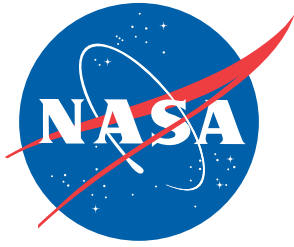


NASA/TM-2010-216877



Guidance, Navigation & Control (GN&C) Design Overview and Flight Test Results from NASA's Max Launch Abort System (MLAS)

*Cornelius J. Dennehy/NESC
Goddard Space Flight Center, Greenbelt, Maryland*

*Raymond J. Lanzi and Philip R. Ward
Wallops Flight Facility, Wallops Island, Virginia*

December 2010

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Report Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

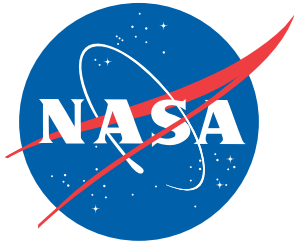
- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.
- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, and organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA STI Help Desk at 443-757-5803
- Phone the NASA STI Help Desk at 443-757-5802
- Write to:
NASA STI Help Desk
NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320

NASA/TM-2010-216877



Guidance, Navigation & Control (GN&C) Design Overview and Flight Test Results from NASA's Max Launch Abort System (MLAS)

*Cornelius J. Dennehy/NESC
Goddard Space Flight Center, Greenbelt, Maryland*

*Raymond J. Lanzi and Philip R. Ward
Wallops Flight Facility, Wallops Island, Virginia*

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

December 2010

Acknowledgments

The authors wish to express their appreciation to their MLAS teammates, their peer reviewers, their engineering support contractors, their NESC management and colleagues, the WFF Code 598 Branch (their GPS Lab in particular), and the Wallops Rocket Club staff for their diverse contributions towards ensuring the success of the GN&C team on this exciting flight test project. The authors also wish to express special thanks to Joel Simpson, Jim Beaty, Brett Vincent, Carl Snow, Dan Yuchnovicz, Bob Beil, Omar Torres, and Brian Tibbetts for their noteworthy personal technical contributions to the success of the MLAS GN&C system. Dee Bullock, an NESC technical editor, is acknowledged for her detailed review and editing of this paper. Scott Glubke, the GSFC Code 590 Chief Engineer, is acknowledged for his thoughtful review of and detailed commentary on this paper.

<p>The use of trademarks or names of manufacturers in the report is for accurate reporting and does not constitute an official endorsement, either expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.</p>

Available from:

NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320
443-757-5802

Table of Contents

1.0	Introduction and Background	1
2.0	Baseline Orion Launch Abort System Design	3
3.0	MLAS Pad Abort Flight Test Objectives.....	4
4.0	MLAS Design Concept	4
4.1	Passive Flight Control	6
5.0	MLAS Pad Abort Flight Test Operations	7
4.2	Landing and Recovery System (Decelerator) Events Overview.....	9
6.0	MLAS FTV Elements	10
7.0	Driving Technical Issues for MLAS Design and Development	12
7.1	Critical Event Command Initiation Methods	12
7.2	Initial Turning Maneuver During Early Boost.....	14
7.3	Aerodynamic Stability.....	14
7.4	Relative Separation Distances	15
7.5	Parachute Loads Management	16
7.6	GN&C Instrumentation	17
7.7	System Verification Methods.....	18
8.0	Flight Test Results.....	20
9.0	Conclusions and Lessons Learned.....	26
10.0	References.....	27

List of Figures

Figure 1.	Orion LAS.....	3
Figure 2.	MLAS ‘back of the napkin’ drawing.....	5
Figure 3.	Refined MLAS ‘back of the napkin’ drawing.	5
Figure 4.	MLAS FTV on launch stool at Wallops Island.	6
Figure 5.	MLAS pad abort flight test concept of operations.....	8

Figure 6. MLAS FTV flight configuration (left) and expanded view (right).....	11
Figure 7. Definition of GN&C Coordinate Frame.	11
Figure 8. Reorientation initiation (ROI) and CM release decision logic flow.	13
Figure 9. Nominal trajectory traces and event constraint lines for WFF Range Control Center manual operator decision guidance.....	14
Figure 10. MLAS FTV shortly after abort motor ignition: ground view (top)/ helicopter view (bottom).....	22
Figure 11. MLAS CM ground track.....	23
Figure 12. MLAS vehicle’s transverse attitude response (boost and coast phases).....	24
Figure 13. MLAS CM altitude versus range.	25
Figure 14. CM altitude versus time.	25

List of Tables

Table 1. Key GN&C constraints and design goals.	19
Table 2. Test scenarios used to verify flight software and ground command operator.	20
Table 3. Predicted versus as-flown summary trajectory quantities.	23

Acronyms

ACM	Attitude Control Motor
AoA	Angle of Attack
C_d	Drag Coefficient
C_k	Shock Factor
CEV	Crew Exploration Vehicle
CG	Center of Gravity
CM	Crew Module
COTS	Commercial-Off-The-Shelf
CPAS	CEV Parachute Assembly System
CxP	Constellation Program
DOF	Degree of Freedom
ESMD	Exploration Systems Mission Directorate
FBC	Forward Bay Cover
FF	Forward Fairing
FTV	Flight Test Vehicle
GLN-MAC	Gimbaled LN-200 with Miniature Airborne Computer
GN&C	Guidance Navigation and Control
GPS	Global Positioning System
IMU	Inertial Measurement Units
JNS	Javad Navigation System
L&RS	Landing & Recovery Systems
LAS	Launch Abort System
LAV	Launch Abort Vehicle
LES	Launch Escape System
LPD	Landing Parachute Demonstration
LV	Launch Vehicle
MLAS	Max Launch Abort System
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering and Safety Center
OS	Objective System
PortOSim	Portable Object Simulation
RF	Radio Frequency
ROI	Reorientation Initiation
SRM	Solid Rocket Motor
TDT	Technical Discipline Team
TV	Thrust Vector
TVC	Thrust Vector Control
WFF	Wallops Flight Facility

Abstract

The National Aeronautics and Space Administration (NASA) Engineering and Safety Center (NESC) designed, developed and flew the alternative Max Launch Abort System (MLAS) as risk mitigation for the baseline Orion spacecraft launch abort system (LAS) already in development. The NESC was tasked with both formulating a conceptual objective system (OS) design of this alternative MLAS as well as demonstrating this concept with a simulated pad abort flight test. The goal was to obtain sufficient flight test data to assess performance, validate models/tools, and to reduce the design and development risks for a MLAS OS. Less than 2 years after Project start the MLAS simulated pad abort flight test was successfully conducted from Wallops Island on July 8, 2009. The entire flight test duration was 88 seconds during which time multiple staging events were performed and nine separate critically timed parachute deployments occurred as scheduled. Overall, the as-flown flight performance was as predicted prior to launch. This paper provides an overview of the guidance navigation and control (GN&C) technical approaches employed on this rapid prototyping activity. This paper describes the methodology used to design the MLAS flight test vehicle (FTV). Lessons that were learned during this rapid prototyping project are also summarized.

1.0 Introduction and Background

In June 2007, the Associate Administrator for the Exploration Systems Mission Directorate (ESMD) requested the National Aeronautics and Space Administration (NASA) Engineering and Safety Center (NESC) undertake the Max Launch Abort System (MLAS) Project. The MLAS was named after Maxime (Max) Faget. Dr. Faget was the lead designer of the Mercury space capsule and developed its abort system called the “Aerial Capsule Emergency Separation Device”. It was in his honor that the MLAS was named. His innovative spirit and his team’s rapid development of new technologies formed the inspiration for the MLAS Project.

The charter for the MLAS Project was to develop, design, and test an alternate concept for the Orion Crew Exploration Vehicle (CEV) Launch Abort System (LAS). MLAS would be theoretically capable of extracting the Orion vehicle from the Launch Vehicle (LV) at any time from crew ingress at the launch pad through staging and ignition of the second, or upper, stage of the Ares I crew LV. The MLAS Project would conclude with at least one full-scale unmanned pad abort test suitable for demonstrating the viability of this alternate LAS concept. The MLAS Project would be run independently from the Constellation Program (CxP) and Orion Project in order to minimize impact on in-line program resources. It was dictated that off-the-shelf hardware and existing technology would be used on MLAS wherever possible. Design and development work previously accomplished by the NESC would be leveraged for this project. Previous work includes the CEV Smart Buyer Design, Composite Crew Module, and the Alternate Launch Abort System.

The NESC cultivates a problem-solving and technical assessment organizational model that permits it to rapidly assemble inter-center, interdisciplinary engineering teams. This is typically done by exploiting the pre-established Technical Discipline Teams (TDT) built and maintained by each of the fifteen NASA Technical Fellows. The TDTs are the networking mechanism used by NESC to gain access to technical knowledge, expertise and contacts at all the NASA Field Centers. This NESC infrastructure was used to form the NASA-wide MLAS Project team. For example, members of the Guidance, Navigation and Control (GN&C) TDT (see Reference 1) were recruited to serve on the MLAS GN&C team and other members were subsequently recruited to serve as peer reviewers of the GN&C team's work.

Teams were formed based primarily on engineering disciplines and the subsystems of the flight test vehicle (FTV). Several of the NASA Technical Fellows served as leaders of these sub-teams. The teams were purposefully kept small to allow for closer technical interaction, technical agility, and faster design and development decision making. In addition, the existing internal quick response business processes of the NESC were leveraged to rapidly implement new engineering support contracts and hardware procurements with industry and to also help establish the programmatic partnerships with the management, engineering, fabrication, integration, and range support elements at NASA's Wallops Flight Facility (WFF).

