSRM. A comparison of the four and five-segment RSRM thrust is shown in Figure 2. The four and five-segment thrust time histories are documented in the ATK Launch Systems reports "*Ares I-X Ballistic Performance Prediction Summary*"[6] and "*1st Stage Final Ballistics Prediction For Crew Launch Vehicle Design and Analysis Cycle One*"[7] respectively. To compensate for the FTV's lower FS impulse in matching Mach-q, its ignition weight and pitch attitude during ascent were defined using the trajectory optimization capabilities of the POST 3-DOF simulation. The optimization process used the simulator weight and pitch attitude as independent control variables to shape the trajectory and to provide the best possible match of the Ares I Mach-q relationship. The FTV could be built to the weight required to match the Ares I Mach-q, since the USS was an inert stage with no fuel tanks that could be ballasted to a desired weight. The only constraint was that its weight could not exceed the load bearing capability of the FS and frustum. The pitch attitude could also be defined as needed; however, the zero angle of attack constraint (which was active from the time dynamic pressure reached 150 psf to FS burnout) limited control of the pitch attitude to the pitch-over maneuver. During the zero angle of attack phase of flight, also referred to as a gravity turn, the RSRM thrust was directed parallel to the FTV's velocity vector (excluding trim deflections), and the force due to gravity turned the flight path. The rate at which gravity turned the flight path determined how steeply the FTV ascended through the atmosphere and thus defined its pitch attitude during the ascent and its Mach-q relationship. Adjustment of the pitch-over maneuver

pitch rate was sufficient to control the Mach-q relationship, since small changes in the pitch attitude at the end of the pitch-over had a large effect on the rate at which gravity turned the flight path.
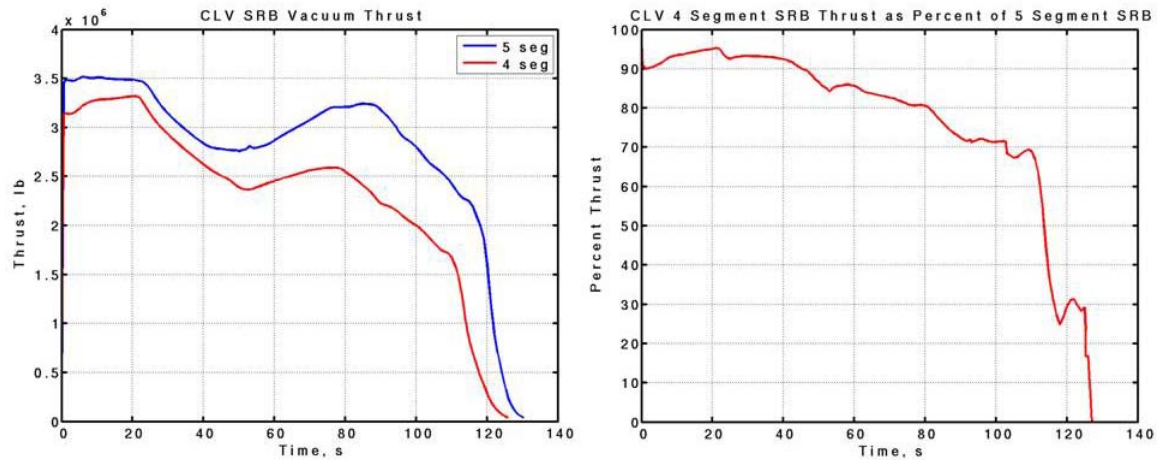

Figure 2 SSP Four-segment RSRM Thrust vs. Ares I Five-segment RSRM Thrust

An optimization metric was defined as the value of the integral of the absolute difference between the FTV and Ares I Mach-q relationships from lift-off up to Mach 4.0. After Mach 4.0, the RSRM reached the end of its web time, approximately 115 seconds, where burnout conditions began and thrust dropped rapidly. The loss of performance during burnout made it infeasible to match the Ares I Mach-q during that period; thus, it was not included in the metric. The metric was minimized using the available independent control variables of the simulator weight and pitch rate during the pitch-over maneuver. The optimal Mach-q match with the maximum simulator weight and ascent plane constraints enforced is shown in Figure 3 for mean annual atmospheric conditions and FS propellant mean bulk temperature (PMBT). The independent control variables are summarized in Table 1. The FTV matched the Ares I Mach-q to within 18 psf or less up to Mach 4.0 with a maximum dynamic pressure (max-q) of 834 psf and a separation dynamic pressure (sep-q) of 134 psf. The max-q was within 98% of Ares I and would limit maximum aerodynamic loads to Ares I levels. However, the sep-q was six times higher than Ares I and would present a risk of stage recontact during the separation maneuver. The ignition weight of 1,844,034 lb was 151,692 lb less than Ares I and was within the load capabilities of the FS motor segments.
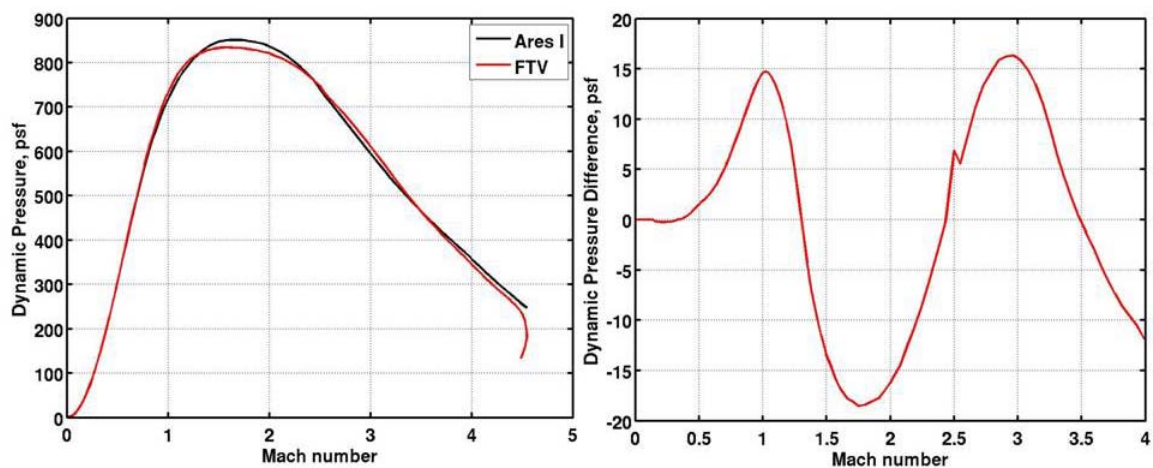

