Entry, Descent, and Landing System Design for the Mars Gravity Biosatellite

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ABSTRACT

Execution of a full entry, descent, and landing (EDL) from low Earth orbit is a rare requirement among university-class spacecraft. Successful completion of the Mars Gravity Biosatellite mission requires the recovery of a mammalian payload for post-flight analysis of the effects of partial gravity. The EDL design for the Mars Gravity Biosatellite is driven by requirements on the allowable deceleration profile for a payload of deconditioned mice and maximum allowable recovery time. The 260 kg entry vehicle follows a ballistic trajectory from low Earth orbit to a target recovery site at the Utah Test and Training Range. Reflecting an emphasis on design simplicity and the use of heritage technology, the entry vehicle uses the Discoverer aeroshell geometry and leverages aerodynamic decelerators for mid-air recovery and operations originally developed for the Genesis mission. This paper presents the student-developed EDL design for the Mars Gravity Biosatellite, with emphasis on trajectory design, dispersion analysis, and mechanical design and performance analysis of the thermal protection and parachute systems. Also included is discussion on EDL event sequencing and triggers, the de-orbit of the spacecraft bus, plans for further work, and the educational impact of the Mars Gravity Biosatellite program.

1.0 Introduction

Having engaged more than 500 students since 2001 in space life science, systems engineering, and hardware development, the Mars Gravity Biosatellite program offers a unique, interdisciplinary educational opportunity to address a critical challenge in the next steps in human space exploration through the development of a free-flyer platform for partial gravity science with full entry, descent, and landing capability. A collaboration between MIT and Georgia Tech, this student-developed free-flyer spacecraft is designed to carry a payload of 15 mice into low Earth orbit, rotating to generate accelerations equivalent to Martian surface gravity. Following completion of nominal on-orbit operations, the spacecraft will re-enter the atmosphere by controlled de-orbit. A mid-air recovery will be conducted over the Utah Test and Training Range (UTTR), and the payload will be delivered to nearby laboratory facilities for further post-flight data collection for partial gravity science. This mission will be longest self-contained biosatellite flight to date [1].

Planned to launch in the 2011 timeframe, the Mars Gravity Biosatellite represents a uniquely affordable platform for quantifying risks and testing hypotheses related to NASA's exploration initiatives. The science planned for the first flight of the biosatellite will characterize the effects of Martian gravity levels on mammalian physiology. Data in this regime may be applicable to the mitigation of microgravity effects in extended-duration space operations. The data is critical to eventual human operations in a Martian gravity environment, where the duration of reduced gravity exposure will extend to a full year or beyond. Additionally, the understanding of these deconditioning processes may provide enhanced understanding of analogous diseases on Earth, such as osteoporosis. This peer-reviewed research will include characterization of musculoskeletal degradation, alterations of vestibular reflexes, and downregulation of the immune response.

Execution of a full entry, descent, and landing (EDL) from low Earth orbit is a rare requirement among university-class spacecraft. Successful completion of the Mars Gravity Biosatellite mission requires the recovery of the mammalian payload for post-flight analysis on the effects of partial gravity. The EDL design for the Mars Gravity Biosatellite is driven by requirements on the allowable deceleration profile for a payload of deconditioned mice and maximum allowable recovery time. The 260 kg entry vehicle follows a ballistic trajectory from low Earth orbit to a target recovery site at UTTR. Reflecting an emphasis on design simplicity and the use of heritage technology, the entry vehicle uses the Discoverer aeroshell geometry and leverages aerodynamic decelerators for mid-air recovery and operations originally developed for the Genesis mission. This paper presents the student-developed EDL design for the Mars Gravity Biosatellite, with emphasis on trajectory design, dispersion analysis, and mechanical design and performance analysis of the thermal protection and parachute systems. Also included is discussion on EDL event sequencing and triggers, contingency operations, the de-orbit of the spacecraft bus, plans for further work, and the educational impact of the Mars Gravity Biosatellite program.

2.0 Spacecraft Overview and Science Mission Objectives

Spacecraft Overview

The Mars Gravity Biosatellite is comprised of three major elements: payload, bus, and EDL. In addition to these major systems is YourNameIntoSpace (YNIS), a fundraising initiative where donors to the Mars Gravity Biosatellite program receive surface area on the spacecraft to place approved decalcomania.   The integrated spacecraft is shown in Figure 1. The total launch mass of the satellite, including margin, is 625 kg (wet mass), with 15% held for launch mass margin.

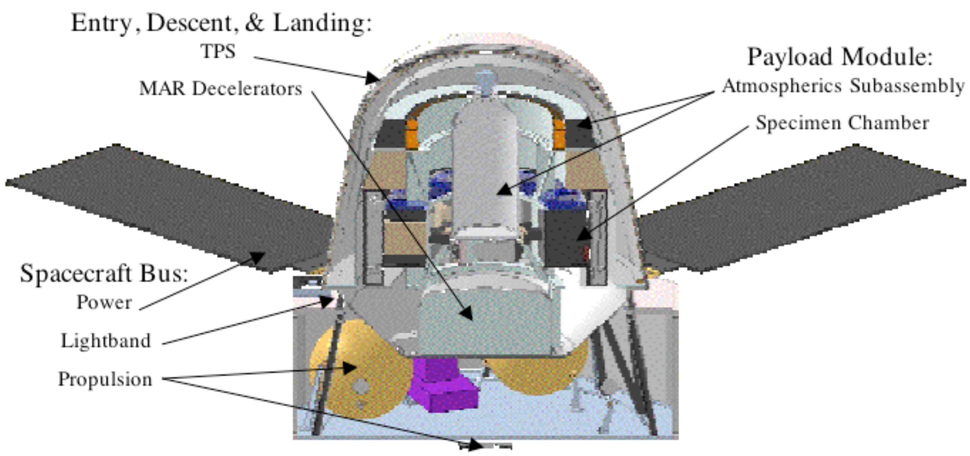


Figure 1. Mars Gravity Biosatellite: Bus, Payload, EDL

Mars Gravity Biosatellite is planned as a primary payload on a domestic expendable launch vehicle, with the SpaceX Falcon IE as the present baseline. The payload has been designed to support animals for up to 7 days from integration to launch, with ground support interfaces for power, data, and atmospheric processing throughout this time. At launch, the vehicle will be placed in a 370 km, 41° inclination, circular Earth orbit. The spacecraft is sun-pointing, with the heatshield providing a means for thermal control of the payload. Power is provided throughout the main flight phases by solar arrays and secondary batteries.

The payload element includes subsystems for environmental control, specimen habitats (including waste management and consumables), payload support structure, independent thermal control, command and data handling, and the sensor suite and data collection hardware. The payload is entirely enclosed within a pressurized aeroshell, with direct interfaces to the bus and EDL systems.

