National Aeronautics and Space Administration

Lunar Polar Volatiles Explorer (LPVE) Mission Concept Study

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LPVE Mission Concept Study

Appendices

Executive Summary

The purpose of this study was to determine the feasibility of a mission to investigate the possibility of volatiles in permanently shadowed areas of the lunar poles - the Lunar Polar Volatiles Explorer (LPVE). The overall science goals and objectives were provided as guidelines by the Decadal Survey Inner Planets Panel, with the goal of determining whether such a mission could be accomplished within a Principal Investigator (PI)-led mission cost cap (i.e., New Frontiers). This study was conducted by Marshall Space Flight Center's, Robotic Lunar Lander Development Project team in partnership with the Johns Hopkins University/Applied Physics Laboratory (JHU/APL) and leveraged previous mission analysis, trades, and options for concepts developed by this team since 2005.

The Lunar Polar Volatiles Explorer concept involves placing a lander and rover (with an instrument payload) in a permanently sun-shadowed lunar polar crater. The rover will carry a suite of science instruments to investigate the location, composition, and state of volatiles. While previous orbital missions have provided data that support the possibility of water ice deposits existing in the polar region, this LPVE concept seeks to understand the nature of those volatiles by direct in-situ measurement. A prospecting strategy is employed to enable lateral and vertical sampling only where higher hydrogen concentrations are detected, thus eliminating the criticality of statistically significant numbers and distributions of samples required by stochastic approaches.

The LPVE concept's deterministic prospecting approach eliminates the need for stochastic sampling strategies. Both a basic and robust instrument suite were developed to meet the science objectives by priorities developed in subsequent discussions with the mission concept's Science Champion. The complete set of instruments includes: neutron spectrometers, downhole imaging, a gas chromatograph/mass spectrometer, x-ray diffraction, exospheric volatiles measurement, surface imaging and a drill/sample acquisition system for obtaining subsurface samples.

The spacecraft is launched on a single Atlas V 401 Launch Vehicle. In order to ensure mission cost caps would be met, this mission concept utilizes a lander to deliver either a battery- or Advanced Stirling Radioisotope Generator (ASRG)-powered rover to the surface. The lander is of a minimal capability, making use of a high-pressure, high thrust-to-weight ratio propulsion system for landing but relying on rover-based avionics and sensors to the maximum extent to enable precision landing in a permanently shadowed crater's Earthshine zone. The lander would be nonfunctional after the rover departs with the instrument suite to prospect for volatiles.

The rover carries the power system (battery or ASRG) as well as all of the instruments. The battery power system supports only 4.4 days of surface operations, accomplishing priority 1 science objectives within battery life restrictions (e.g., not surveying the lateral distribution area suggested by the Decadal ground rules). The ASRG powered rover enables a full year of surface operations that can accomplish all science objectives. A reduced ASRG instrument suite and mission duration was also considered that fully met all priority 1 science objectives within the New Frontiers cost cap.

Development of the LPVE mission would start in FY2013 for an October 2018 launch. Total mission costs vary with the Rover's power system and instrument configurations. The ASRG rover mission with a full instrument complement costs $1132 million, the battery rover mission costs $972 million, and the ASRG-based reduced mission costs $1046 million (all in FY15 dollars, including reserves).

1. Scientific Objectives

Science Questions and Objectives

The polar regions of the Moon have long been known to be a trap for solar system volatiles due to the low temperature of permanently shadowed areas (Urey, 1952; Watson et al. 1961; Arnold, 1979). Additionally, it has long been known that the permanenty shadowed regions near the lunar poles are cold enough to store any volatiles that enter them (Paige et al. 2010; Vasavada et al., 1999). The volatiles trapped there are of interest because they record not only those released from the interior of the Moon during its geologic evolution, but also species derived from the solar wind, cosmic dust, and comets. Thus, the volatiles in the cold traps provide a record of the evolution of the Moon, the history of the sun, and the nature of comets that have entered the inner solar system over the last several billion years.

Several missions have provided data that support the possibility of water ice deposits in the polar regions. The Clementine bistatic radar experiment suggested possible ice mixture inside Shackleton crater near the Moon's south pole. Lunar Prospector detected increased hydrogen levels in the polar regions, as has the LRO neutron spectrometer (Mitrofanov et al., 2010). Neither instrument could determine the chemical form of the hydrogen. The NASA Mini-SAR andM3 instruments on the Indian Chandrayaan-1 spacecraft respctively detected evidence for water ice in north polar craters (Spudis et al., 2010) and bound H_2O or OH in illuminated regions (Pieters et al., 2009). Finally, LCROSS detected the presence of volatiles contained within the ejecta excavated by its impact.

The next stage in understanding polar volatiles is to determine the species and their form and distribution (both horizontally and vertically); those determinations must be made in situ.

Science Questions

Polar volatile deposits contain a record of the volatile history of the Moon and the inner solar system. Our current knowledge is limited to knowing that volatiles exist in some form in the lunar polar regions. The goals of LPVE are to determine the volatile bearing species, their form and their distribution.

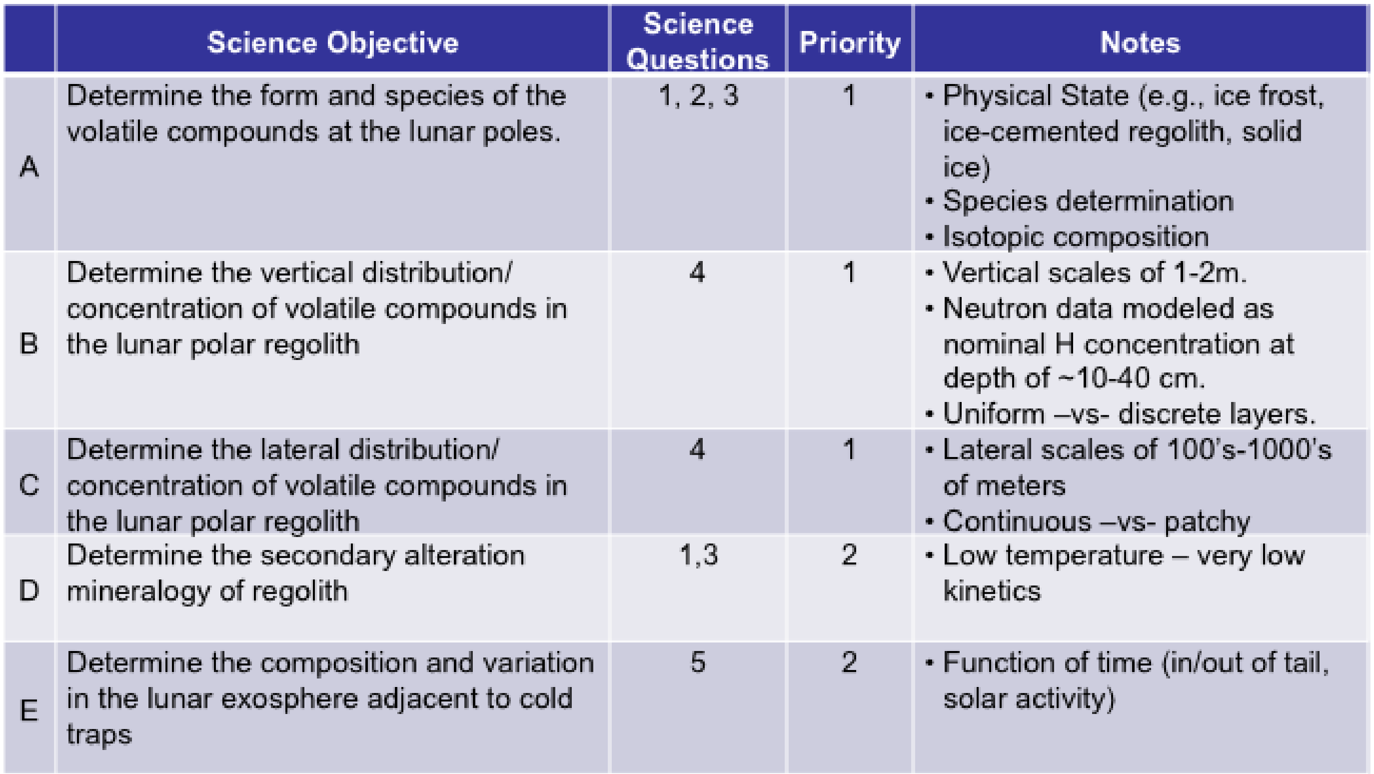
The Inner Planets Panel defined the fundamental science questions to be addressed by the LPVE mission:

1. What is the lateral and vertical distribution of the volatile deposits?
2. What is the chemical composition and variability of polar volatiles?
3. What is the isotopic composition of the volatiles?
4. What is the physical form of the volatiles?
5. What is the rate of the current volatile deposition?

Science Objectives

The Inner Planets Panel identified a series of five specific Science Objectives that address the five fundamental Science Questions regarding polar volatile deposits on the Moon. The primary objectives are to constrain the location, composition, and state of the volatiles.

Table 1: Science Objectives & Priorities



	Science Objective	Science Questions	Priority	Notes
A	Determine the form and species of the volatile compounds at the lunar poles.	1, 2, 3	1	• Physical State (e.g., ice frost, ice-cemented regolith, solid ice) • Species determination • Isotopic composition
B	Determine the vertical distribution/ concentration of volatile compounds in the lunar polar regolith	4	1	• Vertical scales of 1-2m. • Neutron data modeled as nominal H concentration at depth of ~10-40 cm. • Uniform –vs- discrete layers.
C	Determine the lateral distribution/ concentration of volatile compounds in the lunar polar regolith	4	1	• Lateral scales of 100's-1000's of meters • Continuous –vs- patchy
D	Determine the secondary alteration mineralogy of regolith	1,3	2	• Low temperature – very low kinetics
E	Determine the composition and variation in the lunar exosphere adjacent to cold traps	5	2	• Function of time (in/out of tail, solar activity)

The Science Objectives for the Lunar Polar Volatiles Explorer mission concept are achieved through a series of measurements made by the scientific payload package. The instruments considered for this concept include the following:

- Rover neutron spectrometer
- Drill capable of penetrating 2 meters
- Sample acquisition system
- Downhole neutron spectrometer
- Downhole imager
- Gas chromatograph / mass spectrometer (GCMS)
- X-ray diffraction
- Ground penetrating radar
- Exospheric mass spectrometer

Science Traceability

In order to significantly advance our understanding of lunar polar volatiles and what they can tell us about lunar and solar system history, a mission capable of extensive surface exploration is required as numerous samples must be obtained and analyzed.

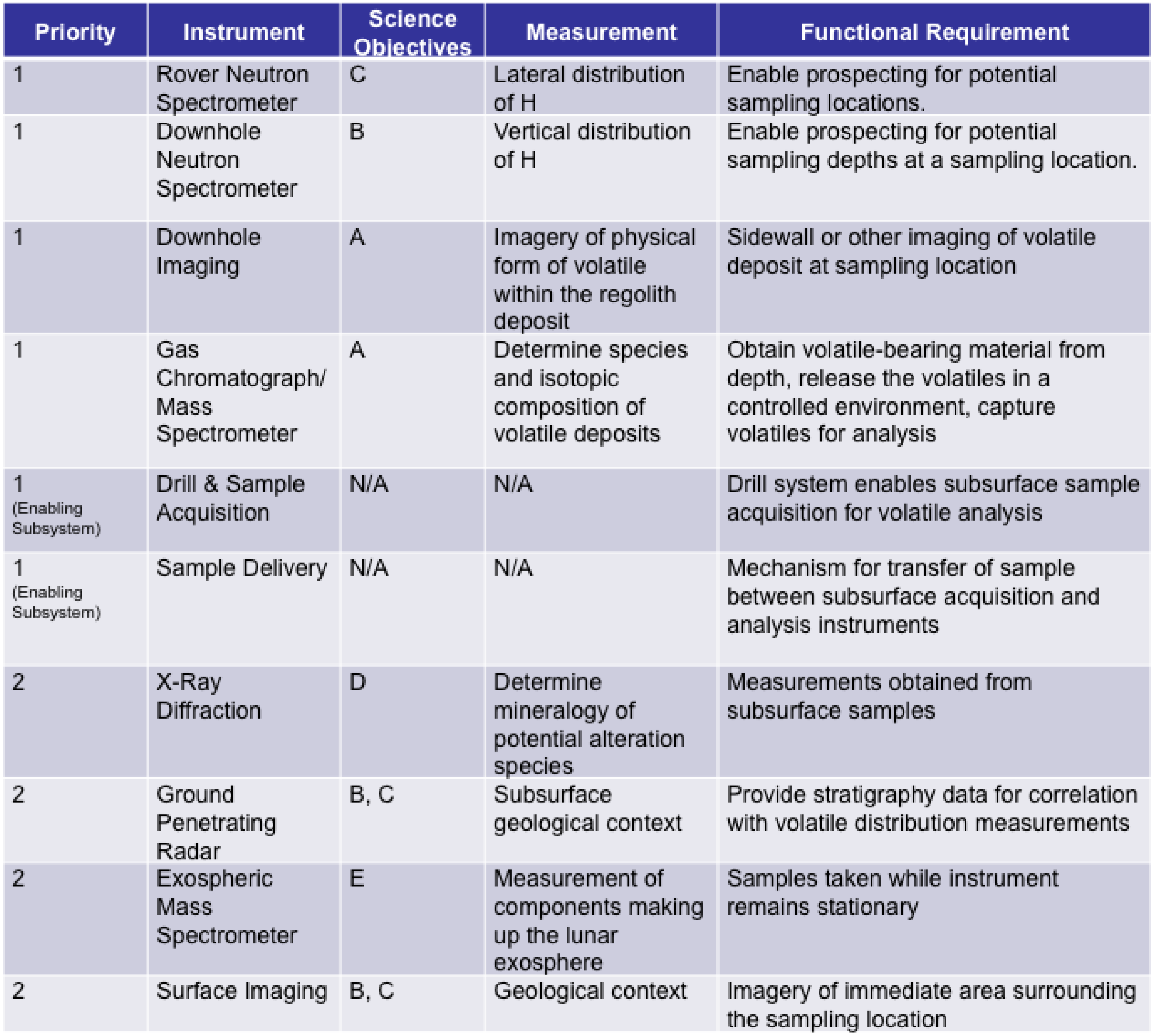
We do not understand the manner in which volatile species are stored, nor how they evolve, once in a cold trap. Since orbital remote sensing data do not have the resolution to map the volatiles within a cold trap, we do not understand how they are spatially distributed (in either the horizontal or vertical dimension). Therefore, a cold trap must be explored to map the distribution.

As noted, since we do not understand the spatial distribution, we do not know a priori where to sample. The sampling strategy defined as part of this study relies on a neutron spectrometer to locate areas of high H content that would indicate H-bearing volatiles. To allow high spatial resolution and detection of low concentrations, and to map the H-bearing areas with sufficient resolution to determine where to sample, the instrument must be in close proximity to the surface and cross the surface at a relatively low velocity. These requirements are best fulfilled by a rover.

The instrument suite identified in the study provides the data necessary to obtain the appropriate samples to answer these questions. First, the rover neutron spectrometer provides information of the lateral extent of the volatile deposits. Additionally it is used to optimize the drilling location. Next, the drill provides access to the upper two meters of the regolith, the upper part of the regolith that is most likely to contain volatile species. Once a borehole has been drilled, several instrument make measurements within it. The downhole imager will look at the physical state of the volatiles, while the downhole neutron spectrometer will measure both the vertical variability and also help determine the best place to sample. Finally, a sample acquisition system will bring samples from chosen depths to the rover for analysis by the GCMS. The GCMS will determine the chemical and isotopic composition of the volatiles.

Table 2 summarizes the traceability of the instruments from the science objectives, to measurements, and to functional requirements.

Table 2: Science Instrument Traceability



Priority	Instrument	Science Objectives	Measurement	Functional Requirement
1	Rover Neutron Spectrometer	C	Lateral distribution of H	Enable prospecting for potential sampling locations.
1	Downhole Neutron Spectrometer	B	Vertical distribution of H	Enable prospecting for potential sampling depths at a sampling location.
1	Downhole Imaging	A	Imagery of physical form of volatile within the regolith deposit	Sidewall or other imaging of volatile deposit at sampling location
1	Gas Chromatograph/ Mass Spectrometer	A	Determine species and isotopic composition of volatile deposits	Obtain volatile-bearing material from depth, release the volatiles in a controlled environment, capture volatiles for analysis
1 (Enabling Subsystem)	Drill & Sample Acquisition	N/A	N/A	Drill system enables subsurface sample acquisition for volatile analysis
1 (Enabling Subsystem)	Sample Delivery	N/A	N/A	Mechanism for transfer of sample between subsurface acquisition and analysis instruments
2	X-Ray Diffraction	D	Determine mineralogy of potential alteration species	Measurements obtained from subsurface samples
2	Ground Penetrating Radar	B, C	Subsurface geological context	Provide stratigraphy data for correlation with volatile distribution measurements
2	Exospheric Mass Spectrometer	E	Measurement of components making up the lunar exosphere	Samples taken while instrument remains stationary
2	Surface Imaging	B, C	Geological context	Imagery of immediate area surrounding the sampling location

2. High-Level Mission Concept

Concept Maturity Level

This study was conducted as a Concept Maturity Level (CML) 3 – 4 study (see Appendix B for Concept Maturity Level Definitions). A staged cradle lander mission architecture matured for the Robotic Lunar Exploration Program (RLEP) was used as a point of departure. Benefits from technology advances and progress from similar mission concept developments were incorporated where relevant. The study documented in this report is intended to look at the trade space and potential feasible solutions against a floor-level mission.