Figure 3 Optimal Mach-q Match for Yearly Mean Atmosphere and PMBT

Table 1 Optimal Mach-q Match Control Parameters for Yearly Mean Atmosphere and PMBT

Ignition Weight / Simulator Weight (lb)	Pitch Rate (degrees/second)
1,844,034 / 500692	1.338

The FTV altitude, sensed acceleration, and ground relative pitch attitude profiles for the unconstrained optimal match trajectory are compared to Ares I profiles in Figure 4 through Figure 6. The altitude versus Mach number (Mach-alt) relationship shown in Figure 4 is equivalent to the Mach-q relationship, because density is a function of altitude, and dynamic pressure is a function of density. The FTV altitude as a function of Mach number is within 770 ft or less of the Ares I altitude through Mach 4. The FTV sensed acceleration, shown in Figure 5, is within 0.05g of Ares I through Mach 1.0, which occurs at approximately 40 seconds. The close agreement is a result of the FTV thrust to weight ratio being approximately the same as Ares I up to Mach 1. The FTV's lower thrust during the first forty seconds of burn was offset by its lower weight. After Mach 1.0, the FTV sensed acceleration diverges from Ares I due to the FTV's thrust as a percentage of the Ares I thrust decreasing throughout the remaining burn (Figure 2), and due to the four-segment's lower mass flow rate. Because of its lower acceleration after Mach 1.0, the FTV climbed over a longer period of time to achieve the Mach-alt and Mach-q matches. For example, Ares I reached its Mach 4 altitude in 90 seconds, whereas the FTV required 101 seconds; thus, the FTV had to fly at a lower pitch attitude than Ares I to maintain the same Mach-alt relationship. The comparison of the Ares I and FTV pitch attitudes is shown in Figure 6.
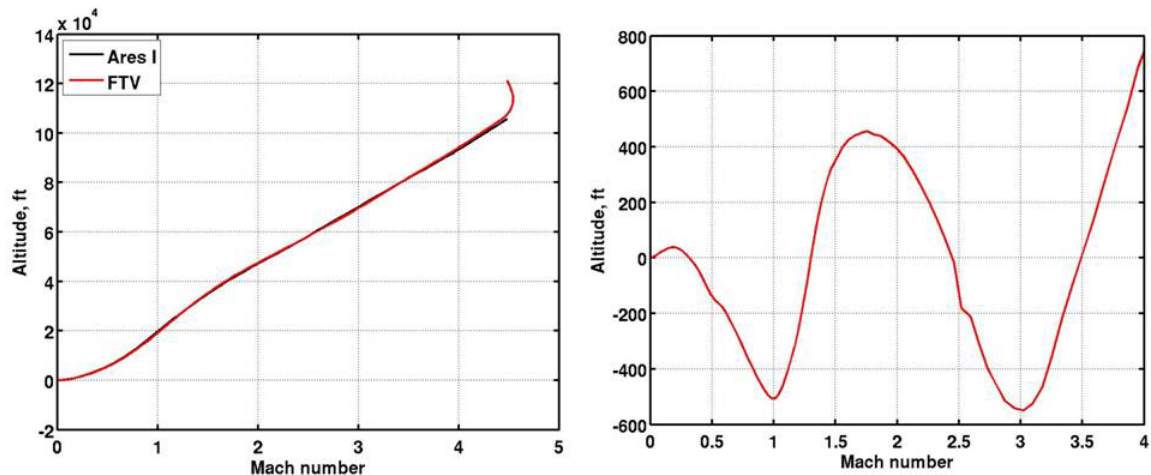