The spacecraft bus includes guidance, navigation, and control, communications, power, thermal, command and data handling, propulsion, attitude determination and control hardware, and software for the entire spacecraft. The spacecraft bus must function from launch vehicle separation through jettison of the entry vehicle (EV) and the subsequent de-orbit of the bus itself.

Science Mission Objectives

The Mars Gravity Biosatellite program is intended to provide a broad level of insight into the physiological issues and opportunities provided by a 0.38-g artificial gravity environment. The current lack of data regarding partial gravity effects supports the decision for a wider investigation perspective, as opposed to focusing on a particular physiological system. A prioritized list of science objectives has been developed in collaboration with the program's external Science Advisory Panel. On the basis of available resources and instrumentation, these priorities have been narrowed to the following:

- Bone demineralization and increased fracture risk
- Changes in both macroscopic and microscopic bone structure
- Atrophy and reduction of strength in major muscle groups
- Changes in both macroscopic and microscopic muscle fiber structure and composition
- Downregulation of vestibular reflexes
- Changes in microscopic vestibular structure
- Reductions in immune status

Data following a 35-day exposure to Martian gravity levels will be compared against physiological data from both microgravity and 1-g environments where possible [2].

To satisfy these objectives, the payload will contain 15 skeletally mature (15-20 weeks old at launch) BALB/cByJ female mice. This particular strain was selected due to its robust skeletal responses to unloading. Females utilize fewer consumables, allowing for a larger number of animals and greater statistical power from the cohort [2]. In addition to the flight experiment, ground controls are planned for comparison against flight, ground, and microgravity data, including vivarium, hindlimb suspension, partial weight suspension, flight habitat effects, and short-radius centrifuge testing [2]. These objectives place requirements on the magnitude and duration of acceleration loads during launch and EDL, the types of sensors and systems developed for the payload, and much of the operations and hardware specifications across the entire spacecraft.

3.0 EDL Overview and Timeline

Entry Vehicle Overview

The Mars Gravity Biosatellite mission requires the domestic recovery of the payload at UTTR, subject to strict constraints on allowable deceleration loading and recovery time. Limits on the maximum allowable deceleration environment (magnitude and duration) are science-derived and specific to the deconditioned, live mammalian payload. Additionally, the science team must have full access to the payload within 2-4 hours after the spacecraft is removed from the 0.38g environment to satisfy program science objectives. These requirements for allowable deceleration environments and recovery time, coupled with a design preference for simplicity drove the selection of a shallow ballistic entry trajectory from 325 km altitude and an entry vehicle utilizing heritage technology.

The entry vehicle, shown Figure 2 still joined with the spacecraft bus, is a 260 kg pressurized Discoverer capsule. The exterior is protected by an ablative heatshield made of PICA and tiled similar to the Orion heatshield design. The pilot and drogue chutes are packaged into a mortar in the aftbody of the aeroshell with the parafoil for mid-air retrieval packaged around the mortar. The thermal protection system and mid-air retrieval systems are discussed in detail in the following sections. The shallowness of the entry trajectory does not permit the performance uncertainties associated with traditional solid de-orbit motors, driving the selection of an IMU-controlled hydrazine monopropellant system to provide the de-orbit maneuver. The de-orbit propulsion is on the spacecraft bus. The outer moldline of the entry vehicle is approximately 1 m in each dimension, shown in Figure 3.

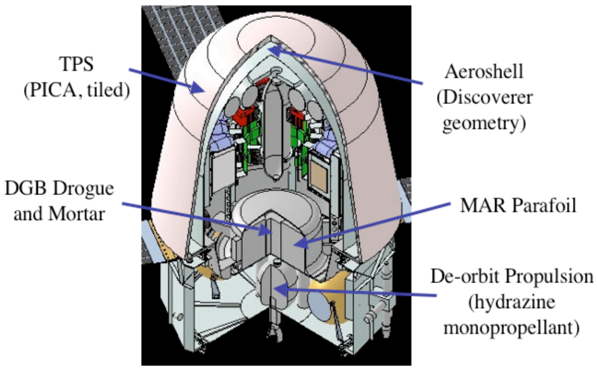


Figure 2. EDL Subsystems

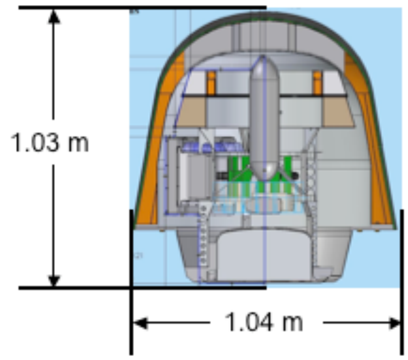
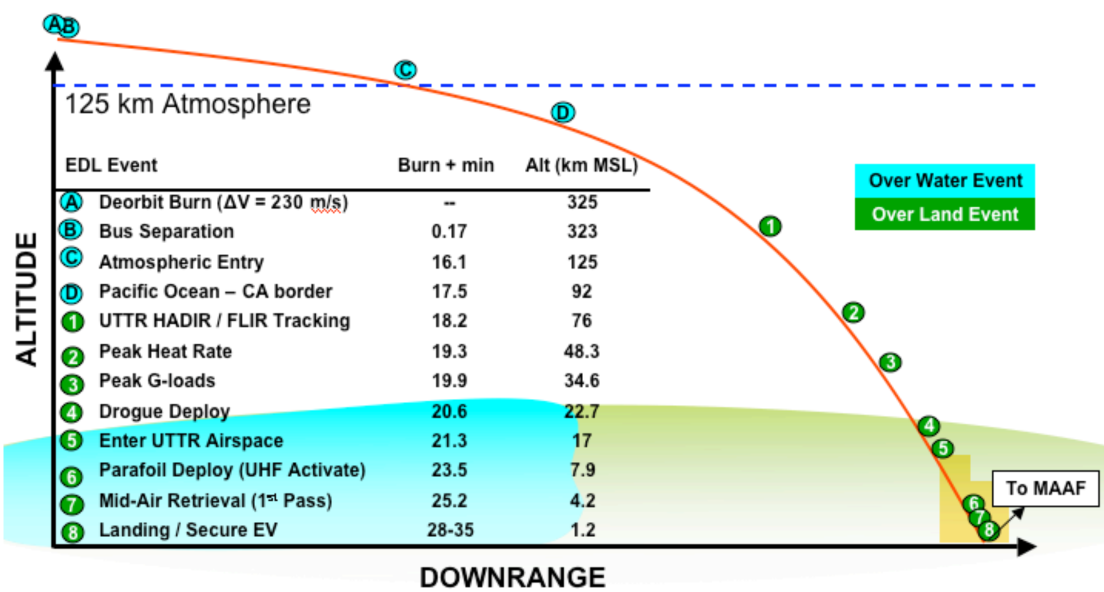