Mission Overview

The following mission constraints and assumptions were defined by the Inner Planets Panel to establish initial ground rules for conducting the study.

1. Launch in the 2018-2023 timeframe.
2. Landing site is unconstrained, but measurement sites must be located in a permanently shadowed region (permanently shadowed from the Sun, either in Earthshine or non-Earthshine) and an environment at a minimum temperature of 25K.
3. Ultimate precision landing is not required except by the constraints of the mission concept of operations.
4. Subsurface access is required. Experience with Phoenix shows that typical robotic arms do not have the required strength to excavate through a frozen regolith; therefore, subsurface access is required consistent with the capabilities of a drill or auger assembly.
5. Instruments may have limited deployment; the strawman payload does not require surface contact (other than that needed for subsurface access).
6. Direct-to-Earth communications is the first-order desire, however it is an open trade as to whether a relay spacecraft would be required.
7. Mission duration is moderate, depending on the concept of operations. It is estimated that a four-week minimum duration could achieve the science goals, although mission length is an open trade.
8. Assume that nuclear power options are available if they are necessary to enable the mission.
9. Investigate if non-nuclear options are feasible in the baseline mission.
10. Science will be accomplished with collection and analysis of ten to twenty samples spaced roughly evenly over an area of 10 km^2.

Two basic mission concepts were advanced. The first, constrained by cost limitations defined by the decadal guidelines, utilizes only battery power for rover operations. This concept would provide up to 20 samples over 5 sites and a total rover traverse of about 6 km. In this scenario, the rover surface mission duration would be limited by battery life to approximately 4.4 days.

The second concept uses an ASRG as the primary power source. This mission concept would be capable of meeting all mission science objectives and could significantly exceed the number of samples and the sample area defined by the Inner Planets Panel. This concept would result in a mission duration in excess of 1 year and an estimated total traverse of 174 km covering 115 sites and 460 total samples. Though this concept exceeds the defined total mission budget ($1.05 billion in FY 2015 dollars), a derivative concept that would still use an ASRG as the rover power source could meet all primary mission objectives and fall within the defined cost guidelines. This “ASRG-Lite” mission concept utilizes the full ASRG mission’s technical design, but constrains the planned surface operation duration to 3 months and includes only the priority 1 instruments in order to limit the mission’s life cycle costs. In this operational scenario, an estimated total traverse of 36 km could be achieved covering 25 sites and a total of 100 samples.

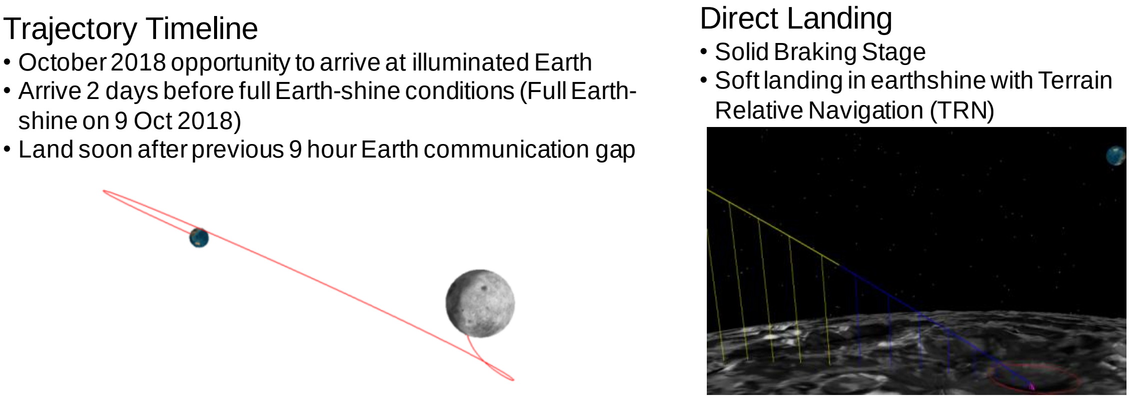
Table 1 provides a comparison of the science objectives obtained by each of these mission options. Specific cost details are provided in section 5. Additional lander and rover descriptions are given in the Flight System section of this report.

Table 3: Science Objectives vs. Rover Options

Science Objective	Priority	Battery Rover	ASRG Rover	ASRG-Lite Rover
Determine the form and species of the volatile compounds at the lunar poles	1	Instrument complement supports if H found	Instrument complement supports if H found	Instrument complement supports if H found
Determine the vertical distribution/concentration of volatile compounds in the lunar polar regolith	1	Instrument complement supports if H found	Instrument complement supports if H found	Instrument complement supports if H found
Determine the lateral distribution/concentration of volatile compounds in the lunar polar regolith	1	Limited lateral measurements due to battery rover range	Instrument complement supports if H found	Instrument complement supports if H found
Determine the secondary alteration mineralogy of regolith	2	Not supported by Instrument complement	Instrument Complement Supports	Not supported by Instrument complement
Determine the composition and variation in the lunar exosphere adjacent to cold traps	2	Not supported by Instrument complement	Instrument Complement Supports	Not supported by Instrument complement

Figure 1 shows the top-level LPVE mission design concept. The integrated lander and rover are launched together as a single spacecraft on an Atlas V 401 from Cape Canaveral, Florida. After ascent, a parking orbit of less than one orbit, and trans-lunar injection, the spacecraft will separate from the carrier and be targeted for its landing site through a series of trajectory correction maneuvers.

A five-day ballistic trajectory will be used with a direct landing approach at lunar arrival. This mission design reduces complexity and allows use of a solid rocket motor for primary descent braking, maximizing the payload mass to the surface while minimizing total mass. The braking stage will provide the vast majority of the ΔV to land. After completion of the braking burn, the lander will separate from its solid rocket motor and perform a soft landing using onboard liquid hypergolic propulsion. Terrain Relative Navigation (TRN) will be used for precision landing within a pre-selected permanently sun-shadowed but non-Earth shadowed region.


Trajectory Timeline
- October 2018 opportunity to arrive at illuminated Earth
- Arrive 2 days before full Earth-shine conditions (Full Earth-shine on 9 Oct 2018)
- Land soon after previous 9 hour Earth communication gap

Direct Landing
- Solid Braking Stage
- Soft landing in earthshine with Terrain Relative Navigation (TRN)

Figure 1: Mission Design Concept

The landing must be in a Permanently Shadowed Region (PSR) shadowed from the Sun but not shadowed from Earth, resulting in “Earthshine” conditions. Based on initial assessment of candidate landing site opportunities, an October 2018 launch was targeted. This would result in arrival just prior to full Earthshine conditions to maximize the direct-to-Earth communication opportunity during initial surface operations.

Once landed, the rover will egress from the lander and begin the surface science phase of the mission. After rover egress, the lander has no further functions. Table 2 provides a summary of the notional rover instruments assumed for the LPVE study along with their associated mass and power with margin allowance.

Table 4: Notional LPVE Instruments

Lander Payload	Objective	Mass kg	Power watts
Rover Neutron Spectrometer	Lateral distribution of H	0.7	2.3
Downhole Neutron Spectrometer	Vertical distribution of H	0.8	2.9
Downhole Imaging	Imagery of volatiles	0.3	1
Gas Chromatograph/Mass Spectrometer	Determine species of volatiles	13	10.4 (avg) 47 (peak)
Drill & Sample Acquisition		41.6	98
Sample Delivery		8.5	34
X-ray Diffraction	Mineralogy	0.9	12
Ground Penetrating Radar	Subsurface geology	3.5	8
Exospheric Mass Spectrometer	Measure exospheric species	6.5	26
Surface imaging	Geological context	1.1	11

The LPVE mission is not without several challenges. As noted above, providing a power system solution that meets full mission science objectives within the desired mission cost constraint is a significant challenge.

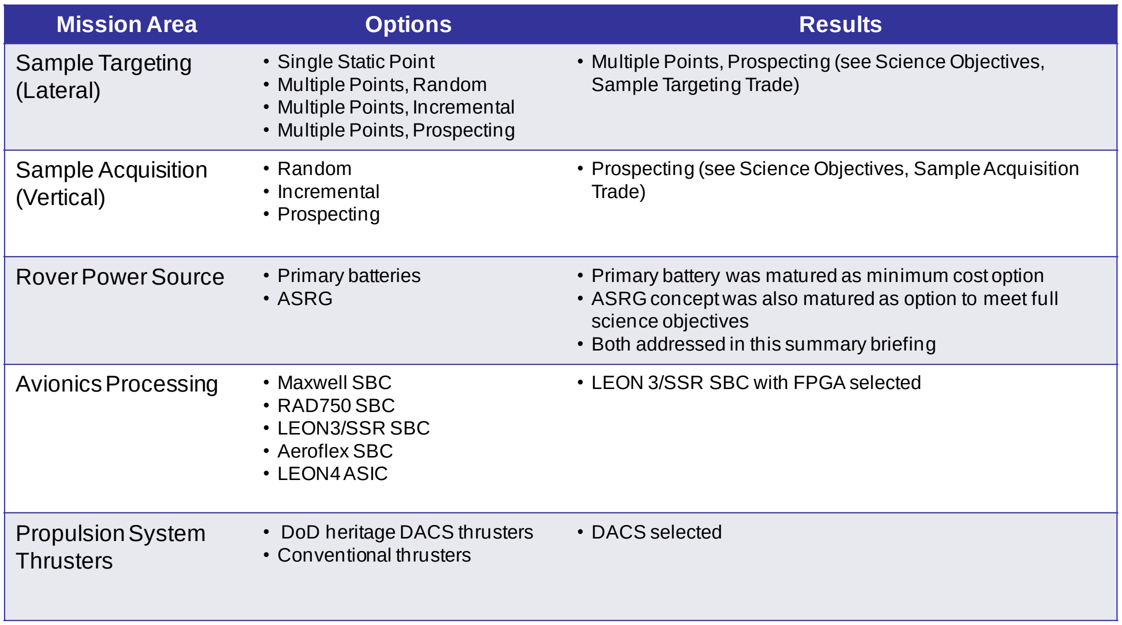
Communication opportunities within a PSR will pose the primary landing site constraint. Because there is no available lunar orbiting communications asset, direct line of sight between the rover and Earth is required in order to provide communication. A direct communication path can only be obtained in a PSR when the landing site is visible from Earth, resulting in Earthshine conditions. The Earthshine present in this scenario is also required to support optical terrain-relative navigation for precision landing.

Rover thermal management is also a primary challenge due to the temperatures of approximately 40K in the surface mission’s permanently shadowed regions. The thermal control system must accommodate cruise operations in a relatively warm environment while preserving heat during the extreme cold of surface operations. Use of a thermally isolated Warm Electronics Box (WEB) and a variable heat transfer link between the WEB and radiator enable a single thermal subsystem to accomplish both.

Key Trades

Table 5 provides a summary of the key trades performed as part of the LPVE study.

Table 5: Summary of Trades Performed



Mission Area	Options	Results
Sample Targeting (Lateral)	• Single Static Point • Multiple Points, Random • Multiple Points, Incremental • Multiple Points, Prospecting	• Multiple Points, Prospecting (see Science Objectives, Sample Targeting Trade)
Sample Acquisition (Vertical)	• Random • Incremental • Prospecting	• Prospecting (see Science Objectives, Sample Acquisition Trade)
Rover Power Source	• Primary batteries • ASRG	• Primary battery was matured as minimum cost option • ASRG concept was also matured as option to meet full science objectives • Both addressed in this summary briefing
Avionics Processing	• Maxwell SBC • RAD750 SBC • LEON3/SSR SBC • Aeroflex SBC • LEON4 ASIC	• LEON 3/SSR SBC with FPGA selected
Propulsion System Thrusters	• DoD heritage DACS thrusters • Conventional thrusters	• DACS selected

Sample Targeting

Data currently available are not sufficient to support selection of specific sample target locations. An operational scenario relying on sampling either at random locations or an evenly spaced pattern of locations (represented in Figure 2, sampling sites at arrow locations) would require sufficient mission duration to acquire statistically significant samples over a given area. This approach would necessitate a prohibitively long mission life for the stated budget objectives. In addition, this study assumes a more direct approach wherein sampling is done only in areas where there is a high probability of obtaining H-bearing volatiles, represented by the shaded areas in Figure 2.

Prospecting using the neutron spectrometer would enable sampling at high volatile potential targets thus addressing the absence of existing data for target selection. The prospecting and sampling scenario established during the LPVE study uses the neutron spectrometer to measure neutron levels on the surface. Neutron minimums would be located while traversing the PSR then a perpendicular profile would be run to define exact sampling locations. Drilling and sampling would be performed at minimum neutron locations.

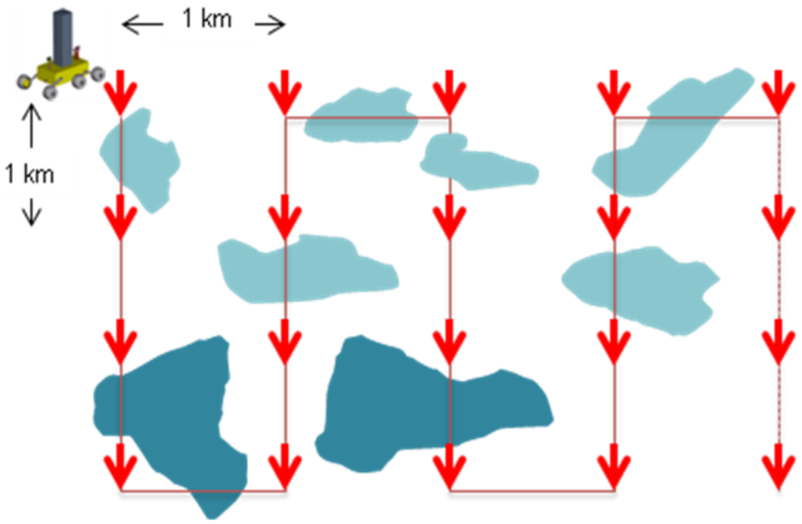


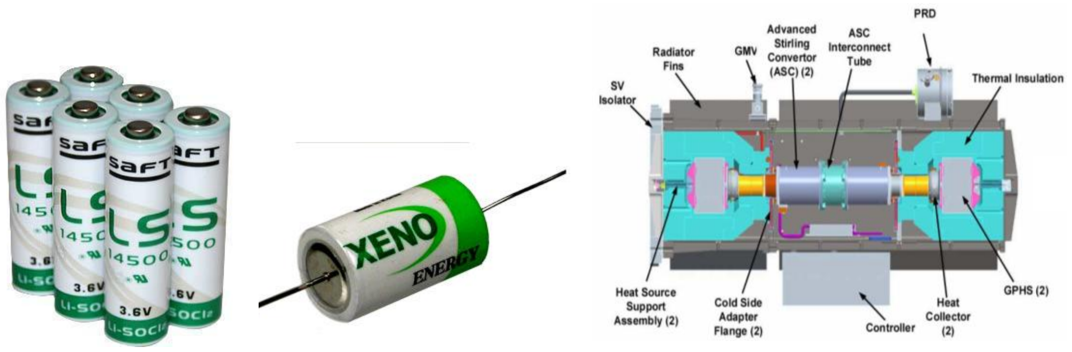
Figure 2: Prospecting and Sampling Scenario

Sample Acquisition Trade

Vertical locations of targets of interest pose similar challenges as lateral sample locations discussed above. Random or incremental vertical samples may not find volatiles or may mischaracterize their vertical distribution. “Down-hole” prospecting, using a neutron spectrometer embedded in the drill shaft, is considered to be the most efficient method of determining the depth at which to sample since it can be done as the drilling is done and does not require a separate downhole experiment.

Rover Power Source

As discussed at the beginning of this section, a primary (non-rechargeable) battery power source for the rover offers the minimum mission cost solution but limits the total surface mission duration to just under 4.5 days. Consequently, the battery rover mission meets Priority 1 mission objectives with limited lateral distribution measurement, but does not meet Priority 2 objectives. The ASRG was assessed as an alternate rover power source. With an ASRG as the primary power source and a relatively small set of rechargeable secondary batteries to handle peak power loads, full primary and secondary mission science objectives can be met. The derivative ASRG-Lite Rover could meet all Priority 1 mission objectives within the defined cost guidelines if the planned surface operation duration is limited to 3 months and the instrument suite is limited to only the priority 1 instruments.



Li-SOCl$_2$ Batteries **ASRG Cross-Section**

Figure 3: Rover Power Sources

Avionics Processing

Several avionics processor options were considered during the LPVE study. A minimum power but also relatively low TRL single board computer with a field programmable gate array (FPGA) co-processor was ultimately selected for the mission architecture. The selected processing approach was driven by high processing rate requirements for precision landing terrain relative navigation as well as the power constrained minimum cost battery-powered rover concept. However, a future trade study is recommended if the notionally selected processing approach proves to be of insufficient TRL maturity or if an ASRG rover is selected.

Propulsion System Thrusters

High thrust to weight Department of Defense (DoD) heritage Divert and Attitude Control System (DACS) thrusters were assessed against conventional thruster technology. The DACS thrusters are significantly lighter and provide smaller volume for packaging compared to conventional thrusters. The smaller packaging volume will also have a positive systems level ripple effect due to lighter mounting structure, reduced thruster plume impingement concerns, etc. Refer to Figure 4 for a sense of the difference in size between a conventional "COTS" 100 lbf thruster and the DACS 100 lbf thruster (lower left and lower right photos, respectively). The DACS thrusters also offer a potential cost savings due to the economy of scale realized by the relatively large production rate for DoD applications.

However, the DACS thrusters are not yet qualified for the assumed LPVE MON-25 oxidizer or the LPVE propulsion system mission duty cycles. Note, however, that risk reduction testing is ongoing in a separate development effort to assess performance with MON-25 and an expected typical lunar lander duty cycle.

