Modeling, Analysis and Simulation Approaches Used in Development of the National Aeronautics and Space Administration Max Launch Abort System

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ABSTRACT

The National Aeronautics and Space Administration (NASA) Engineering and Safety Center was chartered to develop an alternate launch abort system (LAS) as risk mitigation for the Orion Project. Its successful flight test provided data for the design of future LAS vehicles. Design of the flight test vehicle (FTV) and pad abort trajectory relied heavily on modeling and simulation including computational fluid dynamics for vehicle aero modeling, 6-degree-of-freedom kinematics models for flight trajectory modeling, and 3-degree-of-freedom kinematics models for parachute force modeling. This paper highlights the simulation techniques and the interaction between the aerodynamics, flight mechanics, and aerodynamic decelerator disciplines during development of the Max Launch Abort System FTV.

KEY WORDS: Modeling, simulation, computational fluid dynamics, trajectory modeling

INTRODUCTION AND FLIGHT TEST OVERVIEW

The National Aeronautics and Space Administration's (NASA) next generation crewed spacecraft, named Orion, is a part of the overall Constellation Program. The baseline Orion design includes a launch abort system (LAS) with tower, derived from the Apollo design. In June 2007, the Associate Administrator for the Exploration Systems Mission Directorate requested the NASA Engineering and Safety Center (NESC) to design, build, and test an alternate concept for the Orion LAS. Designated as the Max Launch Abort System (MLAS) Project, the MLAS would be theoretically capable of extracting the Orion crew module (CM) from the launch vehicle at any time from crew ingress at the launch pad through staging and ignition of the upper stage of the Ares I crew launch vehicle. The activity would conclude with at least one full-scale uncrewed pad abort test suitable for demonstrating the viability of this alternate LAS concept. The MLAS project would be independent from the Constellation Program and the Orion Project to minimize impact on in-line program resources. The MLAS was named after Maxime (Max) Faget, who was the lead designer of the Mercury space capsule and developer of its tower-based abort system called the "Aerial Capsule Emergency Separation Device".

MLAS Concept of Operations and Flight Test Objectives

The MLAS concept is a fairing-integrated crew escape system. One major difference with the MLAS concept, when compared to the Mercury, Apollo, and Orion, is that it uses side-mounted motors instead of tractor motors in a tower. All of the abort functionality (abort thrust, control, jettison, etc.) was integrated into a single fairing over the CM. A concept was developed for an operational system, called the Objective System (OS) and is shown in the upper portion of

Figure 1. Deployable grid fins were proposed to provide aerodynamic stability during the boost and coast flight phases, followed by reorientation and separation of the CM from the fairing.

The MLAS Flight Test Vehicle (FTV) and flight test was designed to simulate a pad abort of the Orion CM from the Ares I launch vehicle and demonstrate the passively controlled coast flight phase of the MLAS OS as risk mitigation for the Orion LAS attitude control motor development, which was experiencing technical challenges at the time. Due to cost, schedule, and developmental risk concerns, the FTV was not designed to actually deploy grid fins. Instead, it was designed to place an integrated fairing/CM, with flight stability provided by conventional aerodynamic fins, into the flight condition expected at abort-motor burn-out during an OS pad abort profile. From here, the MLAS would complete the OS pad abort profile through reorientation, stabilization, and release of the CM from the fairing, as shown in the lower portion of Figure 1.

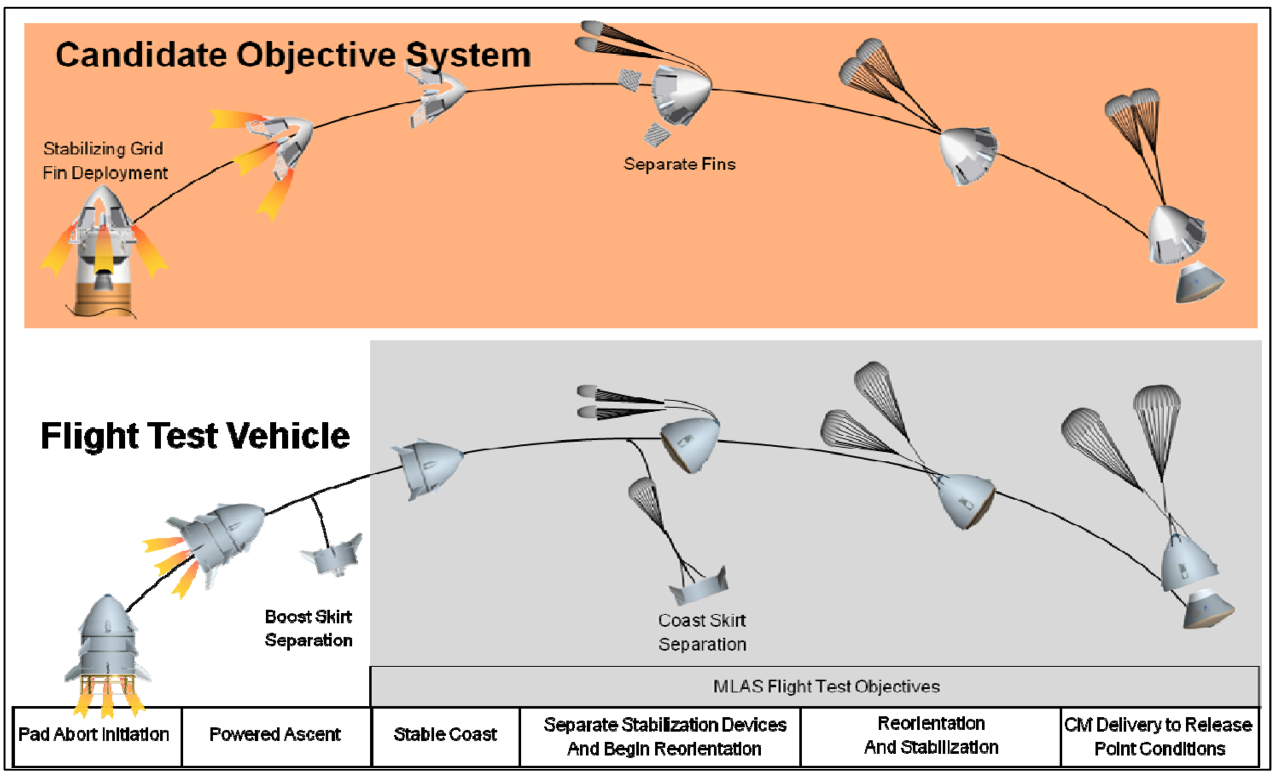


Figure 1: Comparison of MLAS OS concept of operations to the MLAS flight test.

The flight test objectives were defined as:

1. Demonstrate proper MLAS pad abort initiation and event sequencing, including: boost the FTV to the required test conditions, fly a stable coast trajectory to a designated altitude and downrange location, reorient/stabilize the FTV to the CM hand-off conditions provided by the Orion LAS so the CM landing system could be deployed, and demonstrate separation of the CM from the fairing without detrimental recontact.
2. Obtain flight test data that will be used to: determine the structural loads and the integrity of the MLAS fairings and CM during the pad abort; characterize both the aerodynamic

environments experienced by the FTV during the flight and the separation dynamics between the flight test booster, launch vehicle interface, the MLAS fairings, and CM.
3. Demonstrate an alternative main parachute system for CM recovery (incorporated at the request of the Constellation Program).

Flight Test Overview

As illustrated in Figure 2, the MLAS FTV consisted of four major elements, which were attached by frangible joints and bolts, allowing separation at appropriate intervals during the flight test.

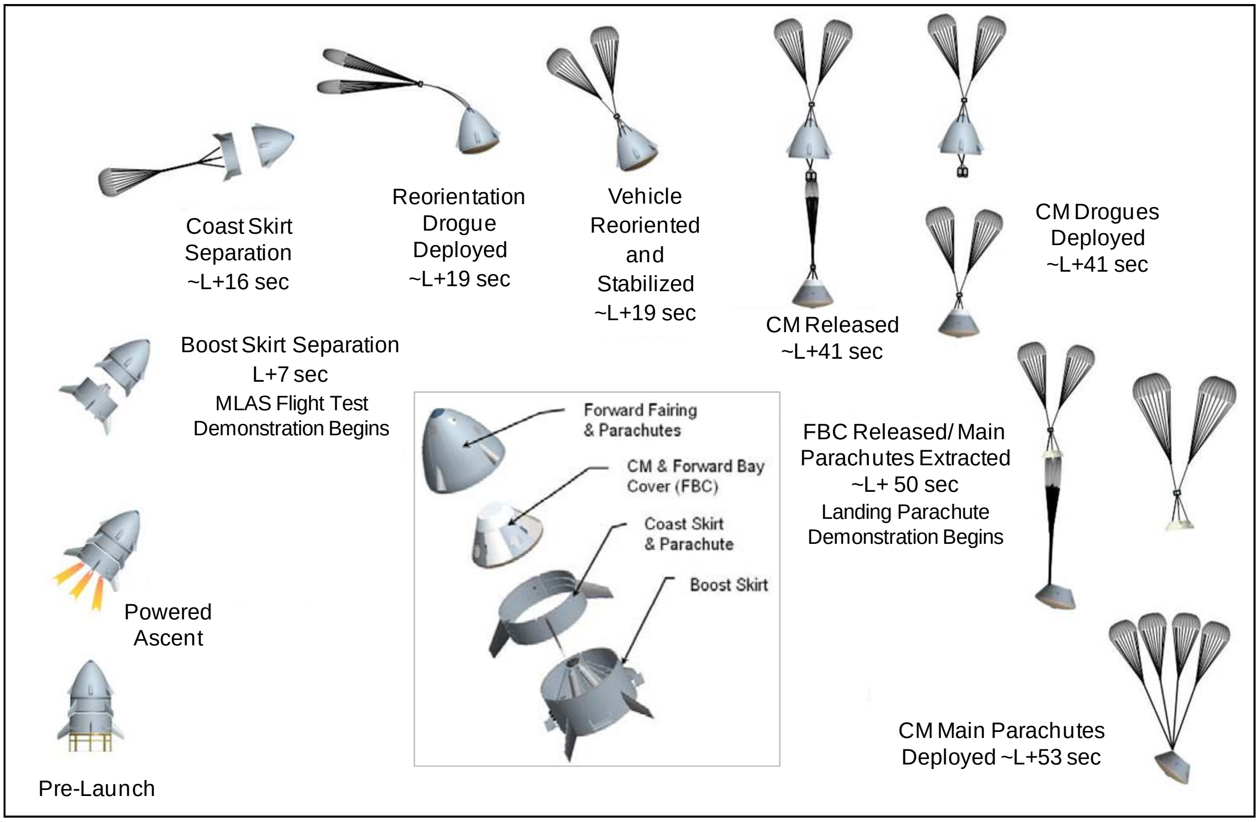


Figure 2: MLAS flight test vehicle configuration and flight test events.

