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# Max Launch Abort System (MLAS) Landing Parachute Demonstrator (LPD) Drop Test

*Christopher M. Shreves*
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May 2011

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National Aeronautics and
Space Administration

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## Acronyms

| | |
|---|---|
| CG | Center of Gravity |
| CM | Crew Module |
| DTV | Drop Test Vehicle |
| FBC | Forward Bay Cover |
| FEM | Finite Element Model |
| GSE | Ground Support Equipment |
| LPD | Landing Parachute Demonstrator |
| MLAS | Max Launch Abort System |
| MSL | Mean Sea Level |
| QA | Quality Assurance |
| SRP | Sounding Rocket Program |
| WFF | Wallops Flight Facility |
| YPG | Yuma Proving Ground |

# 1.0 Introduction

The Landing Parachute Demonstrator (LPD) was conceived as a low-cost, rapidly-developed means of providing soft landing for the Max Launch Abort System (MLAS) crew module (CM) simulator (refer to the MLAS main report for details). Its experimental main parachute cluster deployment technique and off-the-shelf hardware necessitated a full-scale drop test prior to the MLAS mission in order to reduce overall mission risk. This test was successfully conducted at Wallops Flight Facility (WFF) on March 6, 2009, with all vehicle and parachute systems functioning as planned. Target dynamic pressure at main chute line stretch was exceeded by 28 percent, and minor damage was sustained by two of the main parachutes. Nevertheless, the main parachutes survived a loading environment more severe than expected for the MLAS flight test and functioned nominally. The results of the drop test successfully qualified the LPD system for the MLAS flight test.

# 2.0 High-Level Requirements

The following high-level requirements drove the designs of the drop test concept of operations and of the drop test vehicle (DTV):

1. The drop test shall produce loads on the main parachutes similar to those expected during the MLAS mission.
2. The drop test vehicle shall be nearly vertical at the time of forward bay cover (FBC) separation.
3. The drop test concept of operations shall include main chute deployment at or above the estimated MLAS main chute deployment altitude in order to verify that the parachutes can inflate and reach terminal velocity in the vertical distance allowed.
4. The DTV shall consist of a flight-like FBC, flight-like frangible nuts and bolts for FBC separation, and a CM mass simulator ballasted to the estimated mass of the MLAS CM.
5. The drop test shall be conducted over land to facilitate recovery of the test hardware in good condition for post-test analysis.
6. Data from the drop test shall be collected to verify drag performance and load estimates.
7. No part of the DTV or of any operation shall endanger the drop aircraft or its crew.

Derived requirements will not be specifically presented in this report. Instead, key trades and resulting design drivers will be discussed in the next section, and design rationale will be discussed as the hardware and operations are described.

# 3.0 Key Trades and Design Drivers

## 3.1 Test Site and Drop Aircraft Selection

Immediately upon LPD project inception, a trade study was conducted to determine the optimal site and support aircraft for the drop test. Numerous options and factors were considered, with the eventual selection of dropping the DTV from a C-130 at Yuma Proving Ground (YPG), Arizona. The primary factors in this choice were history of similar NASA drop tests being conducted at YPG from fixed-wing cargo aircraft, the large mass of the DTV (approximately 18,000 lb at the time), a large and well-instrumented test range, and the assumption that hazardous systems such as drogue mortars could be better controlled in an aircraft cargo bay. However, as the MLAS project cycle went on, the LPD development schedule slipped considerably, forcing a reevaluation of this trade in an effort to regain schedule.

A key factor in the new trade study was that the LPD drogues were no longer to be deployed via mortars, and would instead be deployed via static lines as the CM separated from the forward fairing. Use of drogue mortars had been a major constraint during the first trade study, precluding the use of a helicopter as a drop aircraft due to safety concerns about ordnance being pointed at the main rotor. Additionally, refined DTV mass estimates and better information about the load capabilities of heavy-lift military and commercial helicopters revealed that a helicopter was indeed a viable support aircraft. In turn, this reopened the trade space for site selection since a large drop range would be required for operations with a fixed-wing aircraft but not with a helicopter. The LPD testing schedule would be shortest with a test at the Wallops Test Range, eliminating the need for hardware shipment, team travel, logistical complications at a non-NASA site, and complicated range scheduling with YPG, but the Wallops site was only compatible with a helicopter-based drop test. With that possibility now having been verified by the new engineering data, Wallops was confirmed as the selected site. That selection was strengthened when support by a Sikorsky CH-53E Super Stallion heavy-lift helicopter was secured from the HX-21 Air Test and Evaluation Squadron based at the U.S. Naval Air Warfare Center, Pax River, Maryland; only a 30-minute flight time from Wallops. (Other candidate helicopters that were evaluated include the CH-47 Chinook and the S-64 Skycrane.) A site on the north end of Wallops Island was evaluated and confirmed as the drop zone for the mission (see Figures 1 and 2).

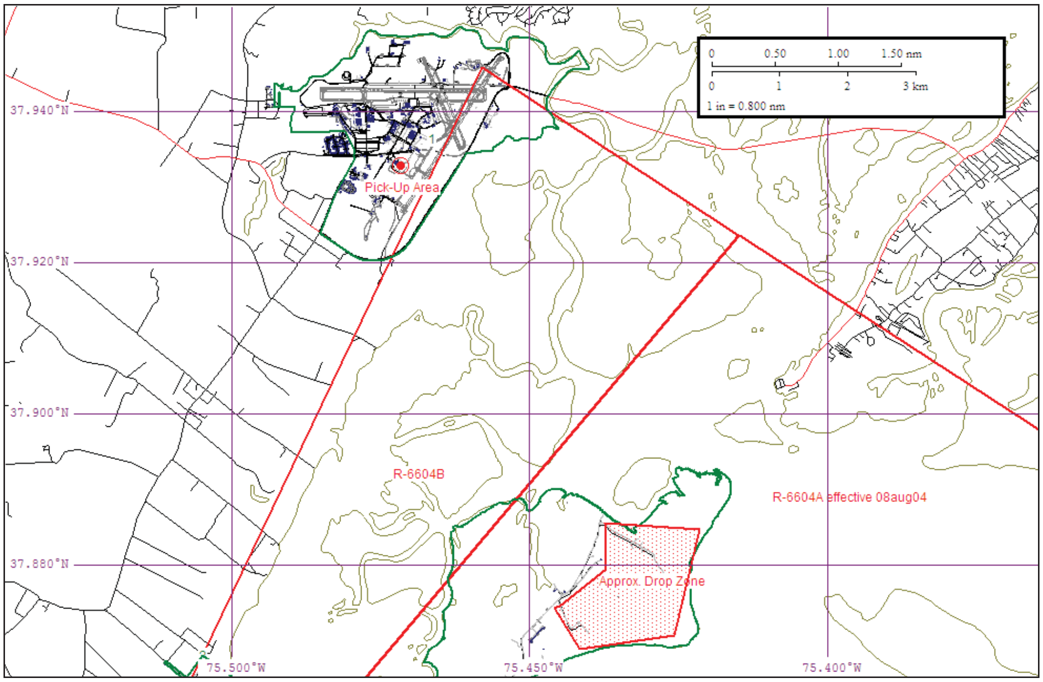


Figure 1. Proposed drop test operations area.

Figure 2. Northern end of Wallops Island with drop zone outlined.

Fixing these test elements produced further schedule advantages by eliminating the need to design and fabricate a DTV platform for integration with the baselined C-130. The platform design and fabrication task was to involve a contractor team. The platform itself would have been a complicated subsystem with its own test-related problems, including the risk of DTV recontact, a DTV/platform separation system, and the need for its own parachute recovery system. The ability to use a helicopter as the drop vehicle allowed the DTV to be merely another external load and simplified interfaces dramatically. All of these factors, plus a significantly lower test cost, factored into the new test site trade study, and the MLAS Configuration Control Board approved the new plan on January 30, 2009.

### 3.2 Drogue/Programmer Parachute(s)

Range safety restrictions, trajectory dispersion analyses, and available land area in the drop zone limited the maximum drop altitude to 2,500 feet mean sea level (MSL), which with the 5.5-second delay would result in FBC separation/main chute deployment at approximately 2,050 MSL. This was higher than the LPD initiation altitude planned for the MLAS flight (1,435 feet MSL), which was optimized to ensure drogue deployment, drogue disreefing, CM deceleration, main chute deployment, main chute disreefing, and continued CM deceleration to steady-state velocity at an approximate altitude of 300 feet MSL while also minimizing the chances of recontact. Since the high-risk elements of the LPD system were the main parachutes and the FBC separation components, the LPD drogues were no longer included in the test objectives and were removed from the DTV design. In their place, an available 28-foot ringslot cargo extraction parachute was to be used as a programmer chute to stabilize the DTV after release from the helicopter and allow the DTV to accelerate to the required test dynamic pressure range in a controlled manner.

### 3.3 CM Mass Simulator Structure

The CM mass simulator had four primary design drivers. First, it had to have a CM-like upper deck to interface with the FBC similar to the flight version. This required three main attachment bolt holes and clearance for the associated separation nuts below them. It also necessitated six stainless steel conical cups to mate with the conical shear pins on the FBC, and a flight-like main parachute fitting attached to the upper deck with six ¾-inch bolts and four 1-inch-diameter shear pins

Second, the mass simulator had to match the weight of the flight CM. Matching the center of gravity (CG) and moments of inertia of the flight CM was not required. However, since the flight weight estimates were being revised frequently, a means of varying the mass simulator's weight until the final stages of integration was needed. It was also possible the weight would have to be decreased significantly from baseline due to changes in the drop altitude and the programmer/drogue configuration.

The third primary design driver was the very short design/analysis/fabrication time available. Design/analysis time was approximately a month, starting in early/mid October 2008, and fabrication time was approximately a month, but overlapped the design/analysis time some. Therefore, the design had to be very simple to draw up, and very straightforward to analyze and fabricate.

The final design driver was interior volume. The mass simulator structure had to provide adequate interior volume to allow the main parachutes to hang freely from the FBC without touching any structure or avionics. Adequate interior volume was also required for the avionics themselves and for additional ballast, if necessary.

For the CM mass simulator, there were three main design trades, the first of which was overall geometry. The upper deck of the mass simulator had to mimic the flight CM in order to interface properly with the FBC, while still maintaining the weight goal and simplicity for rapid fabrication. The original concept was a welded "spool" with intermediate gussets around the circumference, as shown in Figure 3. The upper flange of the spool would give proper thickness and surface area to interface with the FBC. The lower flange would provide a place to bolt on additional weight plates if needed, and the gussets would provide strength and stiffness to the flanges.