By contrast, qualified conventional thrusters are available in the necessary performance range but at a mass, volume, and possibly cost impact.

DACS thrusters were selected for the LPVE mission architecture as the minimum mass solution. The option to switch to conventional thrusters is available should the on-going risk reduction testing of the DACS thrusters prove unsuccessful.

Figure 4: Thruster Options

Recommended Future Trades/Analysis

There were several options not considered because of a lack of time for this study that should be considered in future studies. Primary trades for further consideration are shown below.

Table 6: Future Trades

Trade	Purpose	Notes
Lunar Communications Relay	Enable mission operations beyond Earthshine regions (i.e. PSR with no Earthshine) and time periods	• Relay spacecraft launch would be as co-manifested spacecraft with LPVE • SOMD estimates short duration comanifested lunar relay cost in the $50M range (FY09 $, no reserves)
High TRL Processor	Adjust Avionics architecture to a High TRL solution	• LEON3 solution currently under development; maturity risk to concept implementation • Candidates may include Maxwell SBC, RAD750
ASRG Mission Redundancy	Selective addition of redundancy to reduce ASRG mission risks	

Technology Maturity

Required technologies assessed to be below Technology Readiness Level (TRL) 6 are shown in Table 7. See Appendix C for definitions of Technology Readiness Levels. The table shows the development needed for each key technology, the heritage of the technology, and identifies where risk reduction work is ongoing. Technology areas below TRL 6 are addressed in more detail in the Technology Development Plan section of this report. The required technology advancements noted in Table 7 are believed to be achievable and consistent with the mission schedule outlined in the Development Schedule and Schedule Constraints Section. Any other components not listed here are TRL 6 or above.

Table 7: Technology Maturity

Technology Needed	TRL	Development Needed	Risk Reduction Activity	Notes
Rover LIDAR	4	Miniaturize and qualify advanced LIDAR sensors	Yes	Analogies: Optec; Honeybee 3D MiniLIDAR
Drill & Sample Acquisition	4-5	Demonstrate drill performance in relevant ground environment and regolith preparation. Develop and demonstrate sidewall sample acquisition	Yes	Analogies: Honeybee 1-2m Class Prototype Drills, CRUX
Advanced Stirling Radioisotope Generator (ASRG)	4-6	ASRG being developed and qualified by DoD and Glenn Research Center	N/A	Analogies: Radioisotope Thermal Generator (RTG) missions
Terrain Relative Navigation	4	Demonstrate TRN performance in a relevant approach scenario. Characterize and mitigate effects of thruster firings and dust kick-up on TRN optical sensors.	N/A	Precision Landing technology maturation part of ALHAT Program baseline

3. Technical Overview

Instrument Payload Description

The types of science measurements, corresponding science instruments, and their relationships to overall LPVE science goals and objectives have been described in Science Objectives Section of this Report. This study assumed a competed payload.

The overall instrument suite is selected to enable the Decadal science objectives in the most direct and efficient manner given the mission constraints. The instrument suite on the Battery and ASRG-Lite mission concepts accomplish all Priority 1 science, while the full ASRG mission complements accomplish both Priority 1 and 2 science.

Table 8: Mission Instrument Suites

Instrument	Battery Rover	ASRG-Lite Rover	ASRG Rover
Rover Neutron Spectrometer	X	X	X
Downhole Neutron Spectrometer	X	X	X
Downhole Imaging	X	X	X
Gas Chromatograph/Mass Spectrometer	X	X	X
Drill & Sample Acquisition	X	X	X
Sample Delivery	X	X	X
X-Ray Diffraction			X
Ground Penetrating Radar			X
Exospheric Mass Spectrometer			X
Surface Imaging			X

Each instrument is briefly described below, in the approximate order that they are utilized within the concept of operations. Table 9 provides an integrated list of their physical characteristics, and more extensive data rate information is provided in Tables 18 and 19.

Rover Neutron Spectrometer

The Rover Neutron Spectrometer (RNS) provides a measurement of hydrogen content in the immediate vicinity of the instrument, enabling detection of sites that maximize the probability of holding significant volatile deposits. The RNS is body-mounted on the front of the Rover. As soon as the Rover is deployed from the Lander, the RNS obtains measurement of the local hydrogen signature at the landing site. This data, and the corresponding subsurface sampling at that site, provide a “ground truth” measurement to initially set the RNS thresholds that will be used to determine subsurface sampling sites. The RNS then takes continuous data while the Rover is moving, measuring the lateral distribution of H and enabling the Rover to prospect for the next high H concentration sampling site. The RNS is placed in a standby mode when the Rover is stationary.

Item	Value	Units
Rover Neutron Spectrometer (Lunar Prospector/HYDRA heritage)	1	per Rover
Number of channels	1	serial digital
Size/dimensions	18x12x6	cm
Instrument mass **without** contingency (CBE)	0.5	Kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE + Reserve)	0.65	Kg
Instrument average payload power **without** contingency	1.8	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	2.3	W
Instrument average science data rate **without** contingency	0.5	kbps
Instrument average science data rate contingency	0	%

Downhole Neutron Spectrometer

The Downhole Neutron Spectrometer (DNS) is a single unit integrated within the drill string, just behind the drill bit. Since random or incremental vertical sampling locations may not find volatiles or may mischaracterize their vertical distribution, the DNS is operated during drilling operation to prospect for the highest H concentrations where samples are to be taken for volatile analysis. The DNS data also provide measurements of the vertical distribution of volatiles within the regolith at each drilling site.

Item	Value	Units
Downhole Neutron Spectrometer (Lunar Prospector/D-HYDRA heritage)	1	per Rover
Number of channels	1	counts
Size/dimensions	69 x 2.9(dia)	cm
Instrument mass **without** contingency (CBE)	0.2	Kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE + Reserve)	0.26	Kg
Instrument average payload power **without** contingency	2.25	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	2.9	W
Instrument average science data rate **without** contingency	0.5	kbps
Instrument average science data rate contingency	0	%

Downhole Imaging

The Downhole Imaging Camera is a single unit integrated within the drill string, just behind the DNS. This Camera obtains sidewall images of a sampling site within a drilled hole prior to physically acquiring the sample. These sidewall images provide information on the physical form of the volatiles within the regolith.

Item	Value	Units
Downhole Imaging Camera (MER MI, CRUX Downhole heritage)	1	per Rover
Number of channels	1	each
Size/dimensions	5 x 2(dia)	cm
Instrument mass **without** contingency (CBE)	0.2	Kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE + Reserve)	0.26	Kg
Instrument average payload power **without** contingency	0.8	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	1	W
Instrument average science data rate **without** contingency	50,332	Kb/day
Instrument average science data^ rate contingency	0	%

Drill & Sample Acquisition

The LPVE Drill & Sample Acquisition systems function as enabling hardware for the LPVE instruments. The Drill is body-mounted in the center of the Rover in order to optimize Rover handling characteristics and maximize weight on the drill bit. Once the RNS data has defined the drilling area and the Rover has been parked, drilling will commence. Regardless of the volatile sampling profile, the drill shaft will be lifted from the hole at least every 0.5 meters of penetration in order to ensure power required for cuttings removal doesn't overwhelm the drilling system. Once the downhole sample location has been determined by the DNS, the Sample Acquisition system uses a sidewall coring technique (common in terrestrial applications) to sample a precise sidewall location behind the DNS, and to bring the sample to the surface.

Item	Value	Units
Drill & Sample Acquisition	1	per Rover
Number of channels	1	serial digital
Size/dimensions	1 x 0.5 x 0.5 2 x 0.5 x 0.5	m (1m drill) m (2m drill)
Instrument mass **without** contingency (CBE)	32 50	Kg (1m drill) Kg (2m drill)
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE + Reserve)	41.6 65	Kg (1m drill) Kg (2m drill)
Instrument average payload power **without** contingency	75	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	97.5	W
Instrument average science data rate **without** contingency	10	kbps
Instrument average science data rate contingency	0	%

Sample Delivery

The Sample Delivery mechanism is located on the Rover deck adjacent to the Drill. The mechanism receives the subsurface sample from the Drill, then delivers it through the X-Ray Diffraction (XRD) unit and on to the Gas Chromatograph Mass Spectrometer (GCMS) unit for analysis.

Item	Value	Units
Sample Delivery	1	per Rover
Number of channels	1	serial digital
Size/dimensions	Highly dependent on Drill, XRD, GCMS layout	
Instrument mass **without** contingency (CBE)	6.5	Kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE + Reserve)	8.5	Kg
Instrument average payload power **without** contingency	26	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	33.8	W
Instrument average science data rate **without** contingency	1920	Kb/day
Instrument average science data rate contingency	0	%

X-Ray Diffraction

The X-Ray Diffraction (XRD) instrument is located in the sample delivery pathway between the Drill and the GCMS. The XRD illuminates the sample material with X-rays and measures the scattered X-rays returned to determine the mineralogy and potential alteration species within the regolith. Because this process is non-destructive to the actual volatiles within the regolith, the sample can then be transferred to the GCMS for final analysis.

Item	Value	Units
X-Ray Diffraction (based on MICA design, PIDDP designs)	1	per Rover
Number of channels	1	serial digital
Size/dimensions	10 x 10 x 20	cm
Instrument mass **without** contingency (CBE)	0.7	Kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE + Reserve)	0.9	Kg
Instrument average payload power **without** contingency	9	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	11.7	W
Instrument average science data rate **without** contingency	72,456	Kb/day
Instrument average science data rate contingency	0	%

Gas Chromatograph/Mass Spectrometer

The Gas Chromatograph/Mass Spectrometer (GCMS) receives an unaltered subsurface regolith sample, heats the sample in order to release and capture any volatiles in a controlled environment, and measures the species and isotopic composition of the volatiles. The GCMS is mounted in the vicinity of the Sample Delivery mechanism to minimize disturbance of the samples acquired by the drill. After a GCMS volatile analysis cycle is complete, the remaining sample material is dumped back to the surface and the heating chamber allowed to cool before the next sample is deposited in the GCMS.

Item	Value	Units
Gas Chromatograph/Mass Spectrometer (Viking GCMS, Phoenix TEGA, MSL SAM heritage)	1	per Rover
Number of channels	1	serial digital
Size/dimensions	20 x 43 x 50	cm
Instrument mass **without** contingency (CBE)	10	Kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE + Reserve)	13	Kg
Instrument average payload power **without** contingency	8	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	10.4	W
Instrument average science data rate **without** contingency	48,000	Kb/day
Instrument average science data rate contingency	0	%

Surface Imaging

A Rover-mounted surface imaging camera provides information on the geological context of the sampling locations and measured volatiles.

Item	Value	Units
Surface Imaging (MSL MastCam heritage)	1	per Rover
Number of channels	1	serial digital
Size/dimensions	11 x 29 x 12	cm
Instrument mass **without** contingency (CBE)	0.8	Kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE + Reserve)	1	Kg
Instrument average payload power **without** contingency	8.5	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	11	W
Instrument average science data rate **without** contingency	13,585	Kb/day
Instrument average science data rate contingency	0	%

Ground Penetrating Radar

The Ground Penetrating Radar (GPR) will be operated while the Rover is moving, obtaining data characterizing the subsurface structure of the regolith traversed by the Rover. The resulting stratigraphy data can later be correlated with volatile distribution measurements and surface imagery. It consists of an antenna body-mounted under the Rover, and an electronics box within the warm portion of the Rover.

Item	Value	Units
Ground Penetrating Radar (ExoMars WISDOM heritage)	1	per Rover
Number of channels	1	serial digital
Size/dimensions (underbody-mounted sensor)	10 x 10 x 1	cm
Size/dimensions (electronics)	10 x 6 x 6	cm
Instrument mass **without** contingency (CBE)	2.7	Kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE + Reserve)	3.5	Kg
Instrument average payload power **without** contingency	6	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	7.8	W
Instrument average science data rate **without** contingency	480,800	Kb/day
Instrument average science data rate contingency	0	%

Exospheric Mass Spectrometer

The Exospheric Mass Spectrometer (EMS) measures the species found in the lunar exosphere, providing a ground truth to orbital exospheric measurements. The EMS is mounted in an open area on the top surface of the Rover, and is operated during periods when the Rover is stationary and no other operations are occurring. The EMS measures components making up the lunar exosphere by opening a chamber to the ambient lunar environment, allowing free volatiles within the exosphere to migrate to an open chamber for subsequent analysis.

Item	Value	Units
Exospheric Mass Spectrometer (MOMA, CONTOUR, LADEE heritage)	1	per Lander
Number of channels	1	serial digital
Size/dimensions	20 x 20 x 10	cm
Instrument mass **without** contingency (CBE*)	5	Kg
Instrument mass contingency	30	%
Instrument mass **with** contingency (CBE + Reserve)	6.5	Kg
Instrument average payload power **without** contingency	20	W
Instrument average payload power contingency	30	%
Instrument average payload power **with** contingency	26	W
Instrument average science data rate **without** contingency	48,000	Kb/month
Instrument average science data rate contingency	0	%

Table 9: Instrument Mass and Power

Instrument	Mass (kg)	Mass w/ 30% margin	Average Power (W)	Average Power w/ 30% margin	Size
Rover Neutron Spectrometer	0.5	0.65	1.8	2.3	18x12x6 cm
Downhole Neutron Spectrometer	0.2	0.26	2.25	2.9	69 x 2.9 cm dia
Downhole Imaging	0.2	0.26	0.8	1	5cm x 2cm dia
Gas Chromatograph/Mass Spectrometer	10	13	8	10.4	20 x 43 x 50 cm
Drill & Sample Acquisition	32 (1 meter) 50 (2 Meter)	41.6 (1 meter) 65 (2 Meter)	75	97.5	2m (or 1m) x 50cm x 50cm
Sample Delivery	6.5	8.5	26	33.8	Dependent on Drill, other Instrument layouts
X-Ray Diffraction	0.7	0.9	9	11.7	10 x 10 x 20 cm
Ground Penetrating Radar	2.7	3.5	6	7.8	10 x 10 x 1 cm, plus electronics in WEB
Exospheric Mass Spectrometer	5	6.5	20	26	20 x 20 x 10 cm
Surface Imaging	0.8	1	8.5	11	11 x 29 x 12 cm

The Concept of Operations section provides a further breakdown of the science data rates and volume.

Flight System

The LPVE flight system consists of three elements: a Solid Rocket Motor for braking; a lander stage for descent, precision landing, and rover egress; and a rover for performing the surface science mission.

This study describes two primary rover configuration options. The first uses non-rechargeable batteries to power the rover until depletion, ending the mission. Because this option is so power-limited, and because drilling power increases with depth, the battery-powered rover carries a 1 m drill.

The second option has an ASRG as its principal power source, with batteries recharged by the ASRG to support peak power loads such as drilling operations. The figures below illustrate the integrated flight system and the battery and ASRG rover configurations.

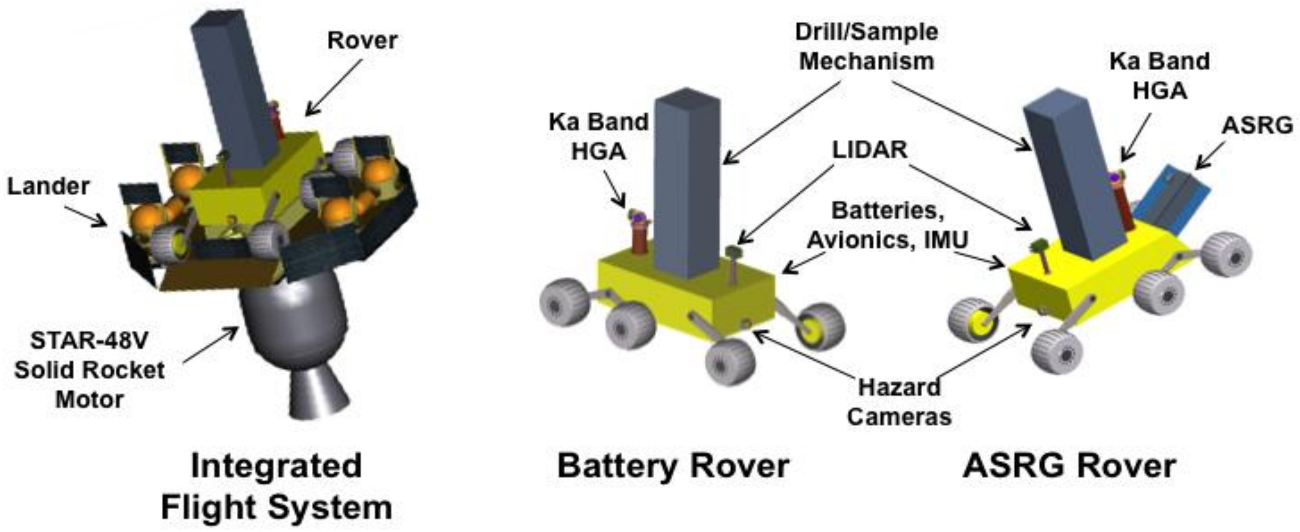


Figure 5: Mission Configuration Options

Because the ASRG rover configuration has lower mass and more power than the battery rover, it carries additional science instruments as well as a two meter drill.

This report also costs an “ASRG-Lite” variant that is the same as the ASRG configuration, but without the additional science instruments. ASRG-Lite also has a nominal mission life of 3 months, vs. 1 year for the full ASRG mission.

Solid Rocket Motor

The baselined Solid Rocket Motor (SRM) is a Star 48-V that performs the primary braking burn before final descent and landing, after which it is jettisoned. It has thrust vector control, with a self-contained battery, to provide attitude control during the burn. In addition, the SRM provides mechanical support for one of two low gain antennas used during cruise.