- **Boost Skirt –** The boost skirt was the aft-most element and held four solid rocket motors, which were used to propel the FTV to the test conditions. Four fins were mounted on the boost skirt to help provide passive stabilization during the powered flight phase and four drag plates were circumferentially attached to this component to facilitate its separation at motor burnout.
- **Coast Skirt –** The coast skirt and fins served as the primary structure to passively stabilize the FTV during the coast phase and simulate the anticipated stability augmentation from using grid fins on an operational system.
- **Forward Fairing –** The forward fairing simulated the MLAS outer mold line (OML), provided the structural load interface between the fairing and CM for coasting flight and

reorientation, and contained the separation mechanisms to release the CM for parachute recovery. The forward fairing held two drogue parachutes that were used to reorient and stabilize the FTV after separation from the coast skirt.

- **Crew Module Simulator –** The CM simulator was designed to be a full-size boilerplate of the Orion CM. The CM was attached to the forward fairing using four frangible bolts/nuts. The CM simulator carried the majority of the flight instrumentation and the Landing Parachute Demonstration.

The operational concept for the flight test is also shown in Figure 2 and includes:

1) **Powered Ascent –** Boost lasts for six seconds after which the boost skirt is jettisoned.
2) **Stable Coast Phase –** Begins the MLAS flight test demonstration after the boost skirt is separated. The FTV coasts toward an apogee of 7,000 feet and 3,000 feet downrange.
3) **Reorientation –** The coast skirt is jettisoned when the dynamic pressure drops below 100 lb/ft^2, or if the vertical velocity becomes negative. A drogue ensures separation of the coast skirt from the forward fairing. Three seconds after the separation, two reorientation drogue parachutes are deployed from the forward fairing to reorient the FTV to a heat-shield-forward attitude and to damp motions.
4) **CM Separation and Drogue Deployment –** The CM is released from the forward fairing at 3,300 ft, within the requirements for the Orion LAS (attitude, rates, altitude and down range). After CM separation, two drogues are deployed from the CM to further stabilize and slow its descent in preparation for splashdown.
5) **Main Parachute Deployment –** At a programmed duration of 9.2 seconds after CM release, the forward bay cover with the attached CM drogues is jettisoned, deploying the four main parachutes. Deployment of the main parachutes using the forward bay cover is the central thesis of the Landing Parachute Demonstration.

MODELING AND SIMULATION IN THE MLAS DEVELOPMENT

To complete the MLAS Project goals in the shortest amount of time, a rapid, concurrent design and build approach to FTV fabrication and assembly was used. Flight test objectives were limited and an operational concept was developed early. Key to the project success was the liberal use of modeling and simulation techniques to evaluate FTV aerodynamic design concepts and flight trajectories to quickly converge on a flight test configuration. Targeted tests were used to anchor models and gain confidence in the simulation results. Throughout the project end-to-end flight performance simulations were employed to assess impacts of FTV design modifications and changes in the physical properties of the vehicle.

Teams were formed base on engineering disciplines and the FTV subsystems. While there were over a dozen engineering discipline teams, this paper highlights the technical efforts of the Aerodynamics, Flight Mechanics and Landing Systems teams, including their approach to modeling and simulation and team interactions. Figure 3 shows a summary of the teams' activities and interactions.

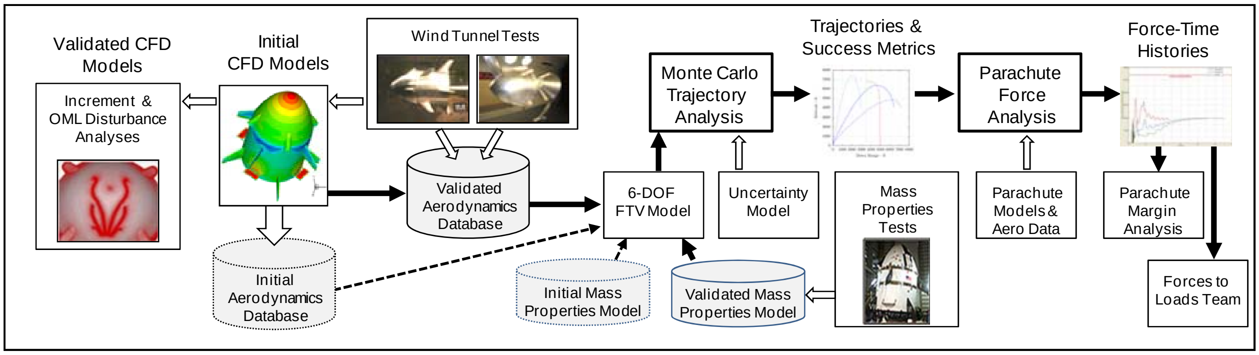


Figure 3: Interaction of modeling and simulation between the Aerodynamics, Flight Mechanics and Landing Systems teams.

Led by the NASA Technical Fellow for Aerosciences, the Aerodynamics team designed the FTV's OML including the fins required to meet a 10-percent stability requirement during the coast phase. They relied almost exclusively on computational fluid dynamics (CFD) and handbook calculations to develop their initial design and aerodynamic database. A series of wind tunnel tests were later performed to validate the CFD results and to further investigate the reorientation and separation events.

The Flight Mechanics team was led by the NASA Technical Fellow for Guidance, Navigation and Control, and designed/modeled the flight trajectory using the FTV aerodynamics database, the Orion CM aerodynamics database, propulsion characteristics, and FTV mass properties.

The Landing Systems team was responsible for the parachutes used during the flight test. Parachute force modeling and structural analysis were based on a set of trajectories provided by the Flight Mechanics team, which encompassed 90 percent of the expected trajectories.

Aerodynamics Modeling and Simulation Approach

Aerodynamics Design Requirements

Elimination of the tractor motor tower led to a more longitudinally compact LAS design utilizing a Sears-Haack fairing with a 1:1 fineness ratio. Longitudinal and, by symmetry, lateral stability is a key design parameter for these types of faired capsule designs. While the Sears-Haack and other ogive-type designs afford considerable drag and aeroacoustic benefits over blunt and conical designs, they have the additional undesired characteristic of moving the aerodynamic center-of-pressure (CP) forward on the vehicle. This forward CP movement, coupled with the aft center-of-gravity (c.g.) characteristic of capsule-based launch abort vehicle designs, creates significant stability challenges. Longitudinal stability has to be maintained throughout the boost and coast phases of flight to ensure the vehicle flies the proper trajectory without tumbling. In the boost phase, the FTV accelerates from rest to a velocity slightly above Mach 0.5, and thus does not encounter strong compressibility or transonic effects. The FTV flies in the coast phase until it gains sufficient altitude and downrange distance to initiate the CM recovery sequence. Early analysis demonstrated that maintaining a CP location at least 0.10 body diameters behind the c.g. provides sufficient aerodynamic stability, despite the potential for numerous perturbations to the FTV during flight.

Use of Modeling and Simulation in the MLAS Aerodynamic Analysis and Design

The rapid-prototype development approach of the MLAS Project constrained the aerodynamic design of the vehicle to rely heavily on CFD and handbook aerodynamics methods to estimate vehicle performance and finalize designs. Aerodynamic design proceeded as follows:

1. **Use of CFD to Perform Aerodynamic Conceptual Designs and Trade Studies –** CFD was used exclusively to develop FTV designs with the required stability in the boost and coast phases of flight and evaluate their performance. CFD allowed numerous stability augmentation trade studies to be performed quickly. Ballasting strategies that met the stability requirement were developed with the Flight Mechanics team.
2. **Develop the Aerodynamics Performance Data Base –** A baseline FTV aerodynamics performance database was established that covered the complete flight regime from lift-off to deployment of the CM simulator recovery drogue parachutes. The database was then used to perform mission design, simulate flight trajectories, and determine parachute forces applied to the vehicle by the Flight Mechanics and Landing Systems teams.
3. **CFD Model Validation and Aerodynamics Database Corroboration-** The CFD results for the baseline design were validated and refined through rapid turnaround wind tunnel tests. While CFD could be used to develop a database of sufficient quality for preliminary design, the high volume of data required for a final flight aerodynamic database was beyond the resources and time available using just CFD. Therefore, wind tunnel testing was used to both validate the vehicle design and fill in sparse regions of the aerodynamic database where CFD could not be efficiently employed to produce adequate coverage.
4. **Use Validated CFD to add FTV Design Increments to the Database and Evaluate Aerodynamic Disturbances from OML modifications –** CFD was used exclusively to perform design enhancements to the FTV's aerodynamic baseline and to evaluate OML disturbances due to landing system and other components. Wind tunnel testing completed in the above step provided confidence that the CFD could be used in this capacity without further vehicle testing.

A discussion of each of these four steps is provided below.

Use of CFD to Perform Aerodynamic Conceptual Designs and Trade Studies

CFD Flow Solvers Used – The primary CFD tool used for the unpowered predictions throughout the flight profile was the Unstructured Mesh Three-dimensional (USM3D) compressible viscous flow solver (Frink, et al. 2000). The USM3D code is an unstructured mesh Reynolds-averaged Navier-Stokes CFD program and has been demonstrated to be a valuable CFD tool for evaluating a wide variety of vehicles, from the F/A-18E to the Mars airplane and is also employed extensively within the Orion and Ares projects.

The methodology used within the USM3D code to obtain steady state solutions was the Harten, Lax and van Leer scheme with contact restoration. Turbulence closure for the flow over the vehicle was obtained using the Menter's Sheer Stress Transport turbulence model. This turbulence model has had some success predicting separated flows around various vehicles and for the relatively short, blunt MLAS configuration, this was a discriminating factor in choosing a turbulence model. Predicted surface pressures were integrated to produce forces and moments, which were converted to coefficient form. To determine whether a solution was converged, flight coefficients were monitored with respect to the rate of change or percent of change over at least the last 500 iterations.

Because no wind tunnel or ground test data were planned or available for estimation of the powered flight performance of the vehicle, multiple CFD codes were used to provide information on sensitivity and uncertainty for these predictions. Three independent analyses were used to predict the propulsion-induced (power on) aerodynamic influence on the MLAS boost configuration. One of these analyses used the previously described USM3D methodology, while the other two simulations utilized an overset structured grid method known as OVERFLOW (Buning, et al. 1988). The OVERFLOW simulations were conducted independently of each other by different analysts using their own grid models. In employing this approach, the Aerodynamics Team recognized that high uncertainties might be associated with these propulsion interference-effect predictions, but an overall team strategy was adopted to design to these uncertainties rather than exhaust valuable resources and schedule on attempting to reduce them.

