20th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar
4 - 7 May 2009, Seattle, Washington

AIAA 2009-2991

A Review of the MLAS Parachute Systems

Anthony P. Taylor[1], Christopher Kelley[2], Eldred Magner[3], David Peterson[4]
Airborne System, Santa Ana, CA, 92704

Jeffrey Hahn[5]
Engineering and Science Contract Group, Houston, TX, 77058

and

Daniel Yuchnovicz[6]
NASA Engineering and Safety Center, Hampton, VA, 23681

Abstract

The NASA Engineering and Safety Center (NESC) is developing the Max Launch Abort System (MLAS) as a risk-mitigation design should problems arise with the baseline Orion spacecraft launch abort design. The Max in MLAS is dedicated to Max Faget, the renowned NASA spacecraft designer.

The MLAS flight test vehicle consists of boost skirt, coast skirt and the MLAS fairing which houses a full scale boilerplate Orion Crew Module (CM). The objective of the flight test is to prove that the CM can be released from the MLAS fairing during pad abort conditions without detrimental recontact between the CM and fairing, achieving performance similar to the Orion launch abort system. The boost and coast skirts provide the necessary thrust and stability to achieve the flight test conditions and are released prior to the test – much like the Little Joe booster was used in the Apollo Launch Escape System tests. To achieve the test objective, two parachutes are deployed from the fairing to reorient the CM/fairing to a heatshield first orientation. The parachutes then provide the force necessary to reduce the total angle of attack and body angular rates required for safe release of the CM from the fairing. A secondary test objective after CM release from the fairing is to investigate the removal of the CM forward bay cover (FBC) with CM drogue parachutes for the purpose of attempting to synchronously deploying a set of CM main parachutes.

Although multiple parachute deployments are used in the MLAS flight test vehicle to complete its objective, there are only two parachute types employed in the flight test. Five of the nine parachutes used for MLAS are 27.6 ft D_0 ribbon parachutes, and the remaining four are standard G-12 cargo parachutes. This paper presents an overview of the 27.6 ft D_0 ribbon parachute system employed on the MLAS flight test vehicle for coast skirt separation, fairing reorientation, and as drogue parachutes for the CM after separation from the fairing. Discussion will include: the process used to select this design, previously proven as a spin/stall recovery parachute; descriptions of all components of the parachute system; the minor modifications necessary to adapt the parachute to the MLAS program; the techniques used to analyze the parachute for the multiple roles it performs; a discussion of the rigging techniques used to interface the parachute system to the vehicle; and a brief description of how the evolution of the program affected parachute usage and analysis.

[1] Technical Director, Space Market, 3000 West Segerstrom Ave., CA 92704, AIAA Associate Fellow.
[2] Design Lead, Engineering Services, 3000 Segerstrom Ave, Santa Ana, CA 92704, AIAA Member.
[3] Design Engineer, Engineering Services, 3000 Segerstrom Ave, Santa Ana, CA 92704, AIAA Member.
[4] Systems Analyst, Engineering Services, 3000 Segerstrom Ave, Santa Ana, CA 92704, Non-member.
[5] Project Manager, Scientific, Engineering, and Analysis Services, 2224 Bay Area Blvd., MS JEB252, Houston, TX, 77058, Professional Member.
[6] Systems Engineer, NESC Systems Engineering Office, MS 112 NASA Langley Research Center, Hampton, VA 23681, Non-member.

An overview of the Objective system, rationale for the MLAS approach and the future of the program will also be presented. We hope to have flight test results to report at the time of the Conference Presentation.