Lander

The lander provides all propulsion and attitude control except during the SRM burn. In addition, it supplies power, provides structural support for the rover during flight, and acts as a platform for rover egress after landing. After rover egress, the lander has no further functions. Therefore, it only carries components that are not needed after landing:

- Propulsion: 12 27 N DACS for attitude control and trajectory change maneuvers, 12 445 N DACS for descent and landing
- Flight-only GN&C sensors: sun sensors, radar altimeter, landing cameras
- Solar arrays for power during flight; rechargeable batteries for propulsion peak loads
- Thermal: heaters, sensors, multi-layer insulation, SRM plume shield

The lander has no legs, but instead lands on 4 small landing pads to facilitate rover egress. Furthermore, it has no star tracker, inertial measurement unit, or LIDAR because these sensors are needed for rover navigation and are therefore contained in the rover. For the same reason, it has no avionics, power system electronics / power distribution unit, or communication system.

The ASRG lander has smaller solar arrays than the battery lander because the rover's ASRG supplies some of the power needed prior to landing.

The lander uses the rover's processor, star tracker, and IMU, as well as its own RADAR altimeter and 2 optical cameras, for control during flight. Between TCMs during cruise, it maintains a 6 rpm rotisserie roll for thermal stabilization, changing to 3-axis fixed pointing for TCMs. During final approach, it uses the optical cameras to execute Terrain Relative Navigation algorithms for precision landing, and a Least Squares Optical Flow (LSOF) frame-to-frame image correlation algorithm to null lateral motion.

Rover

The rover is a mobile platform whose primary function is to support the science measurements by providing the following services:

- Payload mobility, navigation, and hazard avoidance
- Electrical power
- Thermal management
- Data processing and storage
- Communications

In addition, it provides many of these services during the flight phases, minimizing mass and complexity of the lander.

Payload mobility, navigation, and hazard avoidance

The rover's drive mechanism is skid steered, with two front wheels and four rear wheels supported by an articulated shoulder suspension. This architecture permits height adjustments for ground clearance over obstacles and steep terrain, while also allowing the rover center of mass to be lowered when stationary for drilling stability.

The mast-mounted LIDAR serves as the primary sensor for navigation and hazard avoidance. With acquisition and processing of a hazard avoidance LIDAR scan every 3 meters, the rover can traverse ~140 m/hr, or ~3 km/day.

Low-mounted front and rear pairs of hazard cameras support rover egress from the lander in either direction. These cameras are also available as backup navigation and hazard avoidance sensors. During surface operations, the star tracker and IMU facilitate rover navigation and high gain antenna pointing for communication.

Electrical power

The battery mission rover power system consists of 39 Lithium Thionyl Chloride (Li-$SOCl_2$) primary batteries and associated power system electronics and distribution unit. At 80% depth of discharge, these batteries provide 26,200 Watt-hours of electrical energy to power the rover subsystems and science instruments. At a power load of approximately 250 W averaged over the roving, science operations, and communication modes, the rover can operate for approximately 105 hours (4.4 days) before battery depletion ends the mission.

The ASRG rover configuration consists of a 140 watt ASRG with its corresponding power system electronics and distribution unit, supplemented by three rechargeable Lithium Cobalt Oxide (Li-CoO_2) batteries. Since the ASRG's power output is insufficient to supply the rover's 250 W average power load, the batteries provide additional power for high-demand operations such as drilling. When the batteries reach a predetermined depth of discharge, mission operations will command the rover into a low-power hibernation mode to allow the batteries to recharge from the ASRG. At 80% depth of discharge, the batteries provide 2,280 Watt-hours of energy, enough to power the rover's entire 250 W average power load for 11.5 hours.

Thermal management

To preserve heat on the surface, the rover houses critical electronic components in a thermally isolated Warm Electronics Box (WEB) that uses resistive heaters to maintain the internal temperature at approximately 15˚C. The battery rover requires larger heaters than the ASRG rover, which employs waste heat from the ASRG to heat the rover. In addition, the avionics require a radiator on the rover for heat rejection during flight. During the warmer cruise phase of the mission, a passive variable heat transfer link thermally connects the WEB to the radiator. Upon landing and exposure to the cold surface environment, the link opens to isolate the WEB from the radiator.

A resistive heater pre-heats the drill mechanism prior to each use. In addition, resistive units heat the science instruments, the rover drive train, and other rover components outside the WEB, while radioisotope heater units provide this heat in the ASRG configuration.

Data processing and storage

The rover hosts an avionics system based on a low power LEON-3 processor with an 8 Gbit data recorder, housed in a common chassis with the Power Distribution Unit. This processor executes all Command and Data Handling (C&DH), Guidance Navigation and Control (GN&C), and landing functions during flight, as well as the rover navigation, hazard avoidance, and C&DH functions during the surface mission.

The LEON-3 provides 60 MIPS processing throughput while performing descent and landing algorithms, but can be run at lower clock speeds to conserve power during surface operations. The recorder is sized to store the ~910 Mbit/day generated by the ASRG rover for 6 or more days in the event of lost Deep Space Network (DSN) data taking passes.

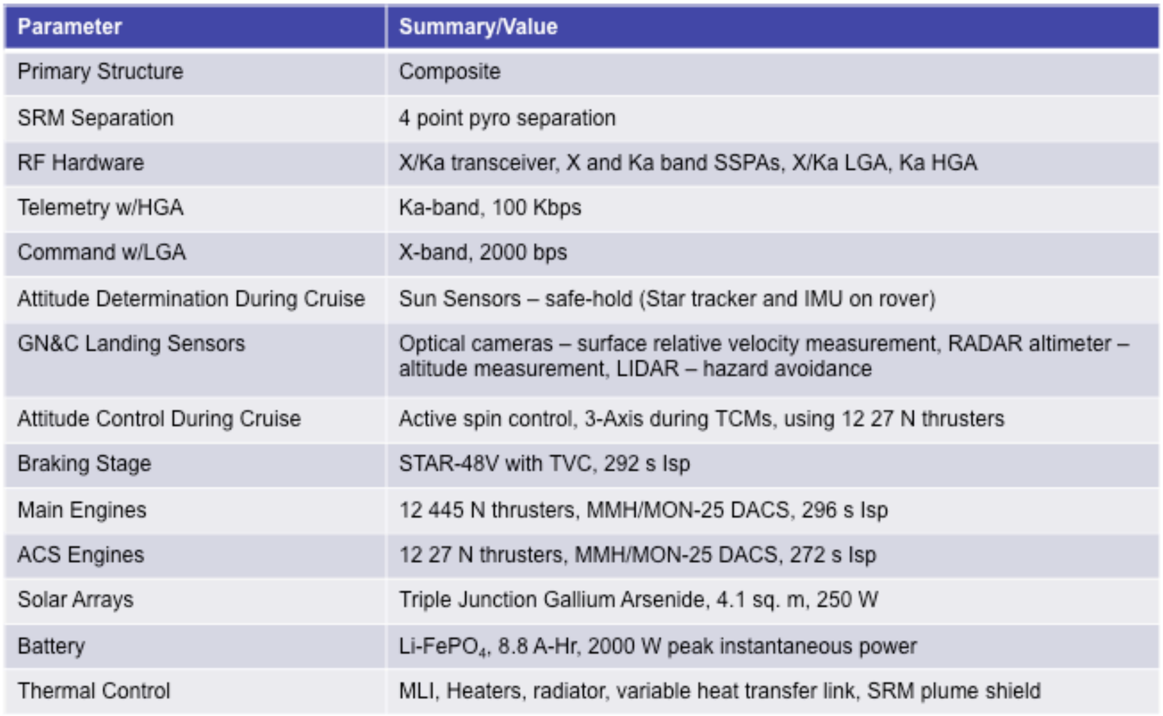
The C&DH software implements a file system on the recorder and uses the Consultative Committee for Space Data Systems (CCSDS) File Delivery Protocol to ensure 100% file data return. The flight software is built on the Core Flight Executive (cFE) message passing framework, developed by the Goddard Space Flight Center, running on the VxWorks real time operating system.

Communications

In normal operations, the rover transmits at 100 kbps over Ka-band using a 14 cm mast-mounted gimbaled high gain antenna, and receives at 2 kbps over X-band using the same antenna. The HGA gimbal tracks the Earth using the star tracker and IMU to maintain continuous communications, whether roving or stationary. For emergency communications, the rover transmits and receives at 100 bps over X-band using a surface-mounted patch low gain antenna. The system radiates 2.5 W RF at X-band and 1 W RF at Ka-band.

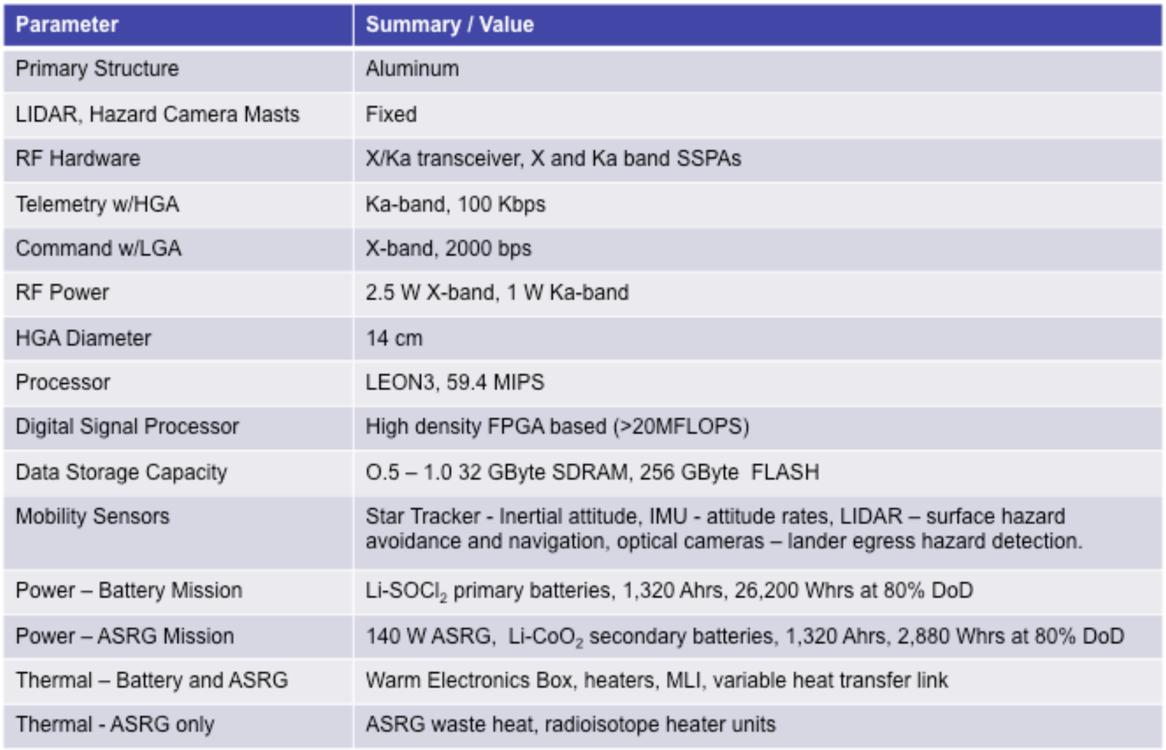
The tables below show the primary characteristics of the SRM, the lander, and the rover.

Table 10: SRM / Lander Characteristics



Parameter	Summary/Value
Primary Structure	Composite
SRM Separation	4 point pyro separation
RF Hardware	X/Ka transceiver, X and Ka band SSPAs, X/Ka LGA, Ka HGA
Telemetry w/HGA	Ka-band, 100 Kbps
Command w/LGA	X-band, 2000 bps
Attitude Determination During Cruise	Sun Sensors – safe-hold (Star tracker and IMU on rover)
GN&C Landing Sensors	Optical cameras – surface relative velocity measurement, RADAR altimeter – altitude measurement, LIDAR – hazard avoidance
Attitude Control During Cruise	Active spin control, 3-Axis during TCMs, using 12 27 N thrusters
Braking Stage	STAR-48V with TVC, 292 s Isp
Main Engines	12 445 N thrusters, MMH/MON-25 DACS, 296 s Isp
ACS Engines	12 27 N thrusters, MMH/MON-25 DACS, 272 s Isp
Solar Arrays	Triple Junction Gallium Arsenide, 4.1 sq. m, 250 W
Battery	Li-FePO$_4$, 8.8 A-Hr, 2000 W peak instantaneous power
Thermal Control	MLI, Heaters, radiator, variable heat transfer link, SRM plume shield

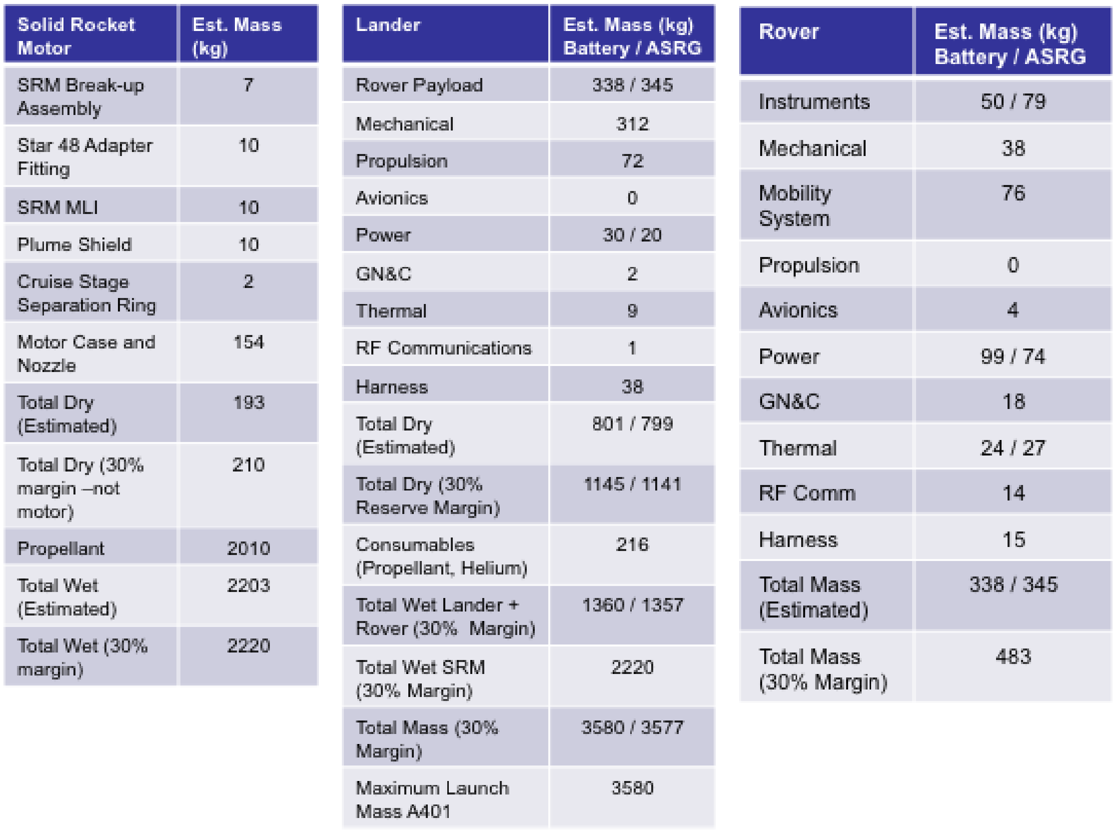
Table 11: Rover Characteristics



Parameter	Summary / Value
Primary Structure	Aluminum
LIDAR, Hazard Camera Masts	Fixed
RF Hardware	X/Ka transceiver, X and Ka band SSPAs
Telemetry w/HGA	Ka-band, 100 Kbps
Command w/LGA	X-band, 2000 bps
RF Power	2.5 W X-band, 1 W Ka-band
HGA Diameter	14 cm
Processor	LEON3, 59.4 MIPS
Digital Signal Processor	High density FPGA based (>20MFLOPS)
Data Storage Capacity	O.5 – 1.0 32 GByte SDRAM, 256 GByte FLASH
Mobility Sensors	Star Tracker - Inertial attitude, IMU - attitude rates, LIDAR – surface hazard avoidance and navigation, optical cameras – lander egress hazard detection.
Power – Battery Mission	Li-SOCl$_2$ primary batteries, 1,320 Ahrs, 26,200 Whrs at 80% DoD
Power – ASRG Mission	140 W ASRG, Li-CoO$_2$ secondary batteries, 1,320 Ahrs, 2,880 Whrs at 80% DoD
Thermal – Battery and ASRG	Warm Electronics Box, heaters, MLI, variable heat transfer link
Thermal - ASRG only	ASRG waste heat, radioisotope heater units

The tables below summarize the mass of the SRM, the lander, and the rover.

