ASTROBOTIC
TECHNOLOGY, INC.

Lander & Rover
Payload User's Guide

Version 2.5

Foreword

Astrobotic Technology Inc. offers low-cost payload delivery to the lunar surface. Customers buy payload capacity by the kilogram, and standard services include integration, power, and communication. Customer's reservations are on a first-come basis with a deposit [1].

The lander is a single-stage spacecraft that lands with precision and generates 500W during sunlit periods. The rover is a data gatherer that traverses terrain at 15cm/s, mounts obstacles 25cm in diameter, and climbs 20 degree slopes. Nominal mission duration is 12 earth days. Extended mission duration is 90 earth days.

Figure 0-1: Mission manifest; Lander (Image left); Rover (Image right); Summary of payload services

Mission	Launch Date	Vehicle(s)	Landing Site	Payload
Moon Cruiser	Dec. 2013 to April 2014	Falcon 9 / Lander / Rover	An Apollo site or skylight entrance to lava tube	110 kg
Polar Excavator	July 2015	Falcon 9 / Lander / Rover	South Pole	110 kg
Customer Driven	Q3 2016	Falcon 9 / Lander / [***Rove***r]	*Customer Driven*	210 [***110***] kg
Actual launch dates and destinations are determined by customer demands; additional targets include lava tubes, circumnavigations, etc. Missions landing without a rover can deliver 210 kg of payload.				

Lander Payload
Mass: Up to 110 kg w/ rover; 210 kg w/o rover
Cost:[2] $1.8M/ kg
Power: 300 Whr per kg mass purchased (Additional watt-hour is $300 / Whr)
Comm: 100 MB per kg mass purchased (Additional megabyte is $2K / MB)

Rover Payload
Mass: Up to 110 kg
Cost:[2] $2M / kg
Power: 150 Whr per kg mass purchased (Additional watt-hour is $600 / Whr)
Comm: 50 MB per kg mass purchased (Additional megabyte is $4K / MB)

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[1] More information on pricing for payload services appears in Section 6: Pricing

[2] Pricing valid through December 31, 2011

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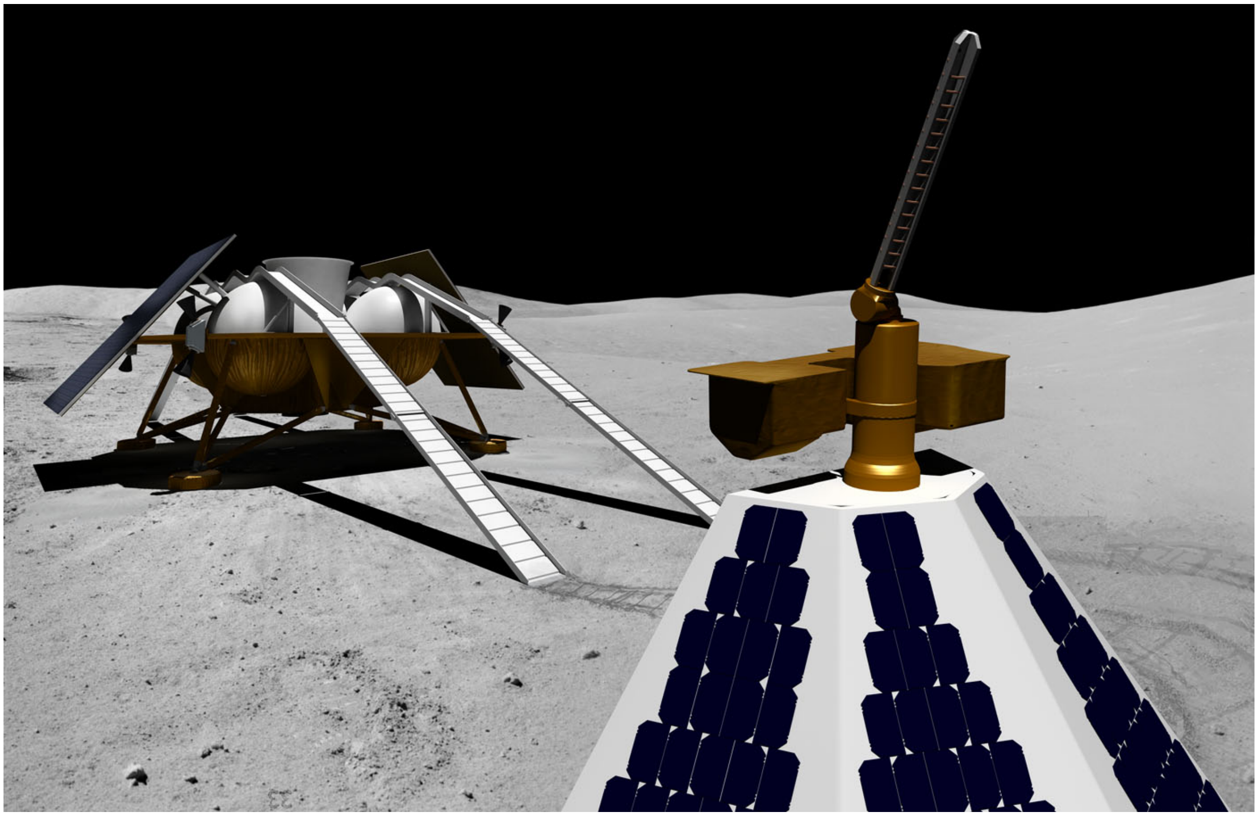


1 Introduction

1.1 Purpose

The Lander and Rover Payload User's Guide enables customers to plan their participation in Astrobotic missions. Input from customers is sought on data required in future versions of the Guide.

1.2 Company Description

A spin-out from Carnegie Mellon University, Astrobotic delivers payloads and collects data for space agencies, aerospace corporations, and academic researchers. Astrobotic's distinctions are low-cost regular lunar surface access, large payload capacities, longevity, and surface mobility. The first expedition as early as December 2013 will carry scientific instruments, engineering experiments, and sample components that space agencies and companies want to test in the lunar environment. For corporate sponsors, it will deliver promotions that involve customers directly in the adventure of lunar exploration. Over time, Astrobotic expeditions will visit Apollo sites and prospect at the Moon's poles for water and methane that can be transformed into propellant to refuel spacecraft for their return to Earth. Other expeditions will explore recently found "skylights" that pierce the lunar soil down to volcanic caves that offer shelter from the Moon's temperature extremes, radiation, and micrometeorites.

Astrobotic Technology and Carnegie Mellon have evolved the technology for robotic exploration over three years of formulation, design, analysis, and prototyping. NASA recognized the progress achieved by Astrobotic by awarding a contract valued at up to $10 million to provide data about the landing technologies to be used in the Company's initial expedition, under the agency's Innovative Lunar Demonstrations Data (ILDD) program. Astrobotic has won five other NASA lunar robotics contracts, primarily focused on methods for mining and site preparation.

1.3 Customer Value

Astrobotic Technology Inc. delivers value in low-cost, large payload capacity, regular access, surface mobility, extended duration operation, and has extensive public impact.

1.3.1 Low-cost

Astrobotic delivers unprecedented low-cost payload delivery to the moon at $1.8M per kg on its landers and $2M per kg on its rovers.

1.3.2 Large payload capacity

Astrobotic is currently the provider of the largest lunar payload delivery capability: 110 kg of third-party instruments in addition to the rover and lander delivered to the surface of the moon. Up to 25kg of the 110kg can be carried on the rover.

1.3.3 Regular Access

Astrobotic intends annual expeditions, although the pause between the first and second expeditions likely will be 18-20 months. Subsequent missions will occur every 12 months.

1.3.4 Surface Mobility and Agenda

The Astrobotic rover delivers mobility and agenda. It enables science (ground truth for orbital data, analyze volatiles, toxicity, morphology, origin), engineering (tribology, investigate exposure effects, quantify thermal regulation), and exploration (mapping, visiting skylights, accessing volatiles).

1.3.5 High Visibility and High Public Impact

Standard lander payload services include visual inspection of payloads from the rover on the lander. Corporate sponsors and payload customers benefit from involvement in an expedition with greater public impact from high-definition video, corporate sponsors' contests, and novelty of Moon Arts projects.

1.4 Pricing

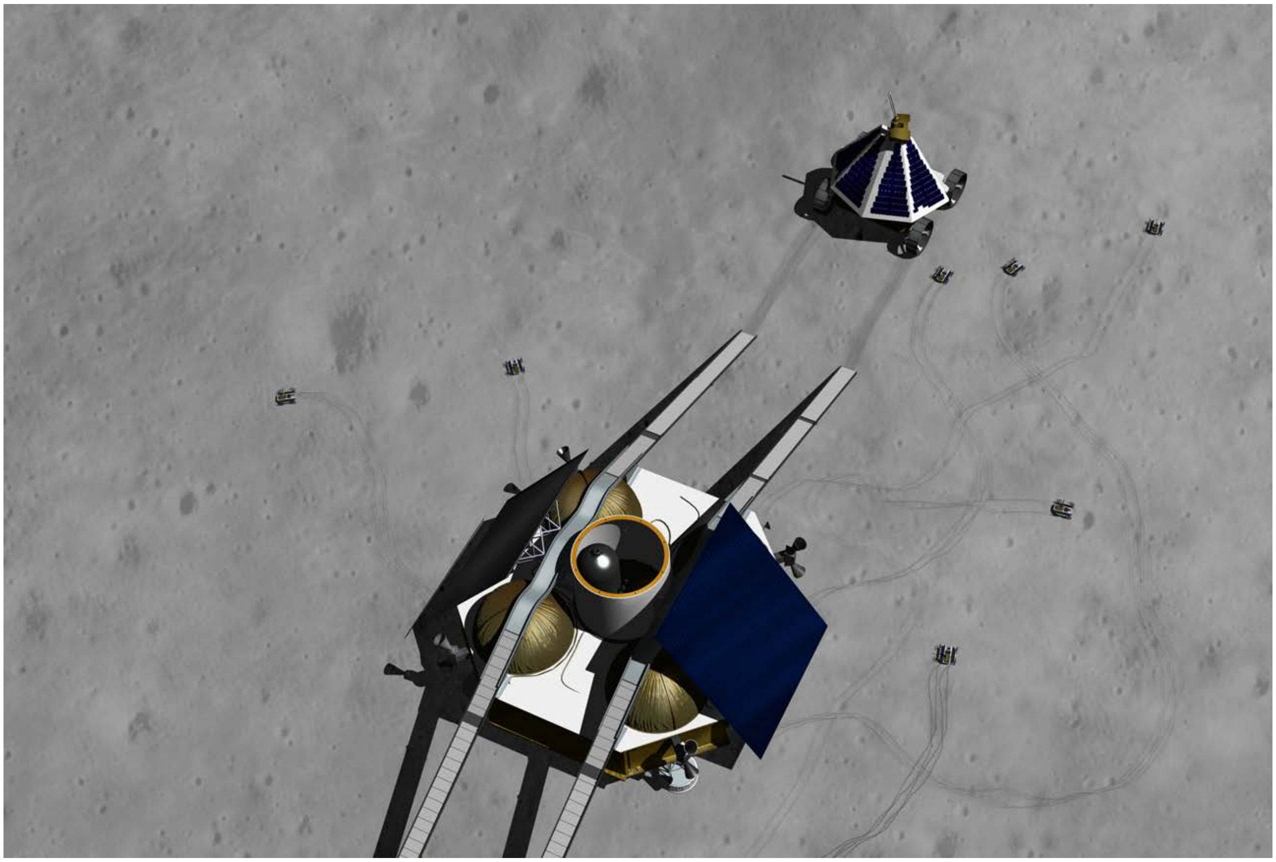
Payloads are priced per kilogram, with a guaranteed minimum of power and communications support for each kilogram purchased. Additional power and communications services can be purchased, at roughly the marginal cost of raising power or communication availability. Volume is generous, but surcharges are possible for payloads that greatly exceed their pro-rata share. Prices are higher for payloads on rovers because they benefit from the extra services of mobility and daytime thermal control. Thermal control is available as a standard service and is evaluated on an individual basis.