Nomenclature

C_D	=	drag coefficient
CEV	=	Crew Exploration Vehicle
COTS	=	Commercial Off The Shelf
CPAS	=	CEV Parachute Assembly System
CM	=	crew module
D_0	=	parachute reference diameter
FBC	=	forward bay cover
FDU	=	Flight Design Unit
IML	=	Inner Mold Line
KAI	=	Korea Aerospace Industries, Ltd.
LPD	=	Landing Parachute Demonstration
MLAS	=	Max Launch Abort System
NESC	=	NASA Engineering and Safety Center
OML	=	Outer Mold Line
RFP	=	Request for Proposal
S_0	=	parachute reference area
S_∞	=	required free-stream parachute reference area
TPS	=	Thermal Protective System
VPCR	=	Variable Porosity Conical Ribbon

I. MLAS System Description

THE flight test of the MLAS system is a pad-abort type test. On initiation of the unguided, passively stabilized vehicle test, four solid rocket motors installed in the boost skirt are ignited to place the system in a launch abort trajectory. After rocket burn-out, the boost skirt falls away from the fairing. On the objective system, there would be no boost skirt, the rockets would be housed in the fairing above the CM and remain with the fairing. The flight test is designed to be a rapid evaluation of the MLAS concept of operation, and some features of the objective system have been modified on the flight test system to reduce complexity without significantly impacting the goals of the test. The NASA Engineering and Safety Center (NESC) was challenged to design, build, and fly the MLAS flight test in a short period of time while minimizing risk. The first goal drove NESC to determine reasonable trade-offs between fidelity to the objective system and ability to meet the time goal. One of the significant methods employed to try to meet the risk mitigation goal was the use commercial off the shelf (COTS) hardware or flight-proven designs wherever possible.

After the boost skirt is jettisoned, there is a period of stable coast. Here again there is a difference between the flight test system and objective system. On the objective system, grid fins are extended at the aft end of the fairing on system initiation to provide stability. On the flight test system, there are fixed fins on the boost skirt, and there is a coast skirt also not present on the objective system with fixed fins to provide stability. At the end of the coast phase, a mortar located inside the coast skirt deploys a 27.6 ft D_0 Variable Porosity Conical Ribbon (VPCR) drogue parachute directly aft of the vehicle. The coast skirt is separated from the fairing 0.3 seconds after the mortar is fired, so that the coast skirt is free before the parachute inflates. The drogue parachute aids in the quick separation of the coast skirt from the fairing.

Three seconds after coast skirt separation, two 27.6 ft D_0 VPCR drogues are mortar deployed at an angle 20º down (aft) from perpendicular to the vehicle vertical axis. On the objective system, the grid fins would be jettisoned just prior to the firing of these reorientation drogue mortars. These drogues are identical to the drogue used to separate the coast skirt, and are used to reorient the fairing to a stable orientation with the CM heat shield down. At this point, the CM is released and two more 27.6 ft D_0 VPCR drogues are deployed via a static line to simulate the Orion Crew Exploration Vehicle (CEV) Parachute Assembly System (CPAS) drogue parachutes. These drogues are connected to a simulated forward bay cover (FBC), to represent the CPAS Flight Design Unit configuration. As the CM nears the water, the FBC is separated from the CM and four modified G-12 parachutes are deployed from the

FBC in a similar manner to the original CPAS Flight Design Unit (FDU) baseline. These four G-12's simulate the three CPAS 116 ft D_0 ringsail parachutes. Figure 1, provided by NASA, graphically shows the differences between the objective system and flight test system concepts of operation through CM separation.