Figure 4 FTV vs. Ares I Altitude, Optimal Mach-q Match with Yearly Mean Values
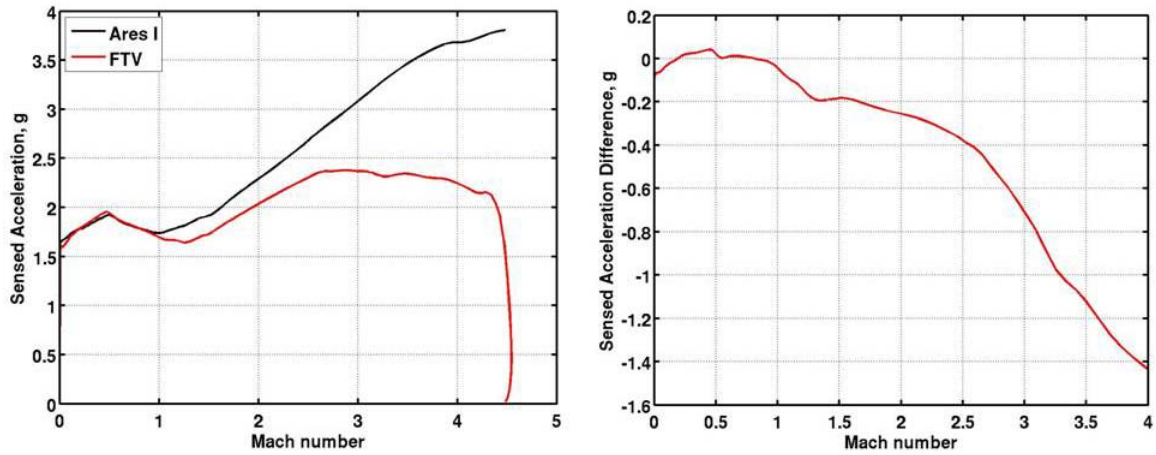
Figure 5 FTV vs. Ares I Sensed Acceleration, Optimal Mach-q Match with Yearly Mean Values
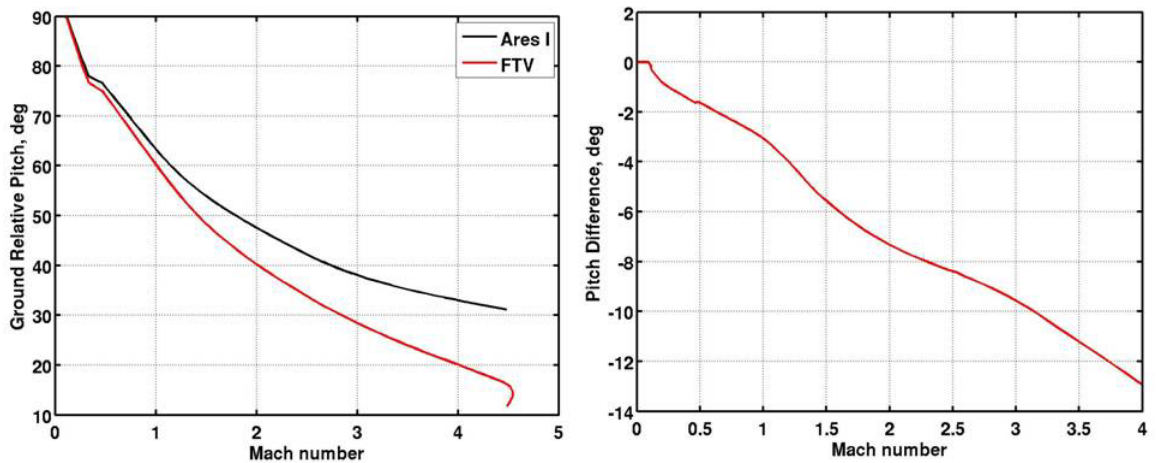

Figure 6 FTV vs. Ares I Pitch Attitude, Optimal Mach-q Match with Yearly Mean Values

A trade study was conducted to determine how much the Mach-q match would degrade if the FTV trajectory were altered to better match the Ares I sep-q. The optimization analysis was repeated with sep-q constrained to 100 psf, 75 psf, 50 psf, and 22 psf (the Ares I sep-q). The trade study results are plotted in Figure 7 and summarized in

Table 2. Constraining sep-q resulted in an overall degradation of the Mach-q match, including higher FTV max-q values and FTV max-q occurring at a Mach number approximately 0.25 lower than Ares I.
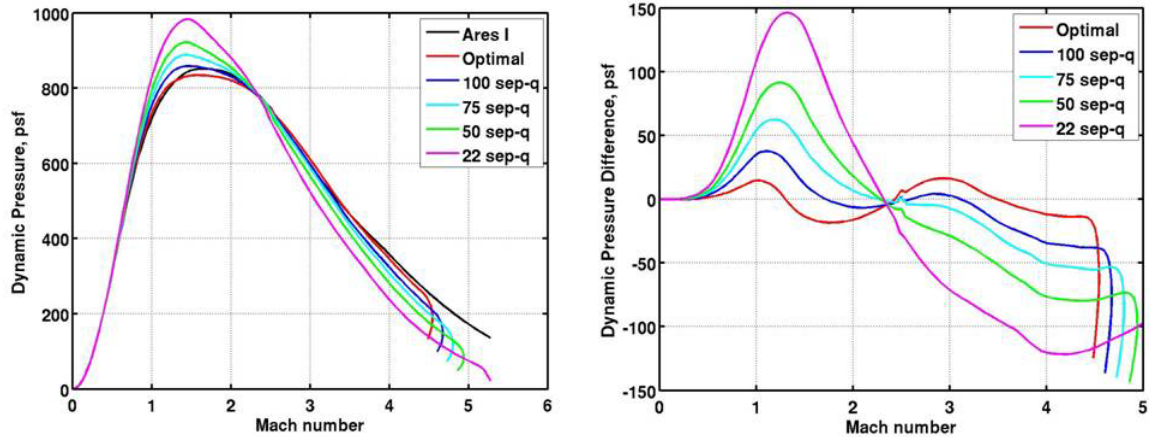
Figure 7 Effect of q-sep Constraint on Mach-q Match, Yearly Mean Values