The MLAS GN&C team was formed in July 2007 and was given the responsibility for modeling, simulating and analyzing the trajectory and attitude dynamics of the MLAS FTV during its simulated pad abort flight. The GN&C team members ensured that the flight test occurred within the envelope defined by the requirements, and they constructed the nominal target flight timeline and trajectory. All of the MLAS trajectory and attitude flight instrumentation equipment, including the Inertial Measurement Units (IMU) and Global Positioning System (GPS) receivers, were selected by the GN&C team. These navigation sensors were chosen to generate flight test data that would permit post-flight reconstruction of MLAS vehicle trajectory and attitude dynamics. Analyses performed by the GN&C team determined ballasting, motor alignment, and launch stand angle requirements. Over the course of the MLAS Project the GN&C team worked closely with System Engineering and Integration, Aerodynamics, Landing and Recovery System (L&RS), Propulsion, Avionics, Software, Structures, and Loads & Dynamics teams and also with the MLAS Chief Engineer.

MLAS team members and the facilities used were distributed across the country. To offset this, team cohesion was maintained by creating a virtual team environment. This meant frequent teleconferences using virtual meeting technology supplemented by periodic Co-Locations. These Co-Locations were week-long gatherings of the entire MLAS team which were held roughly once per month during the early and middle phases of the MLAS Project. Component and scale-model testing, loads analysis, and most of the design was performed at sites across the country, with results integrated with the team during the Co-Locations. The Co-Locations were organized working sessions, not formal meetings or design reviews and were proven to be useful to facilitate rapid decision-making, ensure common understanding between team members, and to generally build teamwork. Focused MLAS Configuration Control Board meetings were an essential forum for the entire team to review critical system design trades, analysis results, hardware and software problems, vehicle assembly and operational steps and to then formulate project decisions as a group for rapid responsive action.

2.0 Baseline Orion Launch Abort System Design

A brief overview of the baseline Orion LAS is given here to provide some background context for the MLAS design and concept of operations. As part of the overall CxP architecture the Orion CEV will have a LAS to remove the crew to safety (i.e., away from the LV) in the event of an emergency either on the pad or during ascent. Orion's current tower-based LAS evolved from the Launch Escape System (LES) used for the Mercury and Apollo Programs (the Gemini Program employed aircraft-style ejection seats for abort functions). The Orion Project-designed LAS will use tractor nozzle rocket motors to pull the crew module (CM) from the top of the Ares I LV and move it to a safe distance where it will parachute to Earth. The design contains a tower motor assembly attached to the forward (top) of an ogive fairing that encases the CM of the Orion vehicle (see Figure 1). The Orion LAS tower has three motors: the abort motor, the attitude control motor (ACM), and the jettison motor. The reverse-flow abort motor propels the LAS away from the LV upon initiation of an abort. The ACM, through eight modulated nozzles, provides launch abort vehicle (LAV) stability and re-orientates the LAV for the different phases of flight. After reaching a safe altitude and distance from the LV, the LAS will release the CM. The CM drops from the fairing assembly and the landing parachutes are deployed. Simultaneously, the jettison motor will carry the LAS away from the CM.

The development of the LAS ACM system hardware and uncertainty in the controllability of the LAV in the transonic abort regime were major challenges facing the Orion team and were drivers for the ESMD leadership to initiate and complete the MLAS Project.

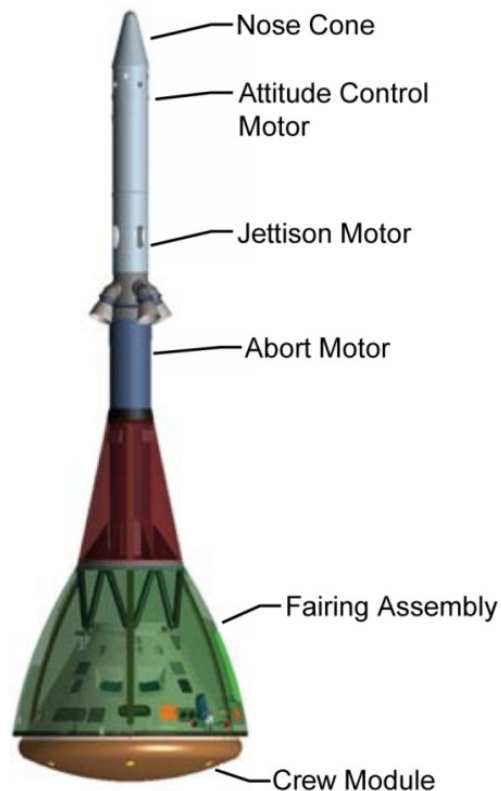


Figure 1. Orion LAS.

3.0 MLAS Pad Abort Flight Test Objectives

At the start of the MLAS Project, the following four primary objectives were identified for the pad abort flight test:

1. Demonstrate that the side-mounted abort concept is feasible for all abort conditions and for a nominal launch.
2. Evaluate the capability of the MLAS to lift the CM from the launch pad to an altitude high enough and with enough distance downrange to permit the CM to execute a nominal landing.
3. Demonstrate proper MLAS pad abort initiation and event sequencing. This includes flying a stable trajectory, LAS and fairing separation, and re-orienting and stabilizing the CM to a recovery condition.
4. Obtain flight test data that will be used to: determine the structural loads and the integrity of the LAS, fairings and CM during the pad abort; characterize the aerodynamic environments experienced by the FTV during the abort, fairing separation, and re-orientation; and characterize the separation dynamics between the LV interface, the LAS, fairings and CM.

One additional MLAS Project objective was to use the experience gained with MLAS to develop a NASA capability for a 'skunk works' like rapid prototype design, fabrication, and testing. This was an opportunity to expose many NASA engineers to a rapid prototype development project. This also prevented the diversion of CxP resources away from their own development activities. Intense technical interactions and brainstorming sessions between the engineers on the MLAS team, with their diverse backgrounds, experience levels, and disciplines, were very common in this dynamic working environment. The significant design innovations, process improvements, and clever problem solutions that emerged from these interactions greatly benefited the project.

4.0 MLAS Design Concept

Beginning in August 2007, the GN&C team supported the initial design of the MLAS pad abort FTV. The origins of the tower-less MLAS FTV can be traced to the initial notional 'back of the napkin' drawing (see Figure 2) that was conceived during a CEV Smart Buyer Design study outbrief brainstorming session in March 2006.

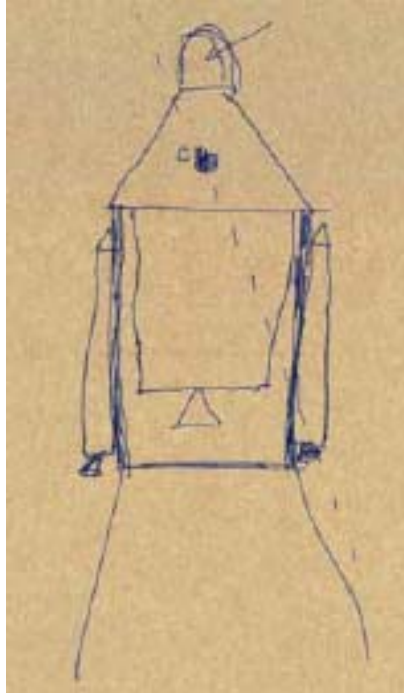


Figure 2. MLAS 'back of the napkin' drawing.

Subsequently a refined MLAS drawing (see Figure 3) was provided to NESC in June 2007 by Scott "Doc" Horowitz, the Associate Administrator for the ESMD at the time MLAS was initiated, as a notional point of departure for the early system level trades and vehicle configuration studies.

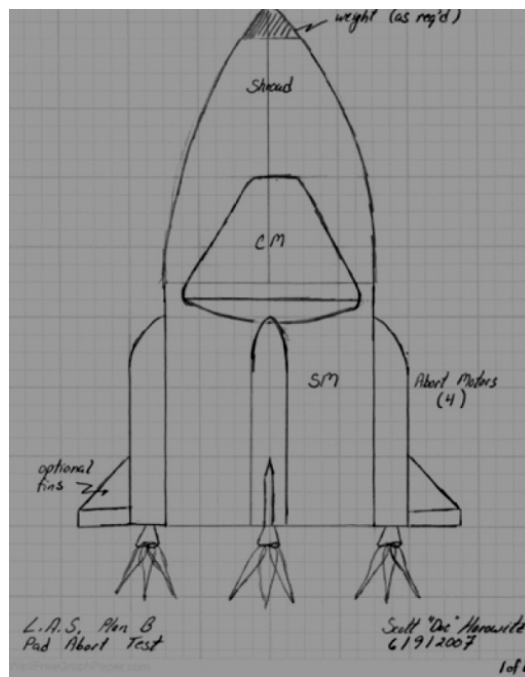


Figure 3. Refined MLAS 'back of the napkin' drawing.

In parallel with their initial design work on the FTV, the GN&C team also supported the development of MLAS objective system (OS) concepts and addressed the need for clear traceability of the envisioned OS to the pad abort FTV. Fundamentally, the MLAS FTV was designed to reduce the risks associated with the passive aerodynamic stabilization approaches used on prime OS candidate design concepts.

Multi-disciplinary system work requiring very tightly coupled technical relationships between the GN&C team and the Aerodynamics, Structures, and L&RS teams, as well as the MLAS Chief Engineer, were required. It is interesting to compare the final MLAS FTV prelaunch physical configuration (see Figure 4) with the original notional drawings depicted in Figure 2 and Figure 3. One can clearly see that the MLAS abort system concept differs from Orion LAS in that it uses side-mounted abort motors instead of a tower-tractor abort motor design that pulls the CM from above. The tower abort motor has been designed out of the MLAS concept and the CM fully encapsulated in a forward fairing (FF).



Figure 4. MLAS FTV on launch stool at Wallops Island.