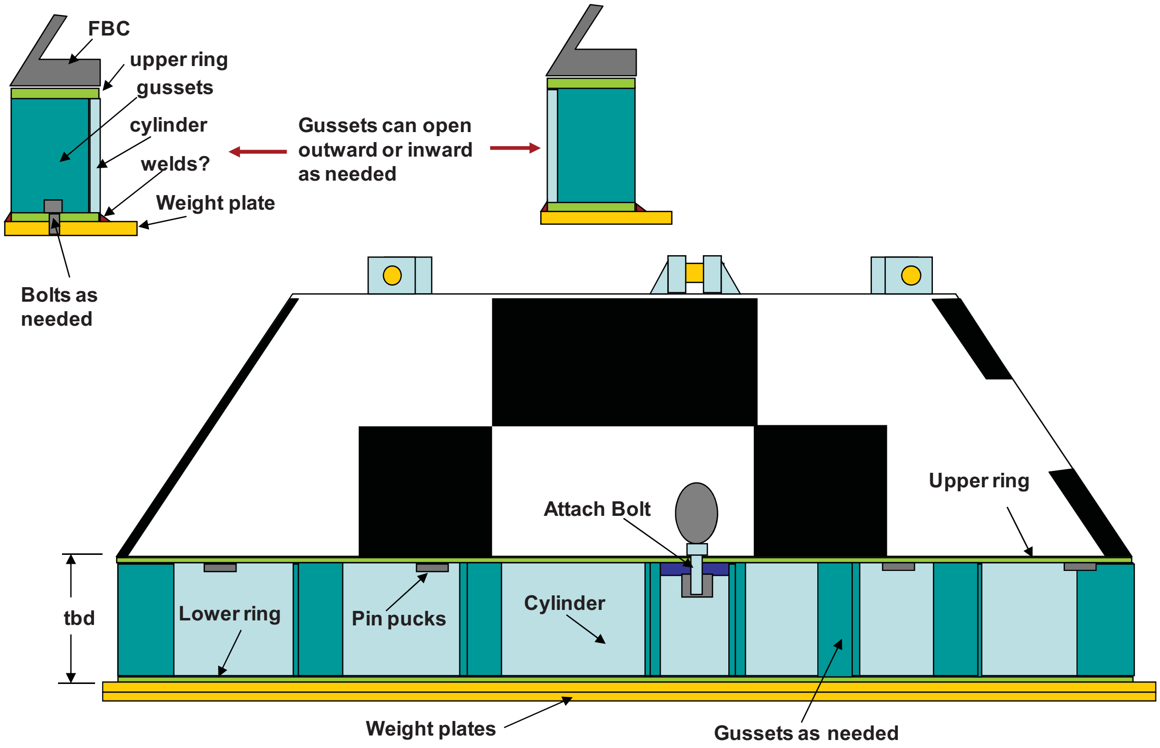


Figure 3. Original CM mass simulator concept.

This concept was deemed too complex, from both fabrication and analysis perspectives. Therefore, a simpler design was selected that used simple stacked annular plates ("donuts"), as shown in Figure 4. This became the final design and its details are discussed below. Note that the avionics were repositioned to the center of the baseplate once adequate clearance from the parachute packs was confirmed.

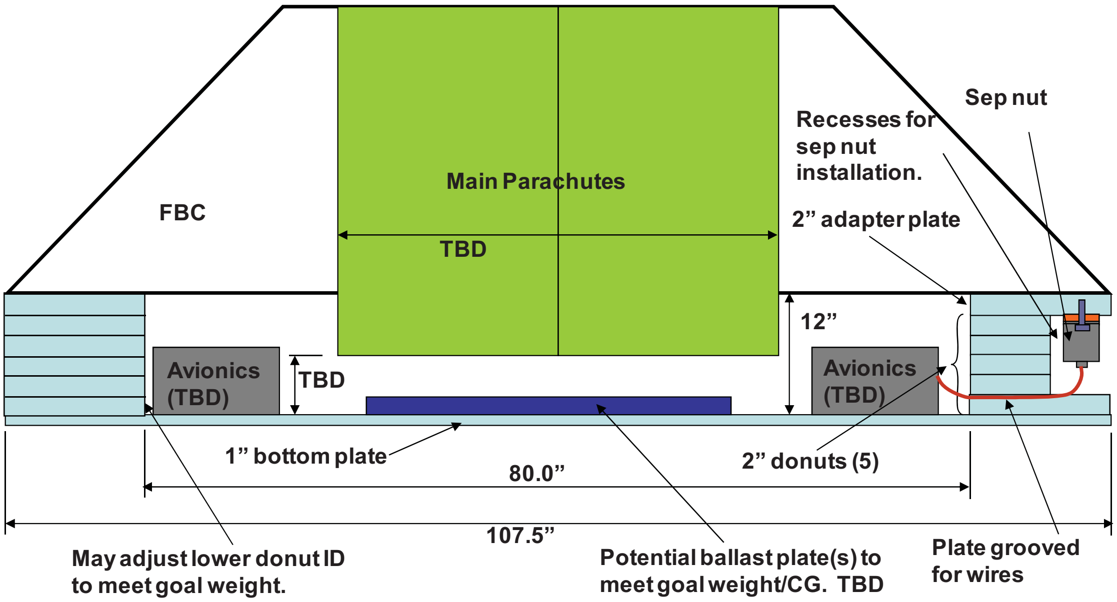


Figure 4. Final CM mass simulator design.

The second major design trade for the mass simulator and the overall DTV was the number and size of bolts attaching the FBC to the mass simulator. The flight design had three 1.25-inch-diameter high-strength bolts torqued into Ensign-Bickford frangible nuts. At the beginning of the drop test design phase, there were not enough frangible nuts available, and their six-month procurement lead time meant they would not be available in time for the original drop test date of mid/late November 2008, or a revised test date of early March 2009. Other, lower-strength explosive bolts (40,000-lb rating) from Quantic Industries were available. However, their lower strength required two bolts at each main interface point rather than the one in the flight article, as shown in Figure 5.

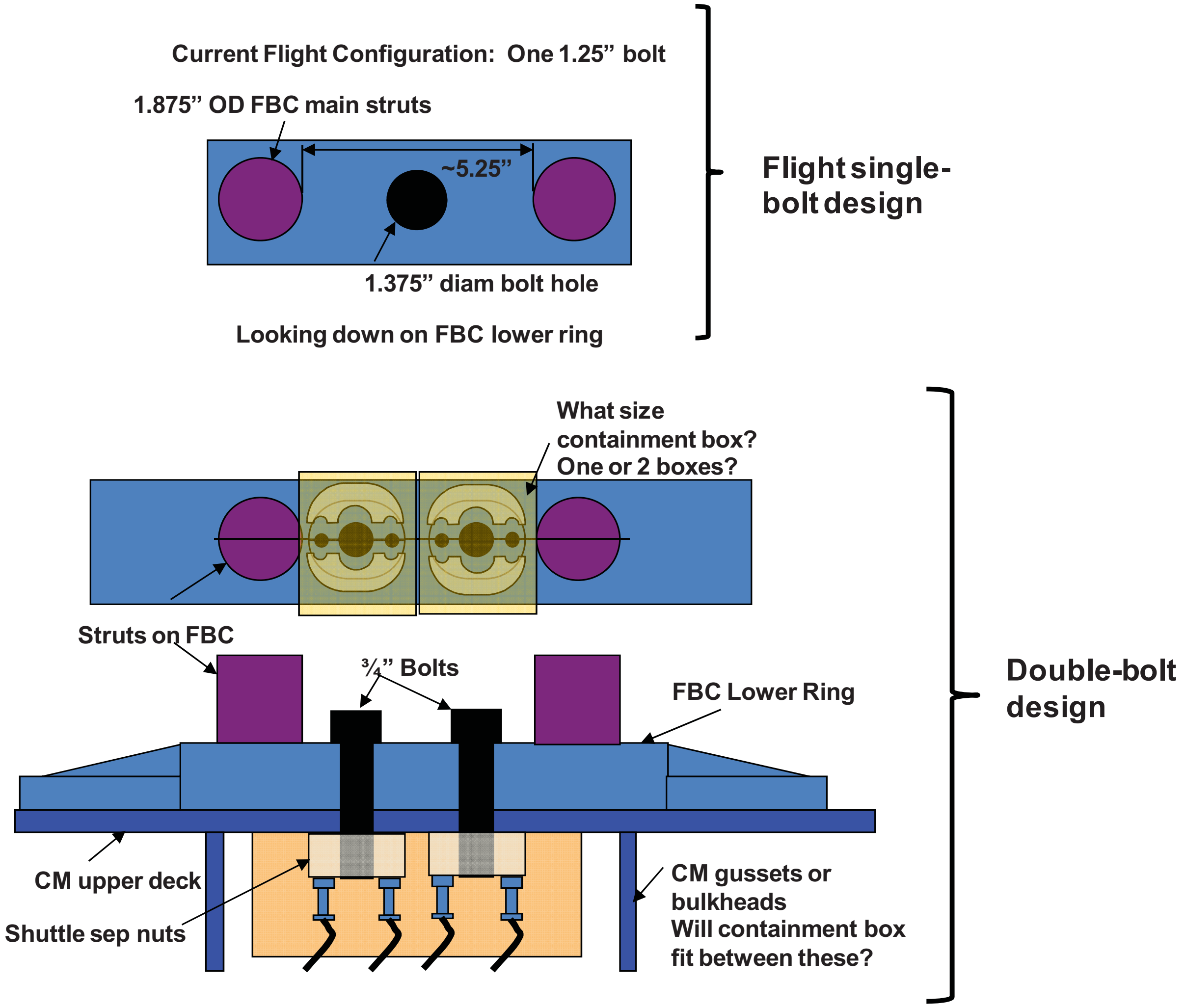


Figure 5. Single versus dual separation bolt concepts.

In the end, the project was able to have three Ensign-Bickford frangible nuts refurbished after previous functional tests and available in time for the drop test. The design then mimicked the flight article with three attach bolts.

The last design trade involved how to assemble the mass simulator. As discussed above, the final design became a set of stacked steel “donut” plates with a full bottom plate. These plates could be bolted all the way through as a full stack, or bolted one at a time to the stack. With the desire to have the weight adjustable until very late in the project cycle, it was decided to bolt the plates one at a time, starting with the bottom plate. Preliminary, conservative hand analysis also showed a potential for bolt bending or plates slipping laterally under a large lateral main parachute load with the long bolts needed in a full-stack bolting configuration. Due to the short fabrication time available, material had to be ordered and machining begun almost simultaneously with the start of the analysis effort. There was little time to run trades on the numbers of bolts needed to tie the plates together, so a conservative estimate of bolt loading was used, and several 1-inch-diameter bolts were used in each layer as described later in the final design section.

### 3.4 Sequence Timer Type

Redundant multi-function electronic timers, a design with extensive sounding rocket flight heritage, were baselined for providing the delay between DTV release from the aircraft and firing of the FBC frangible nuts. However, uncertainty about static discharge from the helicopter to the DTV after release prompted a trade study between the electronic timers and redundant mechanical timers. The concern centered on the possibility of static charge created by the main rotor building up on the helicopter airframe and arcing to the DTV avionics once the DTV was released. Neither the helicopter flight crew nor the helicopter maintenance crew believed this to be a likely scenario, but they also could not guarantee the chances were zero. Lanyard-actuated Raymond mechanical timers, which also had extensive sounding rocket flight heritage but were less accurate, were selected for the test as they were believed to be less susceptible to failure when subjected to electrostatic discharge.

### 3.5 Harness Material

Nylon webbing was baselined for the programmer parachute harness since this would be similar to the flight drogue harness. However, as the DTV design and helicopter interfaces matured, the harness was no longer a stowed part of the drogue/programmer system as originally planned. Instead, the programmer harness and riser would be pre-deployed and under constant load from helicopter take-off to DTV release (i.e., they would be the slings by which the helicopter transported the DTV to the drop zone). In this configuration, a material with lower elasticity was desired to provide more stable elements between the DTV and the programmer parachute. Multi-layer polyester webbing was selected for the harness and riser, with all elements (including links) rated for 15 tons or greater.

## 4.0 Concept of Operations

The drop test concept of operations begins with the positioning of the DTV on the Wallops airfield apron near Building N-159. The CH-53E helicopter would arrive from Pax River, land on the runway, and taxi to a location immediately adjacent to the DTV. With the cargo hook raised interior to the helicopter cabin, the DTV programmer parachute and riser would be routed beneath the fuselage on the starboard side and through the cabin floor opening. First, the Navy-supplied apex fitting would be attached to the cargo hook. The programmer chute deployment bag would then be tied to a bracket on the cargo hook with redundant lines. The two static lines, designed to start the mechanical timers and close the frangible nut pyro circuit, would be attached to brackets on either side of the hook assembly. The hook, riser, and programmer deployment bag would be rotated so that the chute bag was aft of the hook centerline in what was assumed to be its optimal position when the aircraft was in transit. Non-essential personnel would then clear the hazard area while final systems checks and final arming tasks were completed. The helicopter crew would then begin engine run-up and pre-flight checks of the aircraft.