1.5 Destinations

Destinations are customer driven, primarily by the requirements of the payloads carried. While the baseline expedition has been designed for equatorial missions, modest changes enable polar missions to areas outside of craters where a solar-powered rover gets both illumination and access to volatiles. An equatorial mission to an Apollo site or a skylight is planned for as early as December 2013.

The earliest possible polar expeditions would be in July 2014 and July 2015 when the south pole solstice provides optimum illumination and there are good line-of-sight communication angles to Earth.

Figure 1-1: Nano-bots can be released from the lander, which provides communications with Earth



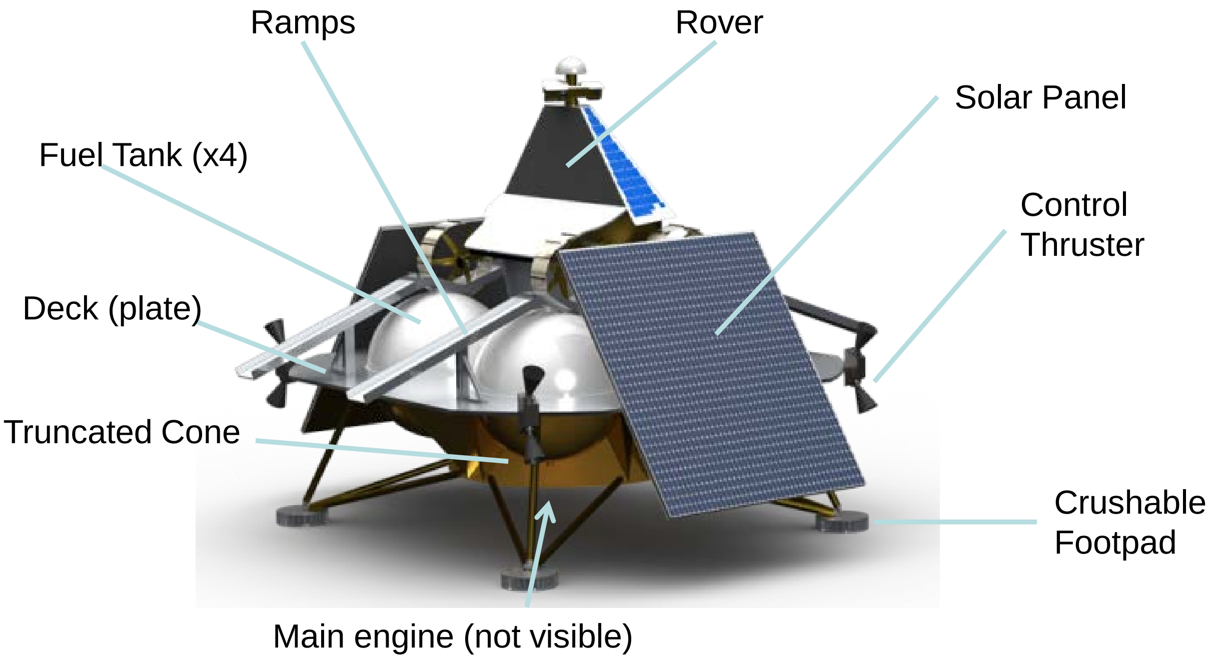
2 Vehicle Description

The lander is a single-stage spacecraft with a single pulsed main engine. The launch vehicle performs TLI. After separation from the launch vehicle, the single-stage lander captures, descends, and lands on the lunar surface. The lander delivers 210 kg of payload; for missions that require mobility, 100 kg of this payload is a rover. The rover is a data gatherer that traverses terrain at 15cm/s, surmounts obstacles 25cm in diameter, and climbs 20 degree slopes. Both lander and rover are designed to survive lunar night to enable sustained operation through several diurnal cycles.

2.1 Lander

The lander delivers the rover and payloads through trans-lunar cruise and to the lunar surface using a controlled soft landing. Structure is aluminum and incorporates flexible mounting and volume for payloads. A 4000N main engine performs lunar orbit insertion, lunar descent, and landing maneuvers, while eight 110N thrusters provide attitude control.

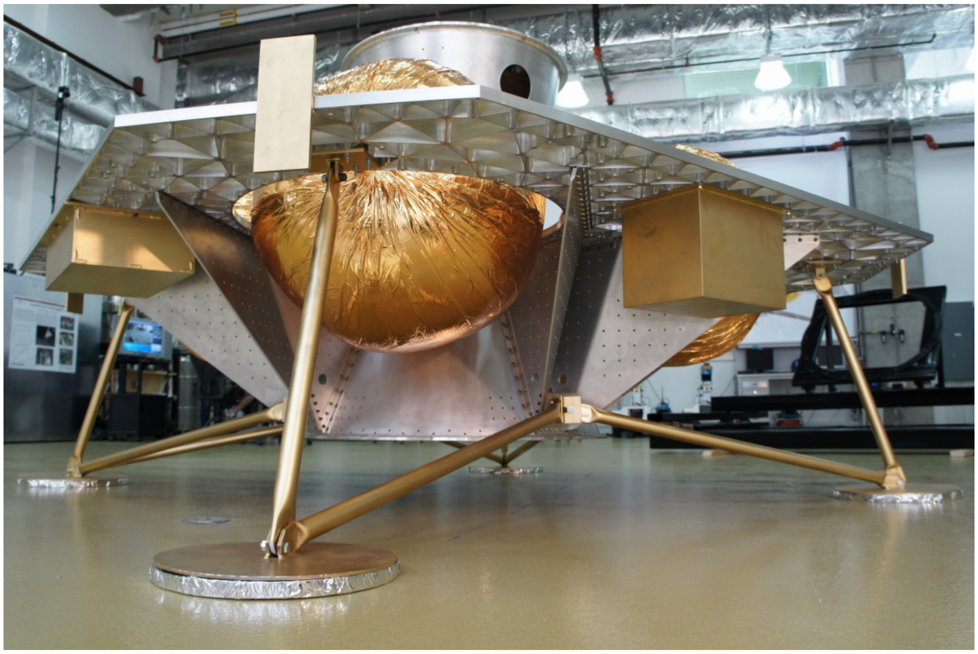
Figure 2-1: CAD model of the lander and rover



During cruise to the moon, ample solar provides power to heaters to maintain temperature within component limits.

Cameras, IMU, radar and lidar enable the craft to achieve a precision landing within 100 m of the targeted landing site and avoid landing hazards. Crushable pads at the outer edges of the structure absorb landing loads and enable the vehicle to remain stable and upright after touchdown.

Figure 2-2: Astrobotic Lunar Lander accommodates large payload volumes (gold boxes are examples but actual payloads can occupy greater volumes)



Once on the surface, lander payloads begin operation. The angled arrays enable operations to occur throughout the lunar day and provide between 465 and 718 W with an average of 537 W to the lander and payloads. A 54 Ahr battery enables short duration, high power needs on a duty cycle. On the lunar surface, the lander uses an S-Band medium-gain antenna to provide telemetry and payload data. This system provides up to 380 kbps data rate on the lunar surface. Radiators and MLI provide passive thermal control on the lunar surface to cool the lander and payloads during the harsh lunar noon environments.

2.1.1 Structure

The lander structure is predominately aluminum and is designed for flexibility of payload support. A conical adapter is the main attach point between the 1.5m launch vehicle ring and the primary load path of the vehicle. Separation occurs at the base of the thrust structure, with only the clamp interface remaining after separation. Above the launch vehicle interface, a flat deck provides mounting and thermal control for payloads and components. A series of four landing pads provide stability during and after landing. The lander maintains a minimum structural frequency of 35 Hz to avoid coupling with the launch vehicle and propulsion modes.

The structure maintains a minimum safety factor exceeding 1.4. Lander verification and validation is done through analysis, protoflight testing, and references NASA STD 7001 & 7002.

2.1.2 Propulsion

The lander main engine and attitude control system (ACS) engines are both pulsed bipropellant. The main engine generates 4000N of thrust; the ACS engines (8) are 110N each.

The main engine is engine is concentric with the spacecraft central axis and performs capture, de-orbit, brake and descent. Eight canted bipropellant ACS engines stabilize the lander during all flight phases.

2.1.3 Guidance, Navigation, and Control

The Guidance, Navigation and Control system (GNC) provides control of the spacecraft trajectory throughout cislunar cruise, lunar orbit insertion, descent, and landing. The navigation system uses a sun sensor array and a star camera to determine attitude and position during cruise. Similar to MRO, the star camera images stars and uses a database within the avionics to compute location and orientation.

During descent, an inertial measurement unit (IMU) measures changes in attitude and rates. Cameras capture images of the ground, and the avionics system compares these images against a database of lunar features to land precisely.