Table 2 Summary of Trajectory Parameters From Sep-q Trade Study

	Optimal	**100 psf sep-q**	**75 psf sep-q**	**50 psf sep-q**	**22 psf sep-q**
Simulator weight (lb)	500,692	471,555	443,640	411,886	353,878
Ignition weight (lb)	1,844,038	1,814,901	1,786,987	1,755,233	1,697,225
Pitch rate (deg/s)	1.338	1.435	1.533	1.640	1.831
Max-q (psf)	834	859	888	922	983
Increase in Integrated Mach-q difference (psf-s)	baseline	51	167	336	635

A response surface was created to provide additional insight into the design space and to provide verification of the optimization analyses. Generation of the response surface was straightforward since there were only two independent control variables. Simulations were run with more than 2500 combinations of the independent control variables over ranges of simulator weight from 350,000 lb to 525,000 lb and pitch rate from $1°$/s to $2°$/s. The response surface is presented in Figure 8 with the optimization metric shown as color contours. Contour lines of constant max-q (black lines) and constant sep-q (white lines), as well as points representing the optimization solutions discussed previously, are superimposed onto it. The metric is a smooth function of the independent variables with a single valley, making it suitable for gradient-based optimization algorithms. The region where the metric is minimized is located between the 800 and 851 max-q contour lines and the 100 and 200 psf sep-q contour lines. The purple triangle represents the optimal solution with the Ares I ascent plane and maximum simulator weight constraints, but no sep-q constraint. The orientation of the optimal region relative to the sep-q lines indicates that sep-q cannot be lowered to the Ares I value of 22 psf without significantly increasing the optimization metric, which would lead to a worse match between the FTV and Ares I trajectories. The response surface also indicates that the only feasible way to decrease sep-q is by reducing simulator weight on the order of tens of thousands of pounds and to increase pitch rate by tenths of a degree per second, such that their combination moves along the valley floor as indicated by the colored circles. The colored circles represent the optimal solutions with the various sep-q constraints applied. Reducing sep-q also results in higher max-q values. Reducing the simulator weight would enable a higher separation altitude in order to reduce sep-q, but the higher acceleration would also result in a higher max-q value. The optimization solutions discussed previously are in good agreement with the response surface.
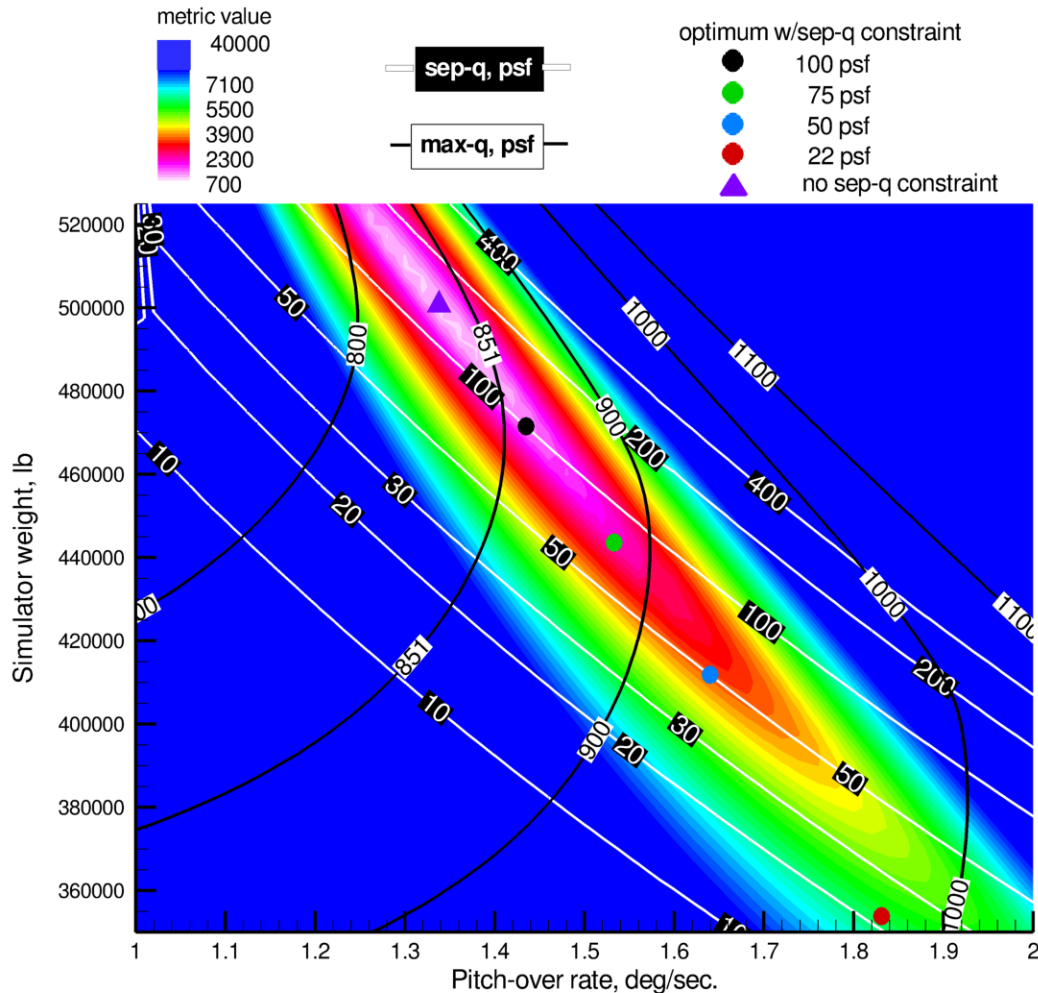
Figure 8 Optimization Metric Response Surface for Mean Annual Conditions