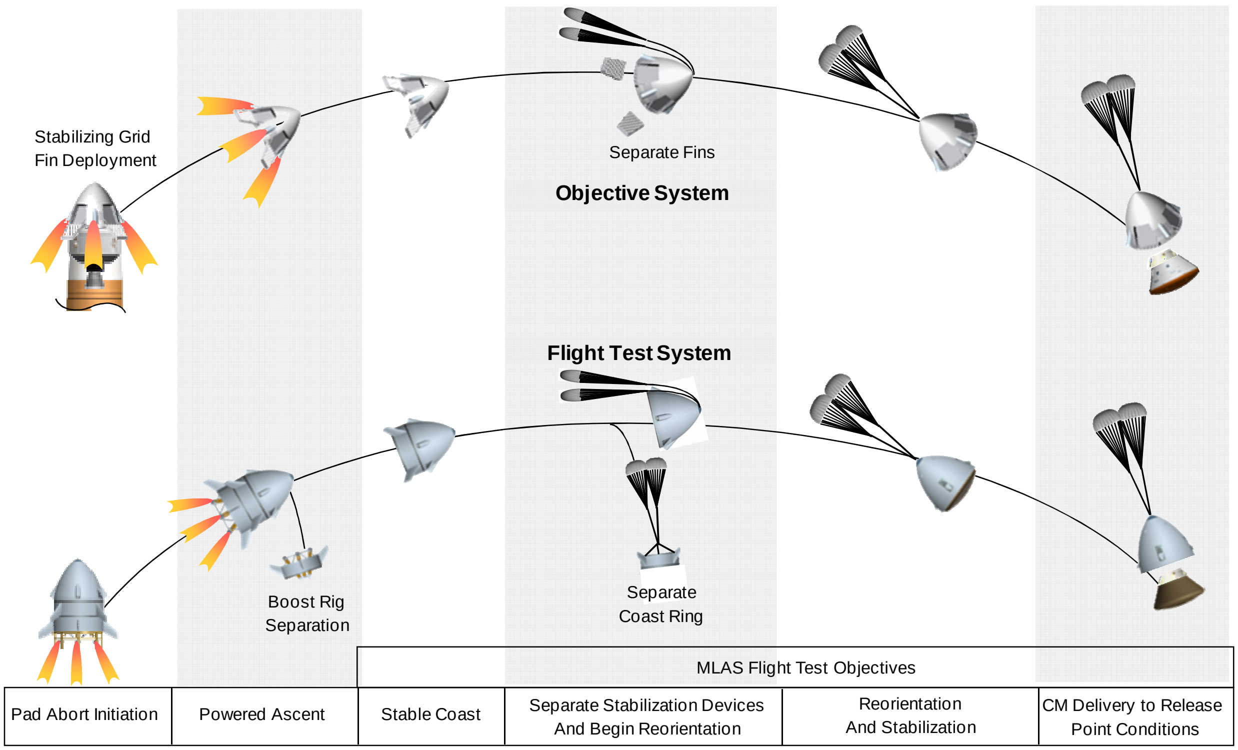

Figure 1. Comparison of Concepts of Operation

II. Parachute Selection

The original MLAS Request for Proposal (RFP) only addressed the reorientation parachutes and requested two mortar-deployed parachutes with a drag area (C_DS_∞) of 258 ft^2 each. In order to correctly size the parachute, this required drag area was adjusted to account for the planform drag coefficient and the forebody wake effects. The measured planform drag coefficient (CD) for the Airborne Systems VPCR parachute is 0.55. The required free-stream reference area (S_∞) is calculated with Equation 1.

$$S_\infty = \frac{C_D S_\infty}{C_D} = \frac{258}{0.55} = 469\, ft^2 \tag{1}$$

Using a design trailing distance of 5 body diameters, the drag loss due to forebody wake is estimated at 20%. The free-stream reference area is then corrected to the required parachute reference area (S_0) and the required parachute reference diameter is determined with Equation 2 and Equation 3.

$$S_0 = \frac{S_\infty}{0.80} = 586.4\, ft^2 \tag{2}$$

$$D_0 = \sqrt{\frac{4 \cdot S_0}{\pi}} = 27.3\, ft \tag{3}$$

Recalling the desire to use flight-proven hardware, a 27.6 ft D_0 VPCR parachute that had been designed as a spin/stall recovery parachute for the F-22 and the Korea Aerospace Industries, Ltd. (KAI) T-50 aircraft was selected for the MLAS reorientation parachute.

Very minor modifications were required to adapt the T-50 parachute for use on the MLAS system. A single reefing stage of 53% for 2 seconds was selected to manage the loads into the fairing and minimize the time required to achieve the full drag area. As the selected drogue did not incorporate reefing, the parachute design was modified to add a reefing system with dual cutters, as well as eliminate the load limiting fitting necessary for spin/stall installations, lengthen the parachute riser, and armor the section of riser that is exposed on the fairing between the mortar and confluence fitting. The mortar used to deploy the T-50 system was selected to deploy the MLAS parachutes. The mortar system was modified from the T-50 design to remove fairings and the load limiting fitting attachment. None of these relatively minor modifications impacted the flight-proven heritage of the drogue and mortar systems.