Security personnel would close Route 175, which separates the Wallops Main Base and Wallops Island, to traffic once the pilot was ready to commence the operation. As the helicopter lifted off and translated over the DTV, ground personnel on the apron would monitor the beacon to ensure that a static line had not inadvertently been pulled. The helicopter would then lift the DTV and begin its transit directly to the north end of Wallops Island. Once the helicopter was clear of Route 175, roadblocks would be removed.

Range controllers would vector the helicopter to one of several pre-determined drop points based on winds at the time. These drop points would have been selected by safety analysts working drift analyses well in advance of the operation. Range controllers would work with the pilot to enter the drop zone at the correct altitude and speed, first with a dry run and then with one or more hot runs. In the event that the test "GO" parameters were not met, range controllers would call an abort and instruct the pilot to circle around for another attempt.

When a hot run looked good, the test director would give a five-second countdown (to cue camera and radar operators on the ground) and then command "RELEASE" for the pilot to actuate the hook mechanism, allowing the DTV to separate from the aircraft. Static lines attached to the hook assembly would close redundant pyro circuit lanyard switches and start the redundant mechanical timers as the apex fitting was released from the cargo hook. After falling a few feet, the programmer chute riser (attached to the apex fitting) would start to take load, opening the programmer deployment bag and beginning the programmer deployment sequence. Once the DTV had begun its descent on the programmer chute, the helicopter loadmaster would reel the hook assembly (with the parachute deployment bag and static lines still attached) into the cabin and monitor the DTV until impact.

With the timers running, the programmer chute would strip out of its bag as the DTV fell away from the helicopter. The chute would then inflate, initially decelerate the system, and stabilize the DTV until the 5.5-second delay expired and the FBC frangible nuts were fired. The CM mass simulator would fall away from the FBC, stripping the main parachutes from their bags stowed in the FBC. As the main chutes deployed, inflated, and disreefed, the DTV would achieve some separation distance from the FBC. Figure 6 shows this sequence of events. Recontact of the FBC with the main chutes would be possible but would occur after the DTV reached terminal velocity on the mains, satisfying test objectives.

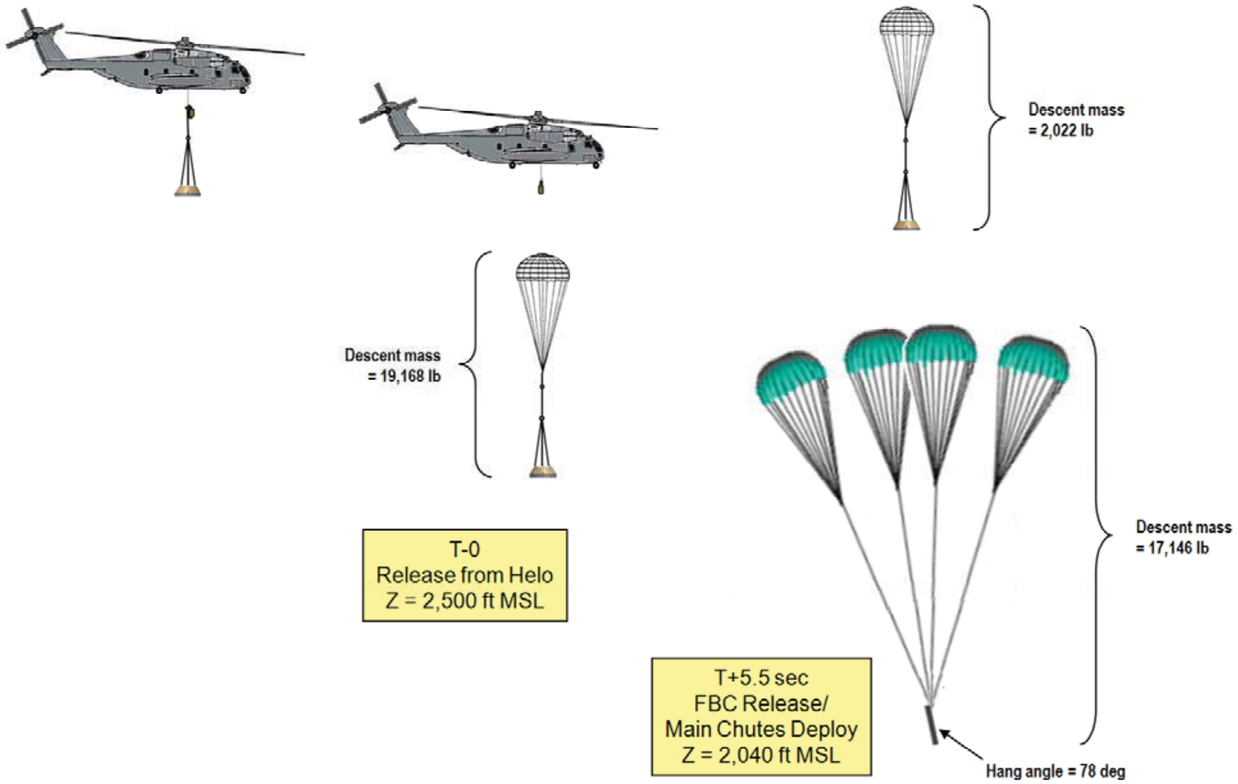


Figure 6. Drop test concept of operations.

After the CM mass simulator and FBC impacted the drop zone, the helicopter would mark its global positioning system location and then return to the Wallops airfield. Recovery personnel would immediately begin operations to retrieve the parachutes and data recorders.

## 5.0 Drop Test Aircraft

The selected support aircraft for the LPD drop test was a CH-53E Super Stallion helicopter, part of the fleet based at HX-21 Air Test and Evaluation Squadron, Naval Air Warfare Center, Pax River, Maryland. The CH-53E is equipped with an electric-powered cargo hook rated for 32,000 lbs (shown in Figure 7), which hangs on a single pendant approximately six feet beneath the fuselage bottom. The hook assembly includes an integrated swivel between the hook load beam itself and the bottom of the pendant. Either the pilot or the loadmaster can remotely release the hook, although the former is standard operating procedure. The hook system is also equipped with a pyrotechnic cutter that can be used to sever the pendant and release the load in the event of an emergency ("pickling").

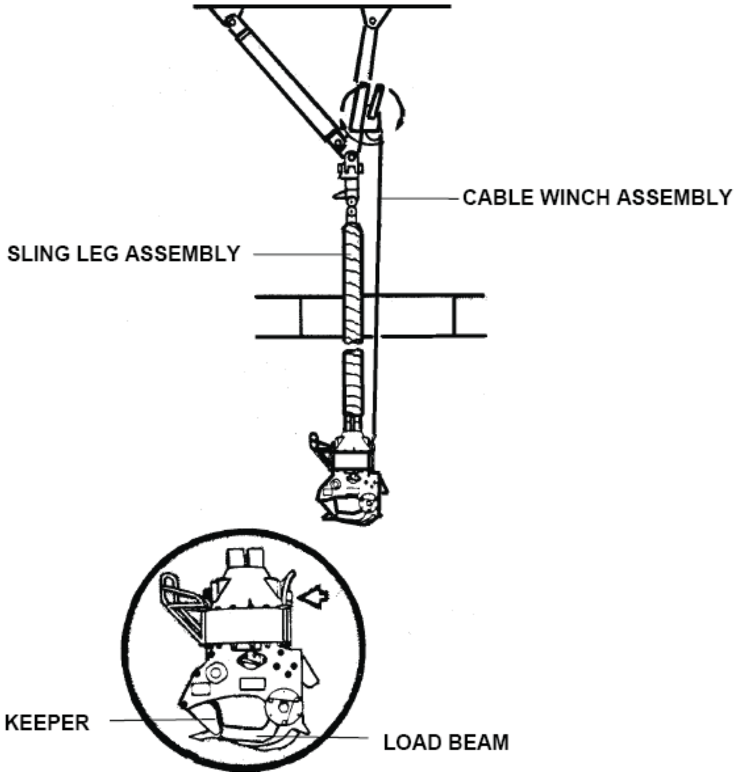


Figure 7. CH-53E cargo hook.

The hook used for the LPD drop test had recently been through a scheduled overhaul and recertification process. Interfacing the programmer parachute pack and the timer/lanyard switch static lines required attachment points on the hook assembly, but the standard hook housing had no such points available. Modifications to the hook would be required, but all attachments would need to be made below the swivel so that the entire system would rotate together as a system (if necessary). The baseline design was to attach steel brackets to the hook housing, but the only attachment locations were the heads of bolts that passed through the hook housing, and their corresponding nuts on the opposite side of the assembly. Rather than risk violating the hook's mechanical reliability by removing these bolts, brackets were designed that could be installed either by only removing the subject nuts or, by using keyhole slots, could be installed over the bolt heads and then rotated beneath the heads before retorquing the bolts (see Figure 8). This method was deemed adequate by inspection considering the low forces involved. The two static lines were tied to the brackets on either side of the hook housing, and the programmer deployment bag was attached to the rear bracket.

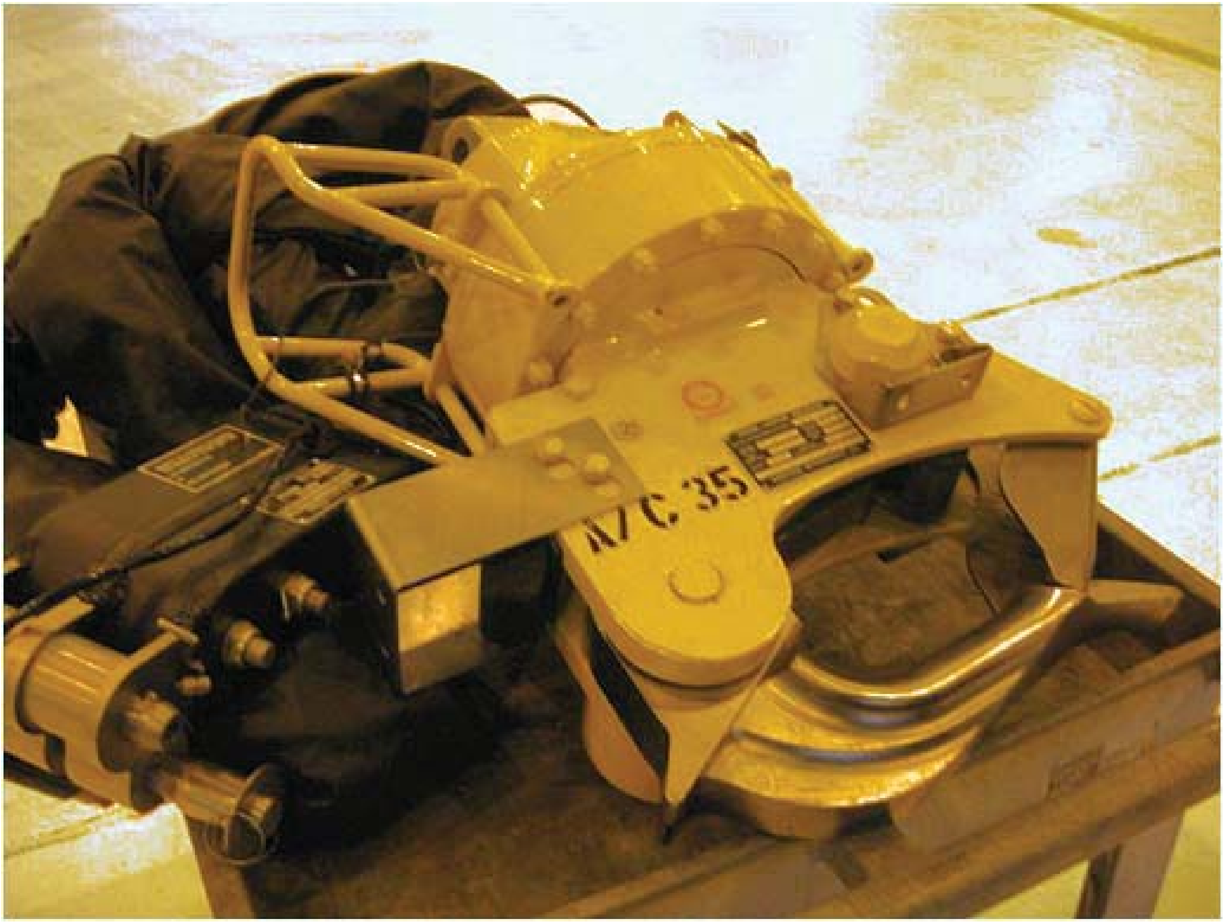


Figure 8. Modified CH-53E cargo hook showing two of three added brackets.

