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MARS GRAVITY BIOSATELLITE: ENGINEERING, SCIENCE, AND EDUCATION

Ashley M. Korzun, Robert D. Braun
Georgia Institute of Technology, United States
akorzun@gatech.edu, robert.braun@aerospace.gatech.edu

Erika B. Wagner, Thaddeus R.F. Fulford-Jones, Elizabeth C. Deems, Daniel C. Judnick, John E. Keesee
Massachusetts Institute of Technology, United States
info@marsgravity.org

ABSTRACT

The Mars Gravity Biosatellite is a novel program aimed at providing data on the effects of partial gravity on mammalian physiology. Physiological problems intrinsic to prolonged stays in microgravity have long been concerns of manned spaceflight and will continue to be a significant obstacle in achieving the goals outlined in NASA's Vision for Space Exploration. This student-developed, free-flyer spacecraft is designed to carry a payload of 15 mice into low Earth orbit, rotating to generate an acceleration environment equivalent to Martian gravity. After 35 days, the payload will be de-orbited and recovered for study. Data collected during the mission and post-recovery will be used to characterize the physiological changes incurred under partial gravity conditions and validate the models used in designing the spacecraft. This paper presents the preliminary design of the spacecraft. By providing groundbreaking flight data on the effects of partial gravity on mammalian physiology and engaging over 500 students to date, the Mars Gravity Biosatellite program is working to enable successful human exploration of the Moon and Mars while training and inspiring a new generation of scientists and engineers.

INTRODUCTION

A demonstrated need exists for free-flyer platforms on which to conduct supporting science. Furthermore, the National Academies report *Rising above the Gathering Storm* and additional studies demonstrate the US is falling critically behind in inspiring and educating students for careers in science, technology, engineering, and mathematics (STEM) fields [1].

Since 2001, the Mars Gravity Biosatellite program (MGB) has engaged hundreds of students, from high school through graduate-level studies. Together with advisors in academia, government, and industry, the team has made significant progress in designing, modeling, prototyping, and managing the development of a new free-flyer spacecraft. The novel satellite platform offers an uncrewed laboratory for artificial gravity research, supporting biological payloads of up to 15 mice for missions as long as five weeks in duration, with the capability of returning the payload safely to Earth for analysis.

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.

Planned to launch in the 2010-2011 timeframe, the spacecraft will house 15 mice in LEO for a five week flight. In a spin-stabilized mode, the satellite will provide artificial gravity at 0.38-g, simulating the acceleration environment on the surface of Mars. After 35 days of data collection, the spacecraft will enter the Earth's 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 scientific investigations. This mission will be longest self-contained biosatellite flight to date.

As the first study of mammalian physiology in partial gravity, the inaugural flight of the biosatellite will focus on broad, hypothesis-driven investigations. This peer-reviewed research will include characterization of musculoskeletal degradation, alterations of vestibular reflexes, and downregulation of the immune response.

Beyond basic science, MGB represents a uniquely affordable platform for quantifying risks and testing hypotheses related to NASA's exploration vision [2]. Sized for launch on the SpaceX Falcon I, total mission costs are estimated near $40M. This low-cost endeavour qualifies the spacecraft as both a desirable and unique American capability, as well as an extensive educational enterprise. Current efforts represent collaboration between the Massachusetts Institute of Technology and the Georgia Institute of Technology. MIT leads the science, payload, bus, and systems engineering efforts, and Georgia Tech leads the entry, descent, and landing (EDL) and recovery operations development [3].

SPACECRAFT OVERVIEW

The Mars Gravity Biosatellite is comprised of three major systems: 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 an 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. Detailed discussion of each system is given in the respective preliminary design sections.

MGB 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.