Initially, the use of drag devices similar to the objective system was envisioned to ensure separation of the coast skirt from the fairing. However, due to difficulties in developing a mechanism for symmetric deployment of the drag devices, the same parachute system used for the reorientation system was evaluated for use in separating the coast skirt, with the goal of creating a 200 ft separation between the coast skirt and fairing within 3 seconds. It was found to be adequate for the task with the same reefing schedule used for the reorientation system. The only changes necessary were a re-clocking of the mortar breech to facilitate installation in the coast skirt, and length and material changes to the bridle legs.

For the CM drogue parachutes, the desire was to simulate the CPAS FDU system as closely as possible. Again looking for commonality across the system, the 27.6 ft D_0 VPCR system was once again evaluated for use in this phase. It was found that mortar deployment of the drogues would not be practical for the boilerplate CM drogues due to the difficult issues involved with designing a FBC that could withstand mortar reaction loads and apex-first drogue deployment loads. It should be noted that an operational FBC design was not an objective of the MLAS Project. However, to simplify the FBC design, the drogues could be deployed via a static line attached to the fairing, and this was the configuration selected. Here the only modifications necessary were the addition of deployment bag bridles to facilitate the static line deployment of the bags, and the addition of grommet strips on the deployment bags to allow them to be tied together for deployment.

Since no spare set of CPAS 116 ft D_0 ringsail main parachutes was available, NESC elected to use four off the shelf G-12 cargo parachutes with riser extensions to simulate the three CPAS mains. Evaluation of the loads expected to be encountered during deployment led to modification of the G-12 parachutes to include a single stage of reefing, reinforce the vent, and replace the suspension line to riser links with higher strength links. The reefing selected was 26.5% for 5 seconds based on experience gained in reefing the G-12 for the Short Range Air Launch Target (SRALT) program.

III. Parachute System Description

The 32 gore, 27.6 ft D_0 VPCR canopy and suspension lines are Nylon, with a Kevlar reefing line. Reefing cutters are Robert's Research H1-2 reefing cutters. The riser is constructed of Kevlar cords which feature finger-trapped loops around a confluence girdle also constructed of Kevlar. The canopy suspension lines have finger-trapped loops through the riser cord loops. There are 16 riser cords, each wrapped around one of two radially slotted pins such that there are 32 terminations at the confluence girdle. A flat, two-plate confluence fitting shown in Figure 2 is used to interface the four riser pins (2 for each canopy) to the four bridle legs that connect the parachutes to the vehicle. The sides of the confluence fitting are titanium, with Custom 455 steel parachute attachment pins and Custom 455 steel pins through aluminum bushings for the harness attachments.

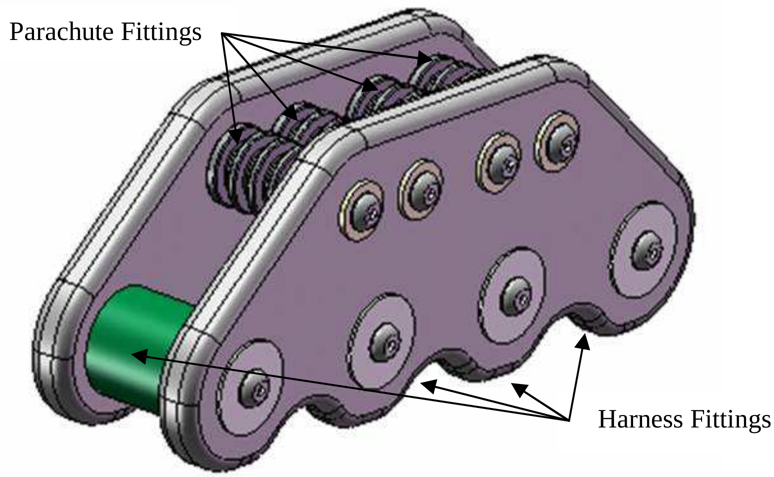

Figure 2. MLAS Confluence Fitting Assembly

The reorientation bridle legs are 15 ft long and each is constructed of a single piece of Kevlar webbing formed into an 8 ply Möbius loop. These bridle legs are attached to the fairing using instrumented pins inserted into clevises. These pins, which are held in place with an anti-rotation fitting, contain internal strain gages which allow measurement of direction and magnitude of a radially applied load.