4.1 Passive Flight Control

Multiple MLAS system-level flight-control design trades were conducted very early in the project. Various mechanisms were considered for maintaining control over the vehicle and accomplishing its pitchover turn along the desired launch azimuth. Active guidance with concepts using thrust vector control (TVC) and potentially active aerodynamic surface control were considered. Since, at the time the MLAS Project was initiated, the highest technical risk for the baseline Orion LAS design was the ACM, the team shifted its focus to MLAS design concepts that eliminated or mitigated the need for complex flight controls. The GN&C team considered and analyzed several passive stabilization schemes for MLAS pad abort boost, coast

and re-orientation flight phases. These passive flight control concepts were investigated to reduce design and development risk for this compressed-schedule flight demonstration project. Ultimately, a passive approach was selected based on its fundamental simplicity and anticipated relative ease of implementation. Cost and schedule constraints, along with the observation that the TVC method is a flight proven vehicle control technology, were the primary drivers that led to the adoption of a purely passive flight control approach. The cost and complexity of designing, building and testing an active closed-loop TVC system (including the necessary testbeds to integrate and validate TVC hardware & software) for this rapid prototype, short-duration, initiative did not trade well against the passive flight control scheme. The GN&C design and development approach leveraged the WFF Sounding Rocket Program expertise, experience, modeling/simulation tools, and flight hardware to the maximum extent possible. Independent simulations were performed of the vehicle's trajectory/attitude dynamics. The results of the WFF Portable Object Simulation (PortOSim) flight-control simulation tool were favorably compared with the results obtained with the generic simulation flight-control simulation tool from Langley Research Center. These comparisons provided early confidence in the feasibility of the team's design concept. Independently generated outputs from another GN&C tool, called the Program to Optimize Simulated Trajectories, were also periodically compared with the PortOSim outputs to perform a technical crosscheck on the MLAS flight performance in general as well as the boost, coast skirt and CM simulator separation dynamics in particular.

The decision to fly with passive control drove the GN&C modeling, simulation and analyses efforts. The GN&C team performed in-depth analyses to fully characterize and understand the sensitivity of the FTV flight performance to the relative relationship between the vehicle's center-of-gravity (CG) and the resultant thrust vector (TV) produced by the solid rocket motors (SRM) used to propel the FTV. Significant effort was expended to identify and validate the specific error sources that made knowledge of the resultant TV orientation uncertain, as well as those error sources that introduced uncertainty into the determination of the vehicle's CG location.

The decision to fly without active closed-loop feedback control also drove the necessity to perform several stages of detailed mass properties testing and the associated mandatory need to rigorously 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.

5.0 MLAS Pad Abort Flight Test Operations

Figure 5 illustrates the MLAS pad abort flight test concept of operations adopted after extensive trade studies and system analysis. From the perspective of the GN&C discipline, the MLAS FTV was an unguided, fin-stabilized projectile, using aft-mounted SRMs to carry the primary article under test, in this case the FF and the encapsulated CM simulator, to the desired altitude, range, and dynamic pressure conditions for reorientation and recovery.

The SRMs were canted so that their TVs nominally intersected on the centerline at the axial station of the CG just after launch. This was done to limit the effect of thrust asymmetries. A

spherical bearing interface was used to transfer the thrust loads into the vehicle at the CM heat shield. The pivot point of this interface was also placed near the CG to ensure that motor cage misalignments would not produce large thrust moments.

The MLAS FTV was launched from a fixed stool on Launch Pad 1 on NASA's Wallops Island and achieved its turn toward the desired launch azimuth using two mechanisms:

1. Launch stool tilt angle: four degrees from vertical along the launch azimuth.
2. Vehicle radial CG offset: approximately one inch from the centerline along the launch azimuth.

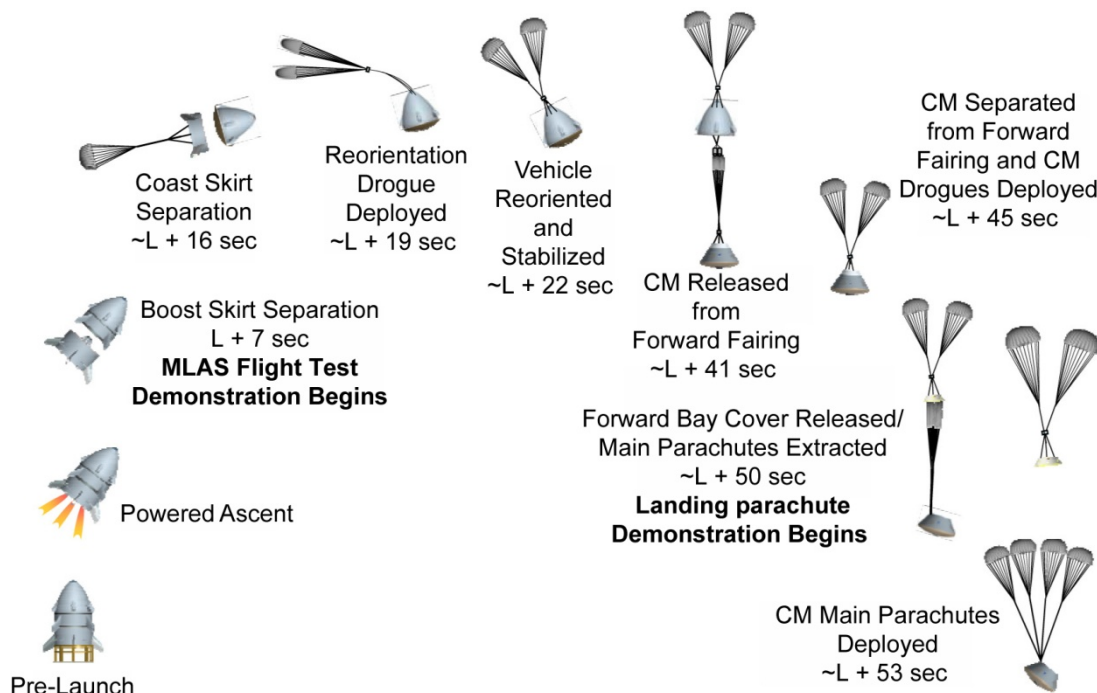


Figure 5. MLAS pad abort flight test concept of operations.

Upon burnout of the SRMs, about six seconds after ignition, the boost skirt was separated via the frangible joint separation device. Four fixed drag plates presenting a total effective drag area of 36 square feet were used to ensure positive separation acceleration between the forebody and the aft boost skirt. The actual MLAS flight test demonstration began next with the stable coast phase. This phase demonstrated the passive stability of the FTV during unpowered flight. The powered ascent phase would place the FTV at an altitude of about 7000 feet and roughly 3000 feet downrange east of the launch site.

When the vehicle decelerated to a velocity corresponding to a flight dynamic pressure of 100 pounds per square foot (psf), the coast skirt, including its four fins, was separated using an identical frangible joint separation device and drogue parachute. This was followed by an on-board timer-sequenced reorientation maneuver beginning with deployment of the two drogue parachutes mounted to the nose of the FF. The two drogue parachutes attached to the FF served to re-orient the FTV to a heat shield-forward attitude in preparation for release of the CM

simulator from the FF. A byproduct of the drogue chute deployment was loss of horizontal velocity, and thus placing the vehicle on a nearly vertical trajectory.

During the subsequent descent, at a programmed altitude of 3300 feet, the separation nuts were fired and the CM simulator was ‘dropped out’ of the aft-facing FF. This would initiate the landing parachute demonstration (LPD). Two drogue parachutes mounted on top of the CM forward bay cover (FBC) were deployed via static lines attaching the drogue bags to the FF. At a programmed duration of 9.2 seconds after CM release, the FBC was jettisoned, pulling the four main parachutes out of their deployment bags that were mounted in the FBC and away from the CM. The CM main parachutes possessed a 5-second reef at 26.5 percent of their total inflated area prior to fully inflating to increase load sharing through synchronous deployment.

The entire flight would last approximately 90 seconds from booster ignition until the last element of the FTV impacted the ocean. All of the elements landed in the ocean off the coast of the launch site. The coast skirt, boost skirt and CM simulator were later recovered.

4.2 Landing and Recovery System (Decelerator) Events Overview

The L&RS major events begin with the separation of the coast skirt and end with deployment of the CM main parachutes. L&RS operational events are:

1. Coast Skirt Drogue Deployment – The single drogue deployment was designed to achieve a separation distance between the coast skirt and FTV that was adequate to deploy the reorientation drogues without entanglement with the coast skirt.
2. Reorientation Drogue Deployment – Dual drogues were designed to reorient the FTV and dampen the FTV motions to the following conditions that were to be provided by the Orion LAS for the CEV parachute assembly system (CPAS) during a pad abort:
 - a. CM Down-Range Distance at Separation > 3300 ft
 - b. CM Separation Altitude > 3300 ft
 - c. CM Handoff Lateral Rates < 40 deg/sec
 - d. CM Handoff Angle of Attack (AoA) < 40 deg
 - e. CM Handoff Dynamic Pressure < 40 psf
 - f. CM Handoff Roll Rate < 80 deg/sec
3. CM Drogue Deployment – As the initial event in the LPD, the CM drogues were deployed to decelerate and stabilize the CM in preparation for main parachute deployment.
4. FBC Release/Main Parachute Extraction – The primary objective of the LPD was to use the FBC and CM drogues to extract the four main parachutes in an attempt to achieve a high degree of load sharing through synchronous deployment.
5. CM Main Parachute Full Deployment – This was the final event that decelerated the CM to a steady-state descent rate prior to splash down. The only project requirement was to achieve steady-state descent prior to splashdown since CPAS main parachutes were not available for the test.

Reference 2 provides an overview of the ribbon parachute system employed on the MLAS FTV for coast skirt separation, fairing reorientation, and as drogue parachutes for the CM after separation from the fairing.