Designing the nominal trajectory with a max-q that was 10% or more above Ares I presented a risk to controllability and to structural integrity due to max-q dispersions expected from vehicle and atmospheric uncertainties. As a result, the test program did not consider the 50 psf and 22 psf sep-q trajectories to be viable options. The 100 psf and 75 psf sep-q trajectories were within 1% and 4% of Ares I max-q, respectively, and were studied further. ATK structural analyses determined the frustum and forward skirt could support the combined USS and CEVS weight required for the 100 psf and 75 psf sep-q trajectories. The Ares I-X Guidance, Navigation, and Control (GNC) team performed a separation analysis of the 100 psf sep-q trajectory to determine stage dynamics during separation and to quantify the risk posed to separation. The analysis results showed that the FS and USS attitudes remained stable during separation as long as the FTV angular rates were nulled prior to separation. The analysis is documented in the Ares I-X Systems Requirements Review presentation "*Stage Separation – 4400*" [8]. Nulling the FTV rates in preparation for the separation maneuver had been planned by the GNC team, and studies confirmed there was sufficient control authority to do so; thus it was concluded that a successful separation could be performed at 100 psf. To fully demonstrate controllability, it was necessary to match Mach-q as closely as possible up to separation to capture the effects of changing mass properties (C.G. location and inertia) and control law gain scheduling on controllability. The 100 psf sep-q trajectory provided the best match up to separation and had a

max-q approximately equal to Ares I; thus, the Flight Test Program chose it as the baseline and accepted the separation risk for the benefits of more fully demonstrating controllability.

The simulator weight and pitch rate required to match Mach-q are affected by the changes in PMBT and atmospheric winds throughout the year. Changes in PMBT affect the propellant burn rate, which in turn affects the thrust vs. time relationship, but have no impact on the overall impulse of the motor. As PMBT increases, the burn rate increases, producing higher thrust early in the burn, but lower thrust late in the burn, and an earlier burnout time to conserve impulse. The converse is true for decreasing PMBT. The pitch-over maneuver and simulator weight must change to compensate for the changes in the thrust profile. Likewise, the direction and magnitude of monthly mean winds change from month to month, requiring changes in the pitch-over maneuver. Optimization analyses were performed for launches in February, April, June, and August to quantify the pitch rate and simulator weight variations for launches throughout the year. The Ares I ascent plane constraint, maximum simulator weight constraint and a 100 psf sep-q constraint were enforced for all months. These months were chosen since they encompass the PMBT and winds aloft variations that could be encountered throughout the year. Launches were assumed to occur near the middle of the month. The PMBT values for each month were obtained from the "*Shuttle Performance Assessment Data Book*" [9], and the RSRM thrust and mass flow time history were scaled according to the scaling equations provided in the data book. The constants used in the scaling equations were specific to the FTV RSRM and are documented in the ATK Launch Systems report "*Ares I-X Ballistic Performance Prediction Summary.*" [6] Mean monthly winds were obtained from "*The NASA/MSFC Global Reference Atmospheric Model – 1999 Version (GRAM99).*" [10]

The Mach-q matches for the selected launch months are shown in Figure 9 through Figure 11 and are summarized in Table 3. Multiple Mach-q comparisons are plotted due to the variation in the Ares I Mach-q profile from month to month. Nearly equivalent Ares I Mach-q matches were possible for the analyzed months with the match metric varying by 3.4% or less. The small variation in weight was due to the PMBT scaling of the four and five-segment thrust not affecting the relative difference between their thrust time histories. The simulator weight required to provide the constrained optimal matches varied by no more than 1626 lb relative to the mean, and could easily be accommodated by the US ballasting provisions. The pitch-over pitch rate varied by 0.17°/s or less which was well within the FTV pitch rate control capability. Thus, it was possible to achieve an acceptable Mach-q match throughout the year, with adjustments of only thousands of pounds in ballast and tenths of a degree per second in pitch rate.
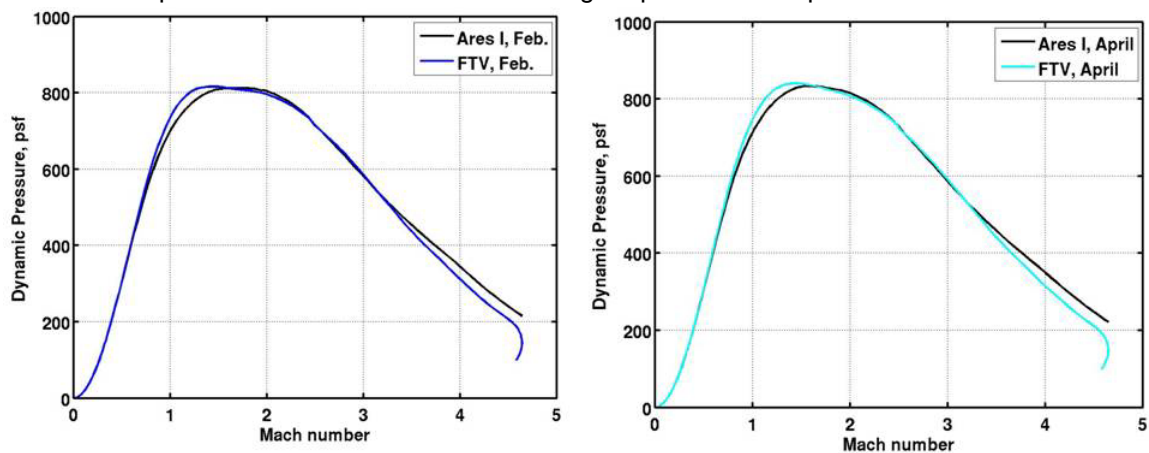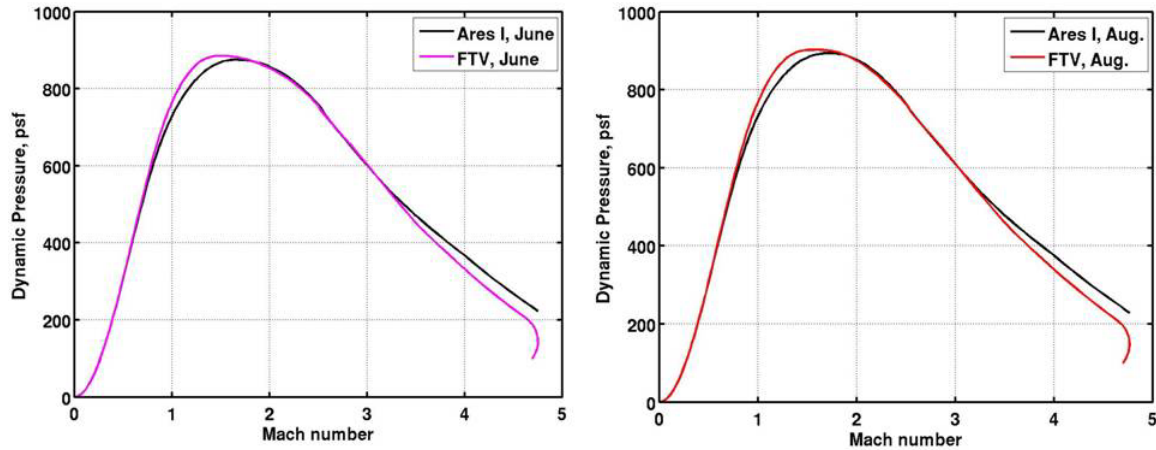