Design Trade Studies – Strategies for moving the aerodynamic center and the c.g. to maintain passive aerodynamic stability were investigated. Trade studies were undertaken of various aerodynamic and ballasting strategies and fin types/sizing that would achieve the target longitudinal static stability margin. Reliance on CFD allowed a large number of concepts to be quickly evaluated, as exemplified in Figure 4, and arrive at a final design with predicted performance much faster than if concept-verification wind tunnel tests had been conducted along the way. To save time and computing costs, the initial concept studies were performed using a half-body CFD analysis since the FTV possessed sufficient symmetry. This allowed the simulations to be performed at about half the cost and twice the speed of a full-configuration analysis.

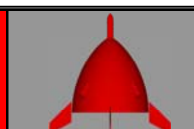
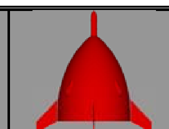
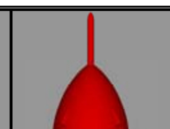
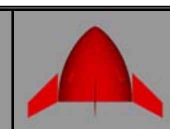
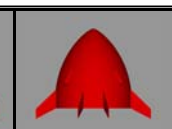
Coast Stability					
Configuration	D2-1A Short Fairing	D2-1A	D2-4A	D2-6A	D2-7

Figure 4: Examples of FTV coast configurations quickly evaluated by CFD.

Of the concepts investigated, the CFD results indicated only the ballast spike, conventional fins, and grid fins demonstrated sufficient control of the vehicle c.g. or CP to be considered as viable options to maintain longitudinal static stability. A concept was ultimately baselined for detailed analysis that included conventional swept fins and internal ballast positioned in the FTV nose. The swept fins were sized and positioned using classical handbook methods, and their performance was further verified using CFD, which is capable of capturing the higher-order interference and interaction effects that were not included in the handbook sizing.

Baseline Configurations – There were three baseline flight configurations analyzed: boost, coast, and reorient. Figure 5 shows the surface grid for the boost, coast and reorientation configurations used in the unpowered analyses while Figure 6 shows CFD results for the boost simulations.

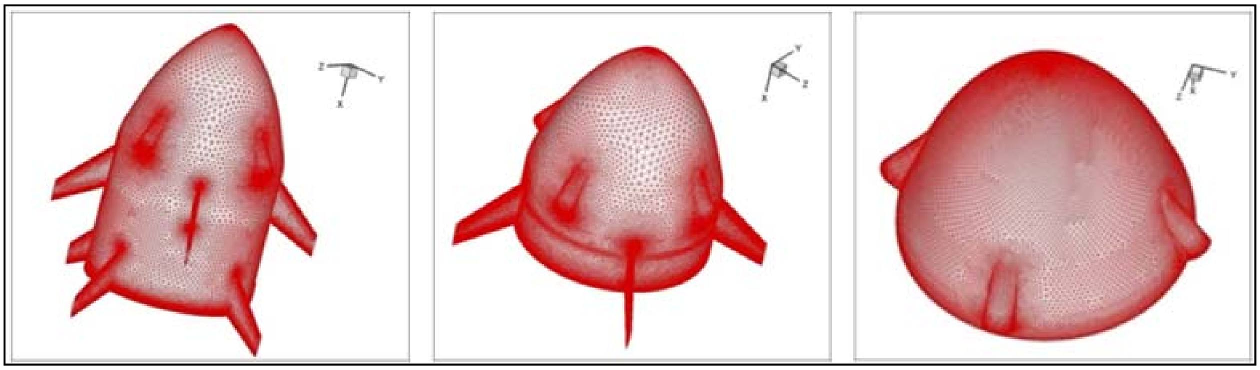


Figure 5: Unpowered flight geometries and CFD surface grids used in detailed performance analysis.

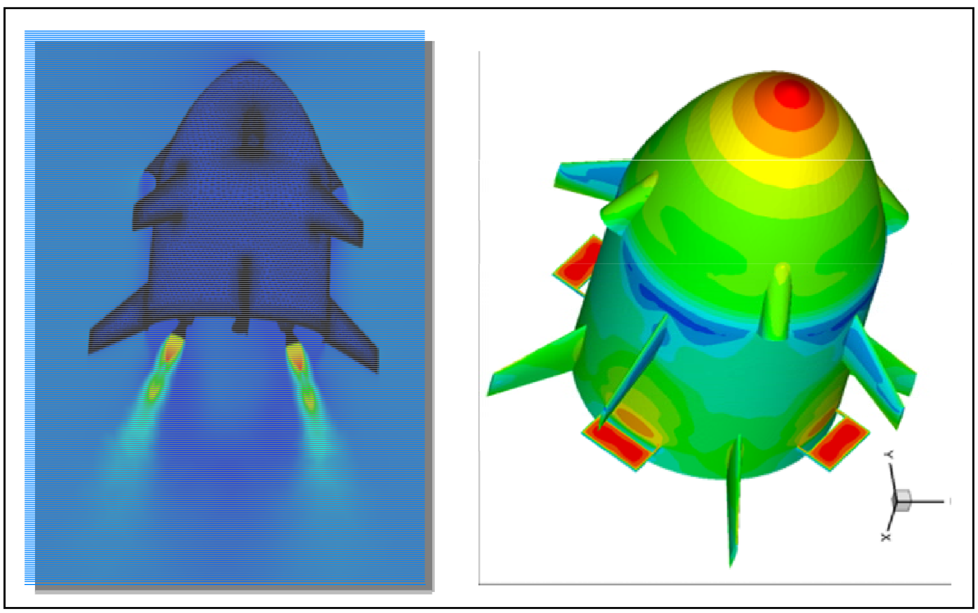


Figure 6: Boost configuration CFD analysis.

Aerodynamics Performance Database Development

The MLAS aerodynamics performance database was developed using a combination of CFD predictions and wind tunnel testing – with the draft release for use by the project being based solely on CFD results early in the design process. This enabled initial trajectory design to commence and in-turn, parachute force predictions to be developed and passed to the Loads team.

The primary database was divided by flight segments and contained the essential aerodynamic parameters required to simulate the vehicle flight as shown in Figure 7.

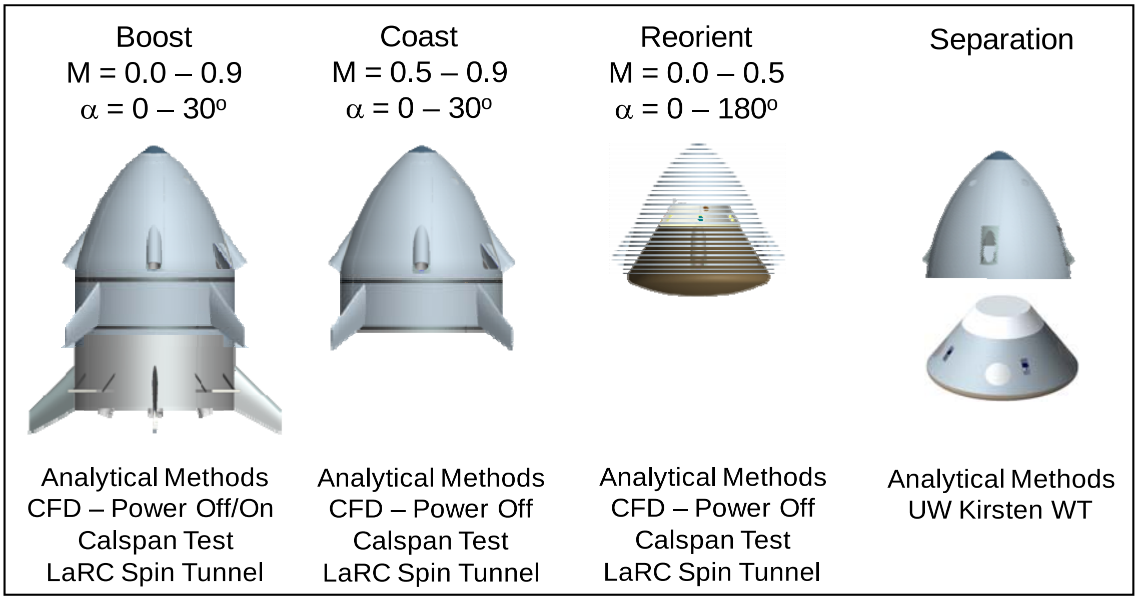


Figure 7: Primary MLAS configuration for included in the aerodynamics performance database.

CFD Model Validation and Aerodynamics Database Corroboration

Wind tunnel testing was used to complement and corroborate the CFD results. The main body of testing was conducted in the Calspan 8-Foot Transonic Wind Tunnel on a high-fidelity eight-percent scale sting mounted model as shown in Figure 8. The objectives of the tests were to provide high fidelity, force, moment, and pressure distribution data for validation of CFD analyses and a matrix of data for vehicle orientations and Mach numbers not evaluated by CFD.

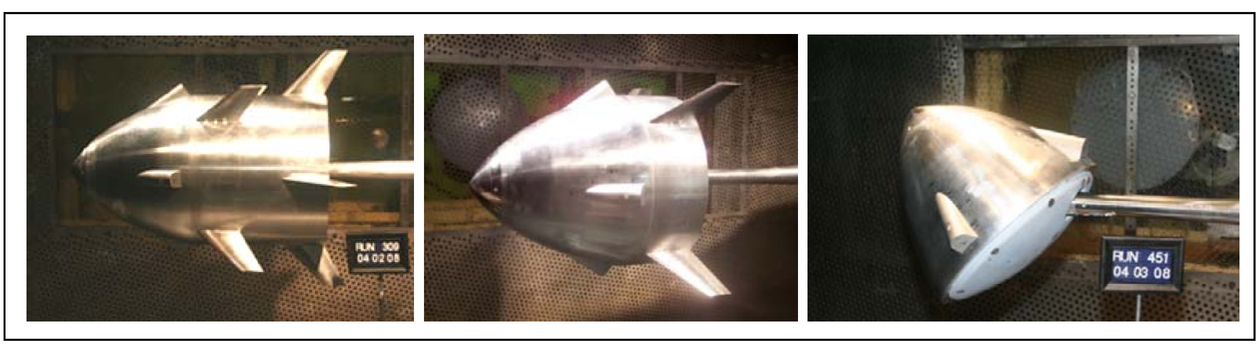


Figure 8: MLAS model (8-percent scale) in the Calspan 8-Foot Transonic Wind Tunnel.