2.1.4 Avionics

An avionics box performs command and data handling for the lander. The system has a processor speed of 133 MHz. The avionics operate on a MIL-STD-1553b serial bus and utilize RS422 interfaces between components. System memory stores up to 3 GB of data for payloads and telemetry. The system consists of 15 cards. Among them are dedicated cards for propulsion, GNC, telecommunications, power, and payload.

2.1.5 Communications

Lander to ground communication is through a transceiver and power amplifier/controller. Transmitted power is 10W with 35W input. Transmitted frequency is S-band with Reed-Solomon coding over CCSDS. During flight phases prior to landing, low gain antennas provide omni-directional communication coverage. During landing and surface operations, a high gain antenna is used to provide bandwidth for control and payload operations.

Two 3.5 dB gain patch antennas operating concurrently provide full line-of-sight to ground during flight. Maximum transmit bitrate during cruise is 10kbps. One 16.0 dB gain helical antenna, oriented to aim toward earth during landing, provides 380kbps landing and surface data transmission. Data is received by the transceiver at up to 10 kbps.

2.1.6 Power

The electrical power system provides electrical power to the avionics, communication system, propulsion system, and payloads. The power system operates on a 28V +/- 4V bus. Max power point trackers maintain a solar power supply consistent with the energy needs of the bus.

A pair of solar arrays attach to the upper deck of the spacecraft. During lunar operations, the combined arrays provide up to 718W of power at lunar noon, after allowing for reduced cell efficiency during this peak temperature condition. The lander mounts the arrays at mirroring 55 degree angles to optimize the power available over the course of the lunar day. The configuration results in an average available power of 537W during the lunar day. During cruise, the arrays provide up to 718W of power to the bus.

A 1500Whr (28V, 54Ahr) battery provides energy storage for shadowing during cruise and descent as well as the ability to duty cycle total payload power up to 580W.

2.1.7 Thermal

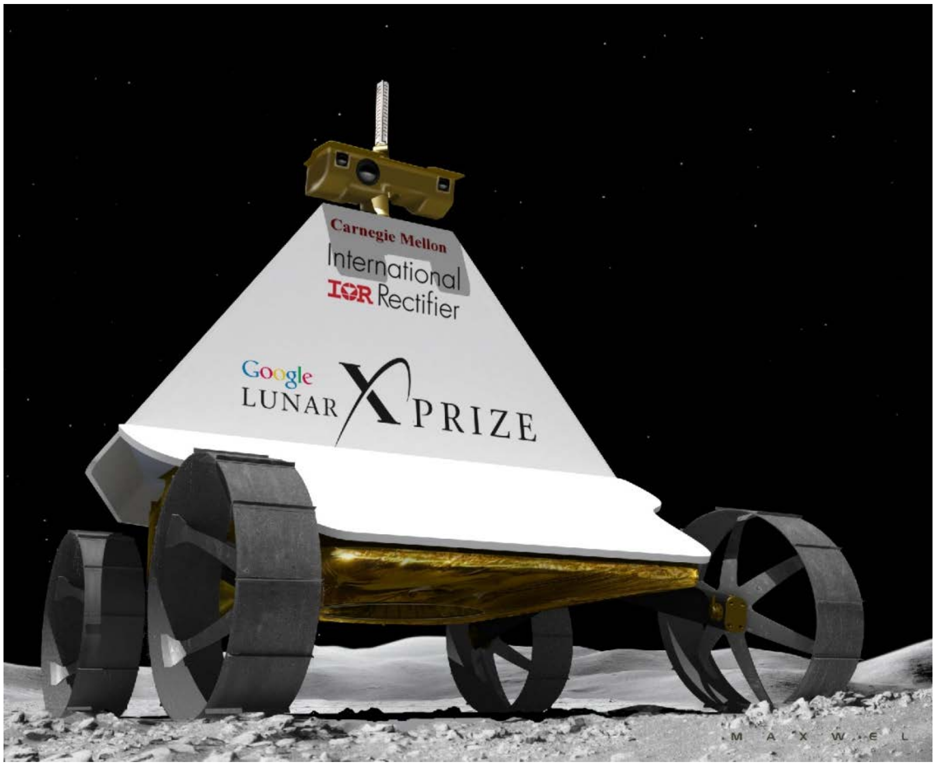
The thermal control system maintains the temperature of the lander within the operating environments of its components and payloads. This system functions under two primary modes: cislunar cruise and surface operations. During cruise, the spacecraft points the rover-topped end toward the sun to provide power to the solar arrays. It spins about its centerline axis (i.e., the line from rover down to the motor) providing uniform heating to the top of the craft. MLI insulates the lander, while temperature sensors monitor internal components for closed-loop heating with component-mounted resistive heaters.

During surface operations, white radiators on the upper surface reflect sunlight and reject heat into space which provides passive cooling for avionics and payloads conductively coupled to the top deck.

2.2 Rover

The rover is a skid-steered, passive link suspension vehicle. It is solar powered with rechargeable batteries sufficient for continuous travel. Direct-to-Earth communication is a pointed helical antenna with three fixed patch antennas as backup. The rover is able to traverse 10km per lunar day. An asymmetric configuration enables orienting solar arrays toward the sun and radiator to space in order to passively cool throughout the lunar day. Despite asymmetry, every azimuth of travel is achieved by the wraparound solar panels and a sensor mast that rotates 180 degrees, enabling travel both toward and away from the sun.

Figure 2-3: Render of the rover on the surface of the moon



The rover in Figures 2.2 and 2.3 is shaped for equatorial environments. For polar missions, it will remain asymmetrical but instead of the solar panels covering a half cone, they would cover a half cylinder to be illuminated by sunlight coming in parallel to the surface.

Figure 2-4: Prototype robot showing four-facet solar panel configuration

2.2.1 Structure

Rover structure is predominately carbon fiber and aluminum honeycomb composite. Design minimizes mass by combining structure with function. The solar panel backing and the radiator surface form part of the rover primary structure. The shape of the structure is driven by the optimal angles for these components.

The primary components of the rover structure are the chassis, radiator, solar array, internal stiffeners, and mast. The radiator is a flat composite panel, with honeycomb material and density selected to increase thermal conductivity through the thickness and high thermal conductivity carbon to spread the heat. The solar array is a single honeycomb composite panel with four facets. The internal supports are composite I-beams. The mast is a carbon fiber tube that supports the rover camera head and antenna. The chassis is carbon/honeycomb composite linking together the mobility, radiator, solar, and the mast. The logo panel, which connects the solar array to the radiator, is a non-load-bearing structure that protects internal components from regolith.

2.2.2 Mobility

The rover is skid-steer with two shoulder-mounted actuators. A roller chain transmits torque from the actuators to the wheels; the chain enables high torques with minimal mass and complexity. Placement inside the chassis insulates actuators from lunar dust and extreme temperatures of the lunar surface and eliminates wire flexure or steering through the suspension. Each shoulder actuator transmits torque to both wheels on one side.

A passive suspension reduces chassis pitch angles and maintains four wheel ground contact on uneven terrain without the use of spring/dampers. The two left/right mobility sidearms rotate freely at the shoulder and a differencing bar mounted on the rear of the chassis links the rotation of the two sidearms.

2.2.3 Avionics

Rover computing utilizes an avionics box which performs command and data handling for the lander. The system has a processor speed of 133 MHz. The avionics operate on a MIL-STD-1553b serial bus and utilize RS422 interfaces between components. The system has capacity to store up to 1 GB of data for payloads and telemetry. The system consists of 15 cards. Among them are dedicated cards for propulsion, telecommunications, power, and payload. Dedicated FPGAs implement computationally expensive algorithms acquisition, processing, and compression of imagery and other data.

2.2.4 Communications

Rover to ground communication is through a transceiver and power amplifier/controller. Transmitted power is 10W with 35W input. Transmitted frequency is S-band with Reed Solomon coding over CCSDS.

During flight phases, communication is patched through short range communication to the lander, then passed to Earth.

During surface operations, one actively pointed 16dB helical antenna points at Earth to provide 380kbps, accommodating transmission of HD video and any high bandwidth data packages required by payload. In the event of failure, three medium gain 8dB patch antennas provide 60kbps transmit rate – sufficient bandwidth for control, navigation, and minimal data transmission.

2.2.5 Power

The rover is powered by a fixed faceted conical solar array. The rover operates much like a sailboat tacking to keep the sun on the solar array and off the radiator. Full motion is achieved with a bidirectional drive train and rotatable camera head.

The rover generates an average power of 140 W over varying sun elevations and rover azimuth angles. Surge power and power for traversing shadows is provided by battery. Each of the four facets of the rover's solar array contains 6 strings of triple junction solar cells at an efficiency of 26.8%. Each string consists of 15 cells arranged in series. At peak power one facet will source 2.54 amps at 33.5 volts, for a total power output of 85 watts at ambient temperatures. The rover battery is composed of four parallel packs of lithium iron phosphate cells from A123 systems. Each pack has a string of nine cells, and is encased in carbon fiber to spread heat evenly so all cells discharge at the same rate. The battery has a nominal voltage of 29.7 V and a total capacity of 9.2 Ahr (273 Whr).

2.2.6 Thermal

An asymmetric design achieves passive thermal regulation, sufficient even for the worst case of a lunar equatorial day.

The angle of the static solar panels was optimized to balance surface area, incident sun angle and panel heating. A thermally conductive continuous carbon facesheet on the solar array structure spreads the heat load across the panels for even solar cell performance. The interior surface of the solar array structure is lined with MLI to minimize radiation from the solar panels to the rover internal components.

Since regolith temperatures on the lunar equator reach 120°C, sensitive rover components must be insulated from the ground as well as from the incident sun. MLI is mounted on the inside of the chassis floor and the bottom of the chassis is covered with co-cured aluminized kapton to act as a thermal barrier from the terrain.