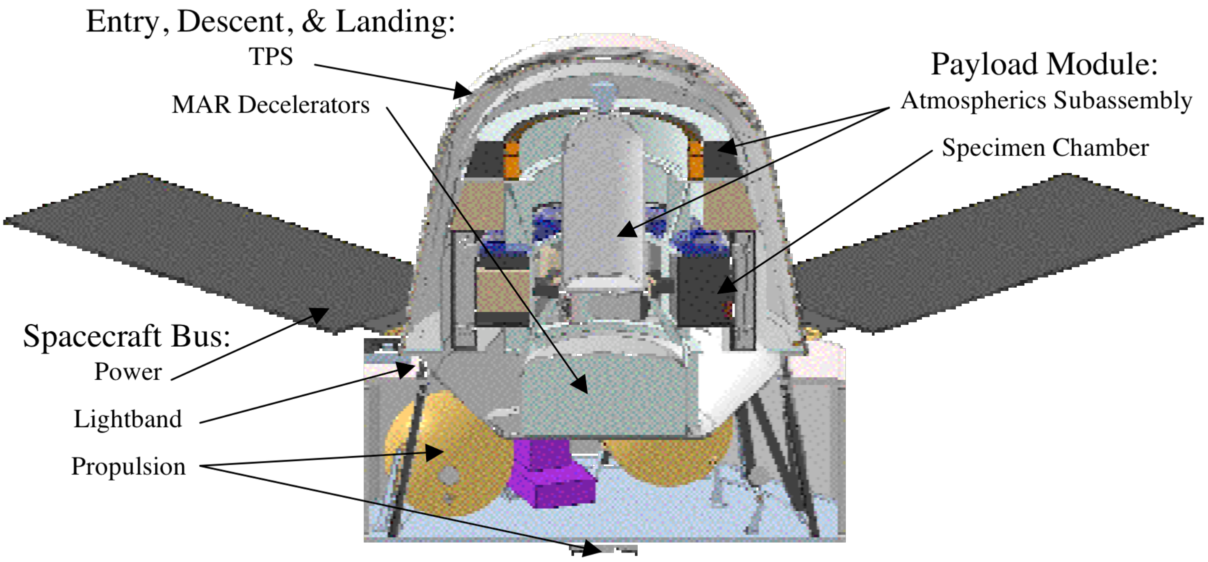

Figure 1: Spacecraft Cut-away

The EDL element includes the hardware and software for protecting and decelerating the payload during atmospheric entry and subsequent recovery by mid-air retrieval. Specific hardware includes the Discoverer aeroshell, drogue chute and main parafoil for mid-air retrieval (MAR), and thermal protection system (TPS).

YNIS includes the decalcomania on the interior and exterior of the spacecraft, cameras to image all exterior artwork, support structure for each camera, and associated computer hardware for processing. Primary activation for this system is scheduled during the first 24-48 hours following spacecraft check-out and spin-up to the nominal rotation rate.

CONCEPT OF OPERATIONS

Baseline mission operations for the Mars Gravity Biosatellite begin with integration of flight hardware elements at a central facility of the mission's lead industrial partner. Following integrated testing, the system will be shipped to the launch site for animal load-in, final testing, fueling, and launch vehicle integration. The pre-launch phase is designed to take no longer than 7 days (with margin). MGB is planned as a primary payload the SpaceX Falcon IE and is also sized to fit on the Minotaur IV. The planned launch site is at Cape Canaveral, Florida.

Upon completion of orbit insertion, the spacecraft is initially 3-axis-stabilized using a hydrazine monopropellant system. The vehicle will spin up to approximately 32 rpm, providing 0.38-g of artificial gravity outwards against the curved floors of the specimen chambers. Once the spacecraft is checked out and stable, the exterior YNIS cameras will acquire images for donors, and the communication subsystem will downlink them to the ground.

Over the next five weeks, the spacecraft will largely operate autonomously, with minimal orbital maintenance or attitude control maneuvers. S-band communication with commercial ground stations will occur at least once every 8.5 hours to monitor the system and animals, as well as downlink telemetry, images, and video footage, and upload software patches as needed. Data will be distributed via secure internet protocols to a Mission Control Center at MIT and to other distributed science users.

On mission day 35, a command from the ground will initialize the entry sequence. Hydrazine thrusters will spin down, reorient, and spin up the spacecraft for its primary de-orbit maneuver. The bus will separate from the entry vehicle, de-orbiting separately to burn up over the Pacific Ocean. Through the EDL sequence, payload batteries will provide power for life support, data collection, and tracking systems. A supersonic drogue chute will decelerate and stabilize the vehicle through the transonic flight regime, then deploy the main parafoil. Helicopters will execute a mid-air recovery at UTTR, then fly the payload to a designated Science Operations Facility.

Within two hours of recovery, the vehicle will be safed, animal habitats will be extracted, and mice will be delivered to a team of PIs for *in vivo* measurements, followed by dissection. Primary PIs will gain access to core science samples, and remaining specimens will be preserved for use through a Biospecimen Sharing Program. Similar operational recovery timelines have been planned for past missions including Genesis and METEOR. The nominal mission phases and durations for pre-launch through post-flight recovery are given in Table 1.

Phase	Time	Description
Pre-Launch	7 days	Integration of mice into flight habitats
Launch	9.5 minutes	LV ignition through orbital insertion
Transition	10 minutes	Separation of LV-S/C, deployment, and spin-up
Orbit	35 days	Nominal cruise, post-spin-up
De-orbit	103 minutes	Spin-down, reorientation, spin-up, de-orbit maneuvers, separation of bus and EV
EDL	36.5 minutes	Atmospheric entry, descent, and capture
Recovery	76.6 minutes	Post-capture transfer of payload to science facilities
Post-flight	1 day	Post-flight operations following delivery to science facilities

Table 1: Nominal Mission Phases and Durations

SCIENCE 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 [4].

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 [4]. 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 [4].
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.