The University of Washington Aeronautical Laboratory Kirsten Wind Tunnel was used to better understand the CM and fairing separation aerodynamic phenomena as shown in Figure 9. The MLAS flight test mission success criteria stipulated that the separation of the CM and the forward fairing be such that there was no detrimental recontact between these components during the separation event. The aerodynamics of the separation event were largely unknown and not readily predicted by analytical or handbook methods. CFD simulations of the event were possible, but the number of independent variables required to perform a comprehensive analysis of the event precluded employing CFD in a timely manner. The wind tunnel test provided critical insights and understanding into the relative behavior of the CM and forward faring during the critical separation event.

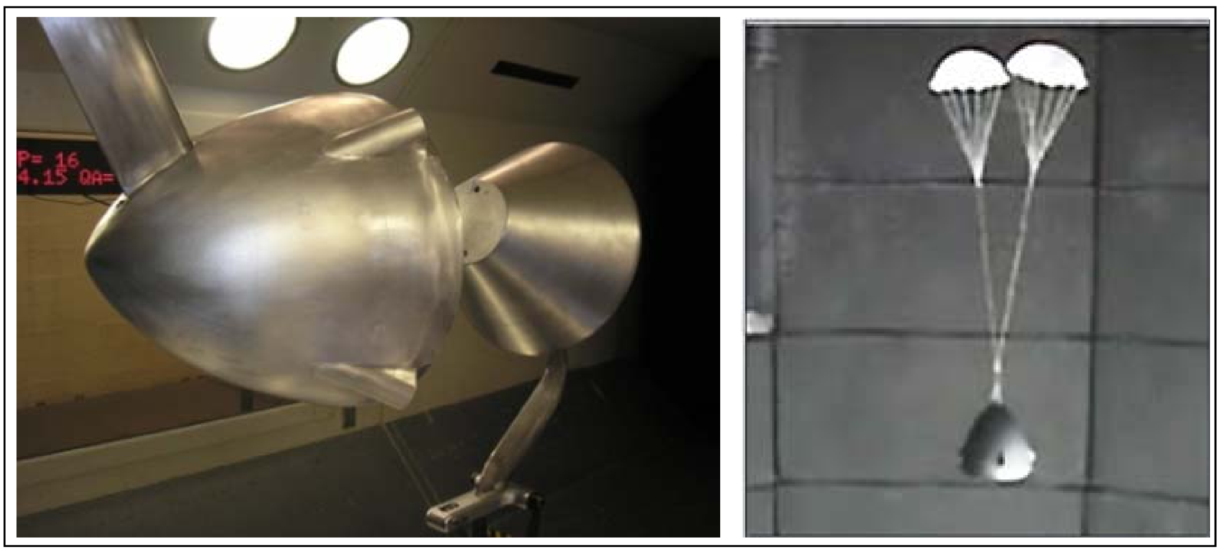


Figure 9: MLAS model (7.4-percent scale) in the Kirsten Wind Tunnel (left) and the 1/29 scale model in the Vertical Spin Tunnel at NASA LaRC.

Early in the project, an investigation of the low subsonic static and dynamic stability characteristics of the MLAS vehicle was conducted in the 20-Foot Vertical Spin Tunnel at NASA Langley Research Center. Using 1/29-scale models, free-flying, dynamically-scaled, and static force and moment tests were conducted, including a series of drogue parachute tests with the free-flight models as shown in Figure 9. The primary objective of the test was to qualitatively assess dynamic stability of the configurations, including the stabilizing performance of drogue parachutes, and to obtain quantitative time histories.

Data from the Calspan wind tunnel testing were found to be in excellent agreement with the team’s early CFD predictions, an example of which is shown in Figure 10. In the figure, vehicle normal force is plotted against angle of attack for each of the boost, coast, and reorient configurations. Similar results were obtained for pitching moment and axial force in this angle of attack range. These excellent comparisons provided the MLAS team with the motivation and confidence to continue to heavily leverage the CFD resources as a primary source for aerodynamic predictions, particularly as the configuration evolved past the as-tested baseline configuration. This was an important efficiency realized by the team and was key to being able to manage costs and schedule by not having to conduct additional wind tunnel testing as the vehicle design evolved.

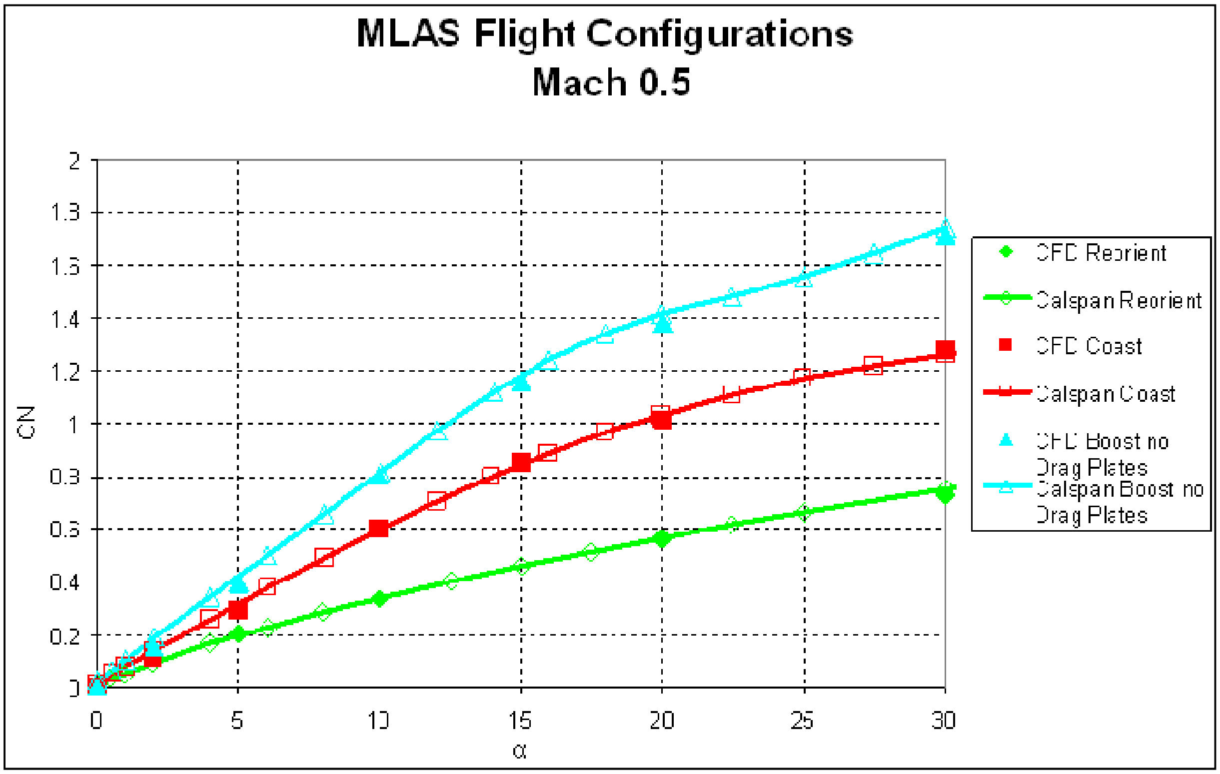


Figure 10: Sample CFD comparison with wind tunnel data at Mach 0.5.

In the reorientation configuration however, differences between the CFD and experimental data were more significant, particularly at the higher angles-of-attack as the vehicle reoriented itself from a nose forward to heatshield forward flight trajectory. Both the CFD and experiment had a number of geometric and physics approximations that could easily result in these differences. Thus, rather than attempt to select one data source over the other as the “correct” source for the database, the team chose to assume that both sources were equally correct and effectively use the average of the two sources to predict the nominal aerodynamic characteristics. Differences between the CFD theory and experiment were treated as additional sources of uncertainty in the aerodynamic coefficients across the flight trajectory

Use of Validated CFD to add FTV Design Increments and Evaluate Aerodynamic Disturbances from OML modifications

The validated CFD models were used to investigate the aerodynamic effects of design improvements beyond the initial aerodynamic baseline. As an example, drag plates were added to the boost skirt to ensure a quick separation after the boost skirt was jettisoned. CFD analysis of an initial drag plate design allowed the plate size to be reduced and still affect the separation required. Figure 11 shows the CFD results from disturbances caused by the reorientation parachute harness routing on the OML (far left) and the parachute harness storage bay (center). The CFD model at the far right in Figure 11 was used to visualize the wake behind the FTV in which the reorientation parachutes would deploy.

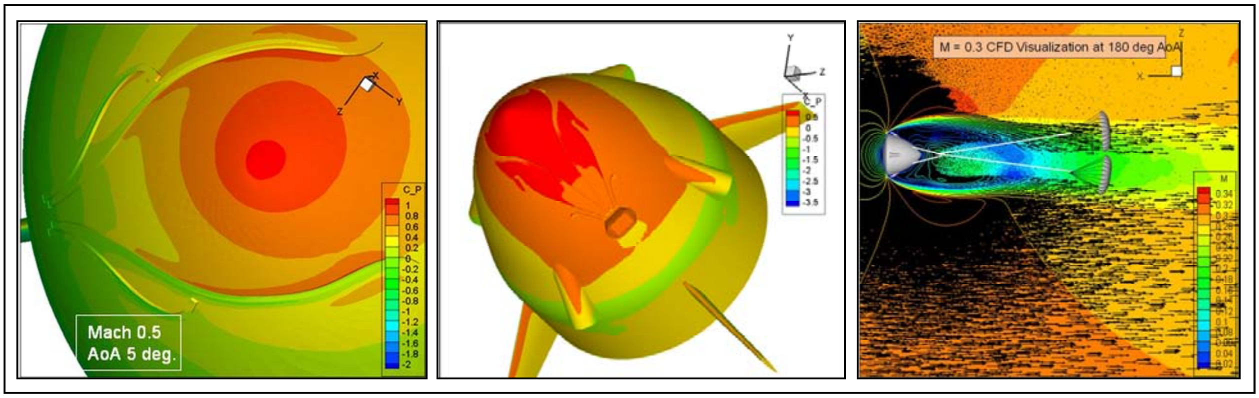


Figure 11: Investigation of aerodynamic effects due to changes in FTV outer mold line.

Aerodynamics Flight Test Results

One of the areas that was compared and analyzed after the MLAS flight test was the pressure on the each of the four panels making up the forward faring. An example of a comparison of measured pressures with the wind tunnel and CFD preflight data on one of the panels showed excellent agreement as plotted in Figure 12.