## 6.0 Drop Test Vehicle

### 6.1 Programmer Parachute/Riser/Harness/Links

The selected programmer parachute was a 28-foot ringslot cargo extraction parachute of all-nylon construction. This parachute is rated for a load of up to 26,200 lbs. The 10-foot-long riser and three 16-foot-long harness legs were all fabricated from multi-layer polyester rated for 16.4 tons. A master link, rated for 15 tons, joined the riser to the upper harness links (see Figure 9). The harness was attached to the FBC drogue pins with links rated for 20 tons each. Four links rated for 15 tons each joined the upper harness eyes and the lower riser eye to the master link. Due to an aggressive schedule, sling and link elements were deliberately specified with very conservative workload limits to ensure that they encompassed all ground support equipment (GSE) requirements, test conditions, and vehicle dynamic loads with healthy margins. The Navy-supplied apex fitting, rated for at least a 32,000-lbs operating load, was used to join the polyester riser to the programmer parachute riser, and to serve as the hook attachment point for lifting. This fitting was essentially an elongated bow shackle equipped with a roller pin. The apex fitting was baselined for this test because of its extensive flight history and long record of reliable hook releases.

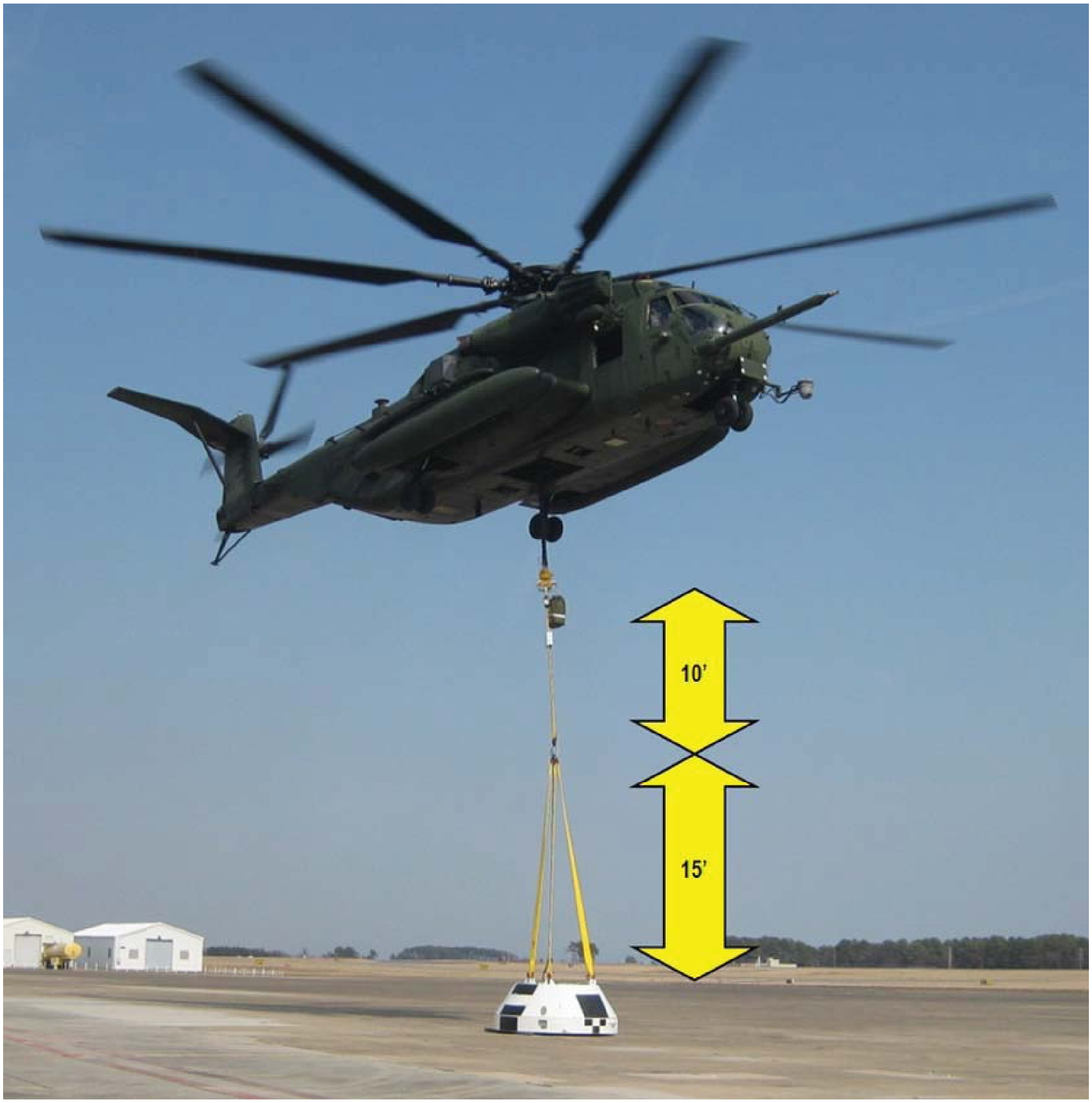


Figure 9.  Riser and harness lengths.

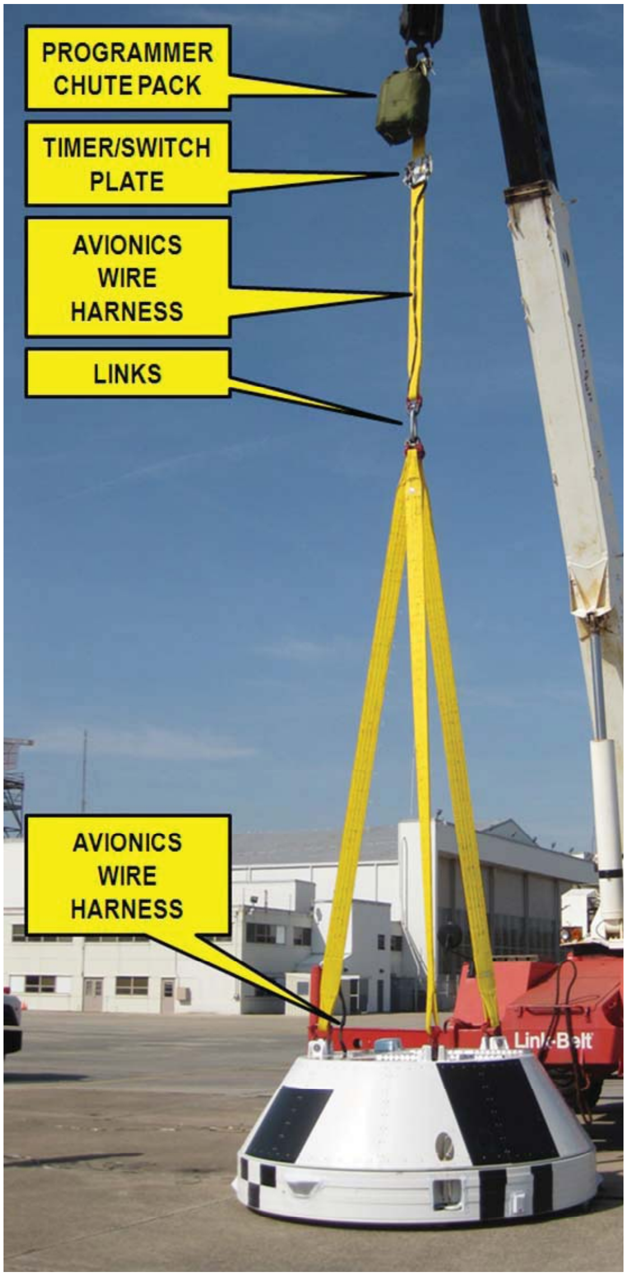


Figure 10. Hang Test of Rigging

### 6.2 Main Parachutes

The main parachutes being tested were four modified 64-foot G-12D flat circular cargo delivery parachutes. The parachutes were acquired from the U.S. Army Natick Soldier Research, Development & Engineering Center. They were retrofitted with reefing, reinforced vent bands, and higher-density packs by Airborne Systems. Reference 1 contains main chute selection details. The main parachute bags were secured in the FBC interior in exactly the same manner as were the MLAS flight main chutes, with the risers carefully routed to pins on the main chute fitting attached to the CM mass simulator.

## 6.3 Structure

### *6.3.1 Forward Bay Cover*

The FBC used for the drop test was structurally identical to the one designed for the MLAS flight test. It was primarily a welded steel structure with fastened aluminum skins. The design carried factors of safety of 1.4 for yield strength and 1.8 for ultimate strength (see Ref. 1 for details). Figure 11 shows images of the DTV.

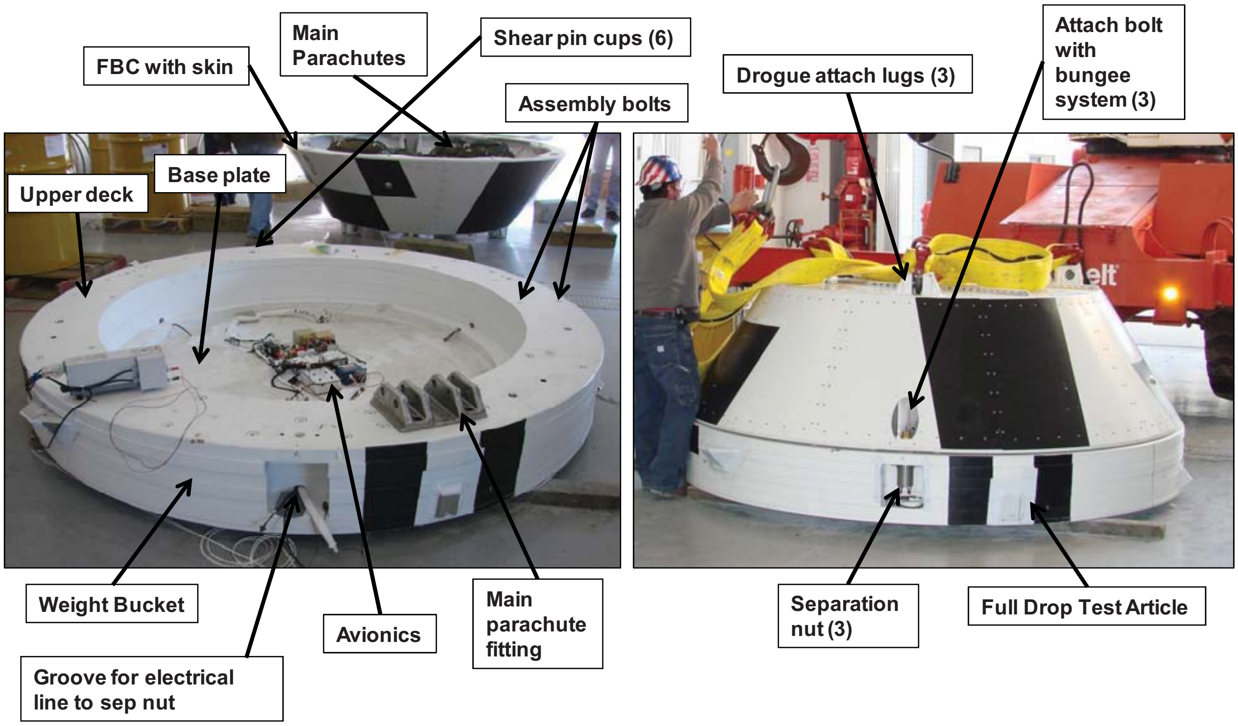


Figure 11. Drop test vehicle.