PAYLOAD PRELIMINARY DESIGN

The payload module serves to provide all life support and scientific data acquisition functions for the spacecraft, individually housing and supporting 15 mice over the nominal mission duration. All subsystems are contained within a pressurized aeroshell, with interfaces for thermal, power, and data to the spacecraft bus. The payload is divided into the following subsystems: environmental control, specimen chambers, thermal control, command and data handling, and sensor and data collection.

Environmental Control

The environmental control subsystem is responsible for regulating the quality of the air inside the payload volume, removing contaminants from the air and maintaining flow rate and oxygen levels. The atmospheric compounds that must be removed from the air include carbon dioxide and ammonia, as well as trace contaminants. Carbon dioxide is caused by rodent respiration and is toxic to mice in high concentrations. Ammonia buildup is a common cause of rodent health problems in laboratory conditions and is one of the core drivers for increased facility-wide air exchange rates. The payload is pressurized to 1 atm, and the temperature is maintained between 18°C and 28°C, in accordance with laboratory animal care and use guidelines.

The baseline design of the atmospheric subsystem uses a lithium hydroxide (LiOH) cannister to remove carbon dioxide, an active carbon bed to eliminate trace gases such as ammonia and methane, and a silica gel canister/condensing heat exchanger hybrid system to control humidity. The current design calls for two separate systems, which are linked through the common air volume within the payload module. The first loop performs air distribution, contaminant sensing, oxygen replenishment, and thermal control. The second loop cleanses contaminants from the air. A condensing heat exchanger is currently under evaluation as a possible addition to the baseline design. A more extensive discussion of the environmental control design can be found in References [5] and [6].

Specimen Chambers

The payload contains 15 independent specimen chambers, each equipped with a waste management system and consumables. The habitats are constructed of thermoformed polycarbonate and cold-pour urethane and have proven capable of withstanding chewing and other mouse abuse over the nominal mission duration. They include integrated launch and orbital mission floor spaces, with interfaces for lighting, video, and habitat sensors and control. The specimen chamber, including waste management and consumables is shown in Figure 2.

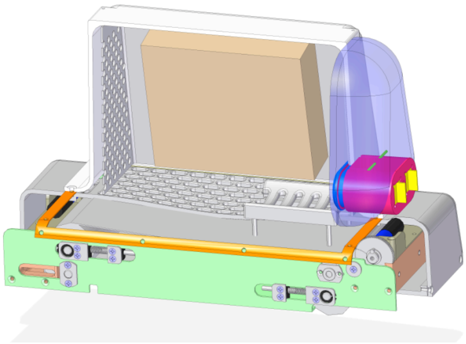

Figure 2: Specimen Habitat (Gravity Vector Down)

A five week mission requires the removal of animal wastes from the specimen chamber in order to maintain proper sanitation. The hardware design depends on artificial gravity causing a directional flow of waste, assisted by the directional airflow through the specimen chamber, from top to bottom. In order to conduct a time sensitive study, attached motors will periodically advance sets of rollers in order to provide clean absorbent membranes and plastic mesh beneath the floor of the specimen chamber. Collection of waste throughout the mission will be used post-flight for identification of urinary chemical markers that indicate bone turnover, bone density loss, muscle wasting, and stress, providing insight into the relation of changes in the mammalian skeletal and muscular systems to time spent in partial gravity.

The payload module consumables include food and water. The baseline food substrate is NASA's Nutrient Upgrade 12D Rodent Food Bar. These food bars remain edible and free from pathogenic bacteria for the nominal mission and pre-launch phases [5]. Dehydration of the food bars is not excessive, and mice fed on these bars for five weeks show good maintenance of body weight when compared with control animals. Water is supplied through two lixit valves which protrude through the wall of the specimen chamber. Bone additive (necessary for post-flight scientific data acquisition) is given to the animals on two pre-programmed occasions during the mission [5].

Thermal Control

Heat will be generated from several components within the payload volume, totaling approximately 80 W during normal operation. As the thermal protection system on the exterior of the spacecraft insulates the payload, this heat must be removed through an alternative path. The primary heat sources are the main computer, mice, and atmospherics (LiOH / CO_2 removal). Thermal distribution within the payload module has heat concentrated along the rotational axis. This is due to the cooler, denser air moving towards the periphery as the spacecraft is spinning [5].

The removal of this heat, given the centrally concentrated thermal distribution, is accomplished by transferring the heat to the bus through the Lightband connector, where it is radiated out through the bus and into vacuum. The Lightband (Planetary Systems) is a metal connection ring used for separation of the EV and bus for entry and also as a multipurpose mechanical, electrical, thermal, and data transfer interface [5]. The Lightband is the only direct connection between the payload module and bus, making it a natural heat conduction path. The thermal resistivity of the Lightband is 0.05 ^{o}C/W.