Table 12: Mass Summary



Solid Rocket Motor	Est. Mass (kg)
SRM Break-up Assembly	7
Star 48 Adapter Fitting	10
SRM MLI	10
Plume Shield	10
Cruise Stage Separation Ring	2
Motor Case and Nozzle	154
Total Dry (Estimated)	193
Total Dry (30% margin –not motor)	210
Propellant	2010
Total Wet (Estimated)	2203
Total Wet (30% margin)	2220

Lander	Est. Mass (kg) Battery / ASRG
Rover Payload	338 / 345
Mechanical	312
Propulsion	72
Avionics	0
Power	30 / 20
GN&C	2
Thermal	9
RF Communications	1
Harness	38
Total Dry (Estimated)	801 / 799
Total Dry (30% Reserve Margin)	1145 / 1141
Consumables (Propellant, Helium)	216
Total Wet Lander + Rover (30% Margin)	1360 / 1357
Total Wet SRM (30% Margin)	2220
Total Mass (30% Margin)	3580 / 3577
Maximum Launch Mass A401	3580

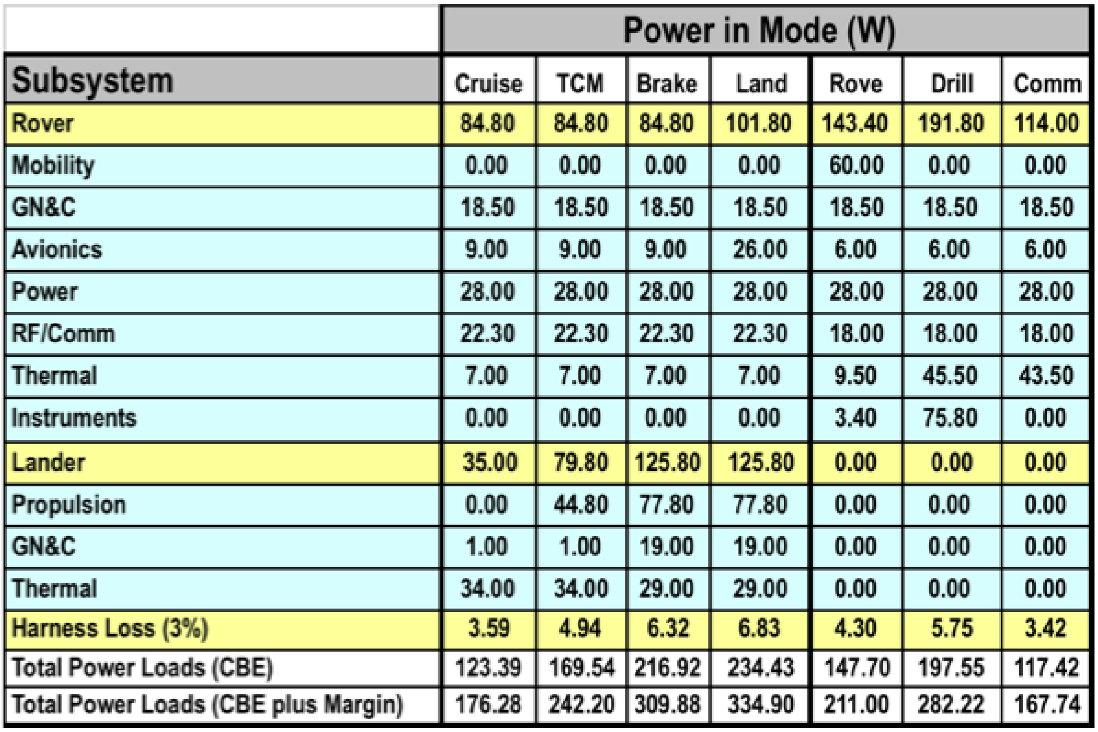
Rover	Est. Mass (kg) Battery / ASRG
Instruments	50 / 79
Mechanical	38
Mobility System	76
Propulsion	0
Avionics	4
Power	99 / 74
GN&C	18
Thermal	24 / 27
RF Comm	14
Harness	15
Total Mass (Estimated)	338 / 345
Total Mass (30% Margin)	483

For the batter-powered rover, the batteries are sized to use all available launch mass to maximize mission duration.

In the ASRG configuration, the reduction in rover battery and lander solar array masses allows the addition of Priority 2 instruments as well as selected system redundancies to increase reliability. Alternatively, the “ASRG-Lite” variant has been defined which retains only the Priority 1 science instruments (50 kg) to retain the long mission life and other benefits of the ASRG configuration while minimizing mission cost.

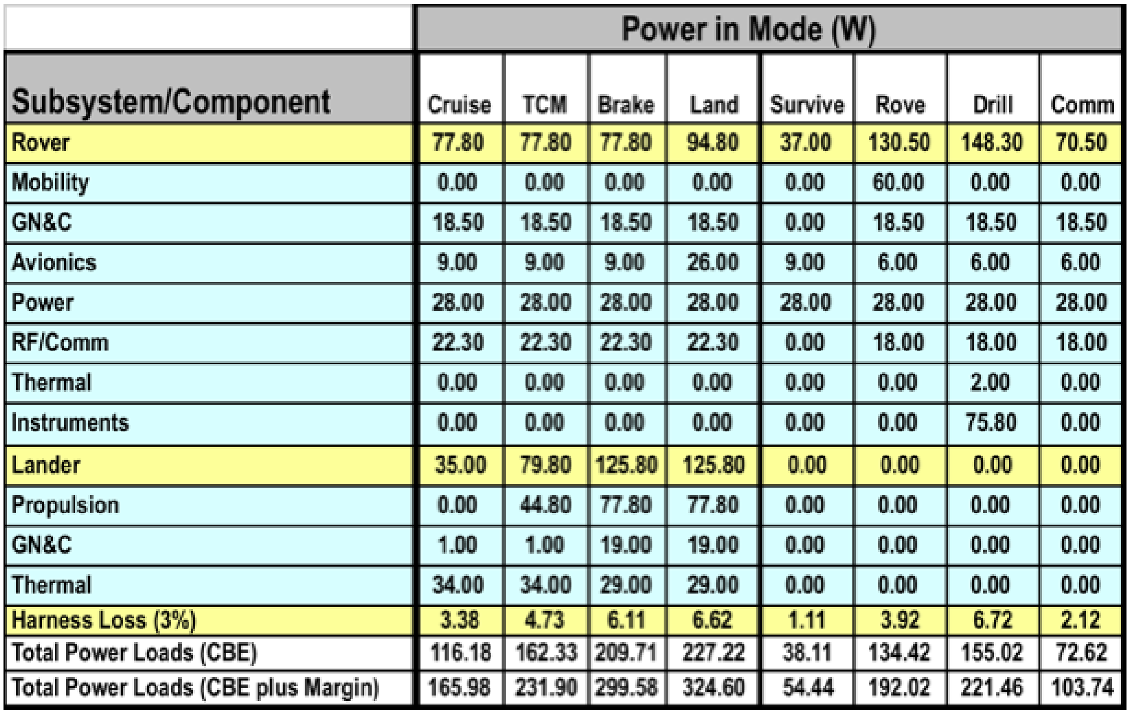
The tables below summarize system power usage for each of the primary system modes.

Table 13: Power Summary – Battery Mission



	Power in Mode (W)						
Subsystem	Cruise	TCM	Brake	Land	Rove	Drill	Comm
Rover	84.80	84.80	84.80	101.80	143.40	191.80	114.00
Mobility	0.00	0.00	0.00	0.00	60.00	0.00	0.00
GN&C	18.50	18.50	18.50	18.50	18.50	18.50	18.50
Avionics	9.00	9.00	9.00	26.00	6.00	6.00	6.00
Power	28.00	28.00	28.00	28.00	28.00	28.00	28.00
RF/Comm	22.30	22.30	22.30	22.30	18.00	18.00	18.00
Thermal	7.00	7.00	7.00	7.00	9.50	45.50	43.50
Instruments	0.00	0.00	0.00	0.00	3.40	75.80	0.00
Lander	35.00	79.80	125.80	125.80	0.00	0.00	0.00
Propulsion	0.00	44.80	77.80	77.80	0.00	0.00	0.00
GN&C	1.00	1.00	19.00	19.00	0.00	0.00	0.00
Thermal	34.00	34.00	29.00	29.00	0.00	0.00	0.00
Harness Loss (3%)	3.59	4.94	6.32	6.83	4.30	5.75	3.42
Total Power Loads (CBE)	123.39	169.54	216.92	234.43	147.70	197.55	117.42
Total Power Loads (CBE plus Margin)	176.28	242.20	309.88	334.90	211.00	282.22	167.74

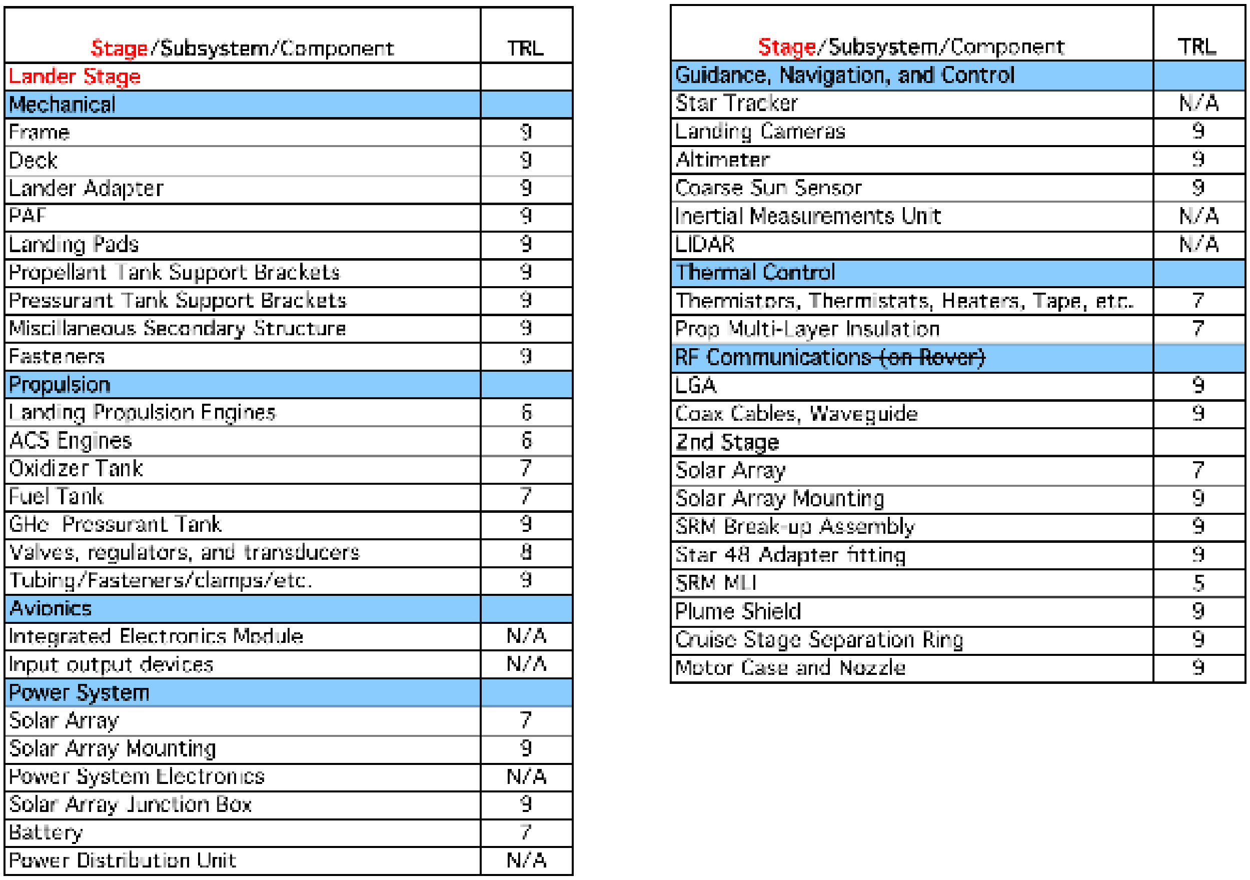
Table 14: Power Summary – ASRG Mission



	Power in Mode (W)							
Subsystem/Component	Cruise	TCM	Brake	Land	Survive	Rove	Drill	Comm
Rover	77.80	77.80	77.80	94.80	37.00	130.50	148.30	70.50
Mobility	0.00	0.00	0.00	0.00	0.00	60.00	0.00	0.00
GN&C	18.50	18.50	18.50	18.50	0.00	18.50	18.50	18.50
Avionics	9.00	9.00	9.00	26.00	9.00	6.00	6.00	6.00
Power	28.00	28.00	28.00	28.00	28.00	28.00	28.00	28.00
RF/Comm	22.30	22.30	22.30	22.30	0.00	18.00	18.00	18.00
Thermal	0.00	0.00	0.00	0.00	0.00	0.00	2.00	0.00
Instruments	0.00	0.00	0.00	0.00	0.00	0.00	75.80	0.00
Lander	35.00	79.80	125.80	125.80	0.00	0.00	0.00	0.00
Propulsion	0.00	44.80	77.80	77.80	0.00	0.00	0.00	0.00
GN&C	1.00	1.00	19.00	19.00	0.00	0.00	0.00	0.00
Thermal	34.00	34.00	29.00	29.00	0.00	0.00	0.00	0.00
Harness Loss (3%)	3.38	4.73	6.11	6.62	1.11	3.92	6.72	2.12
Total Power Loads (CBE)	116.18	162.33	209.71	227.22	38.11	134.42	155.02	72.62
Total Power Loads (CBE plus Margin)	165.98	231.90	299.58	324.60	54.44	192.02	221.46	103.74

The table below lists Lander and Second Stage technology maturity levels.

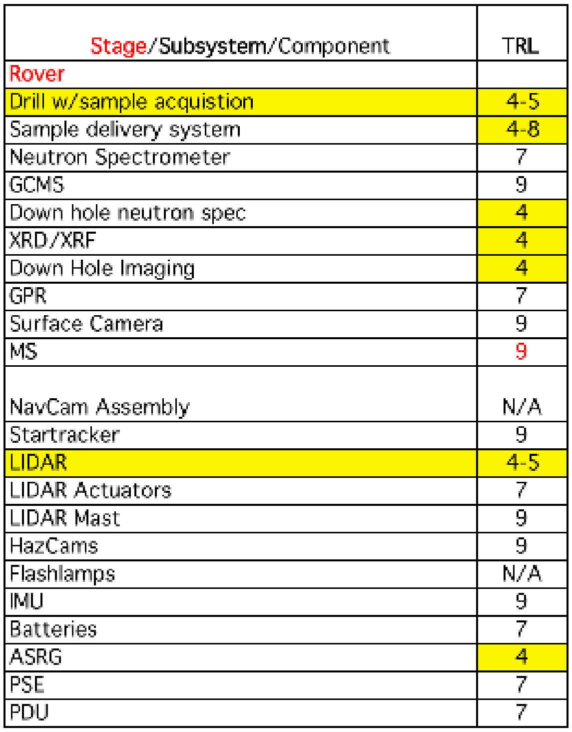
Table 15: Lander/SRM Technology Maturity



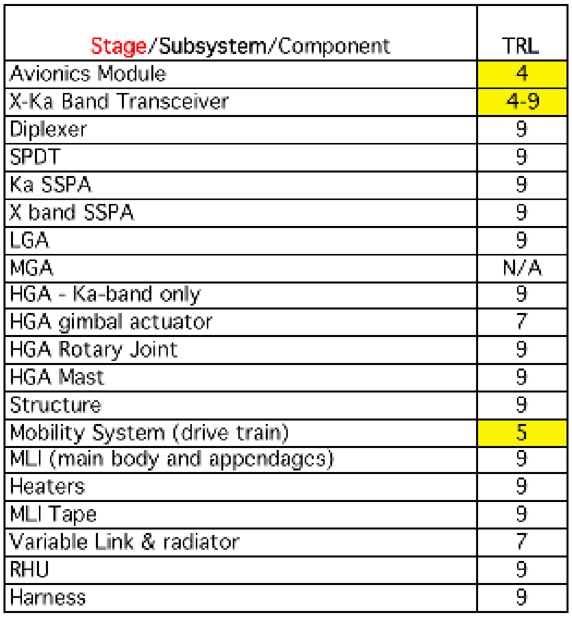
Stage/Subsystem/Component	TRL
Lander Stage	
Mechanical	
Frame	9
Deck	9
Lander Adapter	9
PAF	9
Landing Pads	9
Propellant Tank Support Brackets	9
Pressurant Tank Support Brackets	9
Miscillaneous Secondary Structure	9
Fasteners	9
Propulsion	
Landing Propulsion Engines	6
ACS Engines	6
Oxidizer Tank	7
Fuel Tank	7
GHe Pressurant Tank	9
Valves, regulators, and transducers	8
Tubing/Fasteners/clamps/etc.	9
Avionics	
Integrated Electronics Module	N/A
Input output devices	N/A
Power System	
Solar Array	7
Solar Array Mounting	9
Power System Electronics	N/A
Solar Array Junction Box	9
Battery	7
Power Distribution Unit	N/A
Guidance, Navigation, and Control	
Star Tracker	N/A
Landing Cameras	9
Altimeter	9
Coarse Sun Sensor	9
Inertial Measurements Unit	N/A
LIDAR	N/A
Thermal Control	
Thermistors, Thermistats, Heaters, Tape, etc.	7
Prop Multi-Layer Insulation	7
RF Communications ~~(on Rover)~~	
LGA	9
Coax Cables, Waveguide	9
2nd Stage	
Solar Array	7
Solar Array Mounting	9
SRM Break-up Assembly	9
Star 48 Adapter fitting	9
SRM MLI	5
Plume Shield	9
Cruise Stage Separation Ring	9
Motor Case and Nozzle	9

The table below lists Rover and Instrument technology maturity levels.