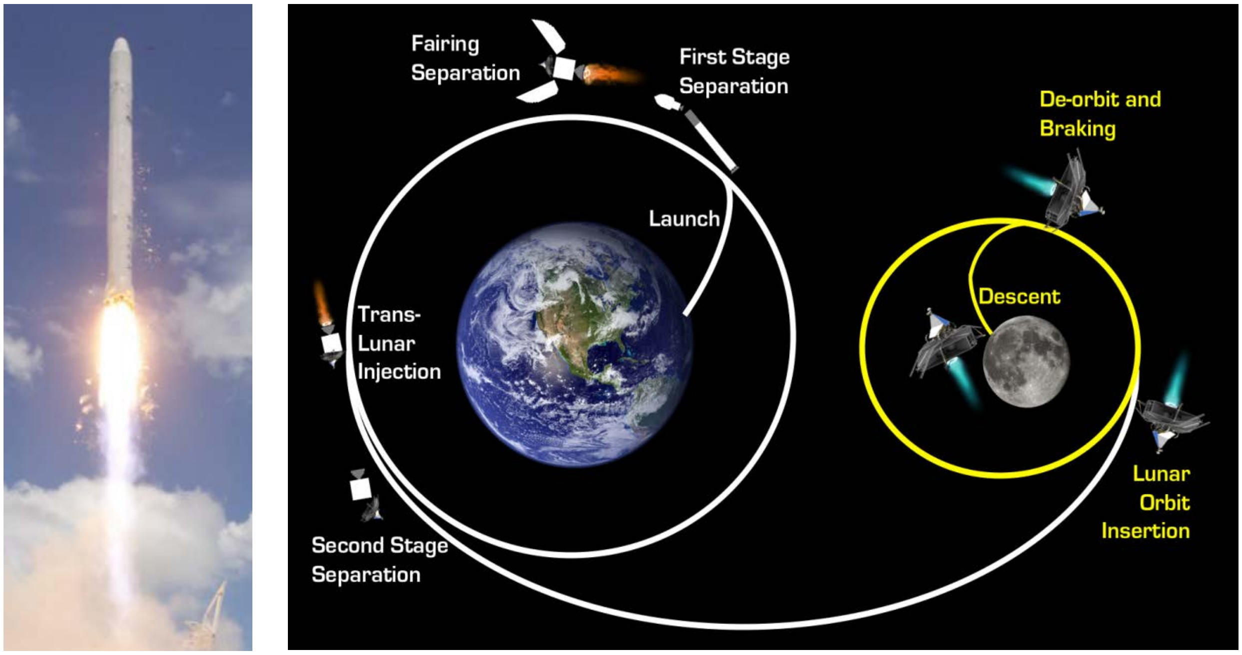
Heat generating components inside the rover are either mounted directly to the radiator or connected to the radiator through high-conductivity thermal pathways that extend into payload compartments for passive conductive cooling.

3 Performance Summary

3.1 Mission

Falcon 9 launch injects the spacecraft to trans-lunar trajectory with second stage restart. The single-stage spacecraft cruises for four days, orbits, descends and lands. The trajectory mimics Apollo in capture, descent, and landing. The lander touches down 36 hours after lunar sunrise, then the rover egresses and embarks on a 12-day trek. Lander generates average 500 W and supports payload operations. Rover departs to fulfill payload objectives. Lander and rover hibernate at night then revive for several diurnal cycles.

Figure 3-1: Illustration of mission architecture; launch an F9 to TLI, cruise and land as a single stage



Launch
SpaceX Falcon 9 from SLC-40, Cape Canaveral, FL

TLI
Re-ignition of Falcon 9 Second Stage

Cruise
Duration: 4.5 days
Apollo trajectory, low thrust/weight

Land
36 Hours after lunar sunrise

Surface mission
Floor Duration: 4 earth days, 500m
Baseline Duration: 12 earth days, 10km
Extended Duration: 90 earth days, 20km

Ground Operations
Communications: USN 13m dishes
Surface: Astrobotic; Pittsburgh, PA

Delta-v
Lunar Orbit Insertion: 836 m/s
Descent Orbit Insertion: 29 m/s
Powered Descent: 1915 m/s

The spacecraft – lander and rover stacked – is a single-stage spacecraft with no boost or braking stages. It has ample clearances in the standard Falcon 9 payload fairing.

3.2 Lander

The lander is a pallet structure which delivers the rover and stationary payload to the lunar surface. The lander hosts 210kg of payload and provides 537W of persistent power during daylight. It is solar powered with rechargeable batteries for storage and surge power. Baseline communication is a pointed antenna with omnidirectional antennas as backup.

Mass

Lander dry mass allocation:
555 kg

Energy

(2x) 2.9 m^2 solar panels,
inclined at 55 degrees
Average landed power: 537 W
1500 Whr battery pack

Payload

Payload mass: 210 kg of which
rover is allocated 100 kg
Volume: 0.75 m^3
Average payload power: 330 W

Computing

SRAM: 256 KB
Storage: 3 GB
Core clock frequency: 133 Mhz

Communication

Transceiver power: 35 W
RF power out: 10 W
High-gain antenna gain: 10.5 dB
High-gain antenna downlink: 380 kbps
High-gain antenna uplink: 10 kpbs
13m Earth dishes through USN

Figure 3-2: Lander structure prior to addition of egress ramps and upgraded energy-absorbing legs

3.3 Rover

The rover is a skid-steered vehicle with passive suspension. Solar provides power with rechargeable batteries for storage. Inertial and visual sensors determine location, stereo and telephoto cameras enable imaging and navigation. Navigation is teleoperation from Earth with onboard safeguarding. Baseline communication is a pointed helical antenna with patch antennas as backup. The rover includes mobile payloads.

Mass
Rover mass: 100 kg
Payload: up to 110 kg

Mobility
Wheel base: 0.9 m
Track width: 1.25 m
Height: 1.7 m
Speed: 15 cm/s
Wheel diameter: 0.5 m
Max incline traversal: 20 degrees
Max obstacle: 25 cm
Static tip-over: 50 degrees
Static roll-over: 55 degrees

Energy
1.25 m^2 solar panels, inclined at 60 degrees
Average power: 140 W
273 Whr battery pack

Computing
SRAM: 256KB
Storage: 16GB
Core clock frequency: 133Mhz

Communication
Transceiver power: 35 W
RF power out: 10 W
High-gain antenna gain: 16 dB
High-gain antenna downlink: 380 kbps
High-gain antenna uplink: 10 kpbs
Low-gain antenna gain: 8 dB
Low-gain antenna downlink: 60 kbps
Low-gain antenna uplink: 10 kpbs
13m Earth dishes through USN

Imaging
Camera resolution: 1280x720
Max frame rate: 30 frames per second
Field of view: 70 degrees
Pan: +/-190 degrees, Tilt: +90, -20 degrees

4 Payload Information

This section documents payload accommodations, environments, lander and rover resources, and integration specifications. Standard services include a lander to payload or rover to payload ICD which details those sections which are described below. The purpose of this section is to present a technical overview to assist in mission planning.

4.1 Lander Payload Volume

The four payload locations and volumes are defined in Figure 4-1 through 4-4. Depending on the manifest, locations may be selected to maintain a center of gravity within mass properties requirements. Payloads have direct access to the lunar surface: the lander deck is 1.1 meters above the regolith and payloads can extend 0.6 meters down from the deck, providing 50 cm clearance for obstacles when landing. Green volumes also can look to the sky, while the blue regions are blocked by the solar arrays. The green and blue regions indicate where individual payloads can be placed; they are not physical boxes.

Figure 4-1: Payload volumes seen from beneath the lander. Those in green support thermal control while the blue volumes positioned under the solar arrays are for payloads that don't generate heat.

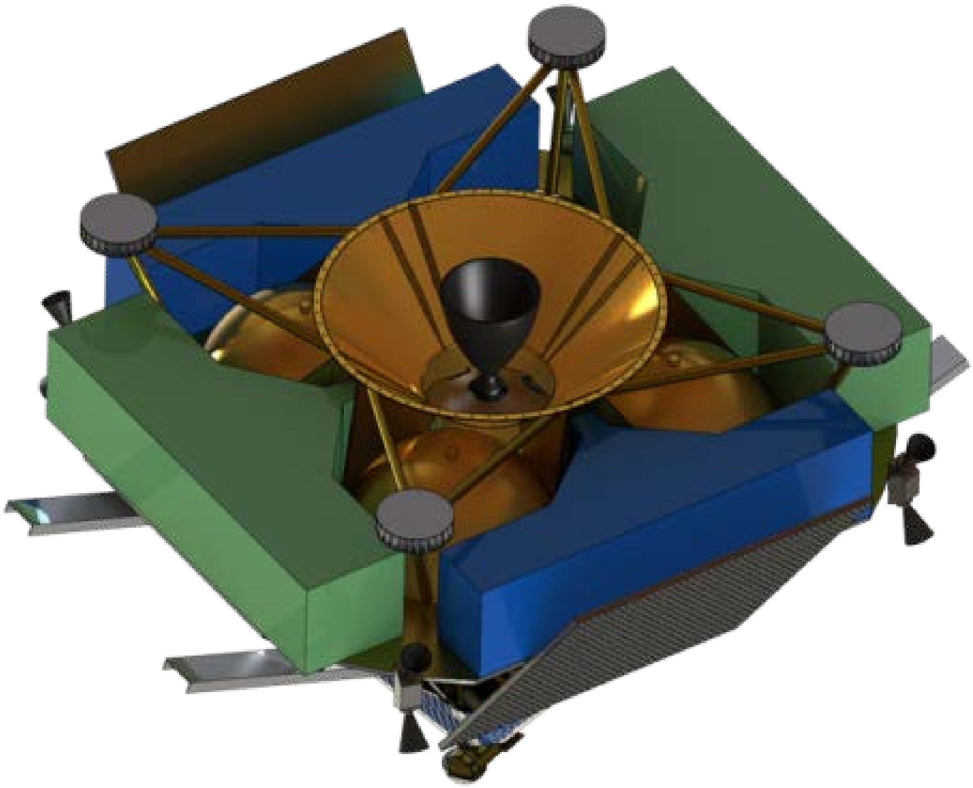


Figure 4-2: Thermally controlled payload volumes exist under the deck on the two edges with ramps. Iso view shows detail of the shape.