### *6.3.2 CM Mass Simulator*

The CM mass simulator consisted of five 2-inch-thick annular plates with a 107.5-inch outer diameter and an 80-inch inner diameter, one 2-inch-thick annular plate with a 107.5-inch outer diameter and a 72-inch inner diameter, and one 1-inch-thick baseplate with 107.5-inch diameter. All plates were ASTM A572 Grade 50 steel, and were cut at the material vendor with a radial tolerance of ±3/16 inches. As shown in Figure 12, the top plate (donut 1) had three 1-inch tapped holes to insert shackles for lifting the entire stack; 29 through holes for bolting it to the second donut; six ¾-inch tapped holes and four 1-inch through holes for the bolts and shear pins, respectively, for the flight-like main parachute fitting attachment (see Figure 11); six 6-inch-diameter counter bores for the 17-4PH stainless steel shear pin pads that mated with the FBC tapered shear pins; and three 1.375-inch through holes for the FBC attach bolts.

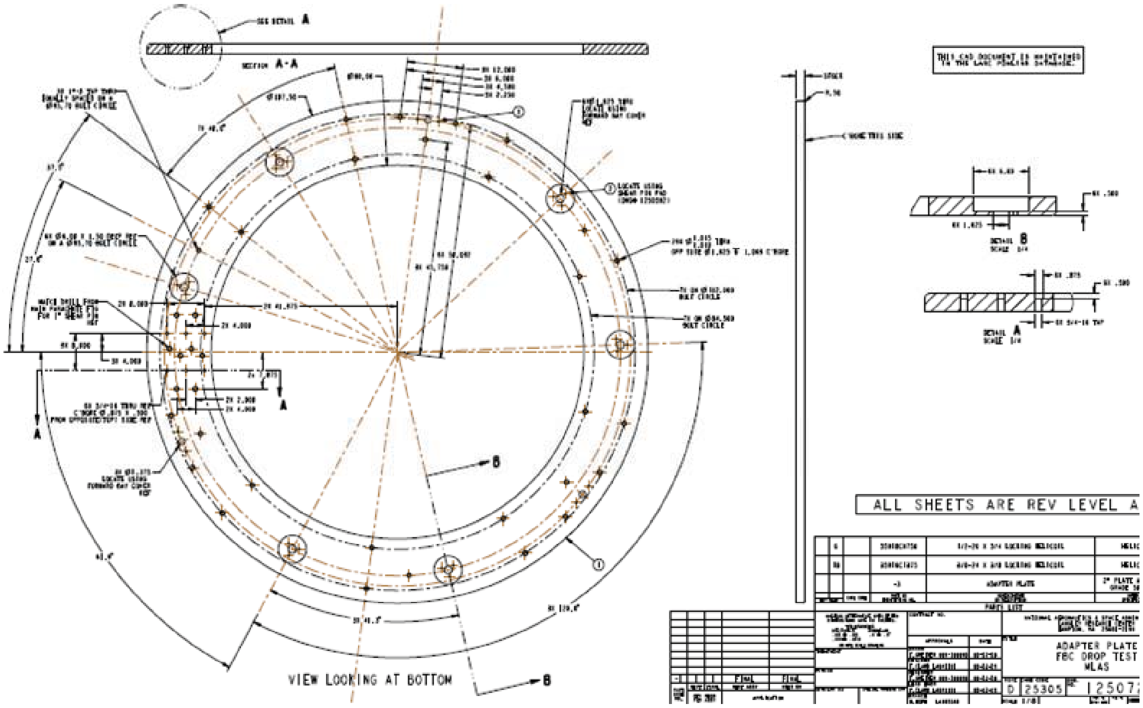
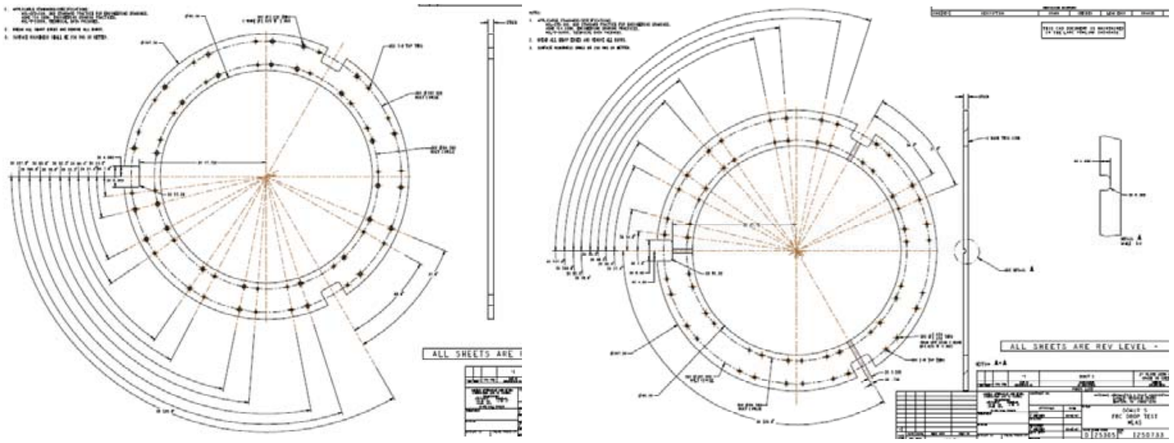


Figure 12. CM mass simulator adapter plate (donut 1)

Donuts 2 through 5 had patterns of through holes and tapped holes for mating with adjacent donuts. In general, the number of bolts decreased towards the bottom of the stack. The 1-inch tapped bolt holes were also used as attach points for the lift shackles to move the plates individually. These donuts also had three scalloped recesses around the perimeter to provide clearance for the frangible nuts. Donut 5 had a radial groove cut on the bottom side at each scallop for frangible nut wireways, as shown in Figure 13. Donut 6 had a smaller inside diameter, which was trimmed as late as possible to give the desired final stack weight, but it had no scalloped recesses on the perimeter. The base plate (donut 7) was a solid circular plate to which the avionics were bolted.



**Donut 4 (typical of donuts 2-4)**

**Donut 5**

Figure 13. CM mass simulator ballast plates (donuts 4 and 5)

The FBC was mated to the mass simulator with flight-like hardware. Similar to the flight article, it was clocked such that the recess in the lower ring (the "garage") fit over the main parachute fitting. The six tapered shear pins on the FBC fit into their respective 17-4PH pucks bolted to the underside of the upper deck (donut 1). The tapered shear pins on the FBC were set and locked such that they produced a slight preload to help ensure their separation from the conical cup. Three 1.25-inch high-strength bolts were threaded into their respective Ensign-Bickford frangible nuts and torqued to 1100 foot-lbs. The bolts each had a bungee retention system, as shown in Figure 14, to prevent them from damaging the parachutes after the frangible nuts fired and the bolts were ejected. This same system was used on the MLAS flight test article.

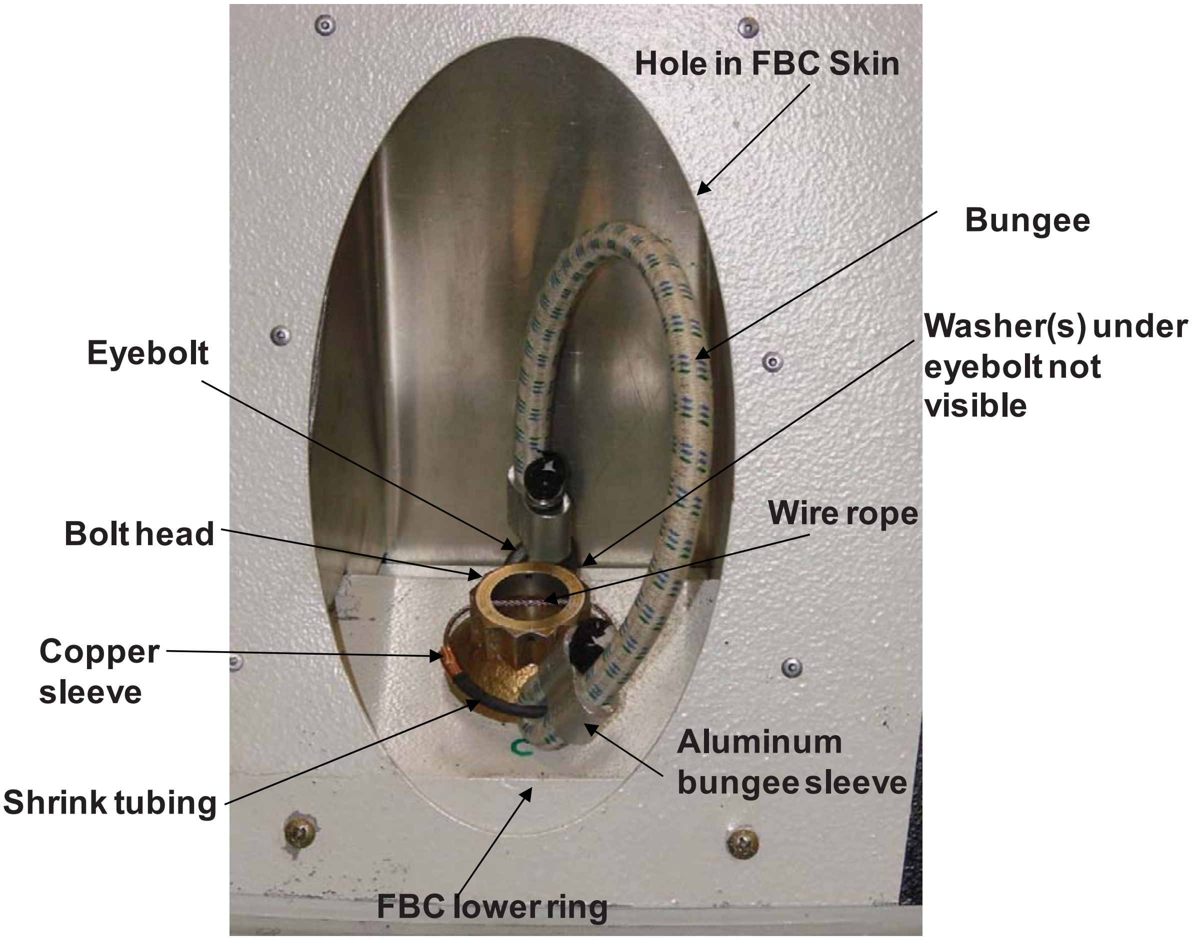


Figure 14. FBC separation bolt retention system.

Finally, the FBC was painted to match the paint scheme of the MLAS flight test FBC. The CM mass simulator also had a paint scheme as shown in Figure 15 to provide visual references during the drop test and subsequent analysis.