Table 16: Rover/Instrument Technology Maturity



Stage/Subsystem/Component	TRL
Rover	
Drill w/sample acquistion	4-5
Sample delivery system	4-8
Neutron Spectrometer	7
GCMS	9
Down hole neutron spec	4
XRD/XRF	4
Down Hole Imaging	4
GPR	7
Surface Camera	9
MS	9
NavCam Assembly	N/A
Startracker	9
LIDAR	4-5
LIDAR Actuators	7
LIDAR Mast	9
HazCams	9
Flashlamps	N/A
IMU	9
Batteries	7
ASRG	4
PSE	7
PDU	7



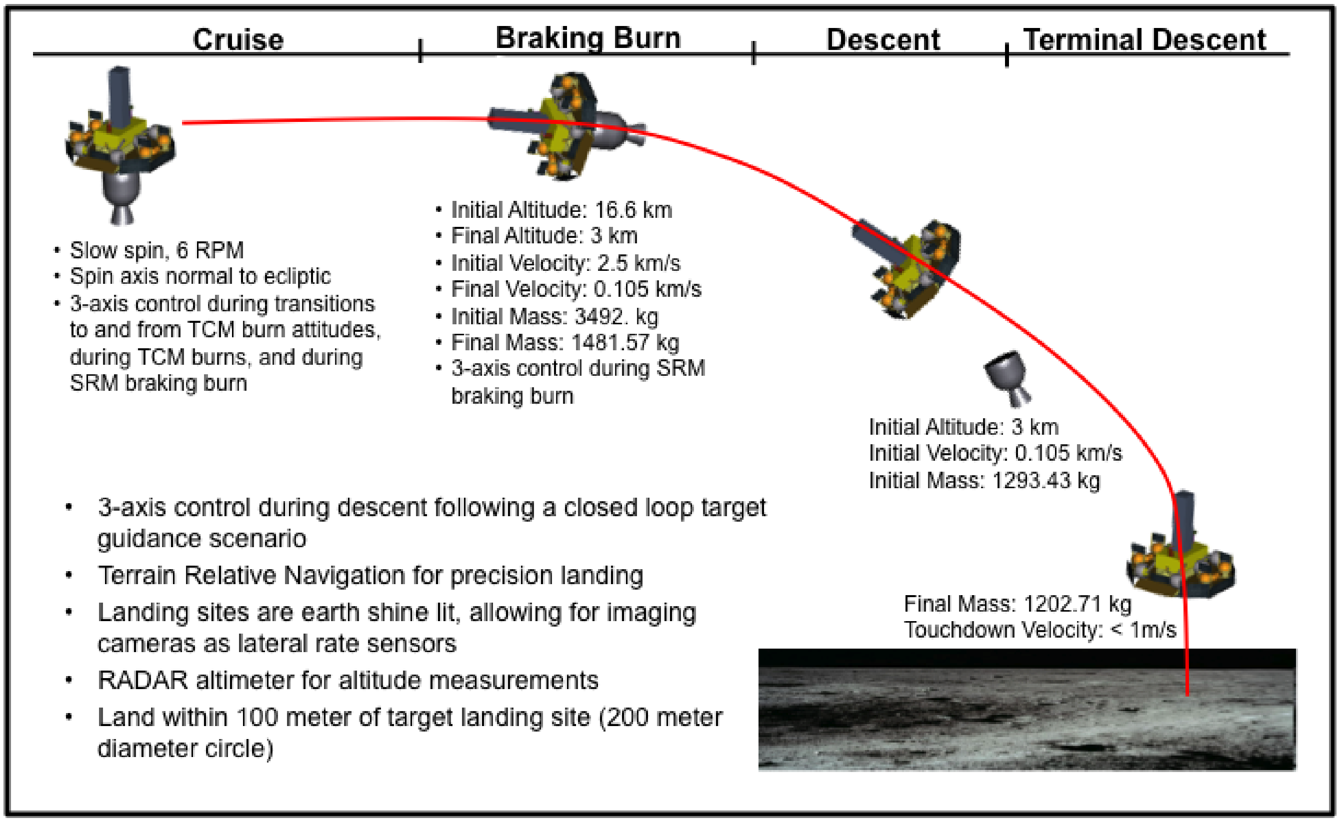
Stage/Subsystem/Component	TRL
Avionics Module	4
X-Ka Band Transceiver	4-9
Diplexer	9
SPDT	9
Ka SSPA	9
X band SSPA	9
LGA	9
MGA	N/A
HGA - Ka-band only	9
HGA gimbal actuator	7
HGA Rotary Joint	9
HGA Mast	9
Structure	9
Mobility System (drive train)	5
MLI (main body and appendages)	9
Heaters	9
MLI Tape	9
Variable Link & radiator	7
RHU	9
Harness	9

Concept of Operations and Mission Design

The LPVE spacecraft would launch on an Atlas V 401 from the Cape Canaveral, FL. After a minimum energy ~5 day Earth to Moon transfer, it would perform a direct to surface descent and landing within a permanently shadowed region pre-selected to maximize the probability of finding volatiles. Precision landing in an Earthshine region is required to enable direct-to-Earth communications via the DSN 34-m subnet.

Launch opportunity windows, nominally available monthly, and daily launch windows are constrained by arrival lighting and communications constraints. For the battery configuration, launch opportunity windows are about 3 days in duration to enable completion of the 5-day surface before Earth-Moon geometry makes direct-to-Earth communications impossible. Similar launch constraints are desirable for the ASRG configuration to allow checkout and commissioning within the initial communications opportunity. This study developed a reference trajectory with launch on October 2, 2018, with landing on October 7, 2 days before full Earthshine.

The following figure illustrates the flight phases of the LPVE mission.



- Slow spin, 6 RPM
- Spin axis normal to ecliptic
- 3-axis control during transitions to and from TCM burn attitudes, during TCM burns, and during SRM braking burn

- Initial Altitude: 16.6 km
- Final Altitude: 3 km
- Initial Velocity: 2.5 km/s
- Final Velocity: 0.105 km/s
- Initial Mass: 3492. kg
- Final Mass: 1481.57 kg
- 3-axis control during SRM braking burn

Initial Altitude: 3 km
Initial Velocity: 0.105 km/s
Initial Mass: 1293.43 kg

- 3-axis control during descent following a closed loop target guidance scenario
- Terrain Relative Navigation for precision landing
- Landing sites are earth shine lit, allowing for imaging cameras as lateral rate sensors
- RADAR altimeter for altitude measurements
- Land within 100 meter of target landing site (200 meter diameter circle)

Final Mass: 1202.71 kg
Touchdown Velocity: < 1m/s

Figure 6: LPVE Flight Mission

The following table lists the delta V and mass associated with each spacecraft maneuver from spacecraft separation through landing.

Table 17: Mission delta-V

Event	ΔV (m/s)
TCMs	70
Cruise ACS	10
SRM Burn	2455
Landing ACS	20
Landing Site Navigation	25
Descent	209
Total (post-TLI)	**2789**

- Launch Vehicle: Atlas V 401
- Total mass on LV: 3577 kg
- Total SRM braked mass: 1482 kg
- Discarded SRM mass: 210 kg
- Total mass to surface: 1182 kg

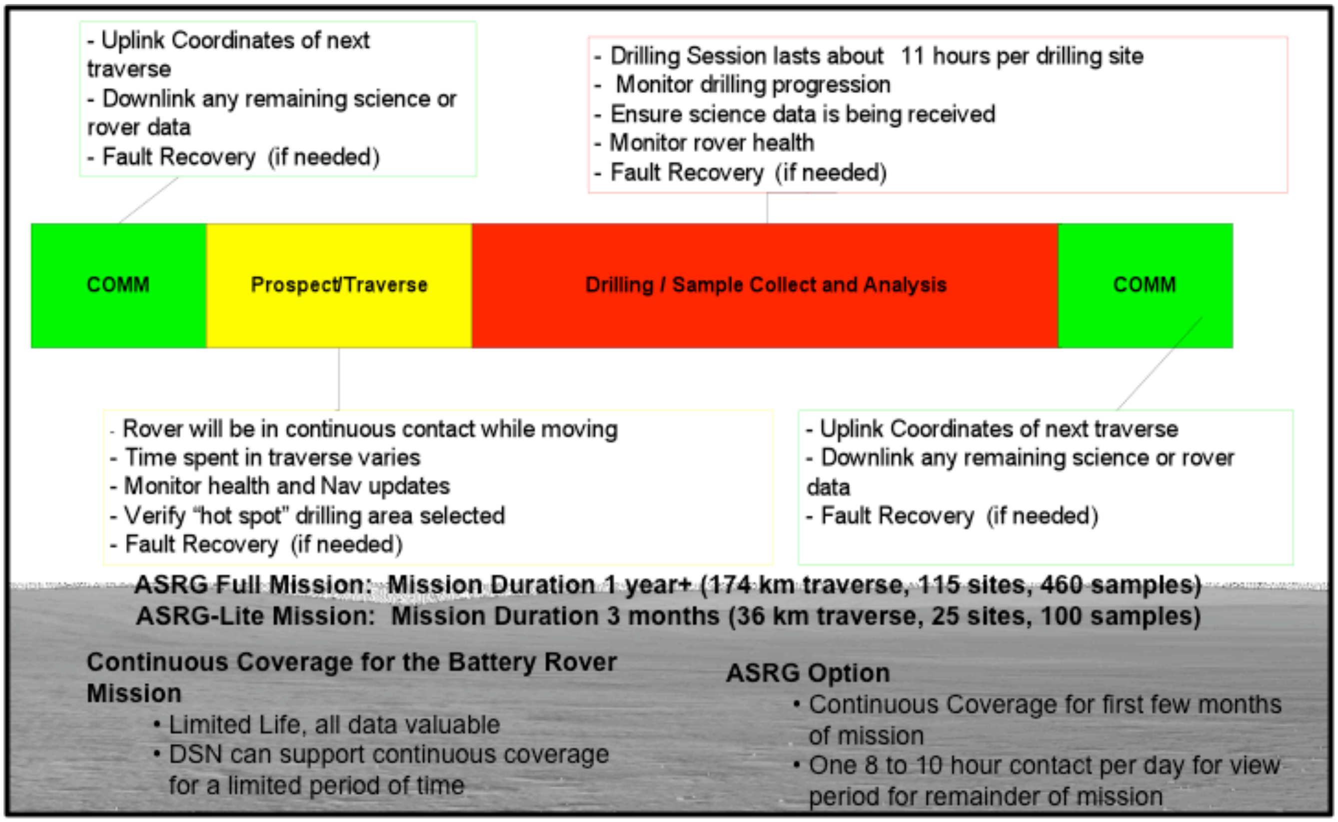
The battery surface mission is limited to approximately 4.5 days because the batteries that power the rover cannot be recharged. As a result, mission operations will use 24/7 DSN coverage for the ~10 days from launch through the end of the mission. The rover will accept commands and transmit science and housekeeping telemetry continuously, using the star tracker and IMU to maintain HGA pointing whether roving or stationary.

In addition, the rover will implement a high degree of autonomy to perform hazard avoidance while prospecting for scientifically interesting sites. When it locates such a site, the science team will command it to stop and perform drilling, sampling, and science data collection. A typical science operation, with multiple samples per site, will nominally take approximately 11 hours. The total number of science data collection sites will vary depending on prospecting results. However, with an approximately even split between prospecting and drilling/analysis operations, the battery mission will support 6 km total traverse, and science operations at 5 sites with 4 samples per site.

Rover operations for the ASRG missions differ from the battery mission because the ASRG provides power for a virtually unlimited time. However, ASRG power output is approximately 140 W, less than the average power needed for either prospecting or science operations (particularly drilling). As a result, the rover uses the combined power of the ASRG and batteries for science operations, and then enters a low-power hibernation mode as necessary to allow the batteries to recharge from the ASRG.

Mission operations for the ASRG-Lite mission are similar to the battery mission because 24/7 coverage is acceptable for its nominal 3-month duration. However, coverage for the year-long full ASRG mission scales back to one 8 to10 hour coverage period per day after the first several months, and operations transition to single shifts.

The figure below illustrates the primary mission operations features for both the battery and ASRG missions.



- Uplink Coordinates of next traverse
- Downlink any remaining science or rover data
- Fault Recovery (if needed)

- Drilling Session lasts about 11 hours per drilling site
- Monitor drilling progression
- Ensure science data is being received
- Monitor rover health
- Fault Recovery (if needed)

- Rover will be in continuous contact while moving
- Time spent in traverse varies
- Monitor health and Nav updates
- Verify "hot spot" drilling area selected
- Fault Recovery (if needed)

- Uplink Coordinates of next traverse
- Downlink any remaining science or rover data
- Fault Recovery (if needed)

ASRG Full Mission: Mission Duration 1 year+ (174 km traverse, 115 sites, 460 samples)

ASRG-Lite Mission: Mission Duration 3 months (36 km traverse, 25 sites, 100 samples)

Continuous Coverage for the Battery Rover Mission

- Limited Life, all data valuable
- DSN can support continuous coverage for a limited period of time

ASRG Option

- Continuous Coverage for first few months of mission
- One 8 to 10 hour contact per day for view period for remainder of mission

Figure 7: Surface Operations

The following two tables detail the data volumes for the battery and ASRG missions, respectively.

Table 18: Battery/ASRG-Lite Mission Data Characteristics

Data Source	Frequency	Data Rate (kbps)	Secs. per Day	Sample Size (kbits)	Samples per Day	Total Raw Data per Day (kbits)	Com-pression Factor	Downlink Data per Day (kbits)
Battery Mission Instruments								
Neutron Spectrometer	While roving	0.5	46,080	-	-	23,040	1	23,040
Drill Deployment	1 per sample	-	-	1,200	3	3,600	1	3,600
Drill	While drilling	10.0	6,000	-	-	60,000	1	60,000
Downhole Neutron Spectrometer	While drilling	0.5	6,000	-	-	3,000	1	3,000
Downhole Imaging Camera	1 per sample	-	-	12583	3	37,749	1	37,749
Sample Collection	1 per sample	-	-	480	3	1,440	1	1,440
Volatile Analysis	1 per sample	-	-	12,000	3	36,000	1	36,000
					Science Subtotal (kbits):	**164,829**		**164,829**
Rover Data								
Engineering Housekeeping	Continuous	0.5	86,400	-	-	43,200	1	43,200
LIDAR	1 per 10 min. while roving	-	-	8,192	77	629,146	10	62,915
Traversability Maps	8 per 10 min. while roving	-	-	5	77	384	1	384
Hazard Cameras *	During egress from lander	-	-	-	-	-	-	-
* No significant contribution to overall data volume					**Rover Subtotal (kbits):**	**672,730**		**106,499**
							Daily Total Compressed (kbits):	**271,327**
							Downlink Rate (kbps):	**100**
							Time to Downlink (min.):	**45**

Table 19: ASRG Mission Data Characteristics

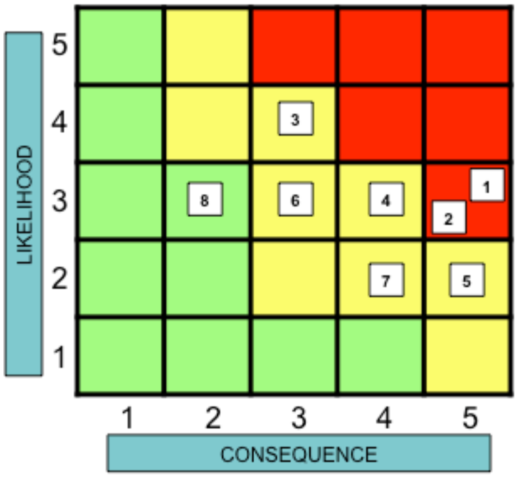
Data Source	Frequency	Data Rate (kbps)	Secs. per Day	Sample Size (kbits)	Samples per Day	Total Raw Data per Day (kbits)	Com-pression Factor	Downlink Data per Day (kbits)
Battery Mission Instruments								
Neutron Spectrometer	While roving	0.5	46,080	-	-	23,040	1	23,040
Drill Deployment	1 per sample	-	-	1,200	4	4,800	1	4,800
Drill	While drilling	10.0	12,000	-	-	120,000	1	120,000
Downhole Neutron Spectrometer	While drilling	0.5	12,000	-	-	6,000	1	6,000
Downhole Imaging Camera	1 per sample	-	-	12583	4	50,332	1	50,332
Sample Collection	1 per sample	-	-	480	4	1,920	1	1,920
Volatile Analysis	1 per sample	-	-	12,000	4	48,000	1	48,000
Additional ASRG Instruments								
XRD/XRF	1 per sample	-	-	18,114	4	72,456	1	72,456
Surfacing Imaging Camera	1 per hole	-	-	13,585	1	13,585	1	13,585
Ground Penetrating RADAR	While roving	10.0	46,080	-	-	460,800	1	460,800
Exospheric Mass Spectrometer *	Infrequently	-	-	-	-	-	-	-
					Science Subtotal (kbits):	**800,933**		**800,933**
Rover Data								
Engineering Housekeeping	Continuous	0.5	86,400	-	-	43,200	1	43,200
LIDAR	1 per 10 min. while roving	-	-	8,192	77	629,146	10	62,915
Traversability Maps	8 per 10 min. while roving	-	-	5	77	384	1	384
Hazard Cameras *	During egress from lander	-	-	-	-	-	-	-
* No significant contribution to overall data volume					**Rover Subtotal (kbits):**	**672,730**		**106,499**
							Daily Total Compressed (kbits):	**907,431**
							Downlink Rate (kbps):	**100**
							Time to Downlink (min.):	**151**

Risk List

The table and 5x5 risk matrix below lists the top risks and consequences for the LPVE concept.