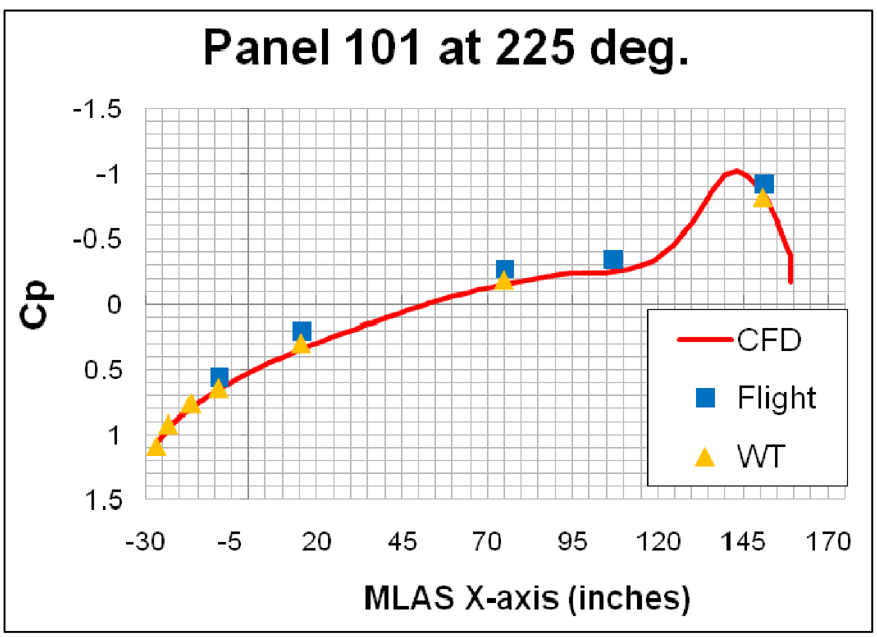


Figure 12: Example of excellent comparison of flight pressures with CFD analysis and wind tunnel data.

Flight Trajectory Modeling and Simulation Approach

Flight Mechanics Design Requirements

Performance requirements from a Flight Mechanics perspective were divided into three major groups as follows:

1. **Constellation Program** – The MLAS performance parameters of altitude, range, CM separation lateral rates, angle-of-attack, roll rate and dynamic pressure were set equal to that of the Orion LAS. In short, the MLAS should deliver the CM to the same hand-off conditions as the Orion LAS.
2. **MLAS Specific –** Performance requirements were set by the project for the boost and coast and separation phases. Above all, the passively stabilized MLAS should achieve the Orion LAS CM hand-off conditions greater than 90 percent of the time.
3. **FTV Specific –** Minimum separation distances were set between the coast skirt and FTV prior to reorientation along with upper dynamic pressure limits at parachute deployments.

The requirement to fly a passively stabilized vehicle without active closed-loop feedback control drove the modeling, simulation, and analysis efforts.

Use of Modeling and Simulation in the MLAS Trajectory Design

The Flight Mechanics design and development approach leveraged the Wallops Flight Facility (WFF) Sounding Rocket Program expertise, experience, modeling/simulation tools, and flight hardware to the maximum extent possible.

The trajectory design proceeded as follows:

1. **Trajectory Design Trade Studies –** Initial trajectory models were developed early using the CFD-only aerodynamics performance database and analytical mass properties model to perform design trades. Trade studies investigated trajectory design drivers including dispersions and ballasting strategies that met the stability requirement. Separation issues involving the FTV components during the flight were investigated to determine the potential for recontact or interference.
2. **Baseline Trajectory Design –** A baseline FTV trajectory was established using the validated aerodynamics database, measured and historical propulsion data, results of the trade studies, and maximum parachute load limits. State vectors representing the range of dispersed trajectories were developed for parachute performance analysis.
3. **Trajectory Model Verification –** The trajectory model was updated with the validated aerodynamics performance database and a validated FTV mass properties model. A new set of dispersed trajectories were generated for parachute performance analysis.
4. **Updated Trajectory Model for Final Predictions –** Trajectory models were updated with the effects of OML modification increments added to the aerodynamics database, aerodynamic uncertainties, updated mass properties, and revised parachute load limits. Update trajectories were generated for parachute performance analysis.

A discussion of each of these four steps is provided below.

Trajectory Design Trade Studies

In-depth analyses were performed to fully characterize and understand the sensitivity of the FTV flight performance to the relative relationship between the vehicle's c.g. and the resultant thrust vector produced by the solid rocket motors used to propel the FTV. Significant effort was expended to identify and validate the specific error sources that made knowledge of the resultant thrust vector orientation uncertain, as well those error sources that introduced uncertainty into the determination of the c.g. location. The requirement to fly without active closed-loop feedback control also drove the team to perform several stages of detailed mass properties testing and the associated mandatory need to track, model, and manage any mass changes that occurred due to modifications in the baseline vehicle design. It was also necessary to develop and implement a simple, physically realizable vehicle ballasting strategy to ensure static stability during the boost and coast flight phases.

Some of the most significant areas of investigation are discussed below**.**

Aerodynamic Stability with Passive Controls – The coast fins and boost fins were iteratively sized by the Flight Mechanics and Aerodynamics teams during concept formulation to accomplish the following objectives:

1. Provide sufficient aerodynamic stability during boost to ensure that the resulting trajectory dispersion was small enough for the vehicle to meet its test condition insertion goals. It was desired that the aerodynamic pitching frequency of the vehicle be representative of the closed-loop bandwidth frequency of a guided objective system under the action of a thrust vector control system.

2. Provide sufficient aerodynamic stability during the coast phase of flight to accommodate and dampen the angular impulse delivered by the asymmetric thrust of unmatched motors during tail-off.

These objectives led to the requirement of a static margin of 10 percent body-diameter to accomplish both goals.

Initial Turning Maneuver during Early Boost Phase – In a pad abort, the launch abort vehicle must deliberately pitch in a specific direction to gain lateral separation from the launch pad and ensure a water landing of the escape system. It was determined early in the concept formulation that producing a thrust moment by offsetting the vehicle c.g. from the centerline was the most effective means of producing the initial vehicle turning maneuver, also referred to as the pitch-over maneuver. This permitted the establishment of a downrange component of velocity early in flight. Flowing from this design decision were stringent requirements on c.g. management, and requirements on aerodynamic stabilizing moments to prevent the vehicle from over-rotating during the pitch-over.

Relative Separation Distances – Ensuring positive separation between the elements of the test article that were separated during various phases of flight proved to be one of the most challenging aspects of the design effort. The boost skirt separation was accomplished using four fixed drag-plates sized initially to provide 2-g's of relative acceleration between the forward and aft bodies. This margin was steadily eroded to 1-g during the vehicle build phase by mass "creep" and aerodynamic effects uncovered by CFD. The coast skirt separation was accomplished utilizing a mortared drogue parachute. The reorient-then-release concept had a side effect that a large amount of rotational energy would be imparted into the FTV, which would require significant parachute hang time allowances to dissipate. During this time, much of the horizontal velocity of the MLAS was also scrubbed off. The significance of this is that there remained no effective means to reliably develop significant lateral separation between the forward fairing, the CM and forward bay cover during final descent. Subsequent trajectory analyses would show recontact of the parts was probable and became an accepted risk.

Trajectory Modeling Tools – The team primarily utilized the Port-O-Sim 6-degree-of-freedom simulation tool which served as the Project's end-to-end predictor of MLAS flight performance (Lanzi 2009). Port-O-Sim is a NASA-developed software application that supports engineering modeling and simulation of launch-range systems and subsystems, as well as the vehicles that operate on them. It is a flexible, distributed, object-oriented, and real-time simulation. A scripting language is used to configure an array of simulation objects and link them together. The script is contained in a text file, but executed and controlled using a graphical user interface.

Initial trajectory results from Port-O-Sim favorably compared with the results obtained with the Generic Simulation (GenSim) flight control simulation tool from Langley Research Center. Independently generated outputs from another flight mechanics tool, called the Program to Optimize Simulated Trajectories, were also periodically compared with the Port-O-Sim outputs to perform a technical crosscheck on the MLAS flight performance in general as well as the boost skirt, coast skirt and CM simulator separation dynamics in particular.

Baseline Trajectory Design

A multi-body trajectory model of the MLAS FTV system was developed early in the project and was refined as the FTV was developed. Referring back to Figure 3, a nominal trajectory initially was built based on the initial CFD aerodynamics performance database and analytical mass properties model. An example of an early trajectory simulation is shown in Figure 13. The nominal trajectory results compared favorably with the results obtained using GenSim and provided early confidence in the feasibility of the team's design concept.

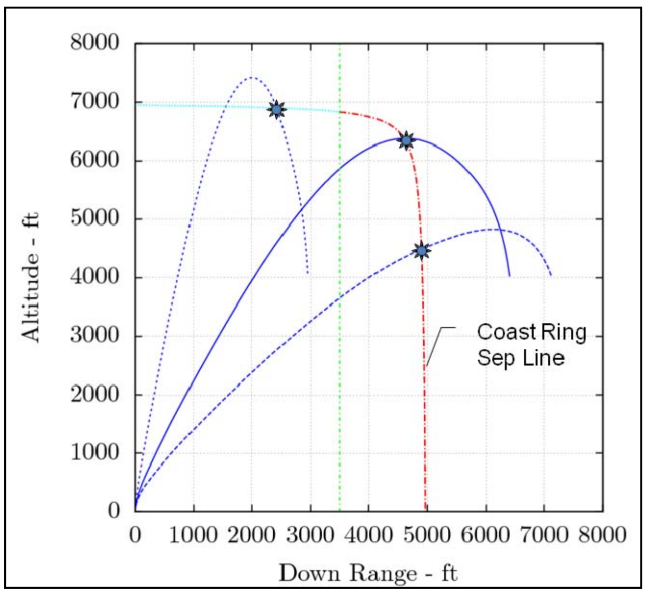


Figure 13: Trajectory model showing the steep (left), nominal (center) and shallow trajectories.

Extensive effort was then directed to developing a flight dynamics uncertainty model that defined various conditions (over 100) that could alter the FTV from its nominal trajectory. These contributors and their 3-sigma magnitudes were introduced to the trajectory model via a Monte Carlo analysis and allowed determination of the trajectory dispersion around the nominal case. Contributors ranged from propulsion and mass property uncertainties to fin misalignment uncertainties.

The nominal trajectory is seen in the center along with a steep and shallow trajectory, the latter two of which bounded 90 percent of the expected trajectories. The shallow trajectory typically was characterized by a lower apogee altitude, higher dynamic pressure and greater downrange distance than the nominal trajectory. The steep trajectory had a higher apogee altitude, lower dynamic pressure and smaller downrange distance than the nominal trajectory.