Figure 3. Entry Vehicle Cutaway

EDL Timeline and Sequence of Events

Figure 4 shows the sequence of events for the entry, descent, and landing phase of the Mars Gravity mission. The EDL phase begins following a ground command to de-orbit, spin-down of the spacecraft, and reorientation for entry. The spacecraft bus and entry vehicle begin entry as a single unit; separation of the entry vehicle from the bus is done using the spring-loaded lightband following completion of the de-orbit burn, imparting an additional 1-1.5 m/s ΔV to the entry vehicle. At Mach 2.0, the mortar deploys the pilot and drogue chutes, decelerating the vehicle to appropriate subsonic conditions for deployment of the parafoil. One of three helicopters stationed in the landing ellipse completes mid-air retrieval of the vehicle. The entire EDL and recovery phase lasts 28-35 minutes. Once the entry vehicle has been safed and the parafoil removed, the capsule is flown directly to the designated Science Operations Facility in the region, requiring an additional 1-2 hours before the program science team has full access to the payload.



EDL Event	Burn + min	Alt (km MSL)
A Deorbit Burn (ΔV = 230 m/s)	--	325
B Bus Separation	0.17	323
C Atmospheric Entry	16.1	125
D Pacific Ocean – CA border	17.5	92
1 UTTR HADIR / FLIR Tracking	18.2	76
2 Peak Heat Rate	19.3	48.3
3 Peak G-loads	19.9	34.6
4 Drogue Deploy	20.6	22.7
5 Enter UTTR Airspace	21.3	17
6 Parafoil Deploy (UHF Activate)	23.5	7.9
7 Mid-Air Retrieval (1st Pass)	25.2	4.2
8 Landing / Secure EV	28-35	1.2

Figure 4. EDL Sequence of Events and Timeline

Events such as mortar firing and parafoil deployment are triggered by g-switches in the payload, backed up by an onboard mechanical timer. All power required during the EDL phase is provided by batteries in the payload. The following sections provide design rationale, methods, and details on the vehicle aerodynamics, trajectory, TPS, aerodynamic decelerators, recovery operations, and de-orbit of the spacecraft bus following separation from the entry vehicle.

4.0 Aerodynamics

The aerodynamics database created for the Mars Gravity entry vehicle is based on the Discoverer geometry. The basic geometry, shown in Figure 5 has flight heritage from the Discoverer and Corona programs of the 1960s and design heritage from the METEOR (COMET) project in the 1990s. Provided the center of gravity can be situated far enough forward, the Discoverer geometry has favorable static aerodynamic characteristics as compared to alternate blunt body entry geometries such as sphere-cones, particularly for stability. Figure 6 (a,b,c) shows the static aerodynamic force coefficients (C_L, C_D, $C_{M\alpha}$) with Mach number (Mach 20 to Mach 3) and angle of attack (-30º to +30º). These trends compare well with the aerodynamic database developed previously for METEOR [3,4].

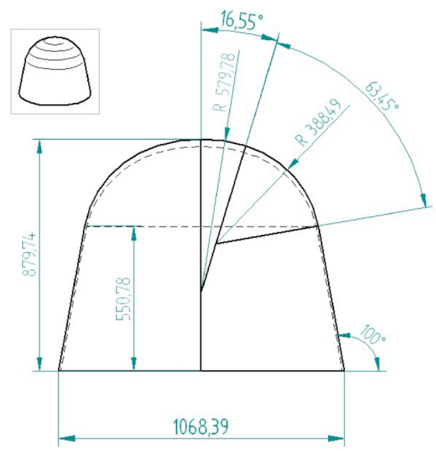


Figure 5. Discoverer Aeroshell Geometry (base dimensions in mm)

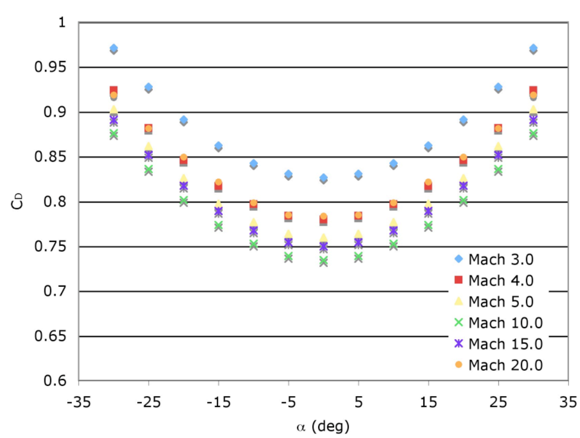


Figure 6a. Drag Coefficient

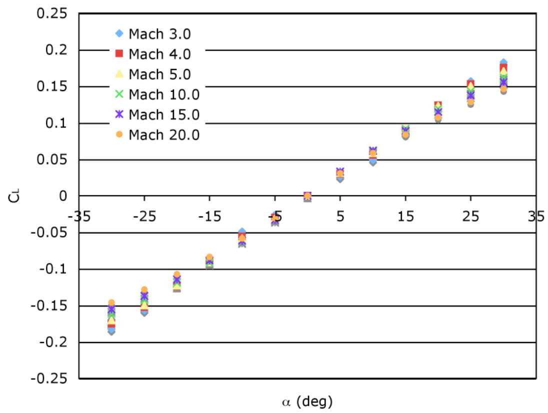


Figure 6b. Lift Coefficient

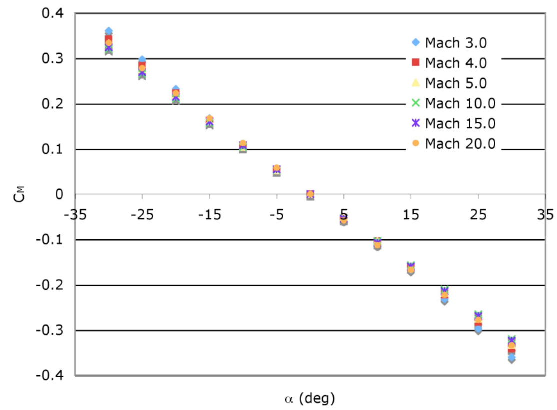


Figure 6c. Moment Coefficient

5.0 Trajectory

Definition of the Nominal Entry Trajectory

The nominal entry trajectory is a shallow ballistic entry from 325 km altitude, with the entry vehicle and spacecraft bus beginning the de-orbit process still joined. Following completion of the 230 m/s ΔV de-orbit burn, the entry vehicle and bus are separated by a lightband, the mechanical adapter joining the two elements together during the launch and orbital mission phases. This separation imparts an additional 1 – 1.5 m/s ΔV to the entry vehicle. The entry vehicle continues along this trajectory until recovery at UTTR. The spacecraft bus completes the EDL phase independent of the entry vehicle; the burn and break up analysis performed for the bus is given in Section 8.0. All trajectory analysis was completed using the Program to Optimize Simulated Trajectories (POST). The 1976 Standard Atmosphere was used for all trajectories.