The coast skirt separation system uses same the confluence fitting design. Since the coast skirt system utilizes a single parachute, only the inner two parachute fittings are used, and blank pins inserted in the other two. The coast skirt bridle legs are 25 ft long and each is constructed of a single piece of Nylon webbing formed into an 8 ply Möbius loop. The coast skirt bridle legs are attached to mount points provided inside the coast skirt.

The decision to use the 27.6 ft D_0 VPCR parachutes as drogues for the boilerplate CM and tight vehicle integration schedule prevented the build of an additional titanium confluence fitting for use in the flight test. However, an existing three to two (3:2) confluence fitting that had been used for a heritage program was adapted with aluminum plates mimicking the parachute attachment features of the MLAS confluence fitting. The 3:2 fitting underwent dimensional inspection and NDE to verify it had not been subjected to overload. Figure 3 shows the confluence fitting with adapter used for the CM drogues. Three 16 ft long bridle legs are used for the FBC drogue system, each constructed of a single piece of Nylon webbing formed into a Möbius loop. The FBC drogue bridles are attached to mount points provided on top of the boilerplate FBC.

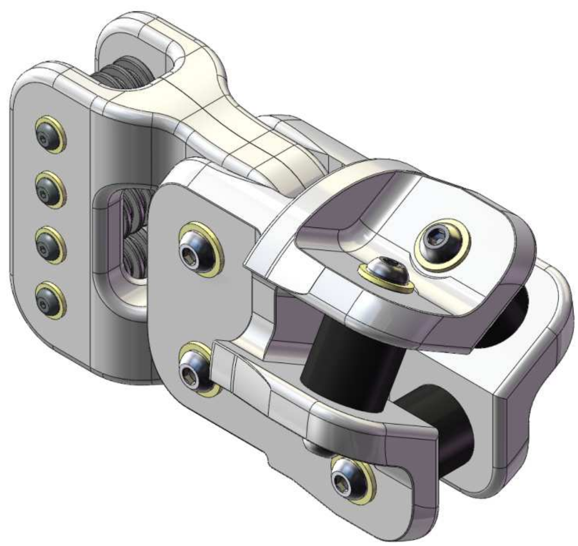

Figure 3. FBC Drogue Confluence Fitting Assembly

The modified G-12 parachutes used to simulate the CPAS main parachutes attach at a single point on the boilerplate CM, so no confluence fitting is necessary. This is similar to the current CPAS FDU baseline which has the main parachutes all attaching to a single gusset in the Orion forward bay. In order for the packed G-12 parachutes and the added riser extensions to fit inside the limited space afforded by the boilerplate FBC, their deployment bags were modified to be shorter, the external riser stowage was made more efficient, pressure packing techniques were used and beckets were installed on the deployment bags to facilitate attachment to the FBC.

IV. Integration of Parachutes into MLAS System

Integration of the parachutes into the MLAS coast skirt, fairing, and CM boilerplate presented some technical challenges to ensure orderly deployment of the parachutes. Most notable were stowage issues. Initially it was planned that everything but the mortars would be stowed inside the fairing nose cone and the bridles would attach to a 3 points along the diameter of the nose cone. After some analysis, the diameter of the nose cone attachment radius was found to likely be too small to successfully dampen the pitch rate after re-orientation. Additionally, the confluence and bridle legs could not have been erected until the drogues were inflating, resulting in large snatch forces as the confluence was lifted and re-accelerated to the vehicle velocity.

Eventually it was found that if the confluence fitting was stowed on the side of the vehicle, two of the bridles could be rigged to be fully extended along the outer mold line (OML) of the vehicle between their attach points and the confluence fitting. An illustration of the rigging is shown in Figure 4. Since the drogues will not develop force until they are aligned with the freestream, and therefore pulling directly on the stretched-out bridle legs, the snatch force on the confluence is eliminated with this configuration. Additionally the 3 point attach became a 4 point attach, and the attach points moved further away from the nose of the vehicle to a point where sufficient leverage existed to dampen the pitch rate. In the figure one can see that the attach fittings are located just above the motor troughs where the motors would be located in the objective system.