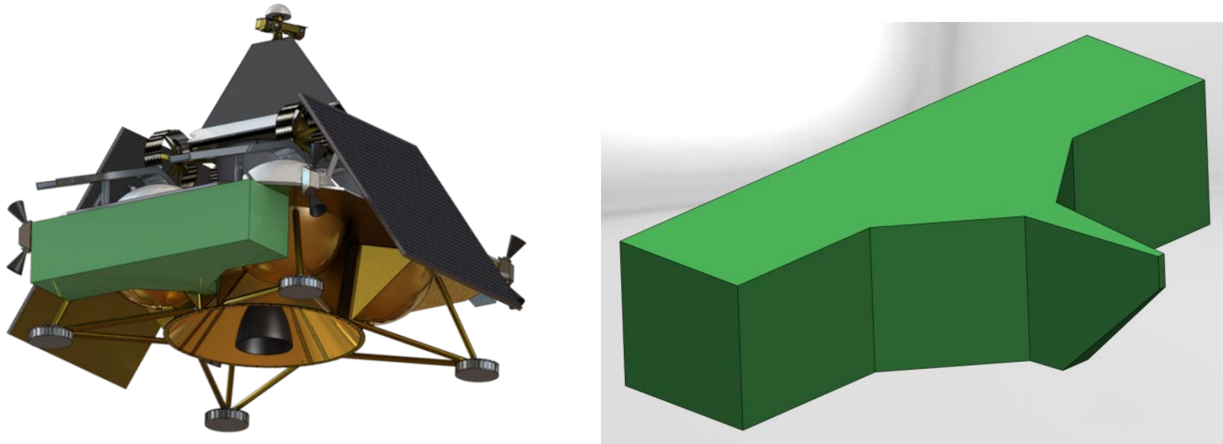


Figure 4-3: Dimensions of the thermally controlled payload volumes (dimensions in inches)

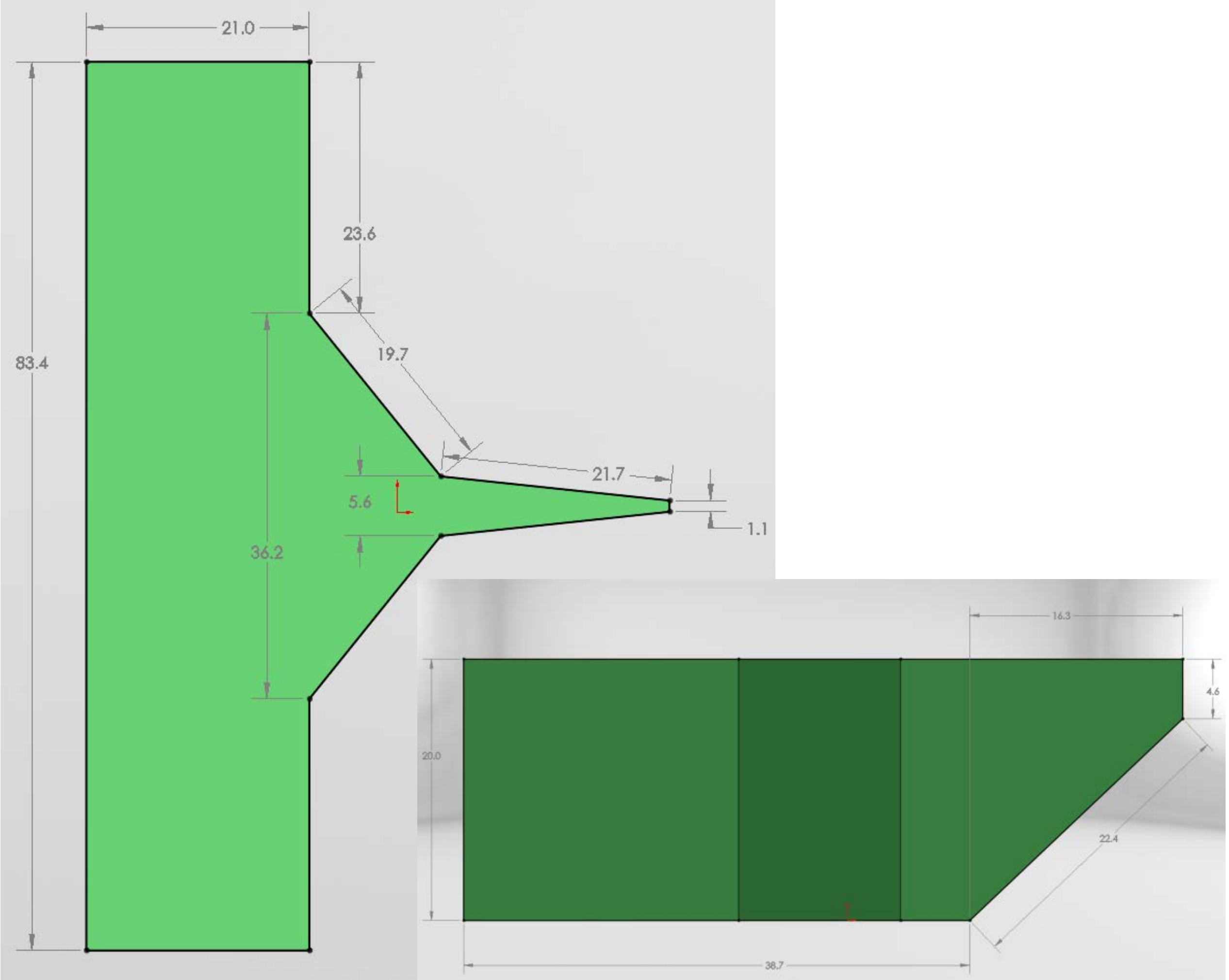
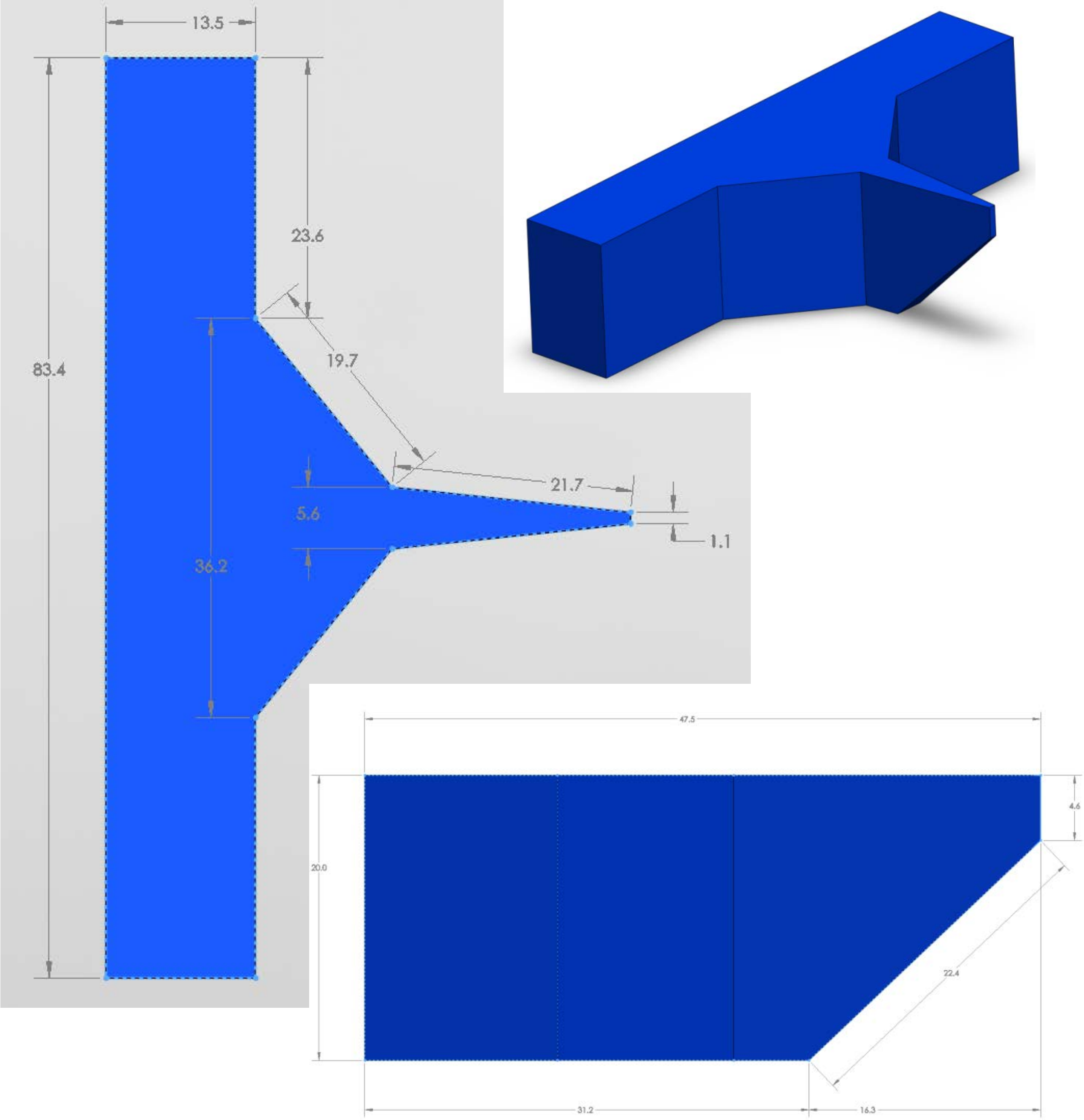


Figure 4-4: View and dimensions (inches) of the non-thermally controlled payload volumes



4.2 Rover Payload Volume

For rover payloads that do not require external access, the payload must fit inside the rover body without interfering with other rover components. The rover dimensions can be seen below. Total rover payload volume depends on payload shape and other rover payloads, but the payload length, including all mounting hardware, must not exceed 940 mm.