6.0 MLAS FTV Elements

As illustrated in Figure 6, the MLAS FTV is comprised of four major physical elements: the FF, CM simulator, coast skirt, and boost skirt. The elements were attached by frangible joints and bolts; allowing separation at appropriate intervals during the flight test. The elements were integrated into the FTV at the WFF, and were then moved by truck and barge to the Wallops Island launch site. WFF was chosen to fabricate and launch the MLAS FTV because it had the required assembly, test and launch facilities and a decades-long history of sounding rocket testing. On an historical note: the LES for the Mercury Program was also tested at WFF in the late 1950s.

The distinctive shape of the FTV came from the Sears-Haack body shape chosen by the Aerodynamics team for the fairing and the short, but wide, dimensions of the boost and coast skirts. The height of the integrated FTV was approximately 400 inches tall from the tip of the nose to the lowest point of the boost skirt fins. The diameter of the shell of the coast skirt and the boost skirt was approximately 216 inches. The launch weight of the FTV was approximately 48,000 lb. A description of the major individual MLAS vehicle elements is given below.

Boost Skirt: The boost skirt was the aftmost element of the FTV and contained the motor cage that held the SRMs in place. The individual motors were installed in the motor cage within the boost skirt, and each one was canted inward. A frangible joint was used to attach the boost skirt to the coast skirt. Four fixed drag plates were mounted near the bottom of the boost skirt, in such a way that they would extend into the free stream, to ensure a rapid separation of the boost skirt from the rest of the FTV. Four fins were mounted on the boost skirt to help provide passive stabilization during the short (six-second) powered flight phase.

Coast Skirt: The coast skirt was attached to the bottom of the FF to provide passive aerodynamic stability. The coast skirt had four fins that provided passive stabilization during the coast phase of the test flight, which lasted approximately nine seconds. The four coast skirt fins were identical to the four fins mounted on the boost skirt. A single aft-facing drogue mortar was mounted on the inside wall of the coast skirt to deploy a drogue parachute from the coast skirt. The coast skirt was mated to the FF with a frangible joint.

Forward Fairing: The FF encapsulated the CM simulator, and the combined package was called the forward assembly. The shape of the FF was based on a Sears-Haack body to minimize drag. The FF contained 1423 lbm of lead ballast in the nose to place the X-axis CG as far forward as possible and to provide a minimum of 10-percent body diameters of static stability margin during the powered and coast phases of flight. Additional lead ballasting in the motor trough¹ provided a small Z-axis CG offset to provide an initial pitch-over moment. The FF housed the two mortar-deployed drogue parachutes that were used to reorient the forward assembly from the vehicle attitude during the coast phase to a heat shield-forward attitude in preparation for separation of the CM simulator and the execution of the LPD.

¹ Vertical protuberances were placed on the outer mold line of the FF to simulate side-mounted motors. Underneath these structures were large channels in the fairing – motor troughs – that provided space for ballast as well as avionics, cameras, etc.

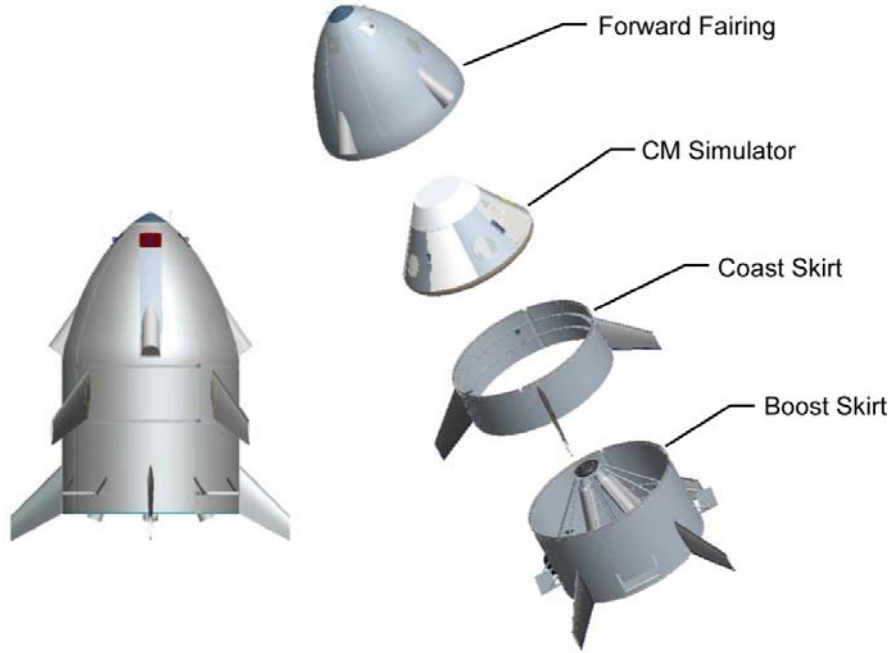


Figure 6. MLAS FTV flight configuration (left) and expanded view (right).

CM Simulator: The MLAS CM simulator approximated the shape and mass of the Orion CM. The CM was attached to the FF using four frangible bolts/nuts. The CM simulator carried antennae, avionics wiring and connectors, two IMUs, a data processor, data recorders, and cameras. Figure 7 shows the relationship between the GNC frame and the MLAS vehicle frame used by the structural engineering team. The GNC frame will be used to represent most of the data that will be presented in this paper.

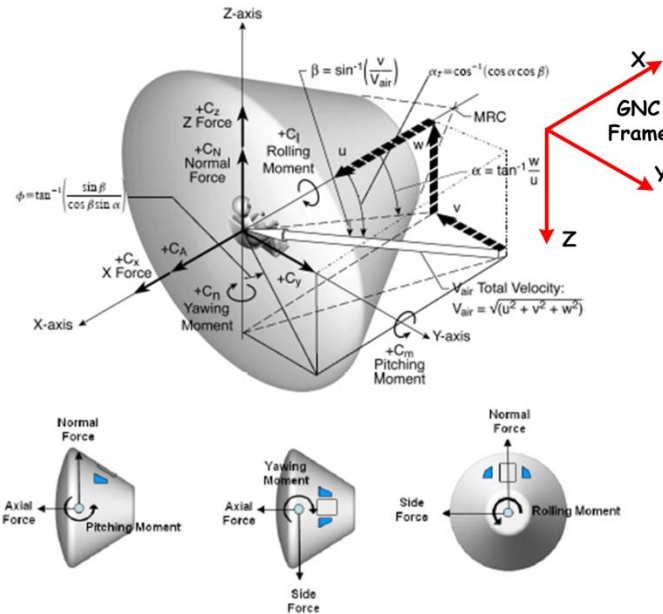


Figure 7. Definition of GN&C Coordinate Frame.

7.0 Driving Technical Issues for MLAS Design and Development

Both the GN&C and the L&RS teams were constrained, or at least strongly influenced, by the following top-level project requirements, needs and MLAS vehicle attributes:

- No active closed-loop flight control elements – passive aerodynamic stability with modest static margins.
- Multiple propulsive, aerodynamic, mechanical, electrical and sensor performance, and operational dispersions (uncertainties).
- Abort SRMs that provided a fixed and finite propulsive capability with thrust dispersions, which exceeded current industry capabilities.
- The need to passively affect a vehicle pitchover maneuver shortly after abort motor ignition to establish a downrange component of velocity early in flight.
- The need to maximize the use of commercial-off-the-shelf (COTS) components to minimize development costs and schedule – in particular, there was the need to identify rapidly available, low cost, flight-proven GN&C instrumentation to permit accurate post-flight trajectory and attitude reconstruction.
- Use of components with flight pedigree in equivalent operating environments to reduce performance risk and development testing.
- Availability of required equivalent parachute drag area in flight-proven COTS packages;
- Parachute material availability – Some Kevlar™ materials had excessive lead times compared to nylon (nylon was used when possible).
- Achieving satisfactory relative separation distances between vehicle elements, identifying ways of ensuring positive separation between the elements of the test article that were shed during various phases of flight proved to be one of the most challenging parts of the design effort.
- System verification with accurate predictions of FTV trajectories, both nominal and dispersed these trajectories and associated metrics established and verified basic MLAS flight performance in general and were the main driving basis from which many other detailed parachute system design requirements were derived. New trajectory predictions were needed soon after each major model change or update to ensure overall design compliance.
- Minimizing, or at least managing, parachute loads in the face of continuous vehicle mass growth over the project duration and no alternative to fundamentally alter the parachute design or material.
- The need to have a redundant capability to precisely sequence the timing of critical flight test events.

The technical issues associated with these project requirements, constraints and influences are described below.

7.1 Critical Event Command Initiation Methods

Early in the MLAS systems design phase it was initially 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, several months into the project, the Monte Carlo flight performance simulations showed large enough dispersions in the MLAS trajectory such that the simple pre-set avionics-event timer-event command concept had to be abandoned and alternative techniques developed and tested.

After careful consideration of all feasible alternatives, the MLAS Project team implemented two independent methods of activating the coast skirt separation/reorient-sequence initiation command and the CM separation command. A flight-termination receiver was activated using the WFF Range system infrastructure and an on-board flight processor with event-triggering decision logic, which were both incorporated into the MLAS FTV design. The logic flow for initiating the reorientation initiation (ROI) and CM release (separation) command functions is shown in Figure 8.

In the WFF Range Control Center, the command logic was implemented manually using visual cues from a single fixed-scale graphical display of total Earth-relative velocity and altitude (see Figure 9). The ROI was commanded by the ground operator when the vehicle crossed the constant dynamic pressure constraint line on ascent. CM release was commanded by the ground operator as the vehicle descended through a 3300-foot constraint line.