Scatter plots of the important events are seen in Figure 14. For example, the red points indicate the reorientation initiation (ROI) event, meaning the dynamic pressure has dropped to 100 lb/ft^2. The cyan points are indicators of apogee while the blue points indicate the programmed CM release altitude. The green points indicate the forward bay cover is released after a programmed 9.2-second CM drogue interval. The black points indicate the altitude at which the main parachutes are deployed from the forward bay cover. The benefit of allowing the FTV to stabilize under the reorientation drogues until 3,300 feet is the altitude dispersions for the remaining events were minimized. Variability in Down Range distance indicated the sensitivity to the factors that caused the pitch-over maneuver early in the flight.

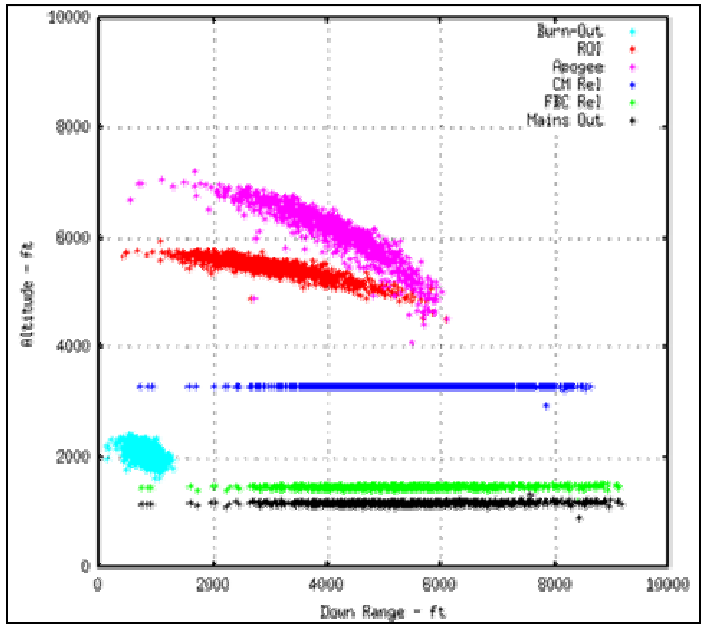


Figure 14: Monte Carlo results for events along the trajectory indicating significant down range dispersions.

Trajectory performance metrics were defined in terms of the CM hand-off conditions, e.g. altitude > 3,000 feet, and tracked to understand the effects of the uncertainties as well as changes to the FTV mass and aero properties. The metrics were depicted by mission S-curves that indicated the percentage of trajectory cases satisfying the 90 percent mission success criteria for the hand-off conditions as shown in Figure 15. This S-curve indicates that over 95-percent of the trajectories met the CM lateral hand-off rates of 40 degrees/second or less.

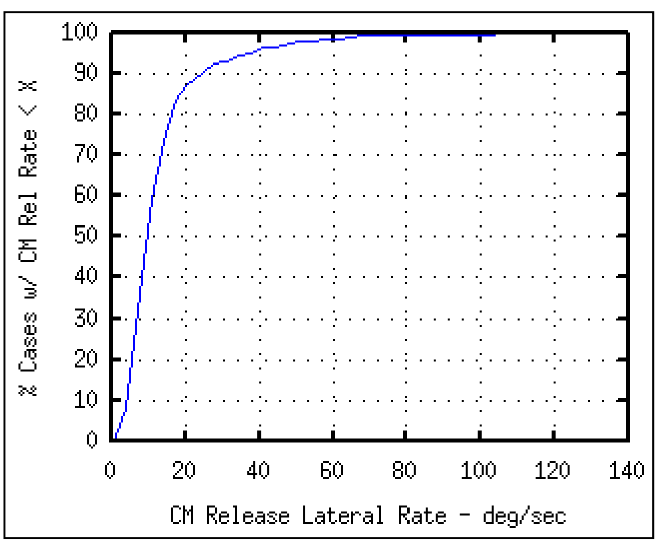


Figure 15: Mission S-curve for CM lateral hand-off rates. Less than 40 degrees/second was required 90-percent of the time.

Critical Event Initiation – A major benefit of the initial Monte Carlo trajectory analysis was the insight gained into the trajectory and overall flight performance sensitivity to modeled dispersion. Early in the MLAS systems design phase it was thought that the timing and sequenced commanding of critical flight test events could all be established prior to flight and implemented with the standard pre-set on-board avionics timers typically used on sounding rockets. On-time activation of the coast skirt separation/reorient-sequence initiation command and the CM separation command were of particular importance. Subsequently, the Monte Carlo flight performance simulations showed large enough MLAS trajectory variations, in response to modeled dispersions, such that the simple pre-set avionics event-timer event-command concept had to be abandoned and alternative techniques developed and tested.

Trajectory Model Verification

Nearly all requirements allocated to the Flight Mechanics team were verified by analysis with the three exceptions of the aerodynamics performance database, propulsion performance, and mass properties. The aerodynamics database was validated through wind tunnel testing. A propulsion recertification test was performed by the Naval Weapons Center at Indian Head, Maryland, to recertify the solid rocket motors used in the flight test. The four MLAS motors were obtained as surplus from the U.S. Navy Standard Missile Program and were near the end of their 20-year certification life. The test results indicated that the motors tested were still performing within original specifications.

Mass Properties Verification – Identifying the need for mass properties model validation was the result of dispersion sensitivity analyses performed to gain insight into which design parameters drove flight performance. It was determined that the vehicle trajectory was most sensitive to the uncertainty in the c.g. radial location (refer back to Figure 14). A radial c.g. produced the thrust moment arm intended to induce the downrange pitch-over maneuver early in the flight. An analytical mass properties model was used to track c.g. location and was continuously updated with actual component weights as they became available. Two major mass properties tests were conducted by making direct measurements of FTV subassemblies and the full vehicle stack.

Event Deployment Algorithm Verification – A battery of 17 distinct test scenarios was created to stress-test and boundary-test the ROI and CM release event triggering algorithms which were to be deployed in flight software as well as from a human-operated ground command system. Each scenario was modeled in the end-to-end 6-degree-of-freedom mission simulator. The simulations were played into a Global Positioning System (GPS) radio frequency simulator attached to a JAVAD Navigation Systems 100 (JNS100) GPS receiver for data capture. The resulting data files were used by the flight software developer to test the flight computer. The simulations were also played into the WFF Range Display Network in the Range Control Center to train the Flight Control Console operators, and verify that they were prepared to issue command functions for the MLAS flight test.

Updated Trajectory Model for Final Trajectory Predictions

A final set of trajectory predictions, presented in Figure 16, were developed shortly before the launch to include the effects of the final loads analyses, final aerodynamic increments and continued mass growth. Again, Monte Carlo simulations were used to update the figures of merit relating to the CM hand-off conditions. This last trajectory update also initiated a final cycle of parachute force simulations and parachute structural analysis. Continued mass growth caused the final trajectory prediction to shift more in favor of a steeper trajectory over prior predictions.

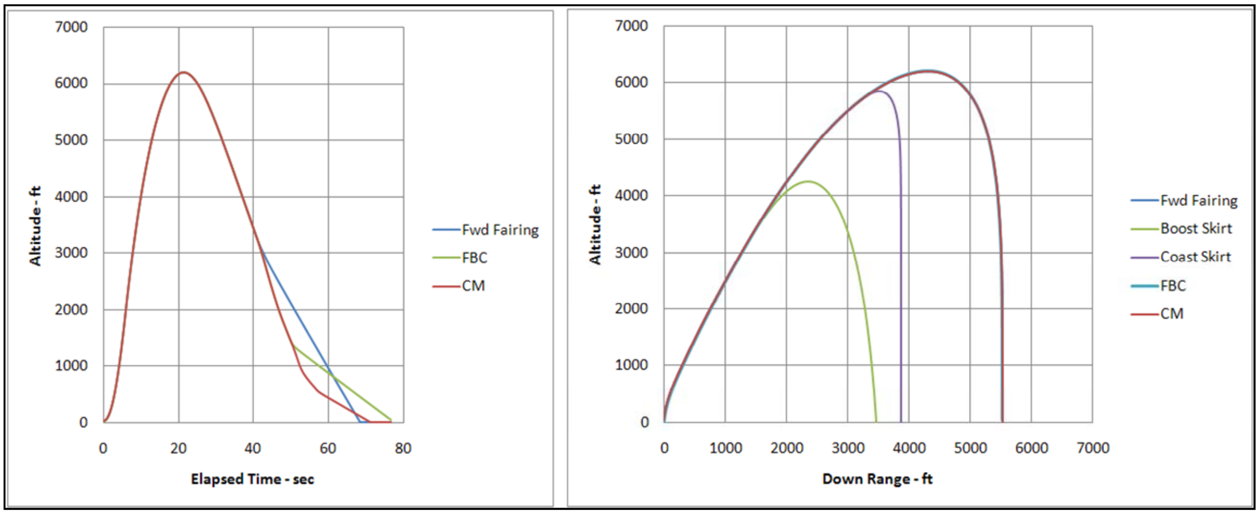


Figure 16: Final trajectory predictions for major FTV components.

Trajectory Flight Test Results

Figure 17 depicts the CM altitude versus range and the CM altitude versus time, respectively. The as-flown flight trajectory was somewhat steeper than that which was predicted in the pre-flight simulation; however, the trajectory deviation from the prediction was within 0.75 standard deviations in all directions.

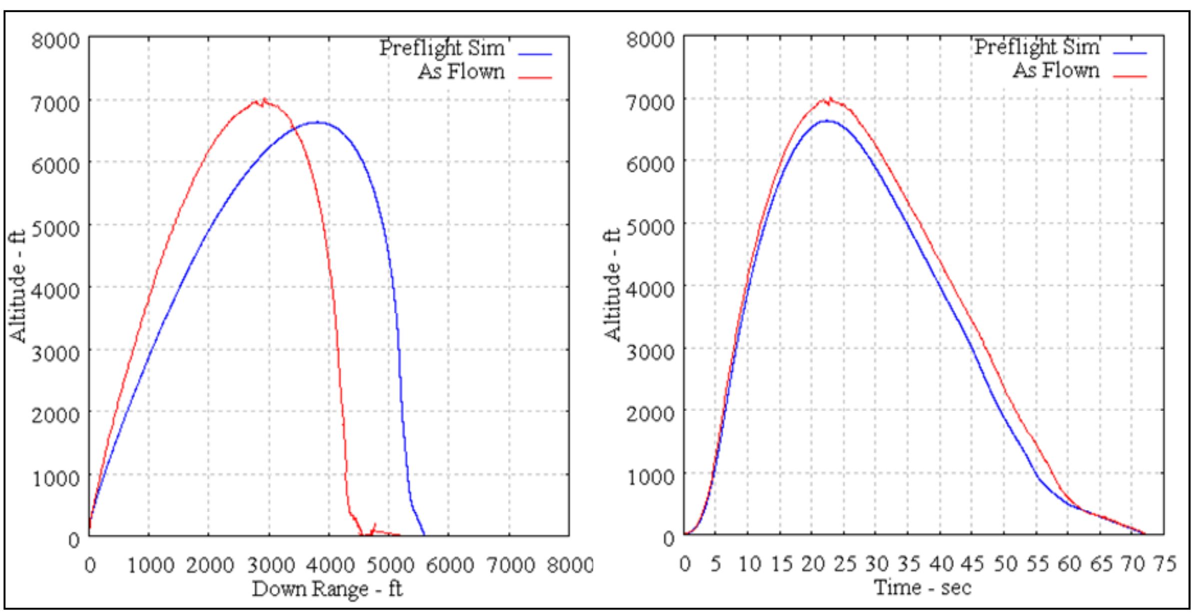


Figure 17: Comparison of flight trajectory with model predictions.