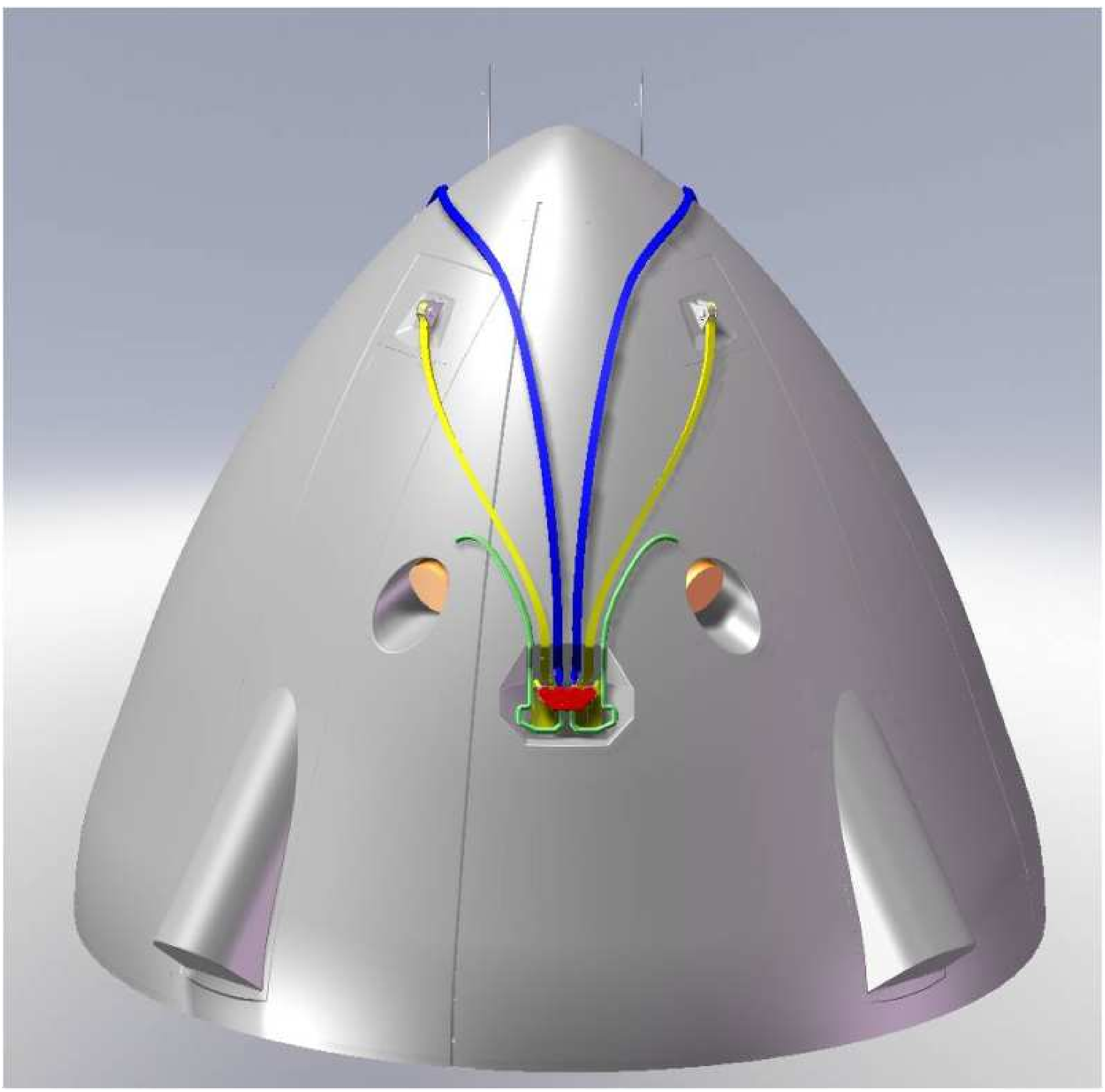

Figure 4. MLAS Fairing with Bridle Leg Routing

The entire length of the bridle legs are covered with stainless steel braided sleeving to protect the bridle legs during deployment. The mortars are mounted to the sides of the motor troughs, clocking the mortars 90 degrees apart. In addition to taking advantage of available structure, this has the advantage of ensuring that only one mortar could be fired directly into the wind should the pitch attitude be severely off-nominal at mortar fire.