Table 20: Mission Risks

Risk	Consequence	Mission
Drill Performance	Mission schedule, mass, or power impacts to ensure drill and sample acquisition system will enable appropriate volatile sampling	All
Thermal Environment Effects	Mission cost and schedule could be impacted to ensure mechanical systems performance in a 40K environment	All
High Thrust to Weight Bi-Propellant Thruster Qualification	Increased propulsion system mass and cost to accommodate conventional thrusters	All
Soft Landing Precision Guidance, Navigation, & Control	Mission Cost and Schedule could be impacted to ensure accurate and safe landing	All
Low Mass and Power Avionics Development	Additional mass and and power requirements to accommodate a higher power requirement from current mature TRL processors	Battery ASRG Full
ASRG Fuel Availability	Sufficient fuel may not be available to fuel an ASRG for LPVE	ASRG Full ASRG-Lite
Battery Mission Mass Growth	Battery Mission duration and sampling could be impacted	Battery
Lack of mission risk classification impact on redundancy	NASA Risk Classification requirements may drive system redundancy implementations beyond available mass and cost reserves	All



Criticality
🟥 High
🟨 Med
🟩 Low

Approach
M – Mitigate
W – Watch
A – Accept
R - Research

Rank	Approach	Risk Title	Impact Type
1	W	ASRG Fuel Availability	T, Sc
2	M	Battery Mission Mass Growth	T
3	R	Lack of mission risk classification impact on redundancy	T, C
4	M	Drill Performance	T, C, Sc
5	M	Soft Landing Precision Guidance, Navigation, & Control	T, Sf
6	M	High Thrust to Weight Bi-Propellant Thruster Qualification	T, C, Sc
7	M	Thermal Environment Effects	T, C
8	M	Low Mass and Power Avionics Development	T, Sc

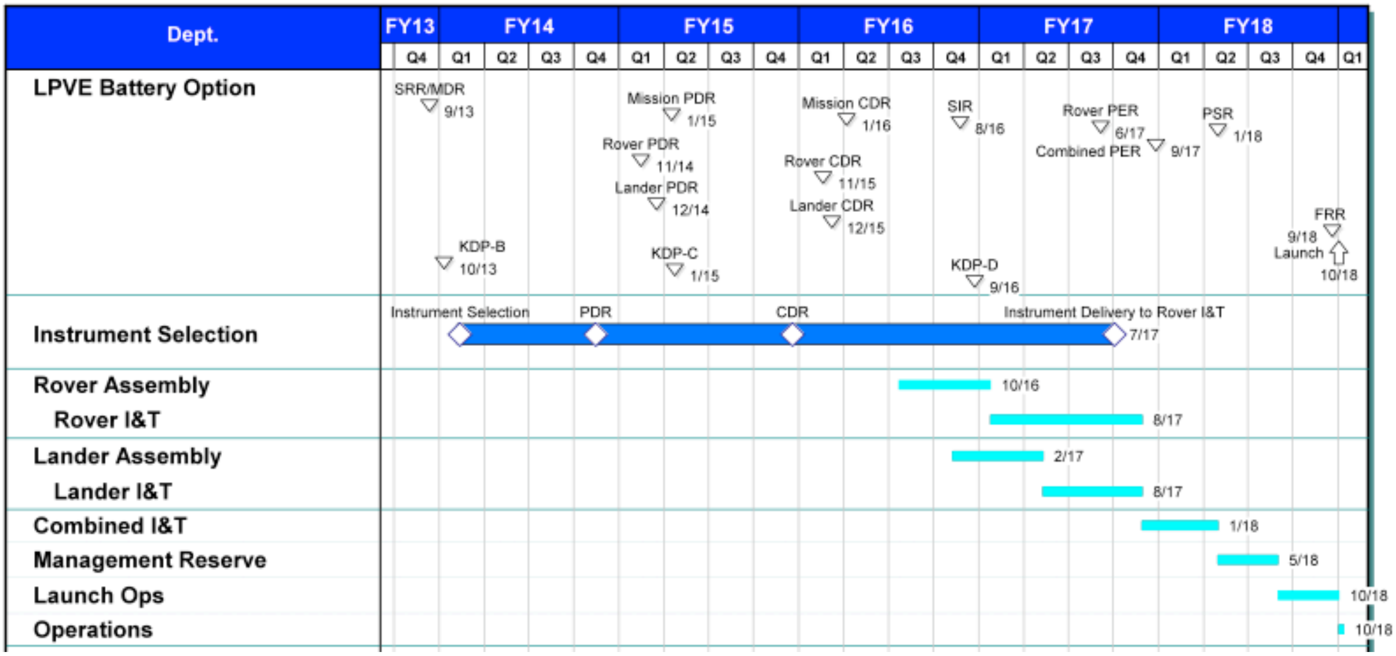
Impact Key (Primary Impact)
C=Cost; Sc=Schedule; T=Technical; Sf=Safety

4. Development Schedule

High-Level Mission Schedule

The high-level mission schedule (Figure 8) is based on previous mission experience and recent concept development efforts. With a conceptual design start in FY 2013, the mission phase durations are described in Table 21. The Lander and Rover developments are distinct "spacecraft" which follow their own development paths, with design integration through Mission-level design reviews and physical integration during a combined Integration and Test (I&T) phase. The instrument development schedule is tied to the Rover development since all instruments are integrated with the Rover rather than the Lander. Introduction of the ASRG into the Mission baseline adds only 2.5 weeks to the overall Mission schedule due to an additional 1.5 weeks of testing with an ASRG simulator ("pathfinder" testing) during Rover I&T, and an additional 1 week in Launch Operations for ASRG physical integration.

Figure 8: LPVE Mission Schedule



Key Phase Duration Table

Table 21: Phase Durations

Project Phase	Duration (Months)
Phase A – Conceptual Design	9 months
Phase B – Preliminary Design	15 months
Phase C – Detailed Design	20 months
Phase D – Integration & Test	16 months
Phase E – Primary Mission Operations (ASRG)	12 months
Phase E – Primary Mission Operations (ASRG-Lite)	3 months
Phase E – Primary Mission Operations (Battery)	1.5 weeks
Start of Phase B to PDR	15 months
Start of Phase B to CDR	27 months
Start of Phase B to Delivery of Instruments to Rover I&T	44 months
Start of Phase B to Delivery of Flight Lander	45 months
Start of Phase B to Delivery of Flight Rover	45 months
System Level Rover Integration & Test	10 months
System Level Lander Integration & Test	6.5 months
System Level Combined Integration & Test	5 months
Project Total Funded Schedule Reserve	7.2 months
Total Development Time Phase B - D	51 months

Technology Development Plan

Enabling technologies that are assessed to be below TRL6 are discussed in this section. A top-level description of the technology is described, although a more detailed technology development plan could be developed as part of a future study.

Power: Advanced Stirling Radioisotope Generator

In order to meet the all Priority 1 science objectives, and to enable Priority 2 science objectives, an ASRG is assumed to be available and utilized. The ASRG, currently in development by Glenn Research Center and the Department of Energy (DoE), incorporates the Stirling energy conversion cycle to significantly increase its thermal energy to electrical power conversion. Maturation of this technology is assumed to be completed outside the scope of the LPVE mission.

Guidance, Navigation, & Control: Terrain Relative Navigation

Landing accuracy of a direct trajectory landing on the Moon can be achieved with an accuracy of tens to hundreds of kilometers without any precision landing implementations. However, the size of the LPVE landing zone (permanently shadowed yet within Earthshine) is on the order of kilometers in width. TRN enables landing within 100 meters of a specific target location within the LPVE landing zone. The Autonomous Landing and Hazard Avoidance Technology (ALHAT) project is developing and testing a TRN capability for the Exploration Systems Mission Directorate (ESMD), and maturation of this technology is assumed to be completed outside the scope of the LPVE mission.

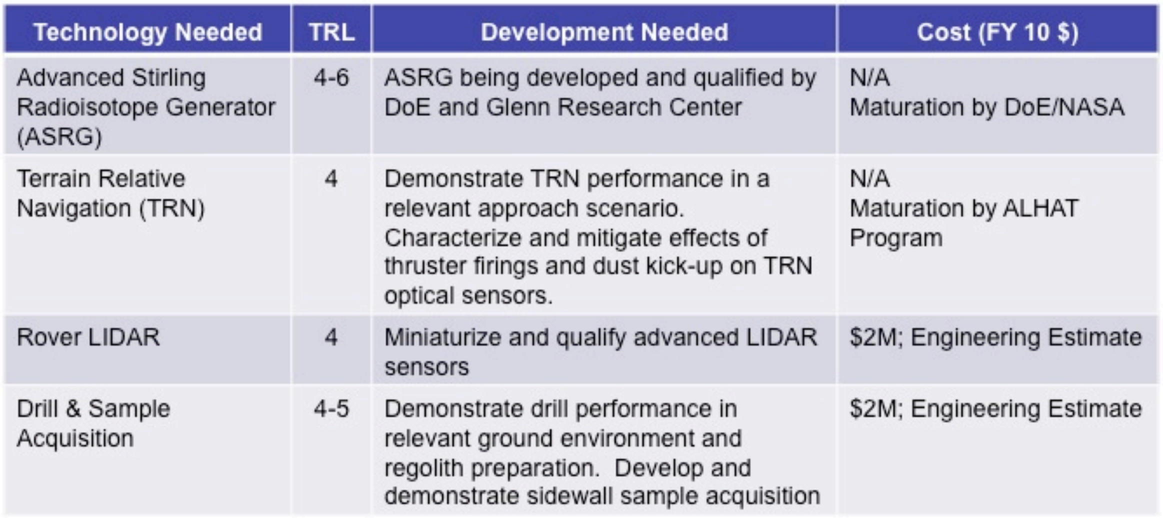
Mobility: Rover-Based LIDAR

Advanced LIDAR sensors are commonly used for terrestrial mobility navigation. Miniaturization and qualification of a small, low power version of these sensors will enable the LPVE rover to autonomously rove and identify hazards.

Instruments: Drill & Sample Acquisition

Flight systems on robotic landers to date have enabled subsurface sample acquisition at depths up to approximately 5 cm. In order to obtain regolith that may hold volatiles, samples must be acquired at depths from 10 centimeters to 2 meters. Drill systems for lunar robotic applications that would enable sampling at these depths are currently at a TRL of 4-5. Sample acquisition systems such as sidewall coring are common in terrestrial application but have not been demonstrated at a scale and power level, nor the appropriate physical environment for a planetary mission. Given that the LPVE science objectives require analysis of samples that can only be acquired through this technology, aggressive maturation of planetary drilling technology and autonomy must be accomplished to enable the LPVE mission.

Table 22: Enabling Technology Development Needs

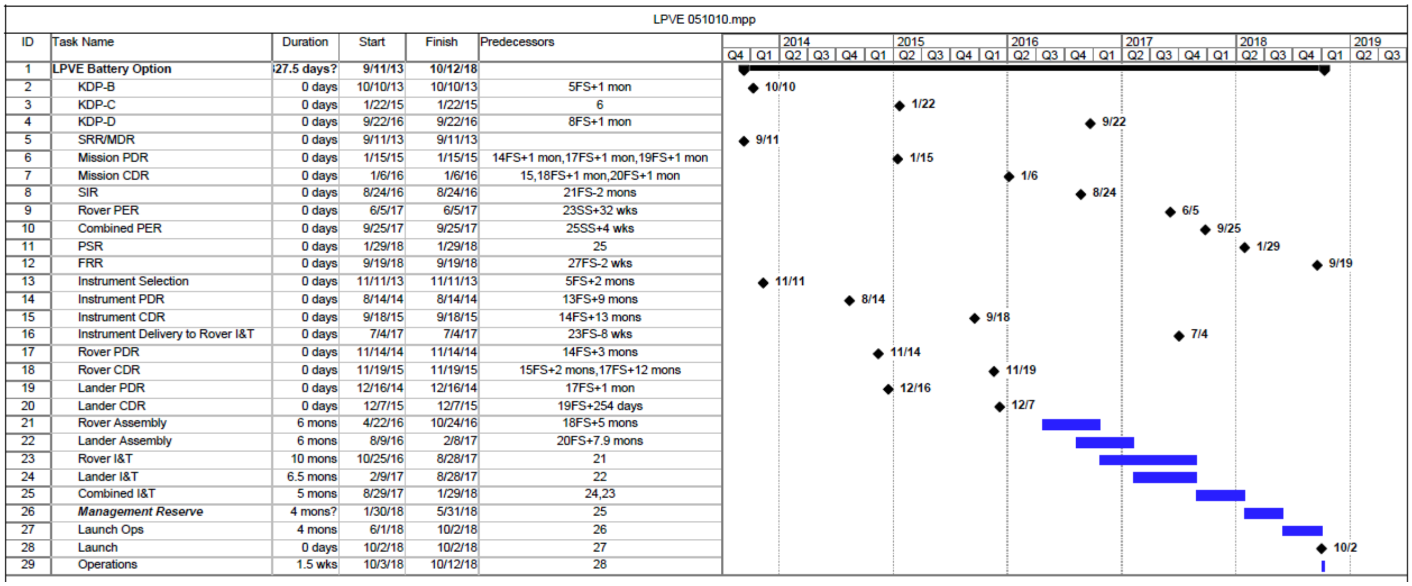


Technology Needed	TRL	Development Needed	Cost (FY 10 $)
Advanced Stirling Radioisotope Generator (ASRG)	4-6	ASRG being developed and qualified by DoE and Glenn Research Center	N/A Maturation by DoE/NASA
Terrain Relative Navigation (TRN)	4	Demonstrate TRN performance in a relevant approach scenario. Characterize and mitigate effects of thruster firings and dust kick-up on TRN optical sensors.	N/A Maturation by ALHAT Program
Rover LIDAR	4	Miniaturize and qualify advanced LIDAR sensors	$2M; Engineering Estimate
Drill & Sample Acquisition	4-5	Demonstrate drill performance in relevant ground environment and regolith preparation. Develop and demonstrate sidewall sample acquisition	$2M; Engineering Estimate

Development Schedule and Constraints

The schedule below shows more details and dependencies for instrument, lander, and rover development schedules from concept development through launch. The development schedule further assumes that flight ASRGs will be readily available as government off-the-shelf equipment when required, therefore no additional development and/or qualification will be needed.

Figure 9: LPVE Detailed Schedule



LPVE 051010.mpp

ID	Task Name	Duration	Start	Finish	Predecessors
1	**LPVE Battery Option**	**27.5 days?**	**9/11/13**	**10/12/18**	
2	KDP-B	0 days	10/10/13	10/10/13	5FS+1 mon
3	KDP-C	0 days	1/22/15	1/22/15	6
4	KDP-D	0 days	9/22/16	9/22/16	8FS+1 mon
5	SRR/MDR	0 days	9/11/13	9/11/13	
6	Mission PDR	0 days	1/15/15	1/15/15	14FS+1 mon,17FS+1 mon,19FS+1 mon
7	Mission CDR	0 days	1/6/16	1/6/16	15,18FS+1 mon,20FS+1 mon
8	SIR	0 days	8/24/16	8/24/16	21FS-2 mons
9	Rover PER	0 days	6/5/17	6/5/17	23SS+32 wks
10	Combined PER	0 days	9/25/17	9/25/17	25SS+4 wks
11	PSR	0 days	1/29/18	1/29/18	25
12	FRR	0 days	9/19/18	9/19/18	27FS-2 wks
13	Instrument Selection	0 days	11/11/13	11/11/13	5FS+2 mons
14	Instrument PDR	0 days	8/14/14	8/14/14	13FS+9 mons
15	Instrument CDR	0 days	9/18/15	9/18/15	14FS+13 mons
16	Instrument Delivery to Rover I&T	0 days	7/4/17	7/4/17	23FS-8 wks
17	Rover PDR	0 days	11/14/14	11/14/14	14FS+3 mons
18	Rover CDR	0 days	11/19/15	11/19/15	15FS+2 mons,17FS+12 mons
19	Lander PDR	0 days	12/16/14	12/16/14	17FS+1 mon
20	Lander CDR	0 days	12/7/15	12/7/15	19FS+254 days
21	Rover Assembly	6 mons	4/22/16	10/24/16	18FS+5 mons
22	Lander Assembly	6 mons	8/9/16	2/8/17	20FS+7.9 mons
23	Rover I&T	10 mons	10/25/16	8/28/17	21
24	Lander I&T	6.5 mons	2/9/17	8/28/17	22
25	Combined I&T	5 mons	8/29/17	1/29/18	24,23
26	***Management Reserve***	4 mons?	1/30/18	5/31/18	25
27	Launch Ops	4 mons	6/1/18	10/2/18	26
28	Launch	0 days	10/2/18	10/2/18	27
29	Operations	1.5 wks	10/3/18	10/12/18	28

5. Mission Life-Cycle Cost

Costing Methodology and Basis of Estimate

Overview

CML-3 cost estimates were generated for three mission options:

- Battery-powered rover with limited science payload and 5-day surface mission
- ASRG-powered rover with full science payload and 12-month surface mission
- ASRG-powered rover with limited science payload and 3-month surface mission ("ASRG-Lite")

The objective of the cost estimates was to place the options within NASA mission cost bins (Discovery-class, New Frontiers-class, or Flagship-class). The cost estimates were derived from a combination of engineering estimates, cost analogies and parametric modeling, including:

- Results from International Lunar Network (ILN) and Lunar Geophysical Network (LGN) analyses
- RLEP-2 cost estimates

The ILN & LGN analyses provided calibrated cost estimating models, relevant cost data and acquisition strategy details; the RLEP-2 analyses served as crosschecks for the current estimates.

Estimates cover the cost elements typical of a robotic space mission and list in the NASA level-2 Work Breakdown Structure in Appendix G of NPR 7120.5D. The estimates also cover the lander and rover test beds and prototypes that will be needed for concept demonstration, design and development, integration and test, and by Mission Operations during Phase E as post-landing test beds.

Ground Rules and Assumptions

Ground rules and assumptions for the LPVE estimates are based on the revision 2 draft of "Groundrules for Mission Concept Studies in Support of Planetary Decadal Survey (dGRPDS)."