The design for the thermal system includes 11 fans placed on 11 heat sinks [7]. One thermoelectric cooler (TEC) will be placed underneath each of 6 of the fan/heat sink units. It has been shown through experimentation that fans and heat sinks alone will not sufficiently cool the payload volume, and the TECs provide the necessary additional cooling capacity. All of these units, with or without TECs, are placed in contact with the baseplate to improve heat transfer efficiency to the Lightband. The airflow within the mockup has been experimentally verified, and the data has been used to construct models of the airflow within the payload module. Fan location has been optimized, subject to both constraints in thermal flow as well as the data from the mockup experiments [5]. A more detailed discussion of the thermal control system can be found in References [5] and [8].

Sensors

The payload sensor suite contains six primary sensors: pressure, CO_2, temperature and humidity, ammonia, oxygen, and airflow. In addition to readability range, the specific sensors were chosen based on resolution, response time, acceptable long term drift, low weight, and low power consumption. The specific performance characteristics and associated software and data handling schemes can be found in Reference [5].

SPACECRAFT BUS PRELIMINARY DESIGN

The spacecraft bus is responsible for supporting the payload and EDL systems during launch, orbit, and de-orbit procedures through the basic functionalities of power, structures, thermal control, attitude determination and control, propulsion, guidance and navigation, command

and data handling, and communications. The bus also separates from the EV for payload return and is destroyed during its own subsequent entry. The total mass allocation for the bus is 217 kg out of the 625 kg total spacecraft wet mass. Significant additional detail on the design and analysis of each of the bus subsystems is provided in References [9] - [17].

Structure

The purpose of the structures subsystem is to maintain structural integrity, provide a mounting point for all the other subsystems, support the payload during launch, and act as a thermal conduit for heat from the payload. The bus is an aluminum octagonal structure with a supporting plate for the entry vehicle and a base plate, as seen in Figure 3. The side panels include stiffeners designed to carry launch loads, and corner beams join the side panels together and attach the EV and base plates. Internal supports prevent deflection of the EV plate during launch. The solar panels are stowed such that the panel is folded downward during launch [10].

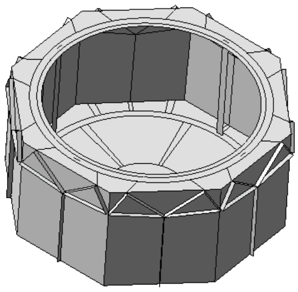

Figure 3: Bus Structure

Thermal Control

The thermal control subsystem maintains temperatures in the bus such that all components are within their thermal operational limits and also ensures removal of excess heat from the payload through the bus, as discussed in the payload preliminary design section. The outside of the bus is painted such that the structures have high emissivity and low absorptivity. Multi-layer insulation is used on the side panels to insulate internal components and tanks. Additionally, K-min boards and patch and line heaters are used for further component insulation, particularly for temperature-sensitive components. The thermal environment is monitored with resistor temperature detectors (RTDs). Thermal switches are mounted with the heaters and sensors to turn the heaters off and on when setpoints are reached. The combination of heaters, paints, and insulation allows for proper radiation of excess payload heat away from the spacecraft [11].

Power

The power subsystem provides power to the entire spacecraft until the point of bus-EV separation. In conjunction with generating power, the subsystem also stores, controls, and distributes power. Four improved triple junction gallium arsenide (GaAs) solar arrays deployed around the bus exterior provide a minimum of 330 W at all times, providing the spacecraft with the minimum 180 W required for nominal operation. Excess power generated from the panels is stored in on-board Li-ion batteries. The bus is regulated at 12.5 V. PMAD functionality is handled by a peak power tracker and converter. Other attributes of the power system are the cabling, switches, fault detection, fault protection and isolation, and decoders [12].

Attitude Determination and Control

The attitude determination and control subsystem (ADCS) is responsible for spin-up, spin-down, sun seek, and preparations for both the EV and bus de-orbit maneuvers using the propulsion system. There is no requirement for orbit maintenance, and no disturbance corrections are planned over the nominal mission duration.

Coarse sun sensors are used during the sun-seek sequence to locate the sun and begin filter convergence, while a finer resolution sun sensor determines the precise pointing of the spacecraft. The magnetometer provides supplemental orientation information, such that a unique orientation can be identified from the sun sensor data. Rate gyroscopes measure the angular velocity of the vehicle, both for ADCS calculations and science data. Twelve ADCS thrusters are used to control attitude throughout the mission. These components are also used for de-orbit [13].

Propulsion

The propulsion subsystem is responsible for providing the thrust to keep the spacecraft in the desired attitude with the necessary spin rate and also to de-orbit the spacecraft. The bus has a hydrazine monopropellant system for both attitude control and de-orbit maneuvers. The average specific impulse of the system is 213 seconds. In addition to the ADCS thrusters, one main de-orbit thruster is mounted on the aft of the bus. A nitrogen blow-down system provides the pressurant for the monopropellant. A fluidic, multi-port valve is used for the propellant, while two 2-port pneumatic valves are used with the pressurant. Table 2 gives an overview of the available ΔV (with margin) in the propulsion system [14].