Requirements limiting recovery time drive the design of the dispersed trajectory to result in the smallest possible landing footprint by using the steepest possible entry flight path angle. However, other requirements limit the severity of the deceleration environment the deconditioned payload can experience during entry, shallowing the entry flight path angle significantly to limit the magnitude and duration of the deceleration g-pulse. The nominal entry trajectory is limited by deceleration and has been defined as the trajectory with the maximum ΔV where, once dispersions are applied, less than 10% of the dispersed trajectories fail. A failed case is a trajectory that exceeds the science requirements on deceleration, lofts or skips out of the atmosphere, or results in a landing site outside of UTTR. This definition results in an entry flight path angle of -2.99º and a de-orbit ΔV of 230 m/s. The target landing site in UTTR is at 40.07ºN, -113.43ºW. The applied 3-σ dispersions are given in Table 1; all assumed a uniform distribution. The nominal trajectory deceleration profile as compared to the deceleration limits specified in the program science requirements is shown in Figure 7. Figure 7 shows only the deceleration profile from the aerodynamic drag of the entry vehicle. Deceleration from events such as parachute deployment and inflation are not included, but the peak loads from these events are below the required limits.

Table 1. Dispersions Applied to the Nominal Entry Trajectory

Parameter	Dispersion
EV Mass	+/- 10%
Altitude at Periapsis (km)	+/- 1%
Orbital Inclination	+/- 0.05%
True Anomaly	+/- 0.05%
Longitude of the Ascending Node	+/- 0.05%
C_D	+/- 4%
De-orbit ΔV	+/- 1%
Thrust (Magnitude and Direction)	+/- 0.3%
Atmospheric Density	+/- 30%

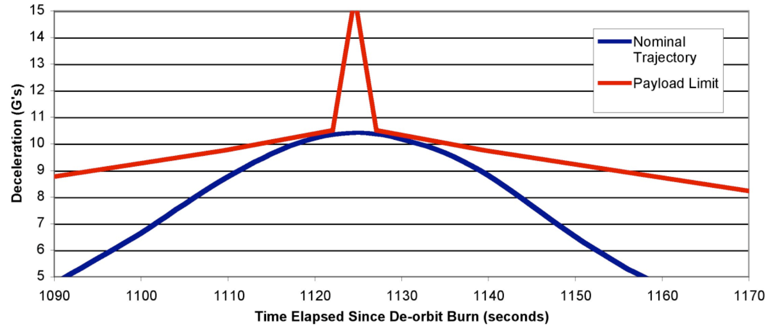


Figure 7. Comparison of Nominal and Allowable Deceleration Profiles

The shallowness of the nominal trajectory results in a very narrow entry corridor. The entry corridor is limited by deceleration and defined as the permissible variation in flight path angle to still land within the bounds of UTTR. The total width of the entry corridor for the Mars Gravity entry vehicle is 0.16º, or +/- 0.08º. For comparison, the Genesis entry corridor was +/- 0.027º (1/3 of the mission requirement), though the entry flight path angle for Genesis was significantly steeper (-8.002º) [5]. The narrowness of the entry corridor led to the selection of an IMU-controlled hydrazine monopropellant propulsion system on the spacecraft bus; uncertainties in performance do not permit the use of a conventional solid rocket motor for the de-orbit maneuver.

Dispersion Analysis

A dispersion analysis was performed to assess the size of the landing footprint relative to the landing target in UTTR. The dispersions applied to the nominal trajectory are given in Table 1. The resulting error ellipse, shown in Figure 8, is 167 km downrange. The crossrange error is due to the dispersions applied to the thrust pointing direction.

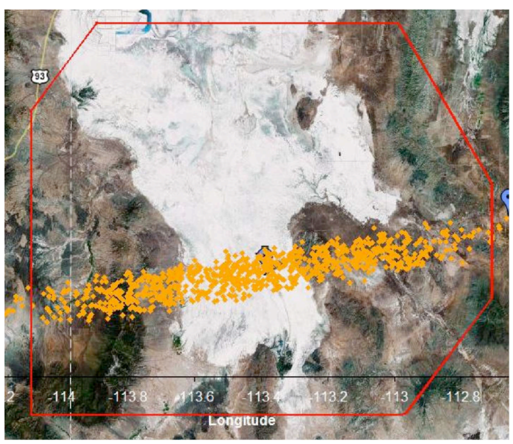


Figure 8. Landing Ellipse within UTTR

The entry vehicle has no active control system or guidance, requiring the spacecraft to be spinning at the start of the EDL phase to null out any adverse lift generated by an offset of the center of gravity of the entry vehicle. This rotation rate has not yet been determined; subsequent 6DOF analysis is required.

6.0 Thermal Protection System

The TPS design for the Mars Gravity Biosatellite entry vehicle is a tiled PICA heatshield. The baseline heating environment is defined by the nominal entry trajectory, described in Section 5.0, with a peak stagnation point heat rate of 191 W/cm^2. While this heating environment is much more benign than the environments typically requiring PICA or a similar material, the CEV TPS Advanced Development Project has offered to work with the Mars Gravity team on understanding the manufacturing, integration, and testing of a heatshield for Earth return from low Earth orbit, necessitating the use of PICA. The dimensions of the Discoverer aeroshell forebody exceed the maximum dimensions for a single block of PICA, resulting in a tiled design. The tiles are set into a titanium-aluminum alloy carrier structure similar to CEV. The overall tile layout (3D and top views) is shown in Figure 9.