Figure 9 Mach-q Match for February and April
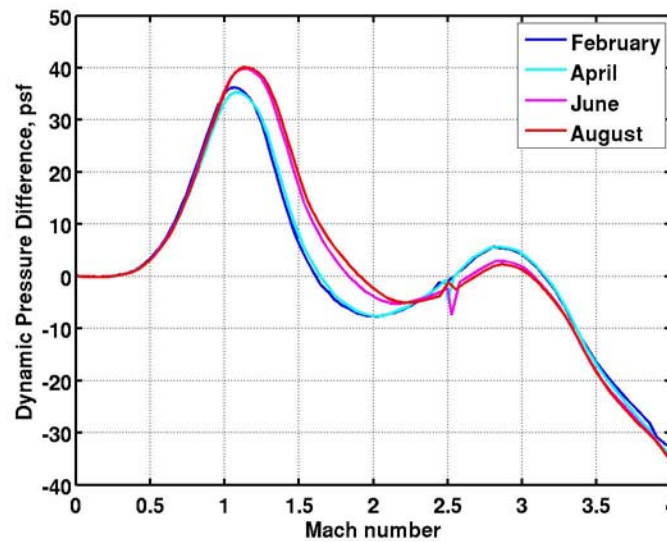
Figure 10 Mach-q Match for June and August

Figure 11 Mach-q Difference for Selected Launch Months

Table 3 Summary of Mach-q Match Parameters for Selected Launch Months

	February	April	Yearly Mean	June	August
Simulator weight (lb)	470,676	473,181	471,555	470,297	470,689
Ignition weight (lb)	1,814,023	1,816,528	1,814,901	1,813,644	1,814,035
Pitch rate (deg/s)	1.601	1.423	1.435	1.361	1.325
Max-q (psf)	816	841	859	885	903
Match Difference (%)	-1.4	-3.0	baseline	+3.2	+3.4

The pitch rate during the pitch-over was much more sensitive to the monthly winds than to variations in PMBT. The pitch rate increased for months that had higher magnitude winds aloft in the direction of the flight path. The East wind component (positive toward the East) is shown in Figure 12 for the analyzed months. Tail wind had the effect of increasing the atmospheric relative velocity flight path angle (FPA), and because a zero angle of attack constraint was enforced, pitch attitude was also increased. Figure 12 shows the difference between the atmospheric relative FPA and ground relative FPA for each month, where the difference is defined as atmospheric