Figure 4-4: Rover top view with solar panels removed, dimensions in meters

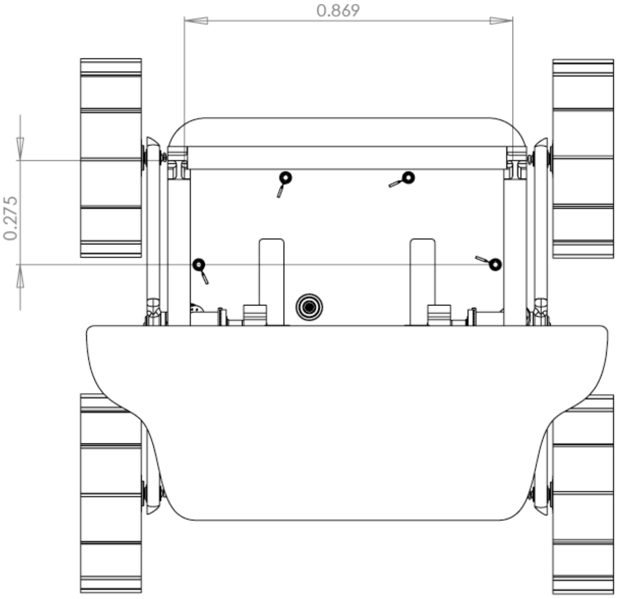


Figure 4-5: Rover side view with solar panels removed, dimensions in meters

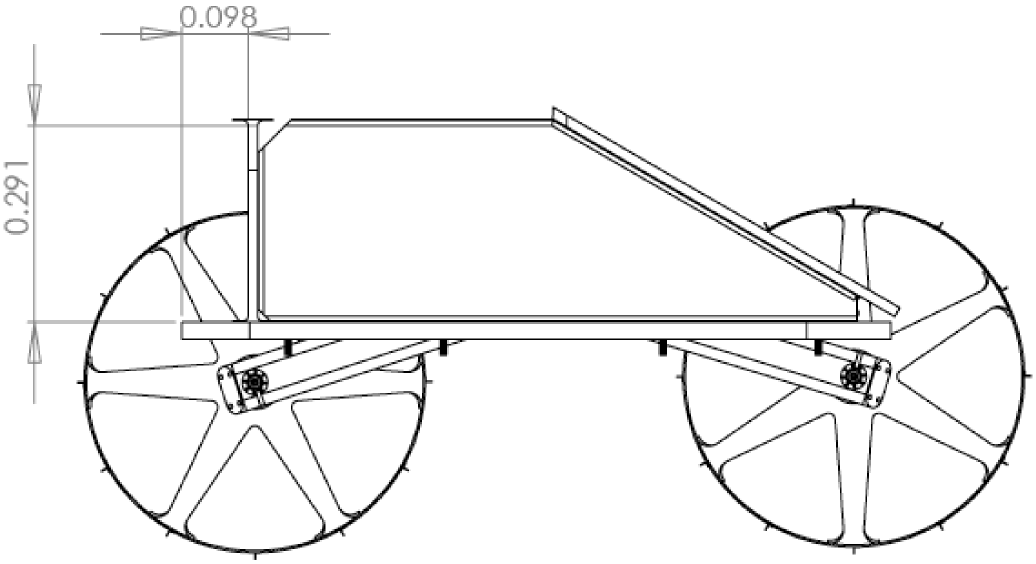
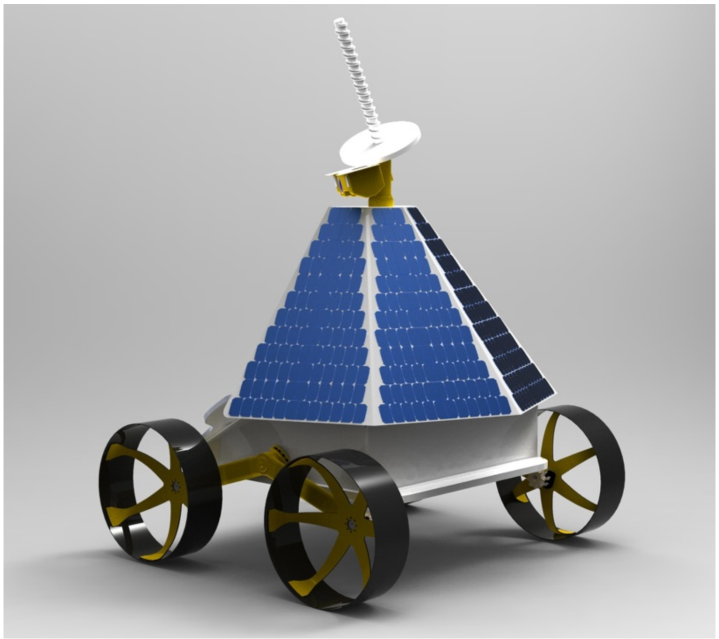


Figure 4-6: Rear view of rover payload shelf



In addition to space inside the rover, there is a payload external access shelf at the rear of the rover. The shelf is 90 mm wide. All external payload components must be stowed within this 90 mm width until after the rover egress from the landing spacecraft. Access between the rover interior and the payload shelf is limited to a size 25 shell connector.

4.3 Environments

4.3.1 Transportation

Lander and rover will be crated and transported by truck. The solar arrays are removed and crated individually. The rover is crated in a 2m x 2m x 2m cube case. The lander is crated in a 3.6m x 3.6m x 2m rectangular case. The lander case travels, as a legal load, edgewise, with vertical dimension of 3.6m upright on a double-drop-deck trailer. The cases are heavily padded and cushioned to cap the maximum loads at 3.7g.

4.3.2 Assembly and Integration

In hanger:	Temperature 21°C +/-3°C; Humidity 50% +/-5%
During rollout:	Temperature 21°C +/-3°C; Humidity 50% +/-5%
On pad:	Temperature 21°C +/-3°C; Humidity 20% to 50%

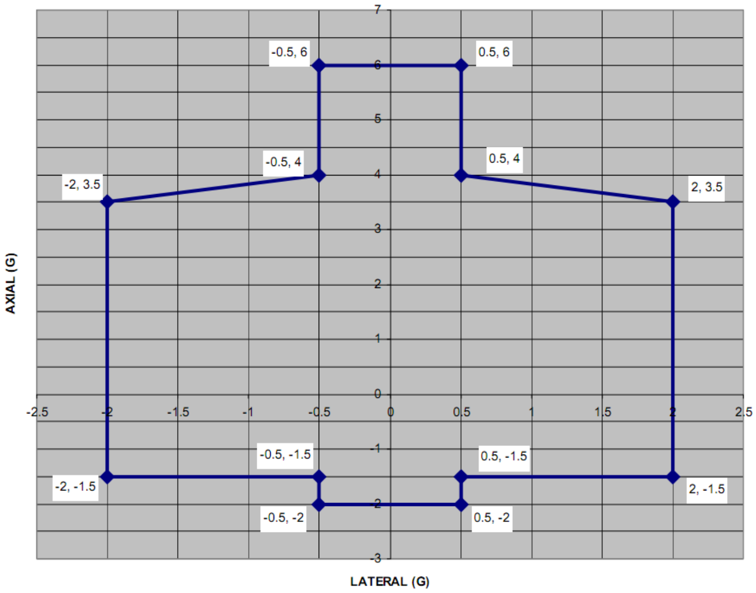
4.3.3 Launch

The following launch loads are excerpted from the Falcon 9 Payload User's Manual version 1.

4.3.3.1 Static Loads

During flight, the spacecraft will experience a range of axial and lateral accelerations. Axial acceleration is determined by the vehicle thrust history and drag, while maximum lateral acceleration is primarily determined by wind gusts, engine gimbal maneuvers, first stage engine shutdown, and other short-duration events. Falcon 9 design load factors are shown using the envelope plotted in the figure below. A positive axial value indicates a compressive net-center of gravity acceleration, while a negative value indicates tension.

Figure 4-7: Plot of Falcon 9 static loads experienced during launch



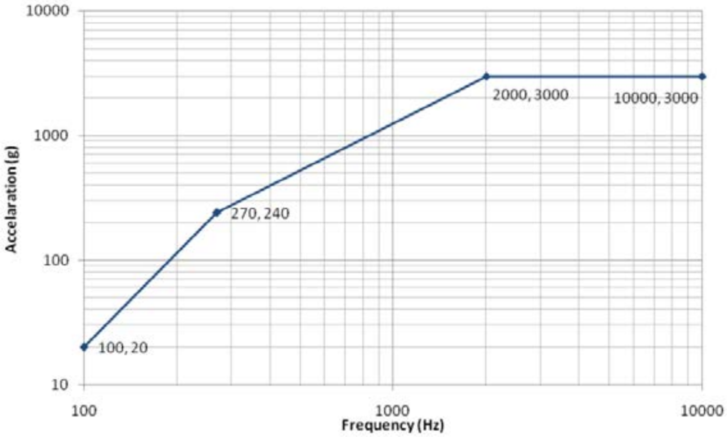
4.3.3.2 Shock

There are four shock events during flight that are characterized as shock loads:

(1) Vehicle hold-down release at lift-off
(2) 2nd stage separation
(3) Fairing separation
(4) Payload release and separation

Of the shock events, (1) and (2) are negligible for the payload relative to (3) and (4) due to the large distance and number of joints over which shocks (1) and (2) will travel and dissipate. Maximum shock loading (3) and (4) is measured and scaled for various preloads required for the payload fairing and lander separation systems. The resulting maximum shock environment predicted at the launch separation ring during fairing separation and payload separation is shown below.

Figure 4-8: Plot of shock experienced at the payload interface on Falcon 9



4.3.3.3 Acoustic

During flight, the spacecraft will be subjected to a varying acoustic environment. Levels are highest at lift off and during transonic flight due to aerodynamic excitation. The environment shown in Figure 4-9 does not include margin for qualification or for acceptance testing. This is the maximum predicted acoustic environment.

Table 4-1: Table summarizing acoustic levels experienced during launch of Falcon 9

Octave Center Frequency (Hz)	F9 Maximum Predicted Acoustic Environment (OASPL = 139.6 dB)
31.5	128.0
63	131.0
125	135.2
250	133.6
500	130.3
1000	126.0
2000	120.0
4000	116.0

Figure 4-9: Plot of acoustic level experienced during launch of Falcon 9

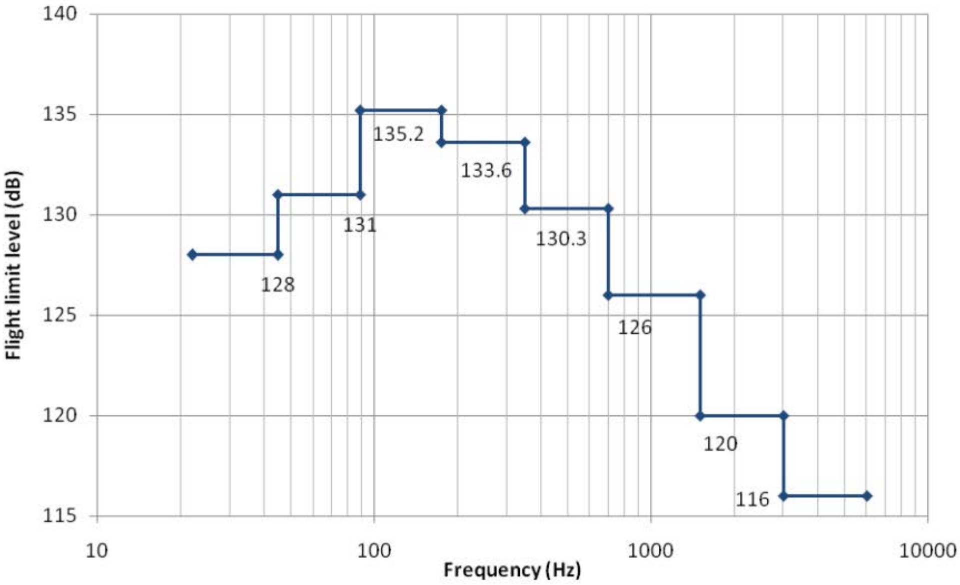


Figure 4-10: Astrobotic's lander structure passed shake table tests for acceleration and with confirmation that first lateral and first axial modes of vibration are sufficiently higher than Falcon 9 requirements

4.3.3.4 Sine-Vibration

A mission-specific sine vibration environment curve will be derived based upon a coupled loads analysis because significant flight history is not available. Actual lander loads, accelerations, and displacements are a function of both the launch vehicle and lander structural dynamic properties and will be accurately determined via a coupled loads analysis.