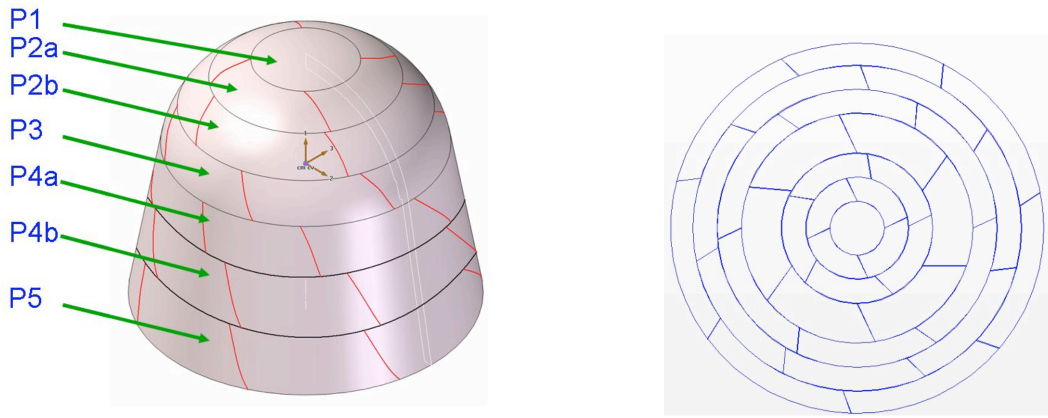


Figure 9. Heatshield Tile Layout (3D View and Top View)

Initial sizing was completed using the Planetary Entry Systems Synthesis Tool (PESST) TPS sizing module, approximating the heat rate away from the nose using a cosine distribution. Compensating for the variation in radius of curvature of the nose, a constant thickness is maintained for the first 16.55º. The tiling layout uses 36 total tiles with a maximum tile dimension of 50.4 cm. Consistent with the CEV TPS design, the gaps are angled 25º to the flow. The gaps are 2 mm wide and filled with RTV. Total TPS mass is 36.38 kg.

The backshell TPS is sized at a constant thickness of PICA. The backshell heating was approximated as 3% of the peak stagnation point heating based on Stardust backshell heating data [6]. Additional analysis will be required to choose the best material for the backshell TPS and obtain a better estimate of the backshell heating environment.

7.0 Aerodynamic Decelerator Design and Recovery Operations

The descent, landing, and recovery of the entry vehicle are completed using aerodynamic decelerators and operations for mid-air retrieval (MAR). This heritage system was initially used to recover orbital and suborbital military payloads and was most recently matured and extended to higher mass entry vehicles for the Genesis mission. The driving requirements for the MAR system are derived primarily from the science responsiveness requirements and inherent trajectory limitations. The nominal trajectory (Section 5.0) gives the entry state used to size the parachutes.

Initial design exploration was completed for three heritage deceleration and recovery systems: a hard ground landing with crushables for shock attenuation (Stardust), mid-air retrieval (Genesis), and a water landing. A water landing was ruled out due to the unavoidable responsiveness problems associated with such a recovery as well as concerns with stresses on the payload due to ocean wave undulation. A hard landing with crushable mass in Woomera, Australia was the prior baseline. However, it was determined that the mass of crushable material required to attenuate impact shocks would be significant with the science requirements on deceleration loading. Additionally, program level concerns were raised as to whether recovery and payload delivery to the science operations facility following a hard ground landing could be completed in the required 2–4 hour timeline.

The decision to change the baseline to MAR was strongly based on the ability to meet the recovery time requirement and the similarity of the Mars Gravity MAR system to the system developed and NASA-certified for the Genesis sample return mission. The "Third-Generation MAR" (3GMAR) system, developed by Vertigo, Inc., is characterized by a pilot-drogue-parafoil deceleration sequence followed by a mid-air snatch of the entry vehicle by a helicopter. Validation during the Genesis program (among other validation programs) demonstrated 100% system reliability. As of 2005, Vertigo had performed over 34 MAR training missions and 22 end-to-end parafoil MAR missions, all of which were successful [6]. With a 30 kg mass savings over a comparable crushable system for a hard landing, the MAR option also eliminates the problem of having to search for the entry capsule after landing. The switch to MAR from crushables also resulted in a switch of the target landing site from Woomera, Australia to UTTR to ease recovery operations by using a domestic site and to allow for the use of range tracking systems installed at UTTR. This section discusses the sizing methodology for the Mars Gravity MAR system, the triggers and mechanisms for deployment and capture, and the recovery operations at UTTR.

Aerodynamic Decelerator Design

The 3GMAR system consists of three parachutes: a small transonic chute, a stabilization and deceleration drogue, and a main parafoil. An engagement line is attached to the parafoil, as shown in Figure 10. The recovery process is divided into three distinct events: intercept, engagement, and pickup.

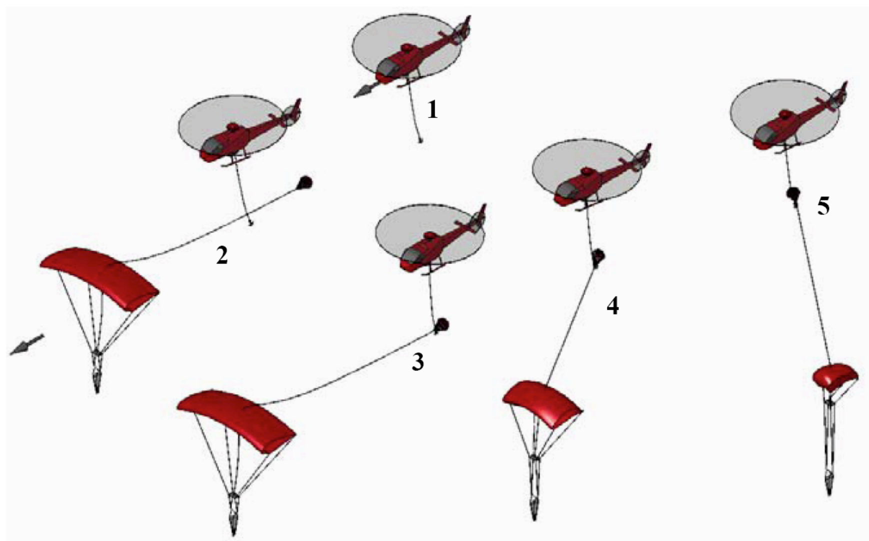


Figure 10. Vertigo, Inc. 3GMAR Schematic [6]

At the start of the intercept phase (steps 1-2 above), the helicopter is loitering at a safety radius. Two helicopters were used for the Genesis Sample Return mission for redundancy, each one positioned at either side of the predicted landing ellipse; a third helicopter will likely be required to handle the size of the ellipse for Mars Gravity. Sophisticated payload tracking at UTTR, such as the High Accuracy Digital Instrumentation Radars (HADIRs) and Forward Looking Infrared (FLIR), provide the helicopters with interception vectors, eliminating the need for a transponder on the entry vehicle itself. During Genesis entry, the SRC was spotted at 300,000 ft and tracked with high accuracy all the way to the ground.