relative FPA minus ground relative FPA, so that positive values indicate a larger or steeper atmospheric relative FPA and pitch attitude. The pitch rate was increased to offset the effect of the tail wind by lowering the pitch attitude during ascent. The monthly pitch rates are consistent with the effect of the monthly wind on atmospheric relative FPA.
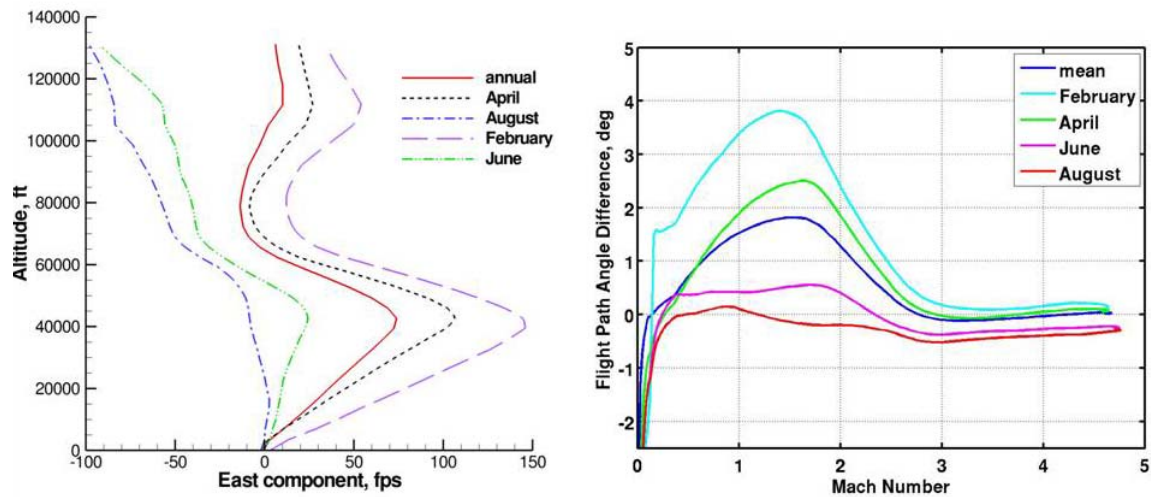

Figure 12 Monthly East Wind Component and Their Effect on Flight Path Angle

Figure 13 shows a comparison of pitch-over pitch rate with and without wind. Without wind, the effect of increasing PBMT on pitch rate was consistent with its effect on thrust. Thrust increases early in the RSRM burn with increasing PMBT, which results in higher acceleration and requires a lower pitch attitude to turn the flight path eastward. The pitch rate increased to lower the pitch attitude and offset the effect of higher acceleration.
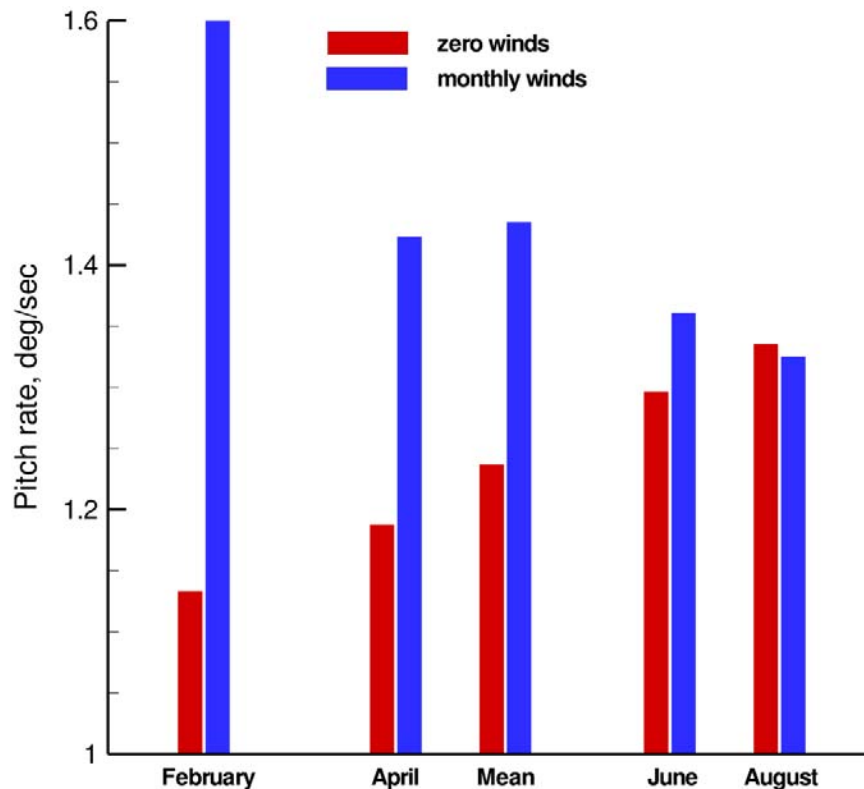