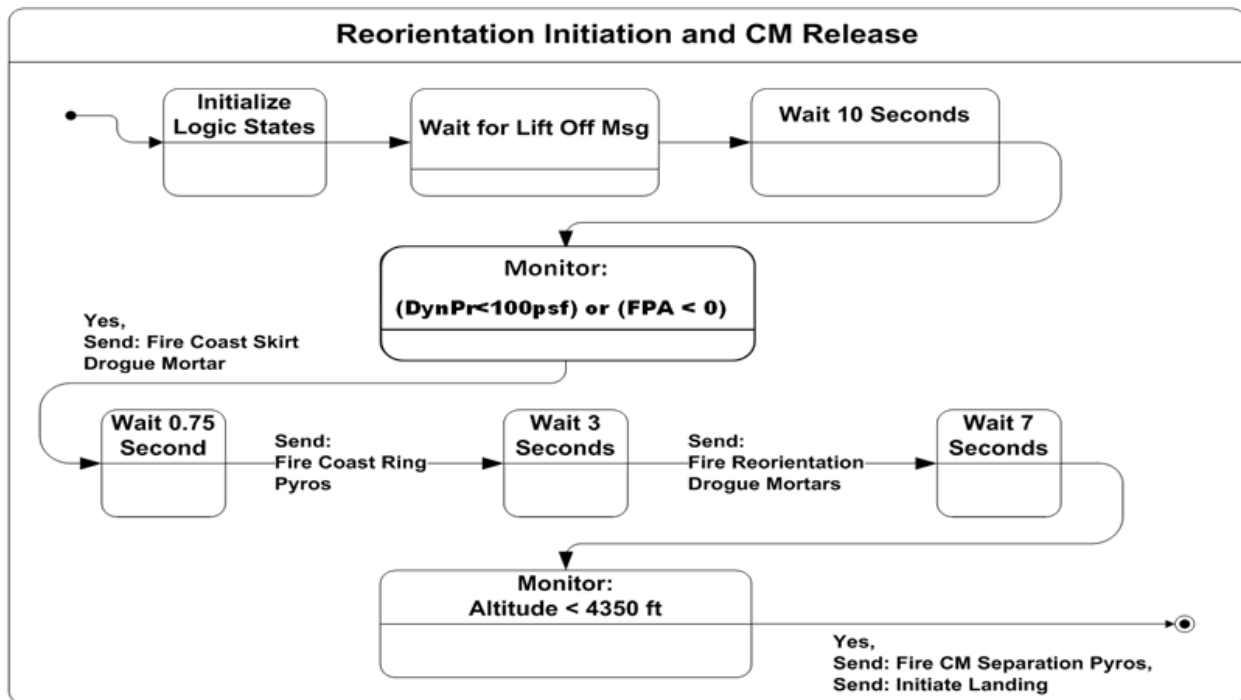


Figure 8. Reorientation initiation (ROI) and CM release decision logic flow.

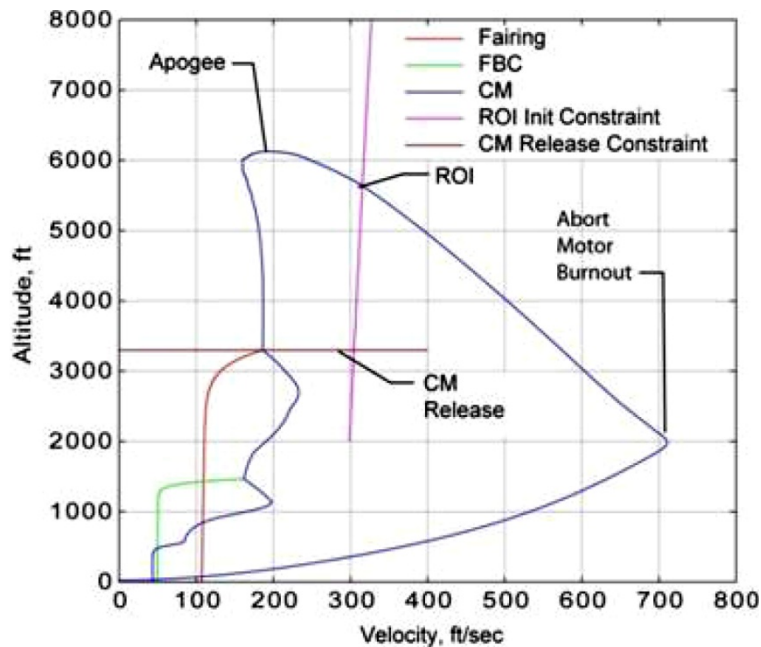


Figure 9. Nominal trajectory traces and event constraint lines for WFF Range Control Center manual operator decision guidance.

7.2 Initial Turning Maneuver During Early Boost

It was determined early in the concept formulation that producing a thrust moment by offsetting the vehicle CG from the centerline was the most effective means of producing the initial vehicle-turning maneuver, also referred to as the pitchover maneuver. This permitted the establishment of a downrange component of velocity early in flight. Flowing from this design decision were stringent requirements on CG management, along with requirements on aerodynamic stabilizing moments to prevent the vehicle from nosing over too far. The vehicle turn could have been accomplished entirely by a radial CG offset. However, a tilt offset of the vehicle launch stool by four degrees toward the launch azimuth was deemed prudent by both the GN&C team and WFF Range safety personnel.

7.3 Aerodynamic Stability

Conventional aerodynamic fins were used on the MLAS FTV, rather than the grid fins² envisioned for the MLAS OS vehicle, in order to reduce project and schedule risks. The coast fins and boost fins were iteratively sized 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

² Grid fins, also known as lattice fins, are often used as a lifting and control surfaces for highly maneuverable aerodynamic vehicles. Deployable grid fins have been used on the Russian Soyuz TM-22 spacecraft to provide aerodynamic stabilization during an abort either on the pad or during atmospheric flight. The main advantages of a grid fin are its low hinge-moment requirement and good high AoA performance characteristics.

goals. It was desired that the aerodynamic pitching frequency of the vehicle would be representative of the closed-loop bandwidth frequency of a guided objective system under the action of a TV 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.

Early analysis demonstrated that a ‘rule of thumb’ static margin of 10-percent body diameter would be sufficient to accomplish both goals. For manufacture, it was desired that all eight fins be identical, so the fins were sized together to yield a minimum static margin of 21.7 inches for both the boost and coast configurations. After exiting the design phase and during the build phase, the FTV’s CG location was rigorously managed to maintain this static margin in the boost and coast phase configurations.

7.4 Relative Separation Distances

Finding ways of ensuring positive separation between the elements of the test article that were shed during various phases of flight proved to be one of the most challenging parts of the design effort. To this effect, a GN&C-led Tiger Team was established during concept formulation to trade a number of mechanisms for accomplishing piece-part separation.

The boost skirt separation was accomplished using four fixed drag-plates sized initially to provide 2 g of relative acceleration between the forward and aft bodies. This approach has been used successfully to accomplish drag separation of sounding rocket stages. The performance loss associated with having the plates out in the flow during boost was considered an acceptable trade for the simplicity of the approach. A rule of thumb criterion of 1 g relative acceleration was determined prudent, and the plates were sized with margin in the initial design. This margin was steadily eroded during the vehicle build phase by mass ‘creep’ and aerodynamic effects discovered in computational fluid dynamics. However, the final pre-launch analysis showed just over 1 g of separation acceleration.

The coast skirt separation was accomplished utilizing a mortared drogue (originally ordered as a spare reorient drogue). Initially, a rule-of-thumb requirement levied to maintain 200 feet of separation between the coast skirt and forward assembly at the time the reorient drogues are mortared out. This was later relaxed to 200 feet of separation at time of reorient drogue parachute line-stretch.

A reorient-then-release baseline of the MLAS test vehicle was established in the earliest days of the design effort. One byproduct of this concept was that a large amount of rotational energy would be imparted into the forward assembly, 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 FF, the FBC, and the CM during final descent.

The team was forced to rely upon differential drag accelerations on the various objects and a somewhat risky parachute deployment timing sequence was set up to race the CM into the water before the FF could overtake it and potentially foul the main parachutes. At the second Independent Technical Review milestone, in April 2008, a timing concept was presented by the

GN&C team that accomplished the goals of maintaining adequate vertical separation between the FF and the CM at CM splash. This separation was quickly erased by mass gains in the FF, which occurred during fairing segment fabrication. The vertical separation was regained by lowering the CM release by 1000 feet; however, these gains were lost again by additional mass gains in the FF that occurred during FTV assembly.

In the end, no requirement was established to prohibit re-contact between the FF, the FBC, and the CM. The only mechanism for developing lateral separation between the three objects was differences in the transient response to the wind variations with altitude. It was not expected that these would be enough to guarantee separation margin with respect to parachute diameters (especially the large diameter main parachutes on the CM). The MLAS Project Management was willing to accept this as a risk, as long as the analysis showed that there was sufficient time to deploy the main parachutes and achieve descent equilibrium velocity prior to a potential re-contact event. The final pre-launch analysis verified this and showed the FF overtaking both the FBC and the CM prior to splash. The FBC was nominally predicted to maintain a 320-foot vertical separation distance from the CM during the flight. The FF was predicted to overtake the FBC at an altitude of 820 feet (at ~10 seconds after CM main parachute line stretch). The FF was predicted to overtake the CM at an altitude of 165 feet, at 16 seconds after CM main parachute line stretch.

7.5 Parachute Loads Management

Of all the technical areas on MLAS where the GN&C and L&RS teams interacted, the problem of determining, managing and minimizing parachute loads was probably the most dynamic point of technical intersection. Addressing the parachutes' loads issues was an almost constant battle on MLAS. This situation arose primarily out of the necessity to procure, very early in the project, low-risk readily available parachutes in flight-proven COTS packages. This had the effect of setting a bound on parachute load-capability performance very early in the project in return for project cost and schedule benefits.

During each of the three major MLAS analysis cycles of parachute forces, the primary influence on parachute loads were:

- Continuous FTV mass increases during the development life cycle,
- Improved knowledge of the FTV aerodynamic performance,
- A fixed and finite amount of propulsive capability, and
- The results of trajectory optimizations by the GN&C team to increase the probability of achieving the stated mission success goals.