In the engagement phase (step 3 above), the helicopter approaches left of the parafoil centerline sliding right laterally until the suspension cable meets the engagement line. The helicopter next climbs until the engagement line meets the latching arm attached to the helicopter's suspension cable. The latching arm automatically traps the engagement line with a grappling hook. In the pickup phases (steps 4-5 above), the helicopter climbs, with the slider reefing system progressively deflating the parafoil. The load is slowly transferred from the parafoil to the helicopter suspension cable and parafoil engagement line as the parafoil is deflated. Prior to packing the parafoil, the slider is placed directly beneath the parafoil so that the canopy is already partially reefed as the parafoil deflates, resulting in dramatically reduced peak opening loads. Once the parafoil is completely deflated, the helicopter can land, and the suspension-engagement line can be replaced by a single cable for extended travel to the science operations facility.

The MAR system is sized using a combination of historical data and bottom-up estimation. A feasibility study conducted by Vertigo defined a system for performing mid-air retrievals on a 272 kg sphere-cone entry capsule [6]. The baseline Mars Gravity entry vehicle is 260 kg, so the sizing and configuration for the 272 kg sample payload provide provided an initial design point to be extended for Mars Gravity. Due to the similarity of the Mars Gravity entry vehicle to the payload tested by Vertigo, the main parafoil for Mars Gravity is assumed to be essentially identical to that of the feasibility study.

The drogue parachute is sized to deliver the entry vehicle to an acceptable dynamic pressure (< 1200 Pa) for parafoil deployment. The drogue is a disk-gap-band (DGB) parachute, a heritage design with proven stability across a wide range of flight path angles for both Earth return and Mars EDL missions. The pilot and drogue chutes are mortar-deployed at Mach 2.0.

An iterative process was used to size the drogue chute, estimating the drogue drag area, checking the dynamic pressure at parafoil deployment, and then adjusting the drag area until the drogue is just large enough to meet the dynamic pressure constraint. The final results of this iterative process are shown in Figure 11 and the sizing results are summarized in Table 2 [6-10]. Figure 12 and Figure 13 show the packaged mortar and integration of the MAR decelerators into the aeroshell aftbody, respectively.

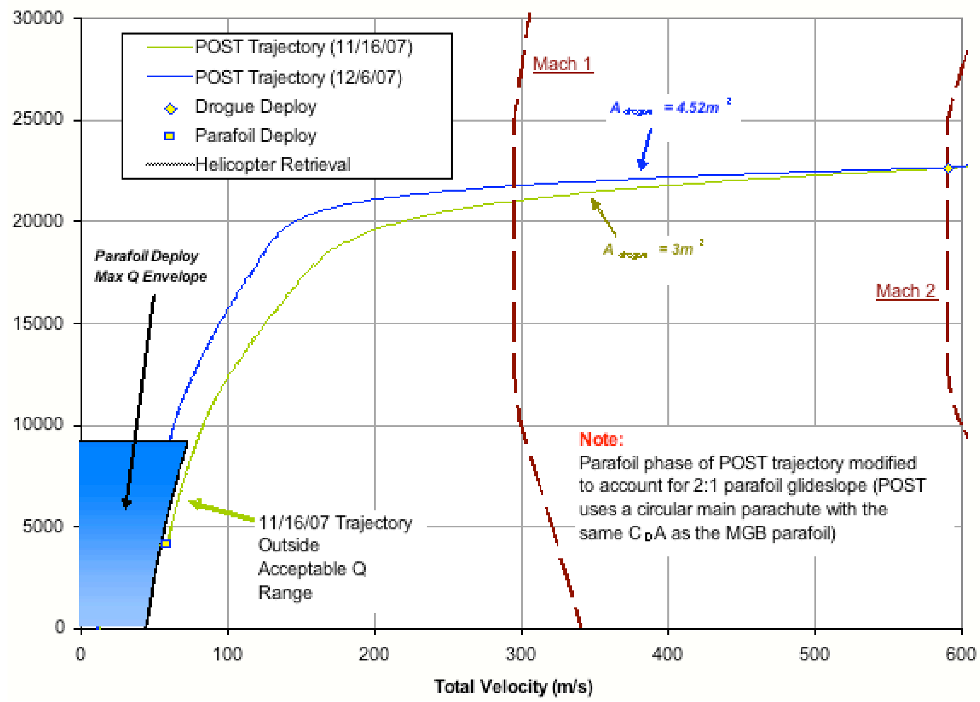


Figure 11. Trajectory Showing Parachute Deployment Conditions and Allowable Inflation Conditions

Table 2. MAR Sizing Summary

Parameter	Value
Mortar Diameter	0.079 m
Mortar Length	0.20 m
Mortar Mass (structure and fittings)	2.27 kg
Drogue + Pilot + Cabling Mass	0.55 kg
Drogue Diameter	2.40 m
Drogue C_D	0.58
Parafoil Mass	4.68 kg
Parafoil Pack Volume	0.0081 m^3
Parafoil Canopy Area	22.50 m^2
Parafoil C_D	0.30
Total MAR System Mass	**7.49 kg**

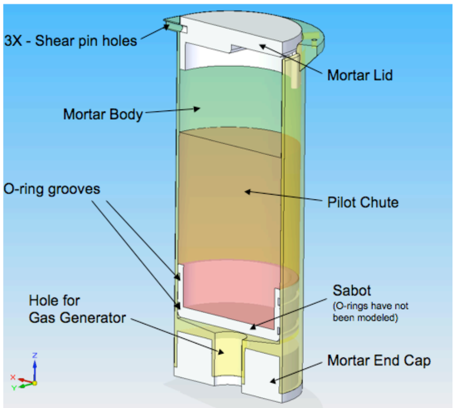


Figure 12. Mortar Assembly with Pilot and Drogue

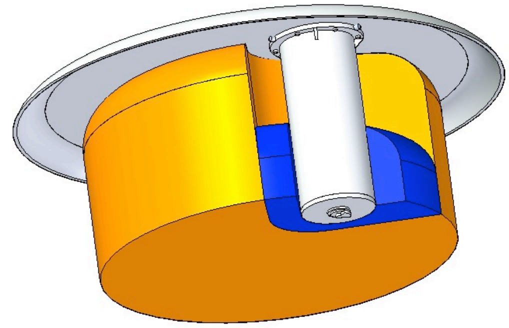


Figure 13. Mortar and Parafoil Integrated into Aftbody

Triggers and Mechanisms

The parachute deployment sequence is triggered by an inertia/acceleration switch. The switch is calibrated to open after peak loading occurs at burn + 19.9 minutes.   The switch itself is custom-made based on required sensitivity levels and the desired contact state derived from the nominal trajectory. In order to mitigate the risk of a single-point EDL failure in the acceleration switch design, redundancy is built into the recovery system software to release the drogue parachute in the event of acceleration switch failure, triggered by an onboard mechanical timer.