Event	ΔV (m/s)
ADCS	7.3
RV De-orbit	204
Bus De-orbit	10.2
Orbit Corrections	10.2
Total	231.7

Table 2: ΔV Budget

Guidance, Navigation, and Control

The guidance, navigation, and control (GNC) subsystem monitors the orbit and commands any necessary trajectory changes throughout the MGB mission. After orbital insertion by the launch vehicle, GNC monitors the spacecraft orbital elements using data from the Global Positioning System (GPS), obtained with an onboard antenna and receiver. The mission orbit (41°, 370 km circular) was selected from an extensive study of orbits and requires no planned orbit adjustment over the nominal mission duration to maintain a given resonance. Hard constraints in this analysis included range safety, orbit lifetime, maximum altitude benefit limit, and landing site location. Additional influencing factors were launch vehicle insertion uncertainty, altitude loss, downlink opportunities, radiation, eclipse time, thermal conditions, and radar coverage [15]. Treatment was also given to the impact of near solar maximum in the mission window of 2010-2011.

GNC hardware components include the GPS receiver (sensor) monopropellant thrusters (actuator) and computer and software for navigation. GPS was selected over SGP4 orbit propagation to reduce error margins within the model and to maintain accuracy over long periods with no ground station contact. The monopropellant thrusters are part of the ACDS and propulsion subsystems. These components are also utilized to de-orbit the spacecraft and have the capacity to be ground-controlled [15].

Communication

The communications subsystem (or telemetry, tracking, and command) provides the link from the ground stations to the spacecraft for the purpose of command and data relay and for providing a means of performing anomaly resolution. For this functionality, the communications subsystem provides a near-omnidirectional field of view, and both the primary and redundant command receivers remain active at all times.

The spacecraft communicates via a commercial ground network on an S-band patch antenna with QPSK modulation. A transponder is used for receiving and transmitting data at 2.3 MHz and 197 kbps. The spacecraft must communicate at least four times a day and at least every 8.5 hours to meet science needs. This architecture satisfies these requirements as well as the requirement for transmitting 127.4MB per day [16].

Command and Data Handling

The command and data handling (C&DH) subsystem serves as the processing unit of the spacecraft, interfacing with the other subsystems through data buses. Through these interactions, C&DH is primarily responsible for two functions: the receipt and distribution of commands and the collection, formatting, and distribution of telemetry. A systems-level study determined the bus will be run from microcontrollers, with the main computer in the payload. The bus has four microcontrollers: general bus functionality, propulsion/ADCS/GNC, thermal, and communications. These microcontrollers will be programmed to perform all necessary bus functions but will not provide long-term data storage. Data requiring long-term storage will be transferred to and from the payload [17].

EDL PRELIMINARY DESIGN

The EDL system's primary responsibilities are the safe de-orbit and recovery of the payload at UTTR and the de-orbit of the spacecraft bus over the Pacific Ocean. System elements include trajectory design, aeroshell configuration, thermal protection system (TPS), aerodynamic decelerators, recovery operations, and bus de-orbit.

The EDL design is driven by science requirements on acceleration loading and recovery time. Science requirements dictate limits on time spent in microgravity, time spent in 1g, and the total time between recovery and full access to the payload at the Science Operations Facility. The impact of these requirements is included with the nominal trajectory discussion.

EDL Timeline

The EDL sequence begins with the ground command sent to the spacecraft to initiate de-orbit and ends with the entry vehicle being delivered to the designated Science Operations Facility. The nominal sequence and timeline are given in Table 3.

Time (min)	Altitude (km)	Event
0	325	Primary de-orbit burn
11.1	225	EV jettisoned from bus
22.2	125	EV reaches atm. interface
24.7	54	Peak heat rate
25	45	Enter UTTR airspace
25.2	40	Peak deceleration
26.2	24	Drogue chute deployed
26.9	19	Parafoil deployed
27.3	19	Heatshield jettisoned
47.6	3	EV captured
54.1	0	EV landed
124.2	0	EV at science facility

Table 3: EDL Sequence and Timeline

The event times and altitudes are similar to the nominal trajectory and mid-air retrieval (MAR) data operations for Genesis [18], [19]. The HH-3 helicopters used for MAR have top speeds near 240 km/s with no vehicle in tow [18]. From discussions with Vertigo and Genesis test data, the helicopter was assumed to be capable of flying at 120 km/hr with the EV in tow [20]. The Science Operations Facility is currently baselined from 80 to 120 km away from the landing ellipse in the Utah Test and Training Range (UTTR), resulting in an average transit time from UTTR of 50 minutes. Total time spent in 1g is 97 minutes. The total time required for the EDL sequence, from de-orbit burn to delivery of the payload to the Science Operations Facility, is 124 minutes.