Figure 18 shows a post flight match to the simulation where performance parameters could be measured and the end-to-end simulation updated and compared with the flight trajectory. A minor increase in the parachute performance allowed for an excellent match between the model and the flight trajectory.

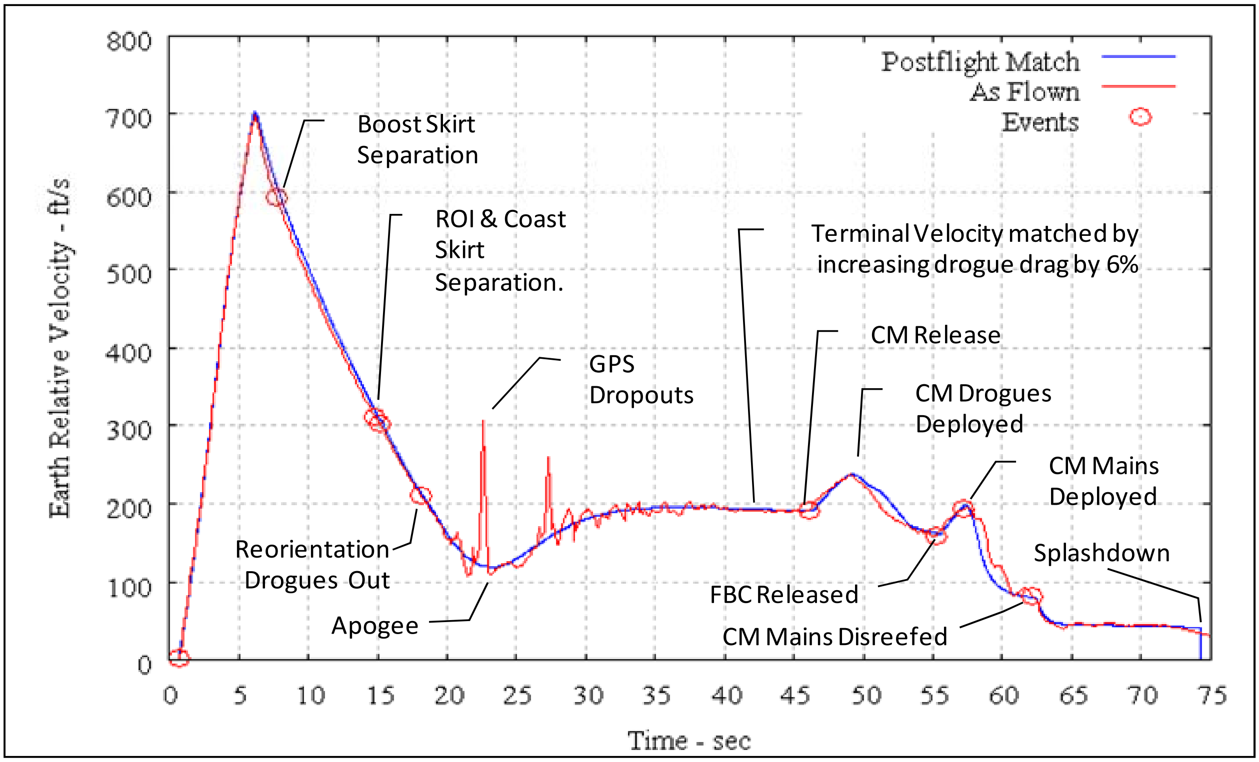


Figure 18: Post-flight trajectory matching graph shows excellent results.

Parachute Modeling and Simulation Approach

Landing and Recovery System Design Requirements

An initial set of FTV trajectories were analyzed to develop a set of performance requirements for the landing system components. The performance requirements called for meeting the drag area requirement while maintaining a minimum structural factor of safety of 1.6 over the range of possible trajectories. The initial parachute requirements to reorient the FTV quickly expanded to include a recovery system for the CM and a separation parachute for the coast skirt. A bounding constraint was that the schedule dictated the use of existing parachute designs to avoid a lengthy parachute development cycle for a one-off flight test. The requirements were categorized as:

- **Coast Skirt Separation –** A flight test-imposed constraint called for a 200-foot separation of the coast skirt from the FTV when the reorientation drogues were fired to prevent entanglement of the drogues with the coast skirt. Analyses indicated the coast skirt would fly in formation close behind the FTV after separation and separate at an unacceptably slow speed.

- **Reorientation Drogue Equivalent Drag Area –** The Flight Mechanics and Aerodynamics teams developed an initial drag area estimate of the reorientation drogue parachute at 258 ft^2. This was the minimum required to reorient the FTV and damp motions to the required CM hand-off conditions. To ensure the mission objective of reorientation was achieved, the drag area was implemented as redundant drogue parachutes with each parachute having the required 258 ft^2 of drag area. Defining the drag area requirements and requiring COTS equipment had the effect of setting a bound on parachute load capability performance very early in the project in return for cost and schedule benefits.
- **CM Recovery System -** Provide a CM recovery system that would allow a splashdown of the CM and recovery of critical on-board flight data recorders. This requirement was implemented as the Landing Parachute Demonstration.

A discussion of each of these three steps is provided below.

Use of Modeling and Simulation in the MLAS Parachute Systems Design

Several parachute analysis cycles were required to determine both the dynamic and static loads applied by the parachutes to the FTV as well as an analysis of margins in the parachute structure when under the applied loads. The primary load drivers were FTV mass and dynamic pressure at the time of parachute deployment.

Each parachute analysis cycle was performed as follows:

1. **Modeling Parachute Forces –** The latest trajectory state vectors, mass properties and aerodynamic parameters were used as input to the parachute simulation to determine both dynamic and static forces, with the results being reported to the Loads team. The simulations also investigated FTV pitch damping for comparison with the end-to-end trajectory analysis.
2. **Determining Parachute Structural Margins –** The peak loads determined by simulation were used to evaluate the structural margins in each element of the parachute system.
3. **Update Simulation with Test Data –** Both the end-to-end trajectory and parachute force simulations were updated with component performance data derived from tests to increase the fidelity of these simulations.

Modeling Parachute Forces

A mortar-deployed stall-spin parachute, used for business jet and military fighter jet testing, was located with the required drag area. This allowed parachute force simulations to be performed using a specific model drogue parachute, with the advantage that the parachute structural margins could be analyzed after each simulation to verify that the factor of safety was maintained. When the safety factor was not maintained, the Flight Mechanics team would design new trajectory to accommodate the parachute performance capabilities.

The steep and shallow trajectories from the trajectory simulations represented 90 percent of the predicted trajectories and so were used to develop upper and lower bounds for the parachute forces as was shown in Figure 13. First, the trajectory simulations containing the body elevation, angle-of attack, pitch rate, etc. along with air data, i.e. dynamic pressure and altitude, were used to develop state vectors at specific points along the trajectory corresponding to the events shown in Figure 14. The events were:

- Beginning of the reorientation initiation, i.e., ROI when the dynamic pressure dropped to 100 lb/ft^2, to analyze the coast skirt drogue performance and reorientation drogue performance;
- Initiation of the separation event to analyze the CM drogue performance; and
- Initiation of the forward bay cover release to analyze the CM main parachute performance during the Landing Parachute Demonstration.

Next, the state vectors, along with the vehicle mass properties and aerodynamics database, provided the data needed to initialize the simulation and determine parachute forces resulting from the deployment events. Outputs from the parachute force simulations were provided to the MLAS Loads & Dynamics team and became driving requirements for the FTV structural design.

Parachute Simulation Tool – Airborne Systems' Decelerator Dynamics (DCLDYN) parachute inflation and trajectory analysis tool was used to predict the parachute forces that resulted from the FTV state vectors (Taylor and Murphy, 2005). DCLDYN has a sophisticated parachute inflation model, which uses parachute-specific parameters to model the inflation process and resulting force time-history. DCLDYN performs 3-degree-of-freedom, planar simulation (pitch and downrange) of the vehicle dynamics while being decelerated by the parachute and includes vehicle mass properties and aerodynamic characteristics. Vehicle dynamics are important because they can add an additional force increment due to, for example, pitching motions, which pull on the parachute harness system. DCLDYN also models the parachute materials, as they are important contributors to force management due to their elasticity (or lack thereof). Port-O-Sim remained the end-to-end trajectory prediction tool due to its 6-degree-of-freedom capability (roll and yaw) and its capability to model the boost segment.

Parachute Loads Management - Parachute loads management was an area where the Flight Mechanics and Landing and Recovery teams jointly worked the problem of determining, managing, and minimizing parachute loads. Parachute deployment forces are essentially a function of the dynamic pressure at which the drag area is deployed plus a shock factor, which is specific to the parachute design. An accepted method to reduce the parachute deployment force is through incremental deployment of the drag area, called parachute reefing. Thus, a reefing study was undertaken with DCLDYN to determine a drag area deployment schedule which best managed the parachute opening forces. Figure 19 shows a force study for the reorientation drogue parachutes. Another reefing study simulation was used to show that a

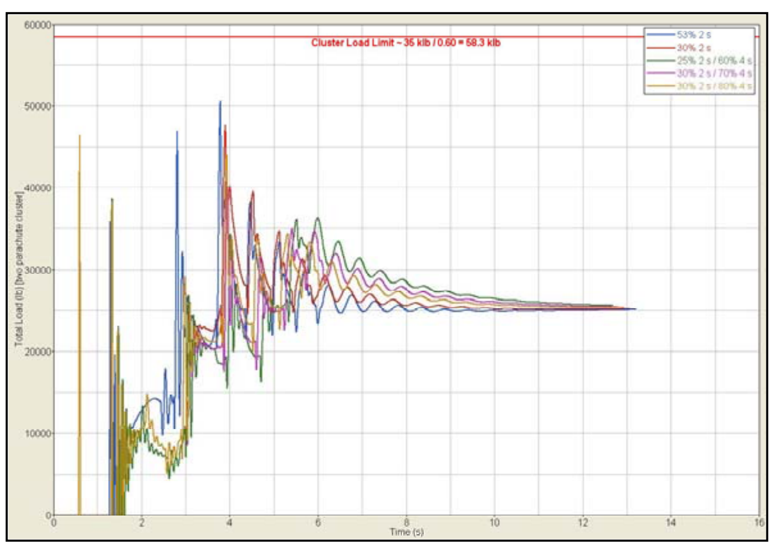


Figure 19: Reorientation drogue parachute reefing study results.

proven reefing schedule used in specially modified G-12 cargo parachutes would work for the CM main parachute system. The four G-12s were used to simulate the Orion CM main parachutes. Cargo parachutes were used due to the unavailability of Orion main parachutes.