The vehicle mass increases continued well after the last planned parachute force analysis cycle, prompting a final but unplanned parachute force analysis cycle. Parachute force is directly proportional to the dynamic pressure and drag area. 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 both the L&RS and GN&C teams and was carefully monitored as the project progressed towards launch.

The GN&C team initially supported the L&RS team by providing a set of FTV trajectories, which were then analyzed to develop a set of performance requirements for the landing system

components. The performance requirements were to essentially meet the drag area requirement and always maintain a minimum factor of safety of 1.6 over the range of possible trajectories. To derive the trajectories the L&RS team, the GN&C team performed special sets of Monte Carlo dispersed simulations using the portable object simulation (PortOSim) tool to characterize a wide range of possible trajectories and parachute deployment conditions. The state vectors, along with the vehicle mass properties and aerodynamics database, provided the data needed to determine parachute forces during all deployment. To develop upper and lower bounds for the parachute forces, the GN&C team provided three state vectors that encompassed 90 percent of the predicted trajectories. These were referred to as the shallow, nominal and steep 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.

Each state vector (shallow, nominal and steep) was used to drive a simulation of parachute deployment forces and thus, was a point estimate for each trajectory and not dispersed. This approach was taken for two reasons: 1) The GN&C team 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 C_d , and opening shock factor C_k were well known from flight test. A range of C_d was analyzed for the CM descent on the drogues and mains to ensure that the CM could achieve a steady-state rate of descent prior to splashdown.

7.6 GN&C Instrumentation

GN&C instrumentation was required for accurate post-flight trajectory and attitude reconstruction. There was a strong push by project management for the GN&C team to identify low-cost COTS sensors for this purpose. The GN&C team identified suitable instrumentation less than two months after project initiation. Three IMUs and two GPS receivers were selected as the on-board GN&C instrumentation set. The Avionics team then assumed responsibility for procuring, physically accommodating, electrically integrating and interface testing the IMU and GPS receiver flight hardware as part of their overall Avionics subsystem development effort. The requirements for, and performance of, final pre-launch functional verification testing of the IMUs and the GPS when the FTV was mounted on the launch stool was the responsibility of the GN&C team.

A total of three Gimbaled LN-200 with Miniature Airborne Computer (GLN-MAC) IMU sensors were flown on the MLAS FTV. This specific choice of IMU was made very early in the MLAS Program, in August 2007, based on its performance capabilities, relatively low cost, low mass/power/volume, extensive sounding rocket flight heritage, and off-the-shelf availability. The GLN-MAC IMU is a standard piece of GN&C equipment used on most of the Wallops sounding rockets. Therefore, the level of engineering familiarity the MLAS Wallops team members had with this type of IMU was also a factor in this unit's selection. The general operating and technical performance characteristics of the GLN-MAC IMU are provided in Reference 3.

Two IMUs were mounted on the avionics pallet inside the CM simulator. A passive vibration isolation system was installed between the avionics pallets and the vehicle structure. This redundant pair was mounted inside the CM to provide the vehicle rate, acceleration, and attitude

data throughout the flight. The IMU-1 and IMU-2 data was both recorded onboard the FTV and sent to the ground via radio frequency (RF) telemetry.

A third identical IMU was mounted in the FF to provide relative motion dynamics information during the CM separation. The IMU-3 data was captured only via RF telemetry to the ground. IMU-3 was added to provide a redundant measurement of the FF/CM separation dynamics that would complement the imagery of the separation event taken by the high-speed camera system. The high-speed camera system was the primary means of obtaining information on the relative motions of the FF and the CM during dynamics information during the CM separation.

The Javad Navigation System (JNS) JNS100 50-channel single-frequency global navigation satellite system receiver board, with raw data and position solution output rate up to 100 Hz, was selected for use on MLAS by the GN&C team. Similar to the IMU selection, this choice of GPS receiver was made very early in the MLAS Program, in July 2007, based on its performance capabilities, relatively low cost, low mass/power/volume, and availability. Unlike the GLN-MAC IMU, at the time of its selection for MLAS the Javad JNS100 GPS receiver was not a standard piece of GN&C equipment used on the Wallops sounding rockets. However, there was a high level of engineering familiarity with this particular receiver, on the part of the GN&C team members, from prior experience on NASA's Autonomous Flight Safety System Project and other efforts. This working familiarity with the JNS100 was also a factor in this unit's selection. It is interesting to note that the JNS100 has since been selected as the Next Generation GPS receiver for the Wallops Sounding Rocket Program. The general operating and technical performance characteristics of the JNS100 GPS receiver board are provided in Reference 4.

For flight on the MLAS FTV, this JNS100 receiver board was packaged by WFF engineering into a GPS receiver unit. After buildup, the MLAS GPS Receiver units were acceptance tested in the Code 598 GPS Development and Test Laboratory at Wallops. In a manner very similar to the IMU integration process, the two JNS100 GPS Receivers were each integrated into the Avionics pallets inside the CM Simulator. These receivers benefited, as the IMU did, from the passive vibration isolation system installed between the Avionics pallets and the vehicle structure.

During the phases of flight leading up to CM release, these receivers were fed by two patch antennae mounted on the outer mode line of the FF. Upon CM release, a lanyard switch was used to switch the GPS receivers to two patch antennae mounted on the CM. This redundant GPS data was used by the on-board flight computer to trigger the ROI sequence and the CM release events in accordance with the logic discussed above.

7.7 System Verification Methods

Nearly all requirements allocated to the GN&C team were verified by analysis. The team primarily utilized the PortOSim 6-degree of freedom (DOF) simulation tool, which served as the Project's end-to-end predictor of MLAS flight performance. PortOSim is a software application that supports engineering modeling and simulation of launch-range systems and subsystems, as well as the vehicles that operate on them (Reference 5). 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.

A PortOSim multi-body model of the MLAS FTV system was first developed and validated. That model was then used to track the effects of vehicle design changes, and as-built variations from the design on the ability of the MLAS to meet many of these requirements. Monte Carlo simulations were used to provide the Systems Engineering and Project Management teams with figures of merit relating to the a priori estimated rate of satisfaction of the various requirements levied upon the test vehicle flight characteristics. Table 1 summarizes the primary requirements tracked by the GN&C team, along with the results from the final 1000-run Monte Carlo simulation performed shortly before launch; along with the related quantities observed during flight using the GPS and IMU sensor complement.

Table 1. Key GN&C constraints and design goals.

<i>MLAS Flight Parameter</i>	<i>Constraints & Design Goals</i>	<i>Monte Carlo % Rate</i>	<i>Flight Observation</i>
<i>CM Deployment Sequence Initiation Altitude</i>	> 3300 ft	98.8	Sequence initiation began with first threshold crossing detected on-board at 3407-ft above pad reference. (CM released at 3250-ft above pad ref.)
<i>CM Deployment Range</i>	> 3300 ft from shoreline	94.5	4004 ft from shoreline
<i>CM Lateral Rate at Release</i>	< 40 d/s	95.9	7.3 d/s
<i>CM AoA at Release</i>	< 40 deg	96.7	1.2 deg
<i>CM Roll Rate at Release</i>	< 80 d/s	100	4.1 d/s
<i>Dynamic Pressure at CM Release</i>	< 40 psf	94.3	37.9 psf
<i>Dynamic Pressure at ROI</i>	< 100 psf	97.0	89.0 psf
<i>Dynamic Pressure at FF Drogue Deployment</i>	< 100 psf	98.1	37.9 psf
<i>Max Alpha Total During Boost</i>	< 30 deg	100	14.6 deg 0.4s after first motion 5.5-deg peak during turn
<i>Max Alpha Total During Coast</i>	< 30 deg	100	2.4-deg peak coast AoA seen at L+12.8-s

Dispersion Sensitivity

Dispersion sensitivity analyses were initially performed early in the project to gain insight into which design parameters drove flight performance. It was determined early that the vehicle was most sensitive to the System CG Radial Location Uncertainty contributor. Much effort went into managing the radial CG knowledge and uncertainty throughout the design, fabrication, and integration phases of the MLAS Project.

Unmodeled Aerodynamic Phenomena

Concern was expressed over the potential for unmodeled aerodynamic phenomena to adversely affect the vehicle flight characteristics during the boost and coast phases of flight. It was the assertion of the GN&C team that the aerodynamic uncertainty model developed and used in our dispersion analysis adequately bounded these types of effects. Given these magnitudes of perturbations, aerodynamic uncertainty effects presented trajectory deviations approximately one order of magnitude lower than those resulting from radial CG perturbations.

Event Deployment Algorithm Verification

A battery of 17 distinct test scenarios (see Table 2) was created to stress-test and boundary-test the ROI and CM release event triggering algorithms that 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-DOF mission simulator. The simulations were played into a GPS RF simulator attached to a JNS100 GPS receiver for data capture. The flight software developer used the resulting data files 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 operator, and verify that he was prepared to issue command functions for the MLAS flight test.

Table 2. Test scenarios used to verify flight software and ground command operator.

<i>Id</i>	<i>Description</i>
1	Nominal Trajectory
2	Steep Trajectory
3	Shallow Trajectory
4	Near 3300-ft Altitude Trajectory
5	Apogee Occurs at 100-psf Q
6	Straight-Up Trajectory
7	Nominal Left-Azimuth Trajectory
8	Nominal Right-Azimuth Trajectory
9	270-deg Roll Case
10	Boost Skirt Fails to Separate
12	Reorient Drogue Deployment Failure
13	Apogee below 3300 ft
14	Back-range Trajectory
15	Parallel to beach North
16	Parallel to beach South
17	1 Motor Fails to Ignite

8.0 Flight Test Results

The MLAS FTV was successfully launched on July 8, 2009 at 1026 Zulu. Figure 10 shows the MLAS FTV shortly after abort motor ignition: the top image was captured by a ground based WFF range camera and the bottom image was taken from a camera mounted on a helicopter hovering offshore from the launch pad. Trajectory and flight dynamics data were gathered using

the two on-board JNS100 GPS receivers and three GLN-MAC IMU platforms. Review of video and event monitoring data by the Avionics team has shown that all flight events occurred as planned.