Nominal EV Trajectory

The nominal entry trajectory for MGB is a ballistic entry. The choice of a ballistic entry reflects a preference for simplicity (no active control system required on the EV). With no lift, the EV must be spun up to a nominal rotation rate to cancel out any lift generated from perturbations to the orientation of the EV relative to the 0º trim angle of attack. The nominal trajectory targets the same landing site in UTTR as the Stardust mission: 40.32ºN, 246.55ºE. All trajectory analysis was performed using the Program to Optimize Simulated Trajectories (POST).

The primary de-orbit maneuver for the spacecraft is performed by the bus, with a ΔV of 200 m/s from an altitude of 325 km. Higher ΔV's translate to smaller landing footprints and shorter recovery times, while lower ΔV's result in lower heat rates, smaller parachute diameters, and less required propellant mass. A range of entry trajectories was completed using POST, varying the de-orbit ΔV between 100 m/s and 450 m/s. The amount of reduction in the maximum footprint diameter levels off near 200 m/s, after which little appreciable change in maximum footprint diameter is seen for large increases in de-orbit ΔV, corresponding to the selection of a 200 m/s nominal de-orbit ΔV [20].

The definition of the nominal entry trajectory is constrained by science requirements on the duration and magnitude of the deceleration environment. The steepest ballistic entry that does not exceed the g-load requirements has an entry flight path angle of -3.45°. Shallower entry flight path angles result in larger landing errors than desired to meet recovery time constraints. The dispersions used in a first-order Monte Carlo analysis to quantify the worst-case landing error are given in Table 4, and the corresponding landing error ellipse is given in Figure 4.

Parameter	Dispersion
Atmospheric Density	+/- 30%
EV Mass	+/- 10%
Drag Coefficient	+/- 4%
Altitude at Periapsis	+/- 1%
De-Orbit ΔV	+/- 1%
Orbital Elements	+/- 0.05%

Table 4: Monte Carlo Dispersions

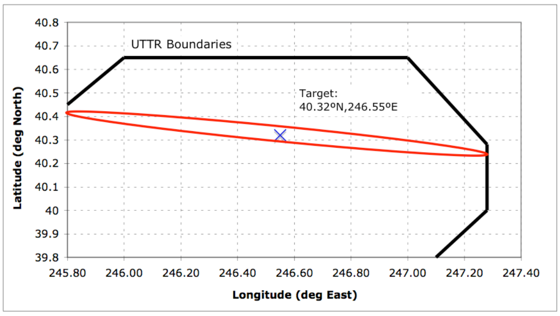

Figure 4: Nominal Landing Footprint (-3.45° Entry Flight Path Angle)

Entry Vehicle Configuration

The Discoverer entry body geometry is the baseline shape for the MGB entry vehicle. This configuration has Earth-entry heritage from the Corona program. Additionally, the shape is known for static aerodynamic stability across a wide range of flight conditions [20], [21], [22]. Scaling the diameter of the EV to fit within the Falcon 1E launch vehicle and comparing interior volume, the Discoverer provides 60% more interior volume than the Genesis or Stardust sphere-cones of equal diameter [20].

Thermal Protection System (TPS)

The TPS was sized using the Planetary Entry Systems Synthesis Tool (PESST, developed at Georgia Tech) and POST trajectory data [23]. The baseline TPS material is PICA, sized to mitigate the stagnation-point heating. 10% was added to the predicted shoulder heat rate, and aftbody heating was scaled from Stardust data [24]. While radiative heating was a significant contributor to the total heating for Stardust (~10-15%), radiating heating has been assumed to be negligible for the lower entry velocity for MGB [24]. The heating and sizing are summarized in Table 5 below.

Material	PICA
Peak Stagnation Point Convective Heat Rate (W/cm^2)	159.4
Total Integrated Heat Load (J/cm^2)	10114
Required Thickness (cm)	5.413
Mass (kg)	19.48

Table 5: TPS Summary

Mid-Air Retrieval

The aerodynamic decelerator and landing/recovery system for MGB has heritage from the mid-air retrieval (MAR) systems developed for UAV recoveries and Genesis. The MAR parachute system consists of a mortar-deployed Disk-Gap-Band (DGB) drogue chute and a flat bottom, low-speed airfoil for the main chute, or parafoil, deployed by the drogue chute. Maintaining consistency with the Genesis design, the parafoil has an aspect ratio of 2.8, 2:1 glide ratio, peak inflation load below 7 g's, a maximum inflation time of 20 seconds, and an average turn rate over 360° of less than 40 seconds [18]. Full sizing for the MGB MAR system was completed using a parachute system for a soft ground landing, and then the main parafoil dimensions were scaled from extensive Genesis test data [18]. The sizing correlation is shown in Figure 5, and the sizing summary is given in Table 6.