Figure 13 Monthly Pitch Rate Comparison

Response surfaces of the optimization metric were created for the selected launch months to provide additional insight into the effect of launch month PMBT and wind on the match, and to provide verification of the optimization analyses. The valleys of the monthly response surfaces were plotted together as contour lines and are shown in Figure 14. Only contours with values of 1000 psf-s and 3000 psf-s were plotted. The launch month shifted the location of the area where the metric is minimized on the order of tenths of a degree per second in pitch rate and on the order of 1,000 lb in simulator weight, but the orientation of its valley relative to simulator weight and pitch rate did not change. The optimization analyses results are consistent with the response surfaces.
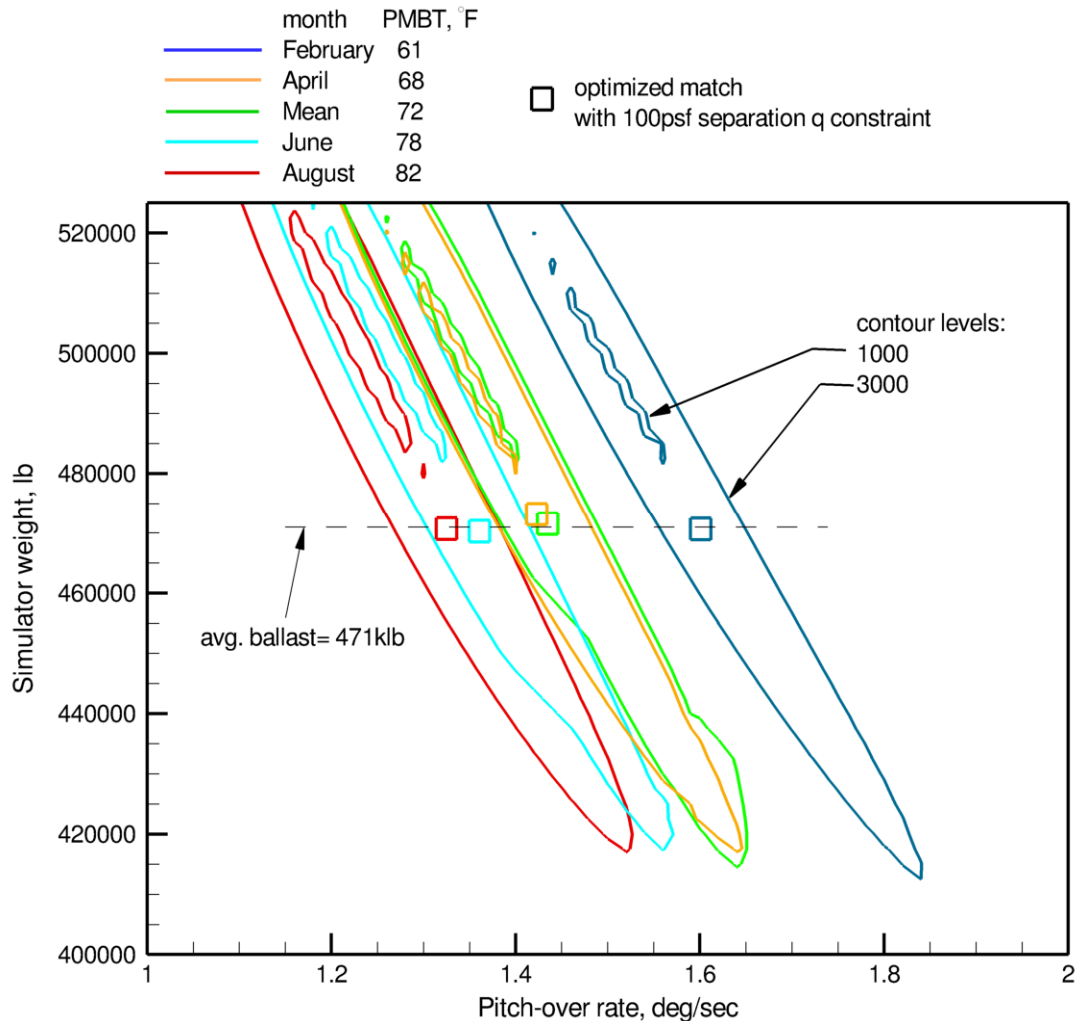

Figure 14 Monthly Optimization Metric Contours

SUMMARY AND CONCLUSIONS

The Ares I-X test flight trajectory was developed to provide a Mach-q profile necessary for meeting the primary test objective of demonstrating controllability of the Ares I concept. The trajectory Mach-q relationship was identified as the key parameter that, when matched, would created similar Ares I flight loads necessary for demonstrating controllability. The FTV was a full-scale representation of Ares I with a similar OML but with lower impulse FS propulsion. Despite the lower impulse, an ascent trajectory was designed that enabled it to fly a similar Mach-q profile as the Ares I vehicle up to Mach 4.0.

By adjusting the weight of the FTV and designing the initial pitch-over maneuver, it was possible to shape the FTV trajectory to match the Ares I trajectory Mach-q relationship. A match metric was defined as the integrated difference between the FTV and Ares I Mach-q relationships from lift-off until Mach 4.0. Optimization analyses were performed that minimized the metric by adjusting the total simulator weight and the pitch-over pitch rate to provide the best possible match of the Ares I Mach-q relationship. The Ares I Mach-q profile was matched to within 18 psf or less through Mach 4 but had a sep-q of 134 psf that was approximately six times higher than Ares I. The 134 psf sep-q was considered too high for a safe separation but analyses indicated a 100 psf sep-q was acceptable. With a 100 psf sep-q constraint, the Ares I Mach-q profile was matched to within 35 psf or less through Mach 4. Analyses were performed for various launch months throughout the year to quantify the effect of changing PMBT and winds on the simulator weight and pitch-over maneuver pitch rate required to maintain the Mach-q match. The analyses showed that the Ares I Mach-q profile match could be maintained for all monthly PMBT and winds with ballast weight changes of less than 1650 lb and pitch rate changes of no more than 0.17 deg/s. These weight and pitch rate variations were well within the FTV capabilities; thus, Mach-q matches were possible for launches throughout the year.

ACRONYMS

CEV	Crew Exploration Vehicle
CEVS	Crew Exploration Vehicle Simulator
CG	center of gravity
CLV	Crew Launch Vehicle
CM	Crew Module
CxP	Constellation Program
DAC	design analysis cycle
FPA	flight path angle
fps	feet per second
FS	first stage
FTV	flight test vehicle
GNC	guidance, navigation and control
KSC	Kennedy Space Center
LAS	Launch Abort System
Mach-q	Dynamic pressure versus Mach number
max-q	maximum dynamic pressure
MLP	mobile launch platform
OML	outer mold line
PMBT	propellant mean bulk temperature
PTI	programmed test input
q	dynamic pressure
RSRM	reusable solid rocket motor
SA	spacecraft adapter
sep-q	Separation dynamic pressure
SSP	Space Shuttle program
US	Upper Stage
USS	Upper Stage Simulator
5SS	5th Segment Simulator
nmi	nautical mile
psf	pounds per square foot

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