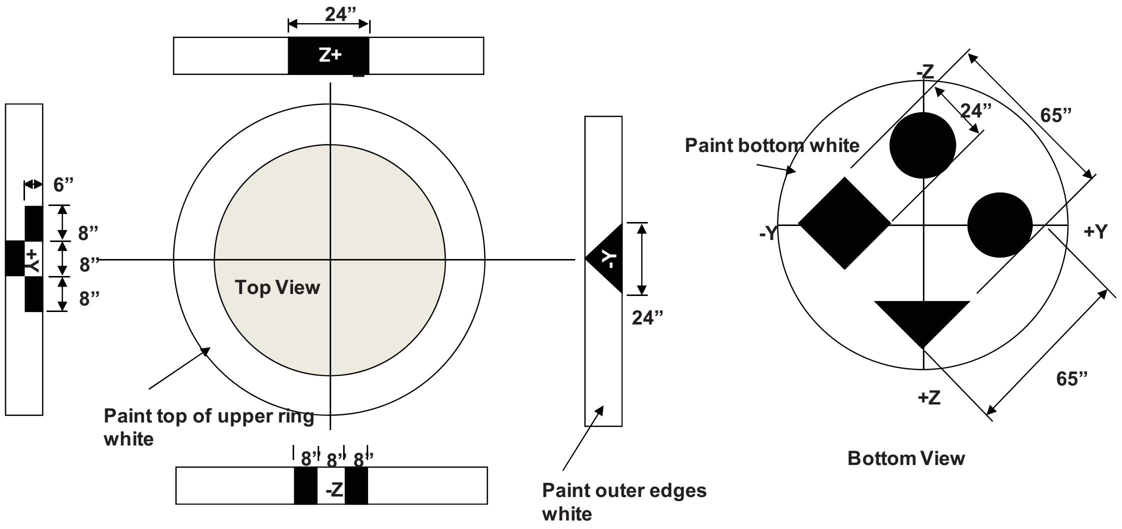
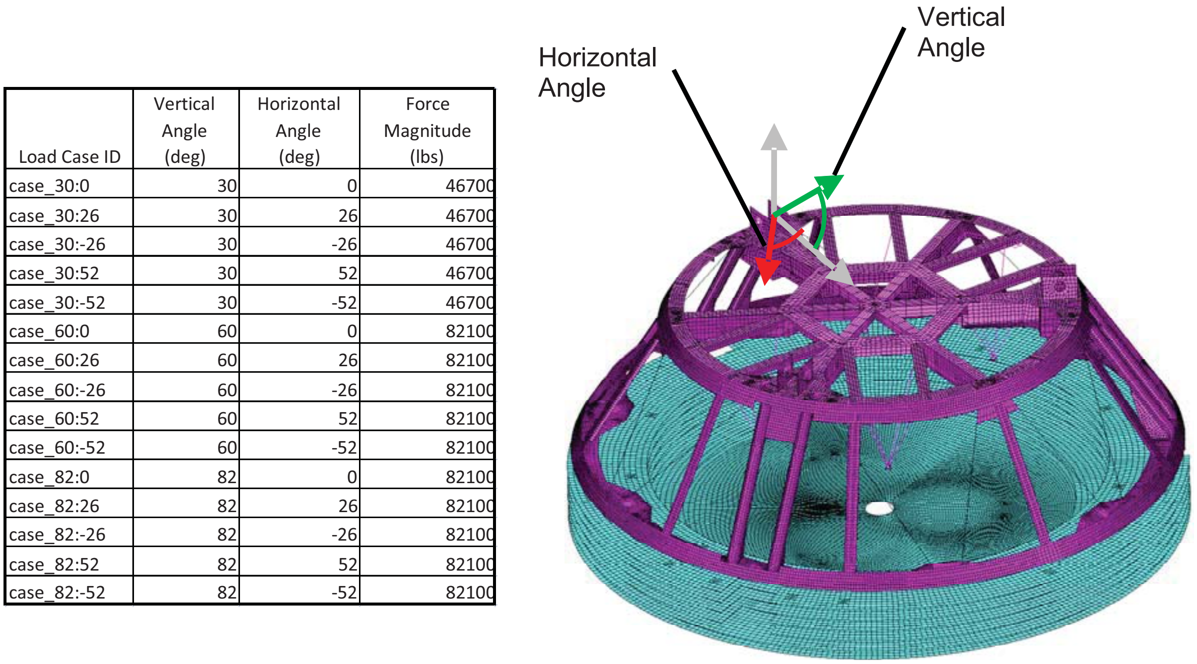


Figure 15. CM mass simulator paint scheme.

### 6.3.3 *Analysis*

The drop test loads were enveloped by the flight test loads, so no new analysis was done on the FBC. The FBC analysis results are described in the structures section of Reference 1.

The CM mass simulator was a very simple design. However, with the concurrent design/analysis/fabrication, very conservative early hand calculations were used to estimate the assembly bolt loads. The applied drogue and main parachute loads and loading orientations were provided by the landing systems group. The table in Figure 16 shows the drogue parachute loads used to analyze the mass simulator, including a 1.7 dynamic amplification factor.

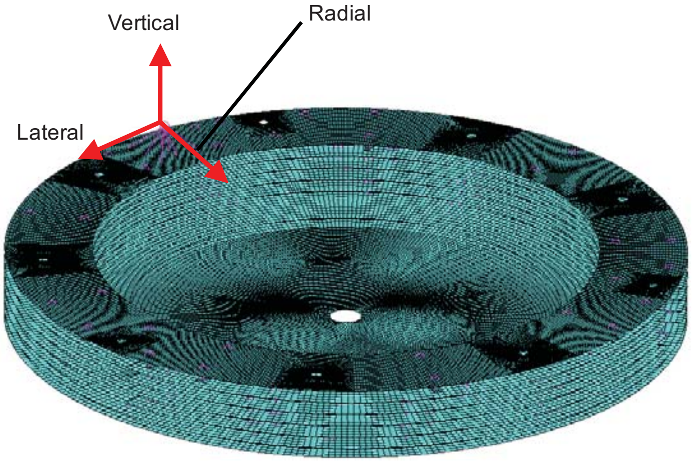


| Load Case ID | Vertical Angle (deg) | Horizontal Angle (deg) | Force Magnitude (lbs) |
|---|---|---|---|
| case_30:0 | 30 | 0 | 46700 |
| case_30:26 | 30 | 26 | 46700 |
| case_30:-26 | 30 | -26 | 46700 |
| case_30:52 | 30 | 52 | 46700 |
| case_30:-52 | 30 | -52 | 46700 |
| case_60:0 | 60 | 0 | 82100 |
| case_60:26 | 60 | 26 | 82100 |
| case_60:-26 | 60 | -26 | 82100 |
| case_60:52 | 60 | 52 | 82100 |
| case_60:-52 | 60 | -52 | 82100 |
| case_82:0 | 82 | 0 | 82100 |
| case_82:26 | 82 | 26 | 82100 |
| case_82:-26 | 82 | -26 | 82100 |
| case_82:52 | 82 | 52 | 82100 |
| case_82:-52 | 82 | -52 | 82100 |

Figure 16. MLAS CM drogue parachute loads.

During the parachute development and analysis process, these loads decreased considerably. The final drogue parachute loads were approximately 43,300 lbs, including the 1.7 dynamic amplification factor.

Figure 17 shows the main parachute loads used in analyzing the CM mass simulator. Based on a previous transient analysis on the CM, performed by Alliant Techsystems Inc. of Beltsville, Maryland, there was little to no dynamic amplification on the CM structure due to the parachute loads. However, per direction of the MLAS loads group, an uncertainty factor of 1.25 was maintained on these loads. The loads in the figure below were a snapshot in time as the main parachute loads were evolving, and consist of a 74,650-lb parachute load and the 1.25 uncertainty factor, resulting in 93,315 lbs. After further refinement of the parachute analysis, the main parachute load dropped to a maximum of approximately 63,400 lbs (without the 1.25 uncertainty factor).



- A main chute load of 93315 lbs was used to create three independent load cases as shown above.
- Load was only applied in one direction at a time with zero load in the other two directions for a given load case.

Figure 17. CM mass simulator main parachute loads.

Hand calculations were used to develop initial bolt patterns for the various plates. The main parachute fitting was flight-like, so the existing bolt and shear pin patterns were used. After the initial bolt patterns were determined, a finite element model (FEM) was built in MSC Patran™. In the FEM, the donuts were represented by two-dimensional plate elements, tied together at the bolt locations only, with no other contact elements. The model was run in MSC Nastran with applied parachute loads and inertial relief, as well as with simple handling/hoisting loads. Stress results were compared against the plate material allowable. Bolt forces were compared against bolt allowables. Factors of safety of 2.0 and 2.6 against material yield and ultimate, respectively, were used for the mass simulator plates. Slight negative margins were found in a few localized areas but were accepted due to the conservative nature of the analysis methods, loads, and construction methods. Results of the analysis can be found in Reference 2.

#### *6.3.4 Significant Issues and Resolutions*

The largest issue was the short time available to design and manufacture the mass simulator. The fabrication contractor was to build two identical FBCs: one for the flight test and one for the drop test. The drop test FBC was already under construction and nearing completion when the mass simulator design started, so it was not an issue. However, the design, analysis, and manufacturing had to occur simultaneously on the mass simulator to have it completed on schedule. The first part of the solution was to make a robust but simple design (the stackable annular plates), then to order the plates from the material vendor (precut) while the design/analysis was ongoing. One donut was left heavy to enable weight trimming later, if necessary. Another part of the solution was to meet immediately with the fabrication contractor (ADVEX in Hampton, Virginia) and discuss the intended design, the need date, and how the design could be made simpler or how the manufacturing process could be streamlined. The last part of the solution was to work closely on a day-to-day basis with the fabrication contractor to answer questions, review/incorporate suggested design/fabrication improvements, and make sure the final result would satisfy the system requirements and delivery dates.

#### *6.3.5 System Verification*

No component-, subsystem-, or system-level structural testing was done on the DTV prior to the actual drop test. The design was approved solely by analysis. However, individual component verifications were performed. Material certification sheets were provided for all plate material ordered and delivered. All assembly bolts also had material certifications/specification sheets. While overall dimensional tolerances on the annular plates were not critical, the assembly bolt patterns were relatively low tolerance (±0.01 inches). The locational tolerances were maintained via the machine tool used to drill the holes and checked by the contractor’s quality assurance (QA) department. Smaller items, such as the pucks in the upper donut and the main parachute fitting, went through material verification and more rigorous dimensional checks at the contractor’s QA department. The final QA was that all the plates mated well and were successfully bolted together.

Throughout the manufacturing process, individual donuts/plates were weighed using the contractor’s certified dynamometers. Smaller parts like the main parachute fitting, pucks, and fasteners were weighed on shop scales. Using these values, the last donut’s (donut 6) inner diameter was finalized to meet the total mass simulator target weight of 16,540 lbs. After final assembly, the full mass simulator was weighed. The first measurement attempt did not work because of a defective dynamometer. However, subsequent weighing with the transport company’s Virginia Department of Transportation-certified crane dynamometer showed the total weight to be 16,500 lbs ± 50 lbs.

### 6.4 Avionics

#### *6.4.1 Forward Bay Cover*

To enhance tracking of the FBC after separation, a C-band radar transponder was installed on the FBC along with two antennas (equally spaced around the FBC circumference) and an independent nickel-cadmium battery pack (see Figure 18). All components were acquired from the Sounding Rocket Program’s (SRP) inventory. Additionally, a strobe beacon was installed on the upper surface of the FBC and integrated into the system so that ground personnel and the

CH-53E loadmaster could monitor the status of the static lines prior to drop. The beacon used the same battery as the radar transponder and was wired to flash when all four static lines (two timers and two lanyard switches) were secured. If any one static line was inadvertently pulled, the beacon would stop flashing and project personnel would be aware of an anomalous situation. The helicopter would then attempt to return to the airfield, set down the DTV, land and power down so that the problem could be addressed and another test sequence could be attempted.