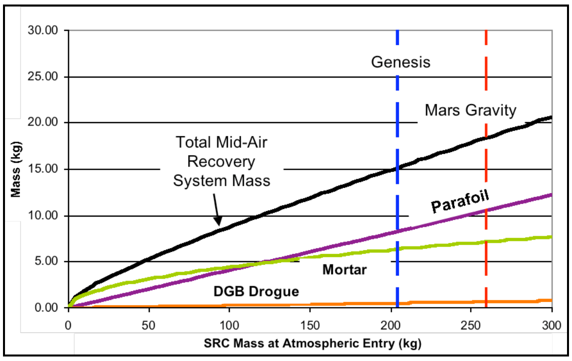

Figure 5: Mars Gravity / Genesis MAR Sizing Correlation (System Mass vs. Entry Mass)

MAR Characteristic	Size
Parafoil Area	39.70 m^2
Parafoil Mass	10.20 kg
Drogue Area	3.95 m^2
Drogue Mass	0.66 kg

Table 6: MAR System Sizing Summary

EDL Summary

The entire EDL sequence lasts 124 minutes, from the de-orbit maneuver through to delivery of the payload to the designated Science Operations Facility. The EDL system mass fraction of the EV is 0.41. Additional design rationale and discussion can be found in Reference [20].

YourNameIntoSpace (YNIS) PRELIMINARY DESIGN

YourNameIntoSpace (YNIS) is a novel microfinancing initiative of the Mars Gravity program aimed at funding the design and launch of the Mars Gravity Biosatellite through private donations. In exchange for donations, approved decalcomania (names, logos, photos, etc.) will be printed on the interior and exterior of the spacecraft. Exterior designs will be imaged by on-board cameras, and interior designs will be returned to donors upon completion of the mission and recovery of the EV. The system is designed to complete its primary operations during the first 24-48 hours following spacecraft spin-up.

Consultation with heatshield manufacturers and other satellite programs with exterior imaging has confirmed the feasibility of YNIS design requirements. Provided the ink/laminate is not permitted to soak into the heatshield material, any applied logos will ablate very early in the entry process, before potentially impacting TPS performance. Additionally, the selected latex-based ink/laminate will need to be compatible with the TPS material.

The YNIS cameras are mounted on the ends of the solar panels, each with an independent support structure to fix the camera to the tip. Data and power lines run the length of the solar panel, adjacent to the existing copper traces required for power management from each solar cell. The cameras are protected from the environment by bistem thermal shields, a series of aluminum Teflon blankets. Each blanket is secured around the entire YNIS camera system, exposing only the lens. This design is both lightweight and flexible, allowing for any changes in the camera design.

The camera CMOS chipset is already in use on a number of satellite missions and will be used for YNIS operations on MGB. This chipset has a resolution capacity of 640 x 480 and the capability to store up to 24 pictures at one time. Low mass, low power consumption, and automatic detection and correction of sensor defects are additional benefits to the chosen chipset. To satisfy a 5-megapixel requirement, four units of this CMOS chipset are placed in a quad formation to achieve CCD-equivalent performance.

The camera lens and lighting requirements are met using a Raman objective lens and xenon flashlamp. The lens can focus light from the ultraviolet (UV) to infrared (IR) wavelengths. The radiation environment the spacecraft will be exposed to will be nearly constant at low intensity during the duration of flight; this lens will not be adversely affected over the duration of operation. The lens selected is also resistant to thermal fluctuation. The xenon flash lighting will enhance image quality and can be easily synchronized with the cameras by the on-board computer system.

SYSTEMS ENGINEERING

The Mars Gravity Biosatellite program has a strong emphasis on systems engineering. The student-led systems engineering team has developed requirements, interface control documentation, mass and power margin policies, and plans for mission assurance, project implementation, and verification and validation. Interface control documentation has been written for the payload, spacecraft bus, EDL, YNIS, ground support, and launch vehicle. The flow of documentation is given in Figure 6.

Mass Summary

The current mass for each element is given in Table 7, including margins and allocations. MGB design margins are set at the component level and based on technology readiness levels. The definition of these levels and margin quantifications are given in Table 8. In addition to component-level margins, a global 15% launch mass margin is held in reserve to total 625 kg.

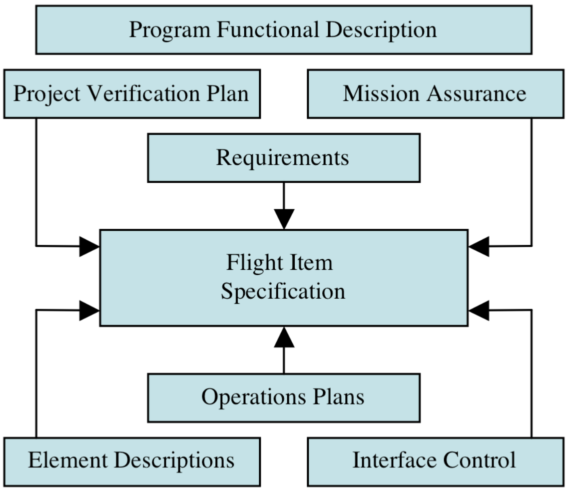

Figure 6: Documentation Flow

	Mass (kg)	Margin	Mass w/ Margin (kg)	Allocation (kg)
LV Capability			625	
LV Mass Margin		15%	93.75	
Allocation, S/C at Launch			531.25	
Payload	89.1	(at component level)	118.0	141
Bus	138.3	(at component level)	180.9	217
EDL	84.0	(at component level)	110.5	119
YNIS	13.2	(at component level)	18.0	34
LV Interface	15.0	30%	19.5	20
S/C at Launch	340.0		445.8	531
S/C in Flight	311.4		427.8	511
EV	173.1		227.4	260