Recovery Operations

The landing site originally planned for Woomera, Australia was changed to UTTR when MAR was selected as the decelerator and recovery system for Mars Gravity Biosatellite. This was necessary to avoid the logistical problems associated with outfitting Australian helicopters with MAR equipment and costly foreign pilot licensure problems. The Vertigo recovery team is already familiar with UTTR procedures from experience gained working on the Genesis Sample Return and Stardust Sample Return recovery operations. Additionally, several radar and infrared payload tracking assets exist at UTTR that are essential for early detection of the entry vehicle.

The United States Strategic Command (USSTRATCOM) uses both classified and unclassified assets (designated System X) to track the entry vehicle and spacecraft bus prior to separation and throughout the upper atmosphere. STRATCOM assets are not the primary entry vehicle tracking method, but the real-time data flow is expected to significantly improve landing ellipse confidence during the descent from low Earth orbit. Weather balloons launched approximately one hour and eight hours before atmospheric entry will also help improve landing ellipse confidence by gathering the most current wind data. The Mission Control Center (MCC) located at Hill Air Force Base (AFB) is responsible for managing the tracking effort and relaying information to Recovery Command at the Michael Army Air Field (MAAF) at the Dugway Proving Grounds.

After traveling over 7000 km downrange of the location of the deorbit burn, the entry vehicle passes over the coast of California. At this time the tracking assets at UTTR positively identify the capsule. These assets include the High Accuracy Digital Instrumentation Radar (HADIR) and the Forward-Looking Infrared Radar (FLIR). Tracking data from all available assets are used during recovery operations. MCC is responsible for collecting and relaying data to Recovery Command so that vectors can be communicated to the retrieval helicopter pilots in real-time. This command flow is modeled after that used for the successful Stardust Sample Return recovery operation (depicted in Figure 14).

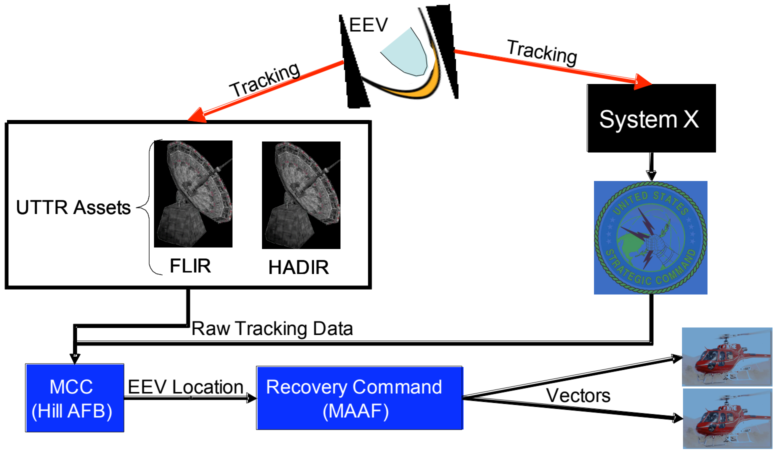


Figure 14. Data Flow During Recovery Operations

Two Eurocopter Astar 350-B2 helicopters outfitted with 3GMAR equipment perform the recovery. Only one helicopter is needed for retrieval, but two or possibly three will be present for redundancy and to cover the large landing ellipse. The primary retrieval helicopter must land and remove the parafoil after the pickup stage is complete before transporting the entry vehicle to the clean room at MAAF. Flight tests during Genesis have shown that it is a very slow process to fly directly to MAAF from the retrieval site due to challenges with carrying the combination entry vehicle and captured parafoil. The secondary helicopter lands first allowing flight personnel to assist in the descent of the primary helicopter. Once the entry vehicle has made contact and the primary helicopter has landed safely, the entry vehicle is secured to the primary helicopter with a single cable.

Astar 350-B2 helicopters are capable of cruising at 155 knots, but the acceptable cruise air speed from the retrieval site to MAAF is much lower in order to protect the science payload. This transport should not take longer than one hour assuming a safe airspeed less than 80 knots and a worst case direct course distance of 55 nautical miles. Due to the visual nature of 3GMAR, daytime visual flight rules weather conditions are required to insure a successful recovery. The mission operations must be timed such that recovery occurs during the season when weather in Utah is most favorable for VFR flight operations.

The Vertigo MAR team is responsible for the safe transport of the entry vehicle to a temporary clean room located at Recovery Command on MAAF. This is where the science team performs any critical operations within 2-4 hours of retrieval to protect the integrity of the science payload. Once these critical operations have terminated, the science payload is transported to a proper science facility at a location to be determined. The aeroshell and PTS are also transported to a post-processing facility for analysis and assistance with trajectory reconstruction.

8.0 Break-up Analysis of Spacecraft Bus

With the entry vehicle and spacecraft bus beginning the de-orbit phase as a single spacecraft, the entry of the bus have been subject to a preliminary burn and break up analysis. The bus de-orbit analysis begins with the entry state immediately after separation of the bus from the entry vehicle. The trajectory for the entire bus is propagated to the ground with no break up to generate loading and heating profiles. These profiles, along with the material properties of the bus are used to estimate the point along the trajectory where the bus begins to break apart. The spacecraft bus, after completion of the nominal orbital mission and de-orbit burn is 251 kg with an aluminum honeycomb primary structure.

Once an estimate of the break up point is made, the trajectories for a sweep of ballistic coefficients (10 kg/m^2 to 1000 kg/m^2) are propagated to the ground. This gives an initial estimate of the debris field for any surviving components of the bus. The components expected to survive are propellant tanks, batteries, and avionics hardware, with all components landing safely in the Pacific Ocean. This preliminary analysis is still ongoing.

9.0 Educational Impact

Since 2001, more than 500 students have been involved with the Mars Gravity Biosatellite program, ranging from high school to post-doctorate levels of study [1]. These students have come from four partner institutions and both domestic and international internships. Mars Gravity is training engineers and scientists in technical design, systems engineering, and project management. While arguments exist for potentially more cost-effective ways to train spacecraft engineers, employers continue to preferentially hire students with spacecraft project experience [11].

The Mars Gravity Biosatellite program is unique among student spacecraft missions. By broad definition, Mars Gravity can be considered a "university-class" spacecraft, where the training of the students involved is as much a primary program goal as the mission itself. It is also "non-flagship", receiving no significant government sponsorship at this point in the program. With a mass of 625 kg at launch, the biosatellite is more than six times heavier than any other university-class mission of the past 20 years [11]. Additionally, most university-class spacecraft lack a true payload; the spacecraft's purpose is either to return its own telemetry or an instrument package has been selected just to have one on-board [11]. In contrast, the Mars Gravity design is strongly driven by its science mission, requiring an independent payload design and interfaces across the payload, spacecraft bus, and EDL systems. Mars Gravity must also execute a full atmospheric entry from low Earth orbit, a rare requirement among student spacecraft.