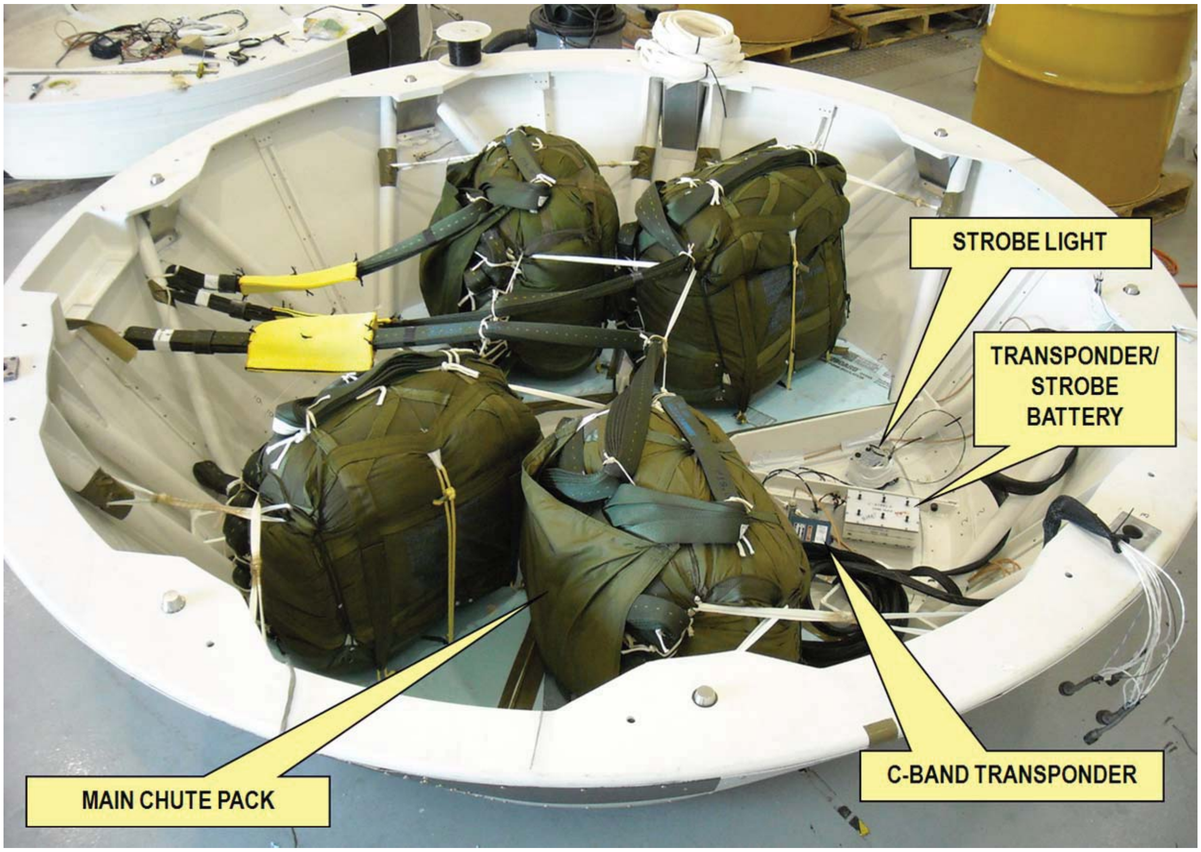


Figure 18. Avionics installed in FBC.

### *6.4.2 CM Mass Simulator*

Similar to the FBC, a radar transponder, two antennas, and a battery pack were installed on the CM mass simulator for tracking purposes (see Figure 19). Because of the hardness of the ballast weights, the antennas had to be surface mounted on the CM mass simulator circumference, which presented a snag hazard to the parachutes. A sheet-aluminum shield was designed to accommodate the antenna mounting, to provide a 30-degree down angle for the antenna beam, and to minimize snagging hazards. The shield subassemblies were bonded to the ballast weights with epoxy.

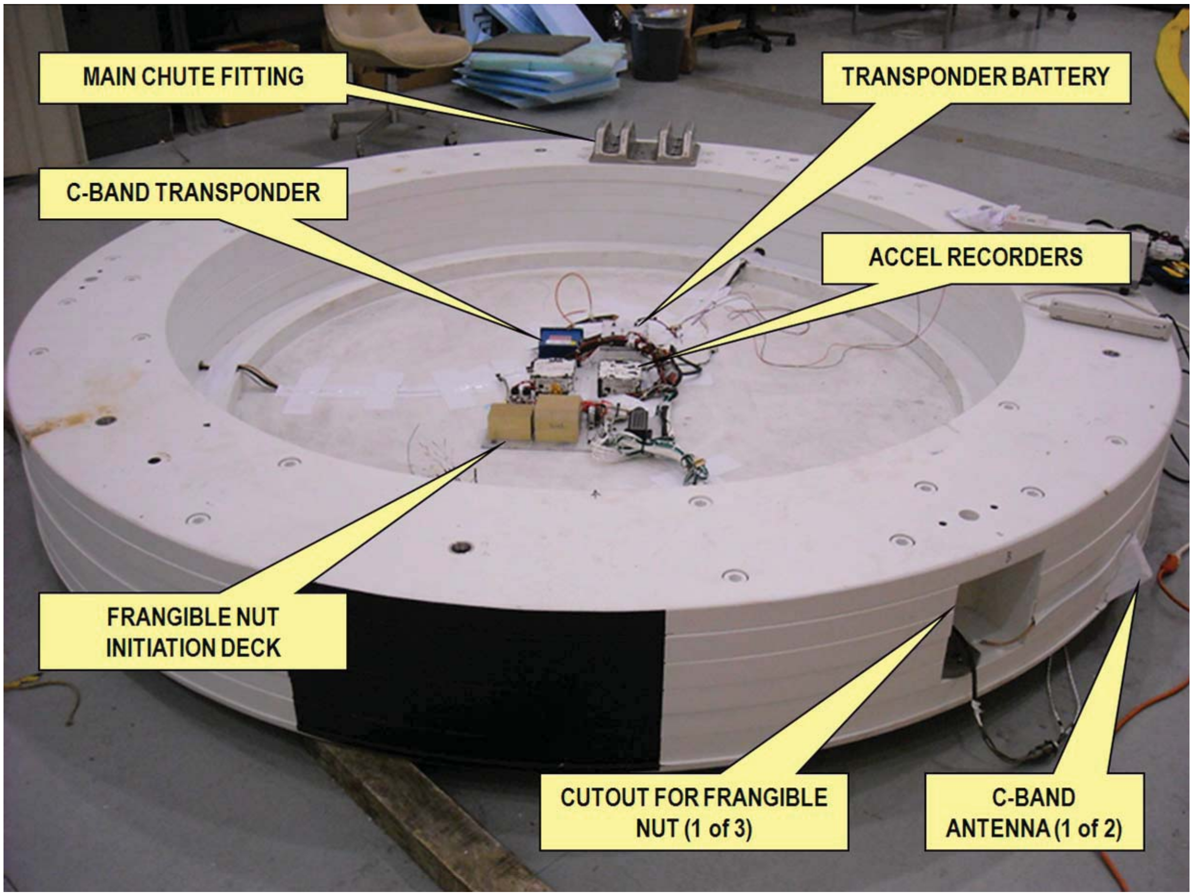


Figure 19. Avionics installed in CM mass simulator.

A capacitive discharge system to fire the frangible nuts was included as an independent subsystem with its own power source. Components included three each capacitive-discharge boxes, two relays, a squib current monitor, and a Ledex switch. This subsystem was previously used for bench testing of the MLAS solid rocket motor firing circuit, designed to simultaneously ignite four Terrier boosters. Repurposing of this subsystem for the drop test significantly shortened the DTV development schedule.

The three frangible nuts were installed in cutouts incorporated in the perimeter of the ballast weight stack. This external access allowed for system checks with the FBC mated with the mass simulator, reducing the duration of hazardous operations and allowing for final arming on the flight line with minimal additional circuitry. Wireway slots were part of the ballast plate design, allowing firing lines to be run from the avionics mounted in the interior center of the CM mass simulator to the externally mounted frangible nuts. The frangible nuts were the same devices used for the MLAS flight, both for the FBC release and the CM release functions. The drop test articles were refurbished test units.

Finally, two self-contained acceleration recorders (Instrumented Sensor Technology P/N EDR-3) were installed on the CM mass simulator in order to obtain data regarding parachute opening forces. The recorders were commercial devices used by the SRP and the WFF Mechanical Systems Branch for many years.

### *6.4.3 Riser/Harness*

In order to keep static lines as short as possible and therefore minimize the risk of contacting the main or tail rotors, the timers and lanyard switches for the avionics system were mounted as close to the hook as possible. This location was approximately four feet below the hook and approximately one foot below the programmer parachute pack. An octagonal aluminum plate was designed for mounting of the two mechanical timers and the two lanyard switches, one each on either side of the riser centerline. The plate was attached to the riser with a backing plate and held in place primarily by friction. Nylon cord stitched through the plates and the riser material provided assurance that the plate would not slip. The timers and lanyard switches both had extensive flight heritage within the SRP. The mechanical timers were each set for 5.5 ± 0.1 second, the time from first motion off the helicopter hook to FBC separation. The timer/switch assembly was encapsulated in a Styrofoam™ housing to protect against ground impact during handling and aircraft take-off.

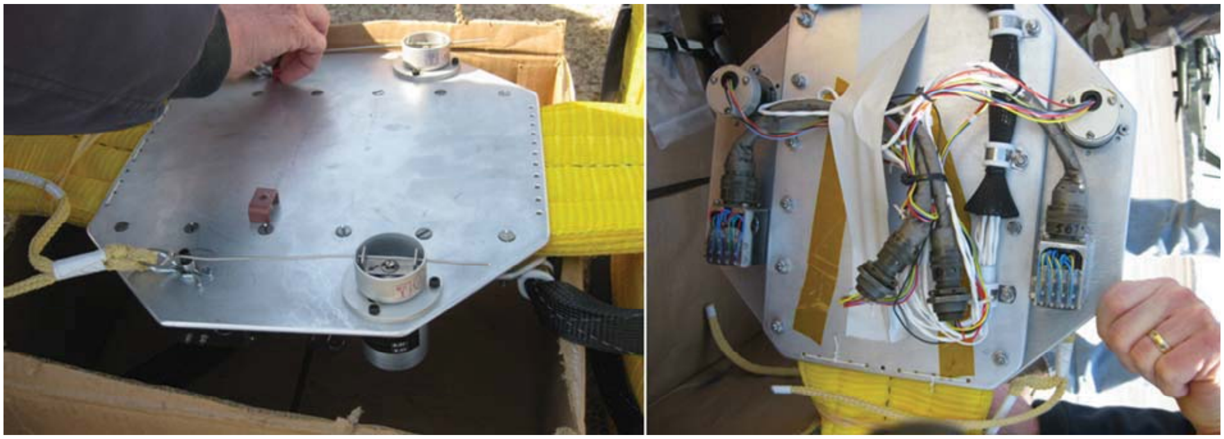


Figure 20. Timers and lanyard switches installed on riser-mounted plate.