The approach is to use results from coupled loads analysis to derive a shock response spectrum on the vibration levels at the lander / launch vehicle interface. For a given modal damping value, a smoothed envelope of peak responses is created that is used to produce a sine-vibration input curve.

4.3.3.5 RF

Spacecraft materials or components will be compatible with both the RF environment on the launch pad and during flight. The lander RF characteristics should satisfy limitations shown in the figure below.

Figure 4-11: Plot of lander RF characteristic requirements on Falcon 9

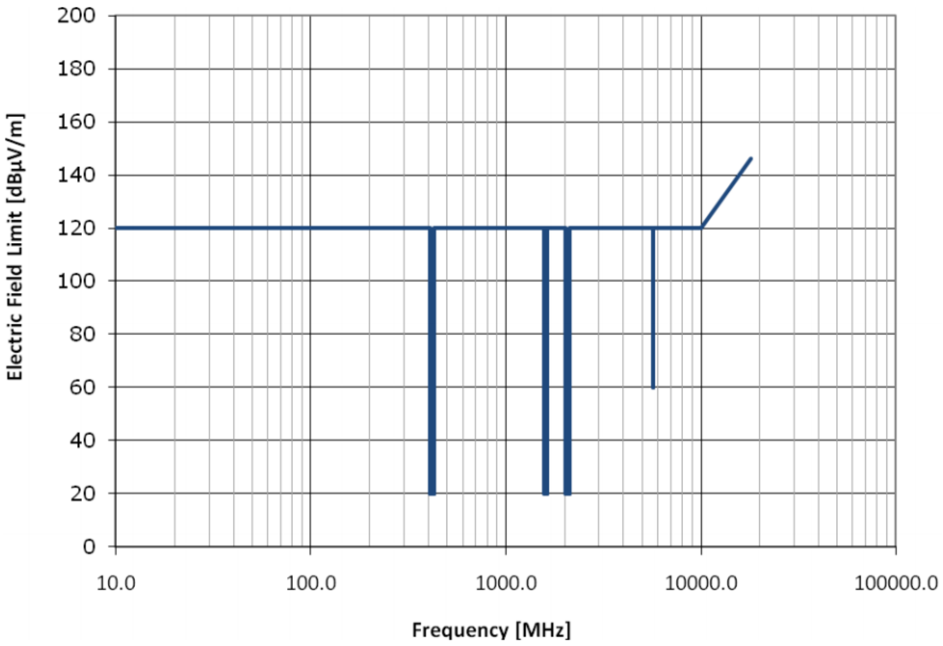
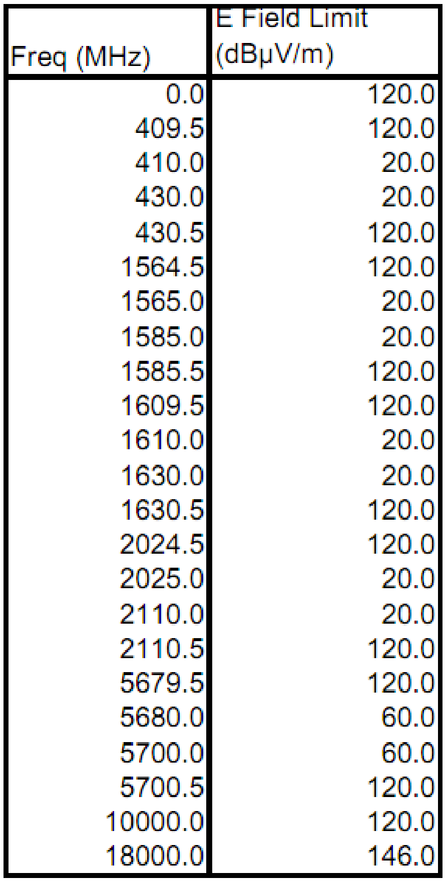


Table 4-12: Summary of lander RF characteristics requirement on Falcon 9



Freq (MHz)	E Field Limit (dBµV/m)
0.0	120.0
409.5	120.0
410.0	20.0
430.0	20.0
430.5	120.0
1564.5	120.0
1565.0	20.0
1585.0	20.0
1585.5	120.0
1609.5	120.0
1610.0	20.0
1630.0	20.0
1630.5	120.0
2024.5	120.0
2025.0	20.0
2110.0	20.0
2110.5	120.0
5679.5	120.0
5680.0	60.0
5700.0	60.0
5700.5	120.0
10000.0	120.0
18000.0	146.0

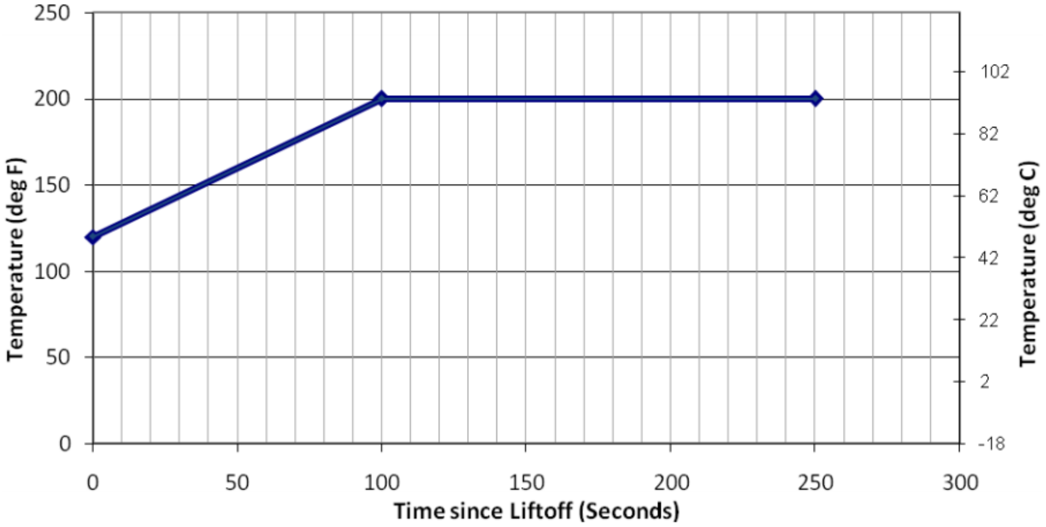
4.3.3.6 Pressure

Payload fairing internal pressure decay rates is limited to 2.76kPa/sec, except for a transonic spike to 6.2kPa/sec.

4.3.3.7 Temperature

Falcon 9 payload fairing is a composite structure consisting of a 1-inch (2.5-cm) thick aluminum honeycomb core surrounded by carbon fiber face sheet plies. The emissivity of the payload fairing is approximately 0.9. Based upon this emissivity, the payload fairing inner wall temperature is bounded as shown in Figure 4-11.

Figure 4-13: Plot of time history of temperature in payload fairing on Falcon 9



4.3.4 Flight

The flight profile is nominally a 1RPM roll about the centerline axis (i.e., the line from the rover down through the motor) for both lander and rover. The purpose of this maneuver is to keep components within operating temperatures.

4.3.4.1 Thermal

Thermal profile of the lander and rover during cislunar cruise, descent, and landing is TBD. Standard services include a coupled thermal analysis to develop requirements for thermal accommodations.

4.3.5 Landing

There is a one-time shock event during landing when the lander touches the surface. Crushable honeycomb absorbs impact to dampen shock. Explicit shock profile is TBD and will be included in a future version of this Guide.

4.3.6 Surface

The lander and rover have distinctly different surface environments. The underbelly of the lander is shaded due to the fact that it has no line of sight to the sun and internal conduction of the lunar soil is substantially low. The rover is constantly driving over terrain that exceeds 100 degrees Celsius.

4.3.6.1 Lander Surface Environment

The thermal environment of the lander on the surface is TBD. Standard services include a thermal analysis for the nominal mission duration of 12 Earth days to assess thermal performance of the payload and develop requirements for thermal accommodations.

4.3.6.2 Rover Surface Environment

The thermal environment of the rover on the surface is TBD. Standard services include a thermal analysis for the nominal mission duration of 12 Earth days to assess thermal performance of the payload and develop requirements for thermal accommodations.

4.4 Resources

The following section describes the resource utilization of the lander and rover and documents allocations for payload.

4.4.1 Lander Resources

The lander resources consist of power and communication bandwidth. Nominally, the lander can provide 350W to payloads with short durations in excess of 600W. Communication bandwidth is 5kpbs uplink and 256kpbs downlink. Duty cycles and specifications are mentioned below.

4.4.1.1 Power

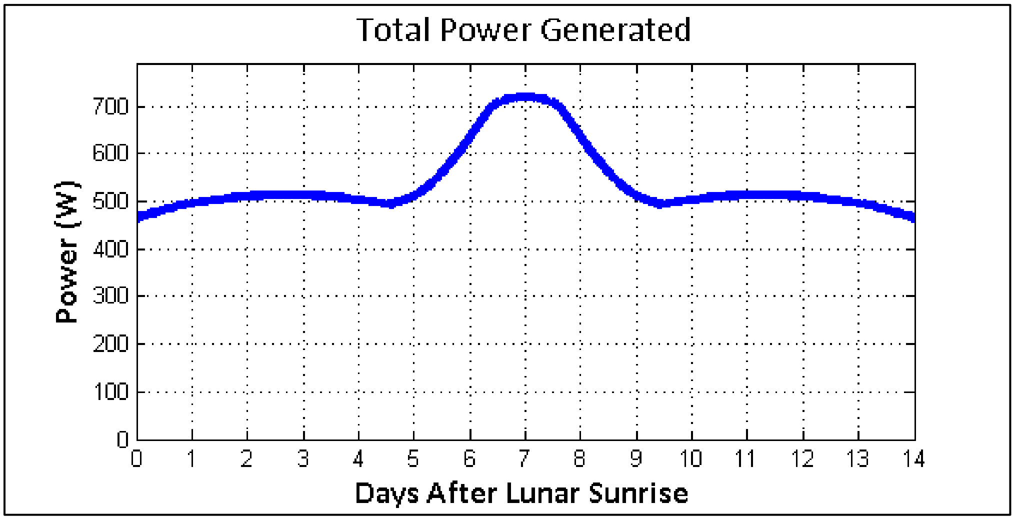
During lunar transit 100W of power is allocated to payload. Thermal and avionics are the next largest power allocation, (allocation to thermal may increase as more detailed thermal analysis for the transit phase becomes available). By pointing the upper half of the vehicle toward the sun, the arrays provide up to 718 W of power to the vehicle. The lander power management system leaves the excess power on the arrays using peak power trackers.