Attachment of the bridle legs to the fairing was also a challenge. The desired solution would be to locate the bridle legs in channels molded into the fairing and protect them with some form of thermal protective system (TPS). However, the fairing molds were too far along in production to incorporate the channels The alternative solution selected was to attach the bridle legs to the outside of the fairing by adhering Click Bonds® to the fairing and tying the bridle legs to the Click Bonds® with 80 lb cotton tape. Figure 5 is a photo of a bridle leg held in place with 80 lb tape through a Click Bond®.

On the coast skirt the bridle legs had to be much longer due to being routed around the inner mold line (IML) of the coast skirt from the mortar location to the bridle leg attach points. These bridle legs are also covered with stainless steel braided sleeving to protect the bridle legs against contact with the edge of the coast skirt. These bridle legs are held under a stiffening ring on the IML of the coast skirt with Click Bonds® and 80 lb cotton ties. In this system the confluence snatch event could not be avoided, so the bridle legs are made of Nylon to decrease the system spring constant. Additionally, the extra length of the bridle legs helps to manage the snatch loads. Snatch loads for the coast skirt system were modeled with LS-DYNA, and the modeling validated with ground testing.

Figure 5. Secured Harness Leg

The simulation of the CPAS parachute system is referred to in the MLAS flight test program as the Landing Parachute Demonstration (LPD). The drogue parachutes used for this phase are, as previously discussed, identical to the parachutes used for coast skirt separation and reorientation, except that they are installed onto the top of the boilerplate FBC and deployed via dual static lines attached inside the reorientation fairing. The drogue parachute deployment bags were tied together, and attached to low profile rails provided on the top of the FBC. The confluence fitting for these drogues is attached to the drogue deployment bags to ensure it is lifted with drogues on deployment. A photo of the installation of the drogues and bridle legs on top of the FBC is shown in Figure 6.

Figure 6. FBC Drogue Installation

One area of concern in deployment of the FBC drogues was in mitigating the snatch forces of picking the drogues up from the FBC once the entire CM had cleared the fairing. To ensure the snatch forces were controlled, an energy modulator was incorporated into the static line. The energy modulator is constructed of a loop of Nylon webbing nominally 22 ft long. Two 6 ft bights were taken on opposite sides of the loop and the length of the bight sewn with rip-stitching to create the energy modulator. The stitching resulted in an average tear-out force of approximately 1,500 lbs per static line. The un-stroked energy modulator length is 10 ft, enough for the FBC to just clear the fairing before the energy modulator starts to stroke. Should one of the energy modulators fail, the other is sufficient to successfully deploy the drogues.

The recovery parachutes for the LPD are four modified G-12 parachutes simulating the three CPAS main parachutes as previously stated. Here the challenge was in rigging the G-12's to the boilerplate FBC. On the flight test vehicle, there is an avionics shelf immediately below the FBC. The G-12's had to be prevented from slumping onto the shelf, and the standard G-12 deployment bag was too large to use in the available volume. Fortunately, the standard G-12 pack is quite loose, so by switching from a hand-pack to using a packing press, the deployment bag could be made dramatically shorter. Further modification to the bag allowed efficient stowage of the excess riser necessary to achieve the proper trailing distance. Successful deployment of the G-12's from the FBC was proven in a drop test conducted by NASA at Wallops Flight Facility in March 2009, shown in Figure 7.


Figure 7. G-12 Deployment from FBC

V. Conclusion

The MLAS flight test employs nine parachutes total; five are 27.6 ft D_0 VPCR parachutes with heritage as a spin/stall recovery parachute, and the remaining four are G-12's with a reefing modification that has extensive air launch target heritage. This level of commonality in the parachutes and usage of proven systems are two key strategies employed in the MLAS program to quickly design, build, and test the MLAS system concept with a minimum of risk. The technical challenges encountered were typical for a rapid response project and all proved solvable. Although the flight test vehicle does differ from the objective system, careful consideration has been given to ensuring that the concept of operation of the reorientation maneuver has not been significantly changed.