### *6.4.4 Interfaces*

The static lines used to actuate the mechanical timers and the lanyard switches were fabricated from ¼-inch Kevlar™ cord, wrapped in plastic-backed fabric tape and loosely attached (to ensure adequate slack existed to prevent accidental actuations) to the riser with rubber bands. The static lines terminated at aluminum pull-pins and steel cotter pins for the timers and lanyard switches, respectively.

Since the timers and lanyard switches had to be located near the helicopter hook (see Figure 21), a wiring harness was run from the CM mass simulator, through the FBC, up one leg of the polyester harness, and up the polyester riser to the timers and switches. This harness was tied to the sling elements with nylon cord sewn into the harness leg and riser, allowing plenty of slack to account for sling stretching and handling. The wiring harness was protected with a braided nylon cable sleeve.

Figure 21. Programmer pack and risers attached to hook.

No special separation connectors were used in the portion of the wiring harness that spanned the FBC/CM mass simulator separation joint. Instead, simple plug and socket crimp connectors were used, with the harness securely fastened to hard points on either side of the separation joint. Care was taken to ensure loose ends of the harness would not interfere with parachute function after FBC release.

A safe/arm plug socket was installed on the FBC outer mold line, and a battery-charging connection was integrated into the arming socket for power source maintenance and checks.

## 7.0 Drop Test Results

The LPD system performed with no major anomalies during the drop test. The hook released the DTV system smoothly, and the programmer parachute deployed from its bag as planned. The forward velocity of the helicopter at time of drop was higher than expected (approximately 18 knots) and a significant head-wind (approximately 15 knots) existed at hook release. These two factors combined to momentarily push the programmer canopy opposite the direction of flight, but the programmer chute recovered quickly as it reached full inflation. The system stabilized and accelerated to the target dynamic pressure more quickly than anticipated; reaching 25 psf by the time the frangible nuts were initiated. The FBC separated from the CM mass simulator with no noticeable angular rates, and the main parachutes deployed from their bags as the mass simulator rotated smoothly into the expected edge-down orientation. The mass simulator did not exhibit any rotational overshoot during this phase. The main chutes decelerated the system for 7.4 seconds after FBC release, then disreefed to nominal fully inflated states (see Figure 22).

Figure 22. Drop test sequence.

The system continued to decelerate to terminal velocity and impacted Wallops Island 39 seconds after release from the drop aircraft. The descending FBC did pass the CM mass simulator as expected, but thanks in part to the helicopter's forward velocity at drop, the FBC was laterally offset enough to miss the main parachute cluster. It impacted the ground approximately 70 feet from the mass simulator (see Figure 23).

Figure 23. FBC (upper left) and CM mass simulator after impact on Wallops Island.

Recovery operations began immediately after the test. Recovery personnel noticed several instances of broken suspension lines while retrieving the main chutes. The avionics (including the acceleration recorders), frangible nuts, tethered separation bolts, polyester harness, polyester riser, programmer chute, and main chute deployment bags were also recovered from the drop zone. Field inspection of major structural components by project stress analysts revealed no structural failures or any other evidence of overloading.

Post-test inspection of the main chutes, in addition to analysis of the test video and photos, revealed significant damage to the suspension lines of two of the chutes (see Figure 24). This damage included six broken lines, twelve nearly broken lines, and 299 friction burns of various size. The other two main parachutes had only a few isolated instances of friction burns on the suspension lines. Extensive attempts were made to find patterns in the damage in hopes of determining a root cause related to packing issues (e.g., how the suspension lines were tied onto stowage panels in the deployment bags) or related to higher-than-expected strip-out velocities, but no clear patterns were found. Nor was there any correlation between the damaged chutes and the rigging technicians who packed them. One test video suggests that the main shackle of one parachute became entangled with the lines of another chute, momentarily maintaining slack in the former's set of lines and allowing extensive interaction between the two sets of lines. The affected shackle became free shortly thereafter when the system started taking on significant load, thus the damage incurred by the lines could be the result of the slack set of lines suddenly being loaded once the shackle came free and rapidly rubbing against lines from the other parachute. However, this hypothesis cannot be confirmed due to the poor clarity of the long-range video.

Figure 24. Example of suspension line damage sustained by two drop test main chutes.

One of the two acceleration recorders measured inertial loads on the CM mass simulator. (The second recorder failed to trigger.) Figure 25 shows a plot of the resultant acceleration data. Peak resultant load measured during the reefed main chute phase was 2.7 g's and during disreefing was 2.1 g's. These values compare well with pre-test models. No corrections for CG offset were attempted.

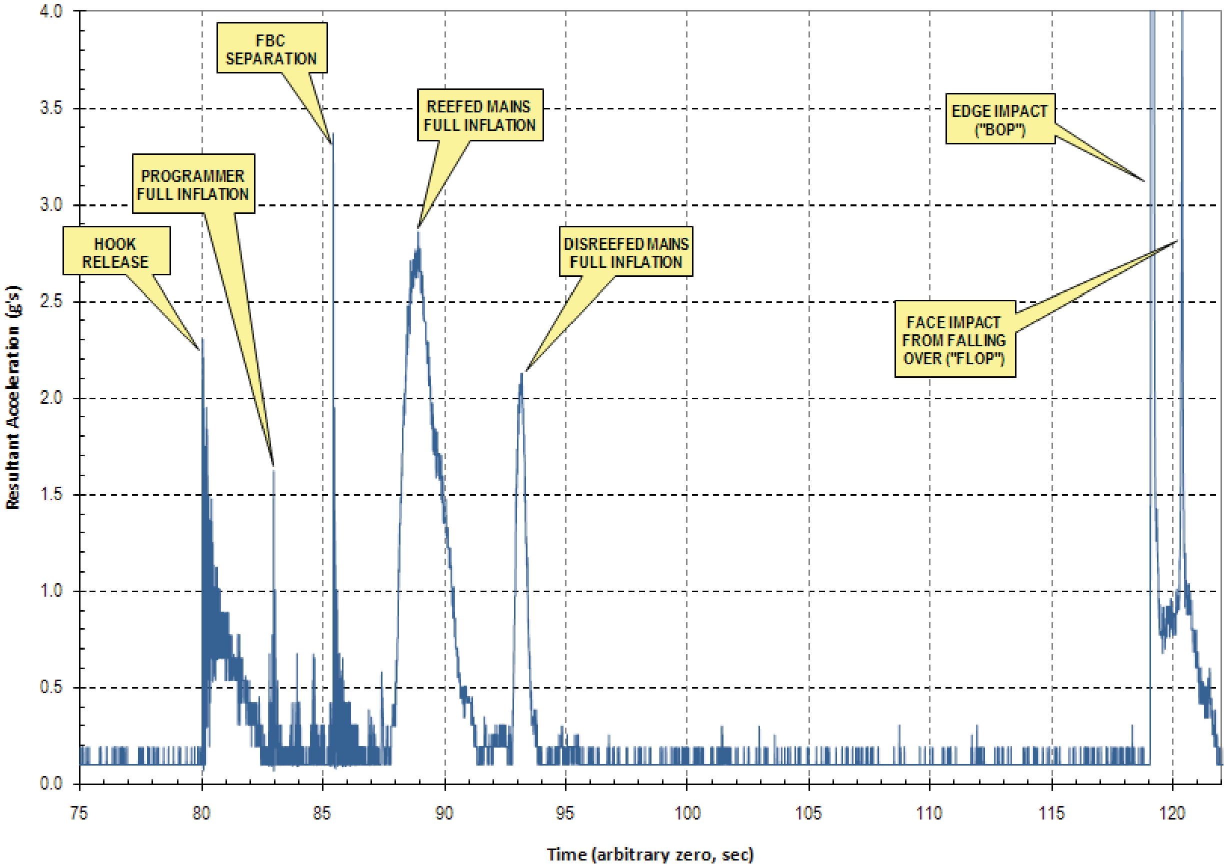


Figure 25. Resultant acceleration encountered by CM mass simulator.

Radar data, accelerometer data, and test video were used to evaluate the performance of both the programmer parachute and the main parachute cluster. Since the programmer parachute was not part of the system being tested, no attempt has been made to date to validate the estimated drag performance of that chute. It was noted, however, that the deployment time (FBC release to line stretch) for the main chutes was longer than estimated (2.2 seconds versus 1.2 seconds), which produced a higher dynamic pressure at main chute line stretch than desired.

Analysis of the drop test data indicated an overall effective drag coefficient of 0.73 for the cluster of four main parachutes. The published base drag coefficient for flat circular parachutes, like the G-12D, ranges from 0.75 to 0.80. This means that the drag performance with degradation by forebody wake and cluster effects was 91 to 97 percent of base drag, which significantly exceeds expectations based on handbook derating factors. This overperformance can likely be attributed mostly to the small forebody area produced when the already-small CM mass simulator rotated into an edge-on orientation during main chute deployment. Target dynamic pressure at main chute line stretch, based on MLAS pre-flight simulations, was 37 psf. Actual dynamic pressure at main chute line stretch for the drop test was 47 psf, proving qualitatively that the modified G-12D parachutes would survive expected flight loads and function nominally.

## 8.0 Lessons Learned

The following details about the drop test preparation and execution offer insight into which aspects worked exceptionally well and which resulted in problems.

1. The decision to move the drop test from YPG to the WTR benefitted the project in several areas:
    a. By using a NASA-owned range, range costs were far lower than originally expected and range scheduling was much more flexible.
    b. Co-locating the test operations at the DTV development site saved the project transportation costs, time associated with shipping and GSE preparation, and team travel costs.
    c. Limited range impact area at WTR forced the use of a helicopter for the drop test, which removed the need for a separate platform for DTV-aircraft integration. Such platforms can be quite complex in design, especially with regard to high-speed extraction from a fixed-wing aircraft, separation from the DTV, and assurance of no recontact with the DTV. Also, the ability for the project team to broker helicopter support resulted in significant cost savings over the cost of traditional fixed-wing aircraft used at YPG.
2. Emphasis from the earliest planning phase was on protecting the aircraft and its crew from any hazards the DTV or the test itself may pose. This philosophy was repeatedly communicated to the aircrew during briefings and during a operational dry run. Many DTV design trades were made with safety as the driving criterion, including the addition of a strobe light indicating system health. Since there was no telemetry from the DTV, this visual indicator would alert ground personnel and the aircrew if a timer or lanyard switch was actuated inadvertently, which would then require a return to base to address the issue.
3. Two self-contained three-axis acceleration recorders were part of the DTV avionics. Redundant units were specified as the recorder model had proven historically to be difficult to program, particularly regarding trigger levels and sample rates. One of the two units failed to trigger during the test, but the other recorded very good data that was essential in analyzing system performance.
4. Three self-contained video recorders were included on the DTV. These recorders required manual power switching prior to system pyrotechnic arming. Unfortunately, the time required for arming, aircraft run-up, aircraft pre-flight checks, and departure from the airfield was greater than expected and exceeded the programmed recording time. No useful on-board video was captured during the test.
5. Radar transponders were used on both the ballast portion of the DTV as well as the FBC. This allowed precision tracking of both bodies and provided valuable data for post-test system performance analysis.

## 9.0 References

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2 Matarese, R. A.: *Weight Bucket Analysis Results*. Charts presented on October 27, 2009. PLATES_012709.ppt.

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**14. ABSTRACT**

The Landing Parachute Demonstrator (LPD) was conceived as a low-cost, rapidly-developed means of providing soft landing for the Max Launch Abort System (MLAS) crew module (CM). Its experimental main parachute cluster deployment technique and off-the-shelf hardware necessitated a full-scale drop test prior to the MLAS mission in order to reduce overall mission risk. This test was successfully conducted at Wallops Flight Facility on March 6, 2009, with all vehicle and parachute systems functioning as planned. The results of the drop test successfully qualified the LPD system for the MLAS flight test. This document captures the design, concept of operations and results of the drop test.

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