Historically, it has been difficult for university-class spacecraft to significantly impact the spacecraft industry. Limited development time within the academic cycle, the expense of space-qualified hardware, and the training of student personnel all contribute to this difficulty [12]. To surmount these challenges, the Mars Gravity program has teamed with advisors in academic, industry, and government and is designed using spaceflight-proven hardware where possible.

Perhaps the most effective way for education-based spacecraft development programs to contribute to the evolution of the space industry is by building research platforms for high-risk/high-return missions [12]. The Mars Gravity Biosatellite mission is driven by the need for partial gravity science and also the need for a platform to perform such science. Beyond training and inspiring a new generation of space scientists and engineers, the educational impact of the Mars Gravity program is in laying the groundwork for future science-driven student missions and collaborative education by demonstrating the ability of universities to simultaneously educate and perform science-driven space systems engineering activities [1].

10.0 Concluding Remarks

The Mars Gravity Biosatellite is a student-led, student-developed spacecraft aimed at providing data on the effects of partial gravity on mammalian physiology after a 35-day mission in low Earth orbit at simulated Martian surface gravity environment. Successful completion of the science mission requires entry, descent, and landing to recover the payload for post-flight study. The EDL design is driven by strict requirements on the allowable severity of the deceleration environment and maximum recovery time. A ballistic entry from 325 km delivers the payload to the target recovery site at UTTR. Heritage systems such as the Discoverer aeroshell, PICA TPS, and mid-air retrieval have been integrated into the design. The mass breakdown is given in Table 3. The total EDL system mass is 109.15 kg (allocation 119 kg), including an 8% wiring margin.

Table 3. EDL Subsystem Mass Breakdown

	Component	Units	Unit Mass (kg)	Total Mass (kg)	Margin	Total Mass (kg), with Margin
Structure				**46.47**		**55.05**
	Aeroshell aftbody	1	12.92	12.92	25%	16.15
	Aeroshell forebody	1	11.09	11.09	25%	13.86
	Parachute cover	1	0.5	0.5	25%	0.63
	Aeroshell bolts	4	0.18	0.72	20%	0.86
	Shear pin	3	0.08	0.24	25%	0.30
	O-Ring	4	0.25	1	25%	1.25
	Ballast	1	20	20	10%	22.00
Avionics				**0.5**		**0.63**
	Mechanical Timer	1	0.5	0.5	25%	0.63
Entry				**30.32**		**36.38**
	TPS carrier structure	1	6.4	6.4	20%	7.68
	TPS insulation	1	0	0	20%	0.00
	Forebody TPS	1	20.2	20.2	20%	24.24
	Aftbody TPS	1	3.4	3.4	20%	4.08
	TPS pyrobolts	4	0.08	0.32	20%	0.38
Descent				**7.5**		**9.00**
	Pilot-drogue-cable	1	0.55	0.55	20%	0.66
	Mortar	1	2.27	2.27	20%	2.72
	Parafoil MAR	1	4.68	4.68	20%	5.62

The Mars Gravity Biosatellite is a student-developed, free-flyer spacecraft designed to support a payload of 15 mice for 35 days in low Earth orbit while rotating to simulate Martian surface accelerations. The data collected on the effects of partial gravity on mammalian physiology will be the first of its kind and contribute significantly to the knowledge required to enable successful exploration of the Moon and Mars. The Mars Gravity Biosatellite program is both an affordable and a meaningful investment in the future that will:

1. Help establish whether Mars-level artificial gravity can serve as an effective countermeasure for mammals against the physiological deterioration that accompanies long-duration spaceflight in microgravity.
2. Validate a low-mass artificial gravity spacecraft and life support system to support future missions.
3. Educate and excite students about real-world aerospace endeavors, providing training and inspiration for the next generation of STEM professionals.

11.0 References

1. Korzun, A.M., Braun, R.D., Wagner, E.B., Fulford-Jones, T.R.F., Deems, E.C., Judnick, D.C., Keesee, J.E., “Mars Gravity Biosatellite: Engineering, Science, and Education,” IAC-07-A1.9-A2.7.05, 58th International Astronautical Congress, Hyderabad, India, September 2007.

2. Science Development and Integration Plan, Mars Gravity PDR Documentation, June 2007, available upon request.

3. Wood, W.A., Gnoffo, P.A., Rault, D.F.G., “Aerothermodynamic Analysis of Commercial Experiment Transporter (COMET) Reentry Capsule”, AIAA Paper 96-0316, 34th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 2006.

4. Desai, P.N., Braun, R.D., Powell, R.W., Engelund, W.C., Tartabini, P.V., “Six-Degree-of-Freedom Entry Dispersion Analysis for the METEOR Recovery Module”, Journal of Spacecraft and Rockets, Vol. 34, No. 3, May-June 1997.

5. Desai, P.N., Lyons, D.T., “Entry, Descent, and Landing Operations Analysis for the Genesis Entry Capsule,” Journal of Spacecraft and Rockets, Vol. 45, No. 1, January-February 2008, p. 27-32.

6. Johnson, C.E., Tran, H.K., Smith, M., Dill, H., “Stardust Backshell and Back Interface Plate Design Verification Tests in the NASA Ames Arc Jet Facilities, AIAA, 1997.

7. Jorgenson, D.S., Haggard, R.A., Brown G.J., “The Past, Present, and Future of Mid-Air Retrieval,” AIAA 18th Aerodynamic Decelerator Systems Technology Conference and Seminar, AIAA 2005-1676.

8. “Sample Return Primer & Handbook,” JPL D-37294, January 2007.

9. “Recovery Systems Design Guide,” Irvin Industries Inc., Technical Report AFFDL-TR-78-151, 1978.

10. Prakash, O., Daftary, A., Ananthkrishnan, N., "Trim and Stability Analysis of Parafoil/Payload System using Bifurcation Methods," AIAA 18th Aerodynamic Decelerator Systems Technology Conference and Seminar, AIAA 2005-1666.

11. Swartwout, M., “Twenty (plus) Years of University-Class Spacecraft: A Review of What Was, an Understanding of What is, and a Look at What Should be Next”, SSC06-I-3, August 2006.

12. Swartwout, M., “University-Class Satellites: From Marginal Utility to ‘Disruptive’ Research Platforms”, SSC04-II-5, August 2004.