Cost estimates are presented in Fiscal Year 2015 (FY15) dollars. Initial estimates were generated in FY10 dollars and then adjusted to FY15 dollars based on the 2.7% annual inflation rate presented in dGRPDS (14.4% total cost inflation from FY10 to FY15). Where necessary, pre-FY10 cost data were adjusted to FY10 dollars using historical inflation rates. Availability of FY10 estimates enables ready comparison of the cost estimates with cost data from current and recently completed programs and with recently prepared estimates for other programs and trade studies.

The cost estimates assume that NASA will fund all LPVE mission costs and that all significant work will be performed in the United States. The estimates as presented include all costs, including fees.

The mission cost estimates cover activities from the beginning of Phase A through the end of Phase E, including the following:

- Technology development
- Instruments, science teams, and Science Operations Center (SOC) preparation
- Spacecraft hardware and flight software development
- Systems integration and test
- Launch vehicle and services
- Mission operations, including development of ground data systems, DSN charges, and Phase E activities
- Project management, systems engineering, and safety and mission assurance
- Education/public outreach (E/PO)
- Cost reserves

The ASRG-powered rover and ASRG-Lite options specify an ASRG for generation of electrical power. Per dGRPDS, these cost estimates assume that an ASRG will be ready for flight by March 2014 at a unit cost of $20 million (FY10), with an additional $15 million charge for nuclear launch compliance.

The estimates assume Phase A costs of $2.5 million, and E/PO costs of 1% of the baseline mission cost.

Technology development cost estimates cover investments for components needed to achieve TRL 6:

- Hot-fire testing for propulsion system qualification
- Maturation of drill and sample acquisition system
- Maturation of Rover Low Power/Mass LIDAR

The integration and test element covers assembly and test of spacecraft subsystems, as well as integration and test of the spacecraft subsystems, instruments, drill and sample acquisition system. In addition, it includes integration of the ASRG for the ASRG-powered rover and ASRG-Lite options.

Launch vehicle and services costs are based on the table provided in the dGRPDS.

Cost reserves are calculated using the dGRPDS guidelines:

- No cost reserves on the launch vehicle and services or ASRG
- 50% reserves on all other Phase A–D costs including technology development and DSN charges
- 30% reserves on non-DSN Phase E costs
- No reserves on E/PO

Costs through landing, checkout and end of initial data collection (15 days after launch) are included in Phase D. Since the time from launch through end of mission for the battery-powered rover option is less than 15 days, estimates for this option include no Phase E costs. The ASRG-powered rover option includes Phase E costs for 12 months of additional science operations and data collection, while the ASRG-Lite option includes these costs for 3 months.

The Phase E science team for the LPVE mission consists of a single Principal Investigator, three Co-Investigators for each instrument, two project scientists, two drill operators/planners, and two additional planners supporting the investigator's working group and their interface to the mission operations team. The science costing assumes that the level of support will be brought on incrementally during Phases A-D.

Cost Methodologies: The tables in Appendix D summarize the methods used to estimate mission costs.

Cost Estimates

Cost estimates for the three options are as follows (FY15 dollars):

- Battery-powered rover option: $972M
- ASRG-powered rover option: $1.132B
- ASRG-Lite: $1.046B

The cost of the ASRG-powered rover option is 16.5 percent ($160M) higher than the cost of the battery-powered rover option, due to the following differences:

- Additional cost of spacecraft, ASRG and nuclear launch costs ($45M)
- Larger (2m) drill ($13M)
- Additional payloads ($33M)
    - XRD, Surface Cam, Exosphere Mass Spectrometer, Ground Penetrating Radar ($30M)
    - Expanded Pre-Phase-E Science Team ($3M)
- Additional year of science data collection ($16M)
    - Mission Operations, including Phase-E Science Team ($8M)
    - DSN charges ($7M)
    - E/PO ($1M)
- Additional Cost Reserves ($52M)

The cost of the ASRG-Lite option is 7.6 percent ($74M) higher than the cost of the battery-powered rover option, due to the following differences:

- Additional cost of spacecraft, ASRG and nuclear launch costs ($45M)
- Larger (2m) drill ($13M)
- Additional payloads (none - $0)
- Additional three months of science data collection ($4M)
    - Mission Operations, including Phase-E Science Team ($2M)
    - DSN charges ($1.75M)
    - E/PO ($0.25M)
- Additional Cost Reserves ($12M)

The table below presents estimated mission costs for the three options mapped to the NASA Level-2 WBS defined in Appendix G of NPR 7120.5D.

Table 23: Cost Comparison in FY15$ Using NASA WBS

		Battery Rover Mission	Battery Rover Mission	ASRG Full Mission	ASRG Full Mission	ASRG-Lite Mission	ASRG-Lite Mission
WBS	Description	FY10$M	FY15$M	FY10$M	FY15$M	FY10$M	FY15$M
	Phase A	$ 3	$ 3	$ 3	$ 3	$ 3	$ 3
	Technology Development	$ 10	$ 12	$ 10	$ 12	$ 10	$ 12
	Propulsion Qualification: Hot Fire Testing	$ 6	$ 7	$ 6	$ 7	$ 6	$ 7
	Drill & Sample Acquisition: Maturation	$ 2	$ 2	$ 2	$ 2	$ 2	$ 2
	Rover Low Power/Mass LIDAR: Maturation	$ 2	$ 2	$ 2	$ 2	$ 2	$ 2
01	Project Management	$ 16	$ 19	$ 16	$ 19	$ 16	$ 19
	Systems Engineering (incl. MD&A, Nav.)	$ 24	$ 28	$ 24	$ 28	$ 24	$ 28
03	Safety & Mission Assurance	$ 11	$ 13	$ 12	$ 13	$ 11	$ 13
04	Science/Technology	$ 10	$ 12	$ 13	$ 15	$ 10	$ 12
05	Payloads	$ 69	$ 78	$ 107	$ 123	$ 69	$ 78
06	Spacecraft	$ 256	$ 293	$ 275	$ 323	$ 275	$ 323
	Lander Stage (Hardware)	$ 89	$ 101	$ 89	$ 110	$ 89	$ 110
	SRM Stage (Hardware)	$ 15	$ 17	$ 15	$ 17	$ 15	$ 17
	Rover (Hardware, excl. Nuclear Power Component)	$ 119	$ 136	$ 118	$ 135	$ 118	$ 135
	Flight, Rover Software, Autonomy Dev. & Test	$ 34	$ 38	$ 34	$ 38	$ 34	$ 38
	Nuclear Power Component	$ -	$ -	$ 20	$ 23	$ 20	$ 23
07	Mission Operations	$ 21	$ 24	$ 28	$ 32	$ 23	$ 27
08	Launch Vehicles & Services	$ 157	$ 179	$ 170	$ 194	$ 170	$ 194
09	Ground Data Systems	$ 15	$ 17	$ 15	$ 17	$ 15	$ 17
10	Systems Integration & Test	$ 22	$ 25	$ 22	$ 25	$ 22	$ 25
DSN	Space Communications Services (DSN)	$ 1	$ 1	$ 7	$ 8	$ 2	$ 3
E/PO	E/PO	$ 6	$ 7	$ 7	$ 8	$ 7	$ 8
	Subtotal	$ 621	$ 710	$ 708	$ 817	$ 657	$ 759
	Excluding LV	*$ 465*	*$ 532*	*$ 552*	*$ 639*	*$ 501*	*$ 581*
	Cost Reserves	$ 230	$ 262	$ 271	$ 314	$ 247	$ 287
	Total, including Reserves	$ 851	$ 972	$ 979	$ 1,132	$ 904	$ 1,046

The following table compares the payloads cost breakdown for WBS Element 05.

Table 24: Payload Cost Comparison in FY15$ - NASA WBS Element 05

		Battery Rover Mission	Battery Rover Mission	ASRG Full Mission	ASRG Full Mission	ASRG-Lite Mission	ASRG-Lite Mission
WBS	Description	FY10$M	FY15$M	FY10$M	FY15$M	FY10$M	FY15$M
05	Payloads	$ 69	$ 78	$ 107	$ 123	$ 69	$ 78
	Payloads, Instruments	$ 67	$ 77	$ 105	$ 120	$ 67	$ 77
	Drill w/ Sample Acquisition	$ 29	$ 33	$ 40	$ 46	$ 29	$ 33
	Sample Delivery System	$ 7	$ 8	$ 7	$ 8	$ 7	$ 8
	Down-hole Neutron Spectrometer	$ 4	$ 4	$ 4	$ 4	$ 4	$ 4
	Neutron Spectrometer	$ 7	$ 8	$ 7	$ 8	$ 7	$ 8
	Gas Chromatograph/Mass Spectrometer	$ 18	$ 21	$ 18	$ 21	$ 18	$ 21
	Downhole Micro Camera	$ 3	$ 3	$ 3	$ 3	$ 3	$ 3
	X-Ray Diffraction (XRD)			$ 3	$ 3		
	Surface Cam			$ 4	$ 4		
	Mass Spectrometer			$ 8	$ 9		
	Ground Penetrating Radar			$ 13	$ 15		
	Payload Management, Engineering	$ -	$ -	$ -	$ -	$ -	$ -
	Payload S&MA	$ 1	$ 2	$ 2	$ 2	$ 1	$ 2

Given the low degree of schedule definition, it was not possible to distribute costs by Fiscal Year to present costs in Real-Year dollars.

Appendices

Appendix A – Study Team

Role	Name	Organization
Science Champion	Chip Shearer	UNM
NASA HQ POC	George Tahu	NASA HQ
Decadal Program Manager	Kurt Lindstrom	JHU/APL
APL Science POC	Ben Bussey	JHU/APL
Project Manager	Todd Holloway	NASA MSFC
Systems Engineer	Doug Eng	JHU/APL
	Danny Harris	NASA MSFC
	Ben Ballard	JHU/APL
Mission Design	Chris Dong	JHU/APL
Instruments	Jeff Plescia	JHU/APL
Propulsion	Huu Trinh	NASA MSFC
Mechanical	Scott Cooper	JHU/APL
Mobility	Eddie Tunstel	JHU/APL
Thermal	Jeff Farmer	NASA MSFC
	Elizabeth Abel	JHU/APL
RF	Brian Sequeira	JHU/APL
Avionics	Dorian Seagrave	JHU/APL
Power	Eric Lowery	NASA MSFC
GN&C	Jim Kaidy	JHU/APL
Software	David Artis	JHU/APL
I&T	Jay White	JHU/APL
Operations	Mike Norkus	JHU/APL
Drill & Sampling	Kris Zacny	Honeybee
Cost Estimation	Larry Wolfarth	JHU/APL
	Sally Whitley	JHU/APL

Appendix B – Concept Maturity Level Definitions

Concept Maturity Level	Definition	Attributes
CML 6	Final Implementation Concept	Requirements trace and schedule to subsystem level, grassroots cost, verification and validation approach for key areas
CML 5	Initial Implementation Concept	Detailed science traceability, defined relationships and dependencies: partnering, heritage, technology, key risks and mitigations, system make/buy
CML 4	Preferred Design Point	Point design to subsystem-level mass, power, performance, cost, risk
CML 3	Trade Space	Architectures and objectives trade space evaluated for cost, risk, performance
CML 2	Initial Feasibility	Physics works, ballpark mass and cost
CML 1	Cocktail Napkin	Defined objectives and approaches, basic architecture concept

Appendix C – Cost Estimating Methodologies

The tables below summarize the methods used to estimate mission costs.

NASA WBS Elements 01-04

Element (NASA WBS)	Method	Comments
Technology Development	Engineering estimates	Effort required to achieve TRL 6
Management (01)	Engineering estimates based on functional analysis	Labor rates based on mix of MSFC, APL & contractor support
Systems Engineering (02)	Engineering estimates based on functional analysis	Labor rates based on mix of MSFC, APL & contractor support
Safety & Mission Assurance (S&MA 03)	Engineering estimates	Labor rates based on mix of MSFC, APL & contractor support
Science (04)	Level of Effort, by phase (A-E)	Includes PI, project scientists, CO-Is, payload planning

NASA WBS Element 05 – Payloads

Payload	Method	Comments
Drill with Sample Acquisition System	Engineering estimate (Honeybee); distinguishes 1- and 2-m drill options	Estimate includes procurement burden
Sample Delivery System	Analogy to MSL delivery system	Final cost dependent on drill & lander configuration
Down-hole Neutron Spectrometer	Analogy to CMIS	
Neutron Spectrometer	Analogies to GRNS, GRAND	Adjustment for design miniaturization
GC/MS	Analogy to INMS (CASSINI)	
Downhole Micro Camera	Analogy to MER MI	
X-Ray Diffraction (XRD)	Analogy to InXitu's XRD instruments	Requires additional design miniaturization
Surface Camera	Analogy to MARCI; MSSS information	
Mass Spectrometer	Analogy to LD-MS	
Ground Penetrating Radar	Analogy to ExoMars WISDOM	

NASA WBS Element 06 – Other: Solid Rocket Motor, Software

Element	Method	Comments
Solid Rocket Motor	STAR SRM pricing; engineering labor estimate	Sources: MSFC, vendor
Structures & Thermal	PRICE-H parametric estimate	
Flight, Rover Software Development	Engineering estimate, based on prior missions; MER Rover software sizing	Includes development and test of flight, test bed, autonomy & rover software

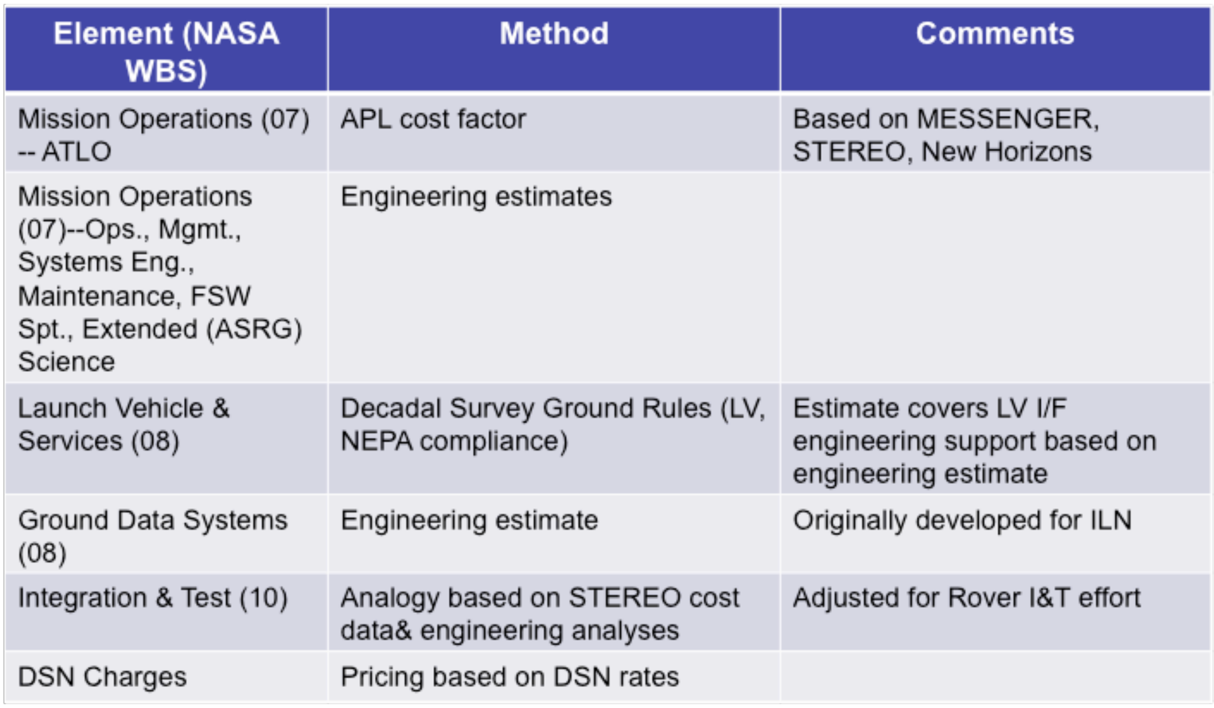
NASA WBS Element 06 – Lander

Element	Method	Comments
Mechanical & Structural	PRICE-H parametric model	Model originally developed & calibrated for ILN, LPV trade studies
Propulsion	Vendor ROMs, engineering estimates (oversight labor)	Based on ILN analysis of DACS propulsion
GN&C	Component ROMs	Sensor code, landing algorithms captured in Rover GN&C
Power: SAA, SAJB, Secondary Battery	PRICE-H parametric model	Model calibrated using APL solar array, MSFC battery data
Thermal Control	Component pricing, engineering labor estimate	Cross-checked during ILN study against APL cost data
RF Communications	PRICE-H parametric model	Antennas only
Harness	PRICE-H parametric model	Calibrated using APL cost data

NASA WBS Element 06 – Rover

Element	Method	Comments
Mechanical & Structural	PRICE-H parametric model	Calibrated using MER Rover, Pathfinder cost data
GN&C	Vendor ROMs, engineering estimates for labor	Covers sensor code generation
IEM, Avionics, PSE, BME, Battery, PDU	PRICE-H, analogies, vendor ROMs	Estimates at component level, results checked against RBSP & other cost data
Thermal Control	Component pricing, engineering labor estimate	Cross-checking during ILN study using APL cost data
RF Communications	Analogy to MESSENGER	SSPA requires technology development
Harness	PRICE-H parametric model	Calibrated using APL cost data
Test Beds	Engineering estimate	Covers design, development & delivery of 7 test beds

NASA WBS Elements 07-10, Other



Element (NASA WBS)	Method	Comments
Mission Operations (07) -- ATLO	APL cost factor	Based on MESSENGER, STEREO, New Horizons
Mission Operations (07)--Ops., Mgmt., Systems Eng., Maintenance, FSW Spt., Extended (ASRG) Science	Engineering estimates	