Table 7: MGB Mass Summary

Level	Description	Payload / YNIS	Bus / EDL
1	Estimate	100%	50%
2	Calculation	35%	25%
3	Experimental	25%	20%
4	Working Prototype	15%	15%
5	Flight-ready	5%	5%

Table 8: Hardware Level Margin Definitions

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. These students have come from four partner institutions and both domestic and international internships. MGB 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 [25].

The Mars Gravity Biosatellite program is unique among student satellite missions. By broad definition, MGB 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, MGB is more than six times heavier than any other university-class mission of the past 20 years [25]. 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 [25]. In contrast, the MGB design is strongly driven by its science mission, requiring an independent payload design and interfaces across the payload, spacecraft bus, and EDL systems. MGB must also execute a full atmospheric entry from LEO, 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 [26]. To surmount these challenges, MGB 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 [26]. The MGB 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 Biosatellite 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.

CONCLUSIONS

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 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 and biomedical endeavors, providing a core training ground for the next generation of STEM professionals.

REFERENCES

[1] National Academy of Engineering. Engineering Research and America's Future: Meeting the Challenges of a Global Economy. Washington, D.C.: The National Academies Press, 2005.

[2] United States. National Aeronautics and Space Administration. The Vision for Space Exploration. Washington, D.C.: 2004.

[3] Program Executive Summary. Mars Gravity PDR Documentation, June 2007. Available upon request.

[4] Science Development and Integration Plan. Mars Gravity PDR Documentation, June 2007. Available upon request.

[5] Payload Element Functional Description and Requirements. MG PDR Documentation, June 2007. Available upon Request.

[6] Fulford-Jones, T., et al. "The Mars Gravity Biosatellite: Atmospheric Reconditioning Strategies for Extended-Duration Rodent Life Support." ICES 2007-01-3224, July 2007.

[7] Heafitz, A., et al. Thermal Test, 2004.

[8] Fulford-Jones, T., et al. "The Mars Gravity Biosatellite: Thermal Strategies for a Rotating Partial Gravity Spacecraft." ICES 2007-01-3078, July 2007.

[9] Bus Program Executive Summary. Mars Gravity PDR Documentation, June 2007. Available upon request.

[10] Bus Structures Subsystem Document. Mars Gravity Technical Documentation, May 2007. Available upon request.

[11] Thermal Subsystem Design Document. Mars Gravity Technical Documentation, May 2007. Available upon request.

[12] Power System Design Document. Mars Gravity Technical Documentation, May 2007. Available upon request.

[13] Attitude Determination and Control Subsystem. Mars Gravity Technical Documentation, May 2007. Available upon request.

[14] Propulsion System Design Document. Mars Gravity Technical Documentation, May 2007. Available upon request.

[15] Guidance, Navigation, and Control Subsystem. Mars Gravity Technical Documentation, May 2007. Available upon request.

[16] Communications Subsystem Design Document. Mars Gravity Technical Documentation, May 2007. Available upon request.

[17] Bus C&DH Commands and Telemetry. Mars Gravity Technical Documentation, May 2007. Available upon request.

[18] Brown, G., Haggard, R., Corwin, R., "Parafoil Mid-Air Retrieval for Space Sample Return Missions," AIAA 01-2018, May 2001.

[19] Vertigo, Inc. Personal Contact with Vertigo Business Managers and Designers. April 2007.
[20] EDL Element Functional Description and Requirements. MG PDR Documentation, June 2007. Available upon request.
[21] Desai, P., et al., "Six-Degree-of-Freedom Entry Dispersion Analysis for the METEOR Recovery Module," Journal of Spacecraft and Rockets, Vol. 34, No. 3, May-June 1997.
[22] Wood, W., Gnoffo, P., Rault, D., "Aerothermodynamic Analysis of Commercial Experimental Transporter (COMET) Reentry Capsule," AIAA 96-0316, January 1996.
[23] Dec, J., Braun, R., "An Approximate Ablative Thermal Protection System Sizing Tool for Entry System Design," AIAA 2006-780, January 2006.
[24] Olynick, D., "Aerothermodynamics of the Stardust Sample Return Capsule," AIAA 1998-167, January 1998.
[25] 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.
[26] Swartwout, M., "University-Class Satellites: From Marginal Utility to 'Disruptive' Research Platforms," SSC04-II-5, August 2004.