The GN&C team used a 6-DOF multi-body end-to-end mission simulation in the WFF Range Control Center as a means of developing a pre-flight estimation of the vehicle response to measured atmospheric conditions (winds, density, pressure, etc.) for the purpose of assessing launch commit constraints. The simulated responses of the vehicle, including the effects of wind as obtained from the final (L-3 minute) pre-launch balloon sonde³, represent the baseline nominal predictions for comparison with the actual flight performance. Key trajectory parameters, derived from flight data and simulation, are summarized in Table 3. The ground track is depicted in Figure 11. The launch time was selected to yield light winds. Generally, the winds were from the northwest; although, from 1000 feet to the ground, the wind direction veers from a north to a northwest direction causing the hook seen in the ground-track (Figure 11) toward the end of flight during the CM descent.

An in-depth analysis was performed to ascertain the degree to which the actual as-flown boost phase and coast phase vehicle dynamics matched pre-flight predictions. Due to the relative sensitivities of the trajectory to various perturbations, it is reasonable to hypothesize that the steepness of the as-flown trajectory was caused by a perturbation in the effective moment arm in the vehicle pitch plane. The amplitude of the vehicle turn is directly related to the moment arm between the TV and the CG. During the boost phase, there will be no difference in the effect of a CG perturbation and of a net TV misalignment/offset. There is no reason to expect that such a perturbation would be fixed in time; however, there is no realistic means to attempt to estimate a time-varying moment arm shift given the available data set. Fixed moment arm reductions, in both the MLAS body Y-axis and the MLAS body Z-axis directions were modeled in the post-flight matching simulation by a static reduction of the radial CG offset. Figure 12 shows the vehicle's transverse attitude response during the boost and coast phases of flight for an iteration where the simulated CG was moved toward the centerline axis by 0.23 inches in the MLAS body Z-axis direction, and by 0.08 inches in the MLAS body Y-axis direction.

³ The sonde is a device typically used by the WFF Range to make *in-situ* meteorological measurements of the atmosphere which a sounding rocket, or in this case the MLAS FTV, will fly through. Some, called GPS-sondes, are equipped with GPS receivers to obtain precise positioning information during data collection and some are simple balloons with reflectors that are skin-tracked by range radars during their data collection periods. Data collected includes wind, density, static pressure and speed of sound.



Figure 10. MLAS FTV shortly after abort motor ignition: ground view (top)/ helicopter view (bottom).

Table 3. Predicted versus as-flown summary trajectory quantities.

<i>Summary Data</i>	<i>Actual</i>	<i>Pre-Flight Predict (Using L-3m Sonde)</i>	<i>Magnitude of Miss</i>
<i>Peak Altitude</i>	7018-ft @10:26:23.0Z	6621-ft @10:26:21.9Z	397-ft (0.75-sigma)
<i>Impact Range/Azimuth</i>	4555-ft / 125.4degT @10:27:12.4Z	5592-ft / 124.2degT @10:27:11.6Z	1042-ft (0.73-sigma)
<i>Peak Velocity</i>	699-ft/sec @10:26:06.2Z	688-ft/sec @10:26:06.0Z	11-ft/sec (1.1-sigma)
<i>Peak Mach Number</i>	0.613 @10:26:06.2Z	0.602 @10:26:06.0Z	0.011 (1.3-sigma)
<i>Peak Dynamic Pressure</i>	517-psf @10:26:06.2Z	498-psf @10:26:05.98Z	19-psf (1.25-sigma)
<i>Burnout Roll Rate</i>	9.9-deg/sec @10:26:07.5Z	2.7-deg/sec @10:26:07.0Z	7.2-deg/sec (1.00-sigma)

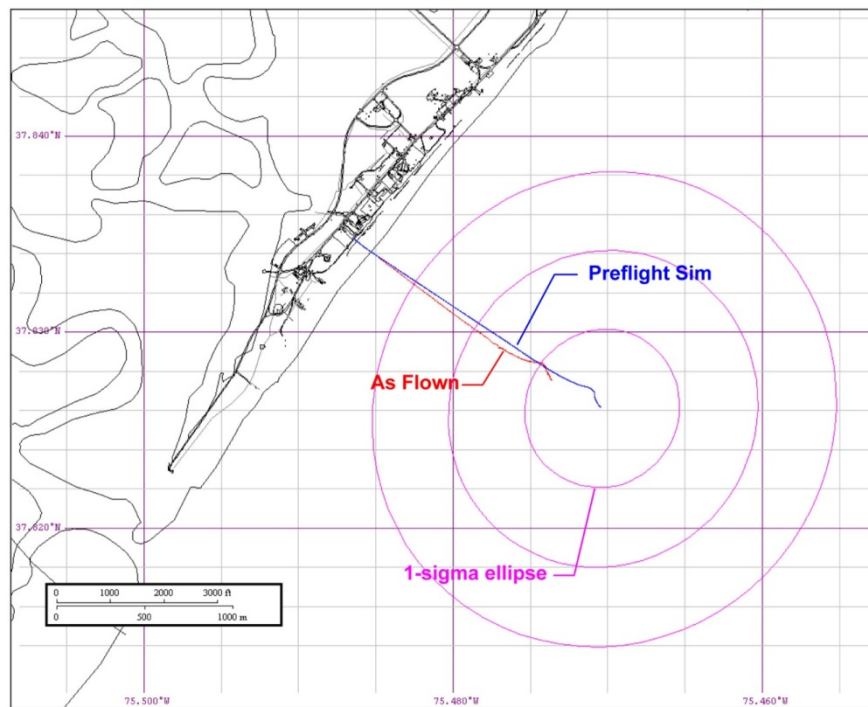


Figure 11. MLAS CM ground track.

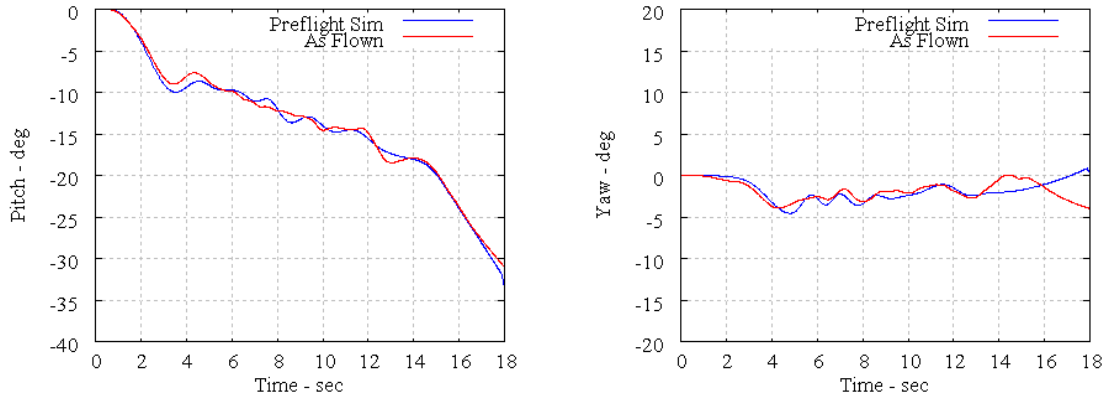


Figure 12. MLAS vehicle's transverse attitude response (boost and coast phases).

A key thing to note from Figure 12 is that there is a close match between flight observation and simulation in both the amplitude and frequency of the vehicle attitude response during both the boost and coast phases of flight. Thus, in order to match aerodynamic pitching frequencies between flight and simulation, the dynamic pressure profile, the aerodynamic forces, the aerodynamic force distribution, and the first/second-moments of the mass distribution must all match. The unlikely alternative is to have a fortuitous cancellation of errors. In order to match the magnitude of oscillation, the initial conditions and disturbance-force environment, caused primarily by the radial CG offset, must also match. By observing the first attitude peak after launch, it is apparent that the vehicle aerodynamic pitch and yaw damping is higher than that computed in the simulation model. This was an expected result. The simulation is fitted with models that compute the damping forces and moments from each fin; however, damping effects originating from body aerodynamic effects were neglected. Given the close match in lateral attitude dynamics, dispersion in the TV-to-CG moment arm was the most plausible scenario found for explaining the steepness of the as-flown trajectory when compared to the simulated pre-launch trajectory prediction.

Figures 13 and 14 depict the CM altitude versus range and the CM altitude versus time, respectively. Figures 13 and 14 show the position data from the GPS receivers alongside the pre-flight predictions made with the wind, density, static pressure and speed of sound data from the L-3 minute balloon sonde. 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.

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

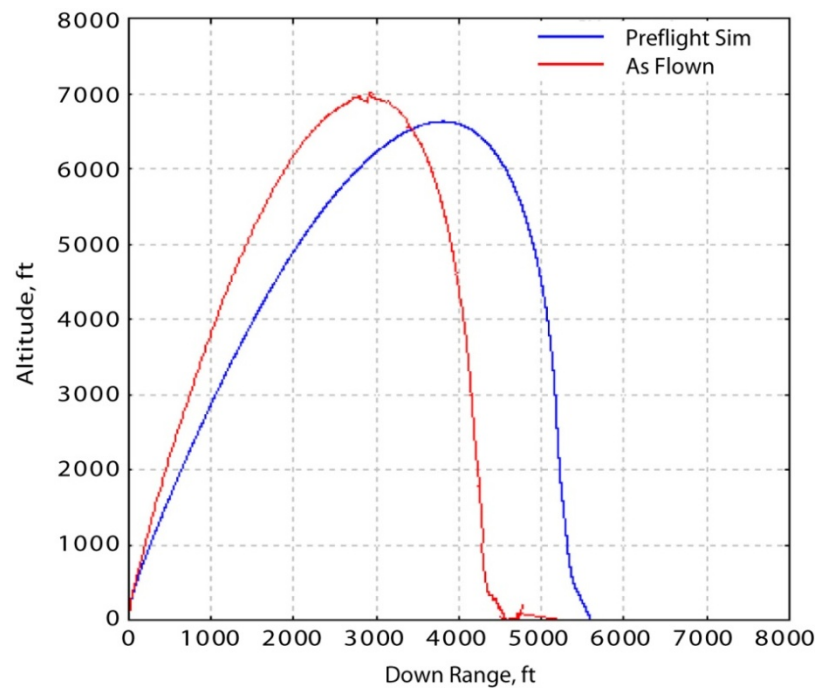


Figure 13. MLAS CM altitude versus range.