During descent, the lander solar arrays will be shadowed by the Moon or at an off angle to the sun for short periods of time. During these periods, the lander relies upon battery power. The batteries supply up to 54 Ahr of power and will be fully charged prior to descent. During the 15 minute landing, the lander will draw up to 400 W to power its systems. This results in a 3.54 Ahr total draw on the battery, leaving 50.46 Ahr margin.

Lunar surface operations size the power system. The power available varies with landing azimuth, time of day, and the temperature of the arrays. The two opposing arrays are angled to provide level power input ranging from 465 to 718 W, with an average of 537 W over the lunar day. During this period, the lander bus draws 99 W of continuous power to support basic functions such as computing and telecommunications. **Error! Reference source not found.** Power for payloads is nominally 330W over 12 Earth days. Some restriction may be placed on power usage during the middle of the lunar day in order to maintain components within thermal limits.

Given the 54 Ahr of battery capacity, payloads may be operated at a power level above the average power allocation for short periods of time. For example, a payload might use 580W on a 25% duty cycle. Allowable maximum power and duty cycle will be determined based on thermal analysis of the lander and payload.

Figure 4-10: Time history of lander power during surface operations



4.4.1.2 Communications

The lander relays state of health (SOH), telemetry, and payload data through the communications system. This includes post launch, lander separation, trajectory maneuvers, braking burn data, system anomalies, evidence of precise landing, video of the landing site, payload inspection, and imagery of the landing path.

During cruise and descent, the Spacecraft utilizes 2 hemispherical patch antennas to transmit data to Earth. These antennas provide 10 kbps down-link from the lander. During lunar surface operations, a high gain antenna directional provides 380kbps down-link from the lander. The patch antennas are used backup in case of off-nominal conditions.

Data requirements are divided into real-time and buffered data packages. Real-time data drives minimum bandwidth requirements while buffered data is transmitted slowly at low priority and is measured in average bits per second.

On the surface, payload data capacity is time shared between the payloads and is sized to provide bitrates of 256kbps total.

Table 4-3: Lander communication budget summary

Package Bitrates	Cruise	Lunar Orbit	Descent & Landing	Surface
Total # kbits sent (buffered)	237179	69120	7776	216750552
Time allocated for transmission (hours)	96	12	0.67	288
Link availability	100%	50%	100%	80%
Buffered data bitrate (kbps)	0.69	3.20	3.24	261
Real-time (telemetry, SOH) data bitrate (kbps)	4.00	4.00	4.00	15
Total data bitrate (kbps)	4.69	7.20	7.24	276
Overhead for protocol (kbps)	1.17	1.80	1.81	69
Total bitrate before margin (kbps)	**5.86**	**9.00**	**9.05**	**345**
10% Margin (kbps)	0.59	0.90	0.91	35
Total data bitrate	**6.4**	**9.9**	**10.0**	**380**
Channel bitrate	**10.0**	**10.0**	**10.0**	**380**
Channel Utilization	64.4%	99.0%	99.6%	100%

4.4.1.3 Computing

The avionics system utilizes a 133MHz processor. Maximum processing throughput occurs during lunar descent, when basic telemetry, operating system and SOH data needs combine with Lidar, Star Camera and NRT video of the landing. High computational loads are handled by process-specific boards within the flight computer's cPCI chassis. Due to limitations on bus speed within the computer, video data is passed directly to cards. Video data to be transmitted is handled by hardware H.264 encoding and queued for transmission. Hard real-time control is handled by dedicated microprocessors.

The spacecraft maintains 1.2GB of storage capacity to store software and act as a buffer to telecom throughput. While the lander uses the storage capability during cruise and landing, the driving storage needs for lander are from payload allocations.

4.4.2 Rover Resources

4.4.2.1 Power

The rover power budget is displayed below. The solar panels are sized for continous rover operation with component duty cycles as shown. Batteries enable surges to above solar input power as needed, and charge when power draw is lower. Instead of explicit margin, unexpected power in or consumed is mitigated through adjusting overall rover duty cycle to less than 100% operation by entering a low power mode to charge batteries. Mission baseline objectives can be met with less than 50% rover duty cycle.

4.4.2.2 Communications

During flight, communication from the rover is allocated as state of health (SOH) data and transmitted from the rover to the lander via the Lander-Rover communication channel and then via the Lander-Ground communication system to earth. This is book-kept as SOH data in the lander communications budget.

Once on the surface, the rover has two possible communication modes. Under nominal conditions, rover communication occurs through a high-gain actively pointed helical antenna. This antenna provides 380kbps with 3dB link margin. Under off-nominal conditions (e.g., failure of the pointing system, etc.), rover communication occurs through a set of medium-gain patch antennas aimed to cover the sky under all conditions in which the rover can operate. These antennas provide 8dB over a combined 120-degree angle in both horizontal and vertical directions. The patch antenna system provides 60kbps transmission rate.

Table 4-4: Rover communication budget summary

Package Bitrates	Low Bandwidth	High Bandwidth
Total # kbits sent (buffered)	5,994,000	204,073,000
Time allocated for transmission (hours)	288	288
Link availability	80%	80%
Buffered data bitrate (kbps)	7	246
Real-time (telemetry) data bitrate (kbps)	15	15
Total data bitrate (kbps)	22	260
Overhead for protocol (kbps)	5	65
Total bitrate before margin (kbps)	**39**	**326**
10% Margin (kbps)	4	32
Total data bitrate	**43**	**358**
Channel bitrate	**60**	**380**
Channel Utilization	72%	95%

4.4.2.3 Computing

The avionics system utilizes a 133MHz processor. Rover processing is dominated by state estimation, antenna pointing, video processing, and compression. High computational loads are handled by process-specific boards within the flight computer's cPCI chassis. Due to limitations on bus speed within the computer, video data is passed directly to these process specific cards.

The flight computer's chassis accommodates up to seven boards in addition to the main processor and cPCI controller. Therefore, this design leaves a 72% margin in available computation.

The rover maintains 100GB of storage capacity to store software and act as a buffer to telecom throughput. Storage needs are dominated by high definition video. At 380 kbps, a maximum of less than 100GB of data will be transmitted throughout the mission. The requirement for high storage capacity derives from the need to sort and prioritize stored video prior to transmission. Payloads are nominally allocated 256 MB of storage to buffer data transmission.

4.5 Payload Interfaces

4.5.1 Lander Payload Interfaces

4.5.1.1 Mechanical

Payloads are attached on the spacecraft in the four locations specified in Figure 4-1, Figure 4-2, and Figure 4-3. Details of the attachment interface will be defined as payloads are manifested.

4.5.1.2 Electrical

Electrical interface is TBD but is nominally either MIL-STD 1553b or SpaceWire interface. Connectors for interfacing are TBD and largely depend on customer specifications.

4.5.1.3 Thermal

The lander is capable of both passively and actively thermally regulating temperature of payloads. Details of the thermal interface will be defined as payloads are manifested.

4.5.2 Rover Payload Interfaces

4.5.2.1 Mechanical

Payloads are attached on the spacecraft in the locations specified Figure 4-4, Figure 4-5, and Figure 4-6. Details of the attachment interface will be defined as payloads are manifested.

4.5.2.2 Electrical

The entire 110 kg of rover payload may draw up to 20 W average power. The maximum peak power draw is 50 W. The available voltages are 28 V, 12 V, 5 V, 3.3 V and 1 V DC. The connectors used are dependent on payload power needs. Electrical interface is TBD but is nominally either MIL-STD 1553b or SpaceWire interface. Connectors for interfacing are TBD and largely depend on customer specifications.

4.5.2.3 Thermal

Passive thermal control can be provided for payloads as a standard service. The maximum heat production for an individual payload will be determined when the full payload manifest is determined. Should the rover payload fail when exposed to the mission thermal conditions, the failure must not damage rover components. Payloads requiring passive thermal control must mount to the main thermal strap in the rover chassis. The thermal strap is high thermal conductivity carbon composite. The thermal interface to the strap is T-pli 220.

4.6 Integration

4.6.1 Lander Payload Integration

4.6.1.1 Schedule

The lander payload is integrated 3 months before launch.

4.6.2 Rover Payload Integration

4.6.2.1 Schedule

The rover payload is integrated 3 months before launch.

5 Pricing

Payloads are priced per kilogram, with a guaranteed minimum of power and communications support for each kilogram purchased. Additional power and communications services can be purchased, at roughly the marginal cost of raising power or communication availability. Volume is generous, but surcharges are possible for payloads that greatly exceed their pro-rata share. Prices are higher for payloads on rovers, because they benefit from the extra services of mobility and daytime thermal control.

Lander Prices
Mass: Up to 110 kg w/ rover; 210 kg w/o rover
Cost:[3] $1.8M / kg
Power: 300 Whr per kg mass purchased (Additional watt-hour is $300 / Whr)
Comm: 100 MB per kg mass purchased (Additional megabyte is $2K / MB)

Rover Prices
Mass: Up to 110 kg
Cost:[3] $2M / kg
Power: 150 Whr per kg mass purchased (Additional watt-hour is $600 / Whr)
Comm: 50 MB per kg mass purchased (Additional megabyte is $4K / MB)

5.1 Payment Plan

A sample standard contract follows the general timeline shown in Table 5-1.

Table 5-1: Sample payload contract payment schedule

Time	Progress Payment
Contract signing	15%
Launch – 24 months	15%
Launch – 18 months	20%
Launch – 12 months	20%
Launch – 6 months	20%
Post-mission	10%

5.2 Contacts

For more information, please contact:

David Gump

President, Astrobotic Technology Inc.

412-682-3282

David.Gump@astrobotictech.com

6 Appendix

6.1 List of acronyms

ACS	Attitude Control System
GNC	Guidance, Navigation, and Control
IMU	Inertial Measurement Unit

6.2 List of figures

6.3 List of tables