Reefing schedules of 30-percent and 53-percent for two seconds followed by full open were investigated along with multiple reefing stages of 30/70 percent and 20/80 percent. A reefing schedule of 53 percent for 2 seconds was found adequate to manage the parachute forces. The time-force history plot of the three trajectories during reorientation using the selected reefing schedule is shown in Figure 20.

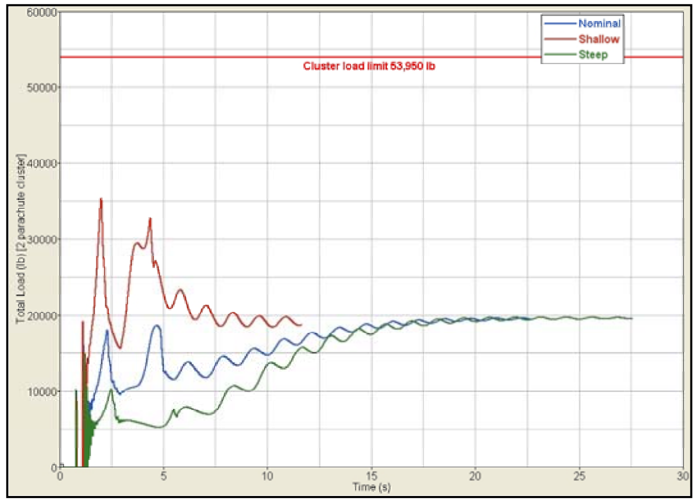


Figure 20: Reorientation drogue parachute forces for the steep, nominal, and shallow trajectories.

The reefing analysis was based on the first set of trajectories available because the pyrotechnic reefing cutters have long lead times. Once the reefing schedule (drag area vs. time) is chosen – it is fixed and cannot be easily altered because the cutters are a part of the parachute canopy, and the canopy is packed and mechanically sealed into the deployment mortar tube when delivered from the manufacturer.

Parachute Simulations: Point Estimates vs. Dispersed Estimates – Parachute simulations from each state vector provided a point estimate of a force-time history. While DCLDYN has the capability to perform Monte Carlo simulations, the project felt it more efficient to provide the dispersed trajectory bounds and obtain the corresponding point estimates. This approach was taken for two reasons: 1) The Port-O-Sim trajectories could bound the expected flight conditions – including the 99th percentile trajectory, and 2) the critical performance parameters of the selected parachutes, primarily the drag coefficient and opening shock factor were well known from flight test and other historical data and had low uncertainty values.

Determining Parachute Structural Margins

The peak forces predicted by DCLDYN were used to determine the forces applied to each element in the parachute systems and determine the strength margins in each element. Since the parachutes were selected very early in the vehicle design cycle, preserving the safety factors in the parachute elements was of continuous concern to the MLAS team and was carefully monitored as the project progressed towards launch. Each time a new set of trajectories were released, a new round of parachute force analysis was needed to show that the structural margins had not eroded into the 1.6 factor of safety. The mass increases continued well after the last planned parachute force analysis cycle, prompting an additional analysis cycle.

Update Simulations with Test Data

The parachute simulation code has a long history of successful use and so a separate validation test campaign was not undertaken. However, both the end-to-end trajectory and parachute force simulations were updated with component performance data to increase the fidelity of the models. The MLAS Project required a test of the Landing Parachute Demonstration, which involved a novel way to deploy the CM main parachutes using the CM forward bay cover and the CM drogue parachutes. Measured parachute drag coefficient and force data were used to improve both the DCLDYN and Port-O-Sim simulations of the main parachute deployment event and descent to splashdown. Additionally, a ground firing of a spare reorientation drogue parachute mortar was undertaken because the MLAS configuration was slightly different from that used in the stall-spin configuration. The successful test provided parachute pack velocity data that also was used to update mortar the models in both simulation tools.

Flight Test Results for Parachute Simulations

An example of the measured FTV accelerations with the predicted accelerations due to the CM drogues is shown in Figure 21. The first peak force occurred within 6-percent of the predicted time and was about 14 percent high, while the second peak force occurred about 20 percent late and was 12 percent under predictions. It should be noted that the DCLDYN prediction was for the pre-flight trajectory and not based on the as-flown trajectory. In addition, note that the uncertainty range in the measured forces is not included in the plot. Predictions of dynamic pressure and altitude were within 10-percent over the same trajectory segment.

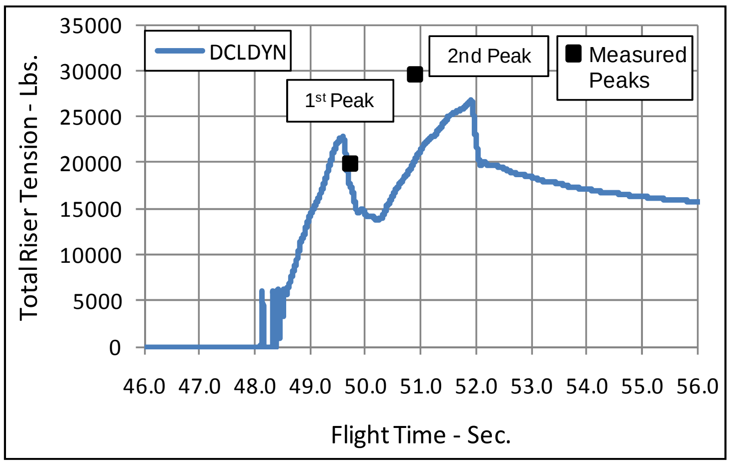


Figure 21: Example of CM Drogue Parachute Forces prediction for the Flight Trajectory.

TEST FLIGHT RESULTS

The MLAS flight test vehicle was successfully launched on July 8, 2009 at 1026Z from a launch stand on Pad 1 at the WFF launch site on Wallops Island. Trajectory and flight dynamics data were gathered using the two on-board JNS100 GPS receivers and three Gimbaled LN-200 with Miniature Airborne Computer (GLNMAC) inertial measurement unit platforms. Review of video and event monitoring data has shown that all flight events occurred as planned.

The actual pad abort test flight was conducted in very close agreement with the operations concept. All the key flight test events occurred in the prescribed sequential order and within acceptable tolerances of the pre-planned time and flight dynamic conditions.

CONCLUSIONS

The launch of the MLAS FTV occurred at 0626 EDT, July 8, 2009. The entire test flight lasted a total of approximately 88 seconds from ignition until the last element of the FTV impacted the ocean. This flight test was the culmination of a nearly 2-year effort to design, build, and fly an alternate LAS capable of recovering the crew of NASA's next generation human spacecraft in event of emergency.

Modeling and simulation played a crucial role in the successful development of the MLAS flight test vehicle and its successful launch. The rapid prototype, concurrent engineering development project required modeling and simulation to be relied upon almost exclusively in the initial design phases. Model validation occurred much later in the project, well after many design decisions had been made to enable the procurement of several key long lead-time components such as the composite OML shape and reorientation drogue parachutes. The successful flight test attests to the growing fidelity of modeling and simulation and how its careful application within validated boundaries can benefit most projects, especially those of a rapid prototype nature.

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BIOGRAPHIES

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Dr. Schuster is currently the NASA Technical Fellow for Aerosciences and is resident at the NASA Langley Research Center in Hampton, Virginia. He led the MLAS Aerodynamics team throughout the project. Dr. Schuster has over thirty years experience in the aerospace industry with the majority of this time devoted to the Aerosciences discipline. He began his career as a Scientist at the Lockheed Georgia Company developing and applying computational aerodynamics tools to a wide range of problems and flight simulations. He later coupled those tools with structural analysis methods to address problems in aeroelasticity and unsteady aerodynamics. He also has extensive wind tunnel test experience, particularly in the area of aeroelastic testing. Dr. Schuster earned his Bachelor of Science Degree in Aerospace Engineering from the University of Cincinnati, and his Master of Science and Doctorate Degrees from the Georgia Institute of Technology. He is an Associate Fellow of the American Institute of Aeronautics and Astronautics

Cornelius Dennehy

Mr. Dennehy served as the leader of the MLAS Flight Mechanics team over the duration of project. He is a member of the NASA Engineering and Safety Center (NESC) organization based at NASA's Langley Research Center in Hampton, Virginia. Mr. Dennehy is the NASA Technical Fellow for Guidance, Navigation and Control (GN&C) and is resident at NASA's Goddard Space Flight Center in Greenbelt, Maryland. In this role, he provides technical leadership for independent test and analysis, risk assessment and problem resolution for the Agency. He has over thirty years of GN&C and space systems engineering experience with an emphasis in the areas of spacecraft attitude determination and control system design, system development, integration & test, and flight operations. He received a BS degree in Mechanical Engineering from the University of Massachusetts at Amherst and a SM degree from MIT in Aeronautical and Astronautical Engineering. Mr. Dennehy is a member of the AIAA.

Daniel Yuchnovicz

Mr. Yuchnovicz is currently a systems engineer in the Systems Engineering Office for the NASA Engineering and Safety Center (NESC) at the Langley Research Center. He led the MLAS Landing Systems team throughout the project. Mr. Yuchnovicz spent over 20 years as a systems engineer to the U.S. Department of Defense in the areas of data communications, simulation and avionics development and certification, and worked for companies including TRW, Unisys, Computer Sciences Corporation and RTI International. Mr. Yuchnovicz joined NASA in 2001 as a reliability and safety engineer and then joined the NESC in 2004 as a systems engineer. Mr. Yuchnovicz received the 1993 Computer Sciences Corporation Technical Excellence Award for Systems Integration and the NASA Exceptional Engineering Achievement Medal in 2010. Mr. Yuchnovicz holds a B.S. Degree in Electrical Engineering from Western Michigan University.