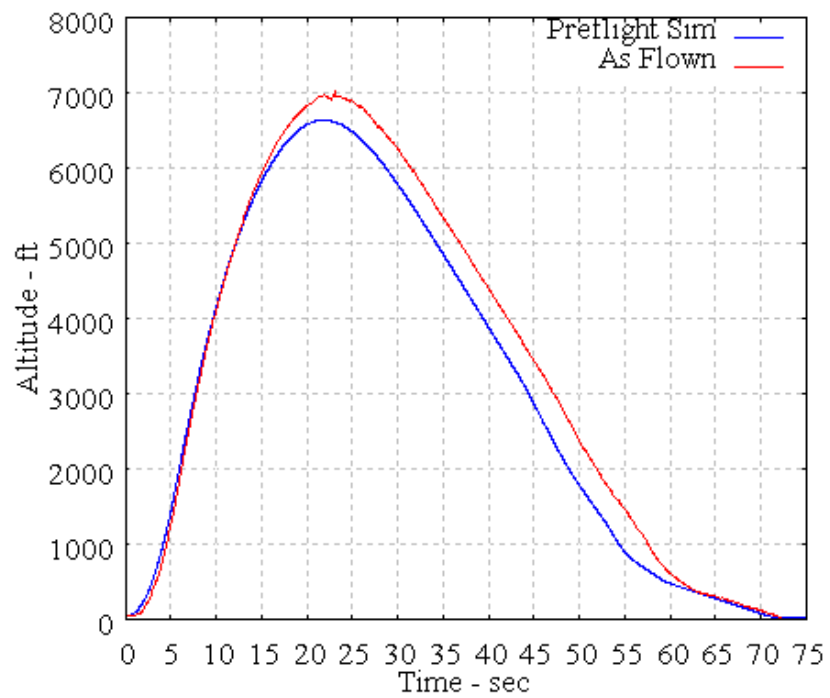


Figure 14. CM altitude versus time.

9.0 Conclusions and Lessons Learned

The launch of the MLAS FTV occurred at 0626 EDT on July 8, 2009, from a launch stand on Pad 1 at the WFF launch site on Wallops Island. This MLAS flight test at Wallops Island marked the first successful pad abort test for a human spaceflight vehicle since 1966. Ignition of the boosters initiated the powered ascent phase, which ended with booster burnout about six seconds later. The powered ascent phase placed the FTV at an altitude of 7018 feet and roughly 3000 feet downrange east of the launch site. The flight test demonstration began next with the stable coast phase. This phase demonstrated the passive stability of the FTV during unpowered flight. Following the coast phase was the re-orientation maneuver using two drogue parachutes to change the FTV attitude to heat shield-forward; concomitantly, the horizontal velocity was scrubbed resulting in a nearly vertical trajectory. When the FTV dropped below 3300 feet, the LPD began. The CM simulator impacted the water at 72.6 seconds after booster ignition. 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 launch abort system capable of recovering the crew of NASA's next generation human spacecraft in event of emergency.

The primary 'big picture' lesson learned from the MLAS experience was the great extent to which the design and integration of a launch abort system can impact and influence the overall Launch Vehicle-Spacecraft system design, overall system reliability, and performance capabilities. One must always keep in mind that a LAS is fundamentally part of the LV used to place the crew in orbit. In the vast majority of launch operations, where liftoff and ascent are nominal, the abort system will not be used and will be jettisoned. Therefore the abort system must be designed to not interfere with the safe operations of, or degrade the nominal performance of, the LV. Striking the correct balance between LV and abort system requirements is a hard optimization problem often necessitating multiple interrelated system-level trade studies. Designers must also carefully consider the demanding flight performance requirements placed upon an abort system. For example, the LAS must be able to perform flawlessly at any point over a wide spectrum of operational regimes. These range from the zero altitude/zero velocity state while sitting on the pad prior to launch, then continuing through problematic transonic conditions, and finally during exoatmospheric flight until shortly after first stage burnout separation. Consider that the abort system also must stabilize and control the orientation of the crew's capsule as it flies not only in the forward direction but in the backward direction as well. Satisfying all these competing requirements while minimizing deleterious impacts on the LV and avoiding the potential pitfall of introducing over-complexity into the overall system, presents a number of unique and demanding abort system engineering challenges for NASA and its industry partners.

Several other important lessons learned came out of this MLAS flight test experience are worth highlighting:

1. The need for all team members to look beyond their immediate discipline task to think, speak up, and act like Systems Engineers for the benefit of the project.
2. The need for planned periodic crosschecks of critical analytical results by having technical 'shoot outs' between different engineering groups using different tools/methods to independently generate analytical products.

3. The need for periodic and informal face-to-face peer reviews; the emphasis should be on reviewing the details of modeling assumptions, analytic methods, uncertainty assumptions, simulation results, control law algorithm designs, software code, etc., and not on preparing formal presentations and responding to action items.
4. The L&RS system design was trajectory driven much more than initially anticipated. Therefore, project management should consider the advantages of integrating the functions of the GN&C and the L&RS teams into one unified technical team; the nature and size of MLAS Project naturally allowed close, almost daily, technical interaction between the GN&C and the L&RS teams but on larger, more traditional, projects having separate teams could lead to inefficiencies and technical disconnects.
5. The need for stringent mass properties testing, and vehicle mass properties configuration control measures and routine periodic reports, especially on a passively controlled vehicle.
6. The degree of difficulty in safely and reliably performing precision alignment of the solid rocket abort motors was initially underestimated.
7. The need to manage and limit insidious unchecked vehicle mass growth which erodes flight performance, degrades system design robustness, increases parachute loads and generally diminishes the probability of overall mission success. Associated with this is the need to incorporate realistic growth margins into the vehicle's design to mass budget. In addition, this can be mitigated in part by defining a robust set of structural loads requirements as early as possible in the project design cycle.
8. A rapid prototyping activity like MLAS can be accomplished using virtual meeting technologies supplemented by periodic Co-Locations of the entire team and by leveraging modern online concurrent data sharing and configuration management capabilities.

10.0 References

1. Dennehy, C. J.: "The NASA Engineering & Safety Center (NESC) GN&C Technical Discipline Team (TDT): Its Purpose, Practices and Experiences." *AIAA Guidance, Navigation, and Control Annual Conference*, Hilton Head, South Carolina, August 2007, AIAA-2007-6332.
2. Taylor, S. P.; Kelley, C.; Magner, E.; Peterson, D.; Hahn, J.; and Yuchnovicz, D.: "A Review of the MLAS Parachute System." *20th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar*, May 4–7, 2009, Seattle, Washington, AIAA Paper 2009-2991.
3. Anon.: *NASA Sounding Rocket Program Handbook*. Sounding Rockets Program Office, Suborbital & Special Orbital Projects Directorate, Goddard Space Flight Center, Wallops Flight Facility, Wallops Island, Virginia, 810-HB-SRP, June 2005, www.nsroc.com.
4. Javad Navigation Systems, Inc.: *JNS100-GG Operator's Manual*. December 2006, <http://www.javad.com/jns/index.html?jns/support/manuals.html> [cited 2/15/2008].
5. Lanzi, J.: *Port-O-Sim Object Simulation Application*. NASA Tech Briefs, September 2009, <http://www.embeddedtechmag.com/component/content/article/5668> [cited 9/10/2008].

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY) 01-12-2010		2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Guidance, Navigation & Control (GN&C) Design Overview and Flight Test Results from NASA's Max Launch Abort System (MLAS)			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Dennehy, Cornelius J; Lanzi, Raymond J.; Ward, Philip R.			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER 869021.03.07.01.03		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Langley Research Center Hampton, VA 23681-2199			8. PERFORMING ORGANIZATION REPORT NUMBER L-19963		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSOR/MONITOR'S ACRONYM(S) NASA		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) NASA/TM-2010-216877		
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category-16 Space Transportation and Safety Availability: NASA CASI (443) 757-5802					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The National Aeronautics and Space Administration Engineering and Safety Center designed, developed and flew the alternative Max Launch Abort System (MLAS) as risk mitigation for the baseline Orion spacecraft launch abort system already in development. The NESC was tasked with both formulating a conceptual objective system design of this alternative MLAS as well as demonstrating this concept with a simulated pad abort flight test. Less than 2 years after Project start the MLAS simulated pad abort flight test was successfully conducted from Wallops Island on July 8, 2009. The entire flight test duration was 88 seconds during which time multiple staging events were performed and nine separate critically timed parachute deployments occurred as scheduled. This paper provides an overview of the guidance navigation and control technical approaches employed on this rapid prototyping activity; describes the methodology used to design the MLAS flight test vehicle; and lessons that were learned during this rapid prototyping project are also summarized.					
15. SUBJECT TERMS Flight test vehicle; Guidance navigation and control; Max Launch Abort System; NASA Engineering and Safety Center					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: help@sti.nasa.gov)
U	U	U	UU	35	19b. TELEPHONE NUMBER (Include area code) (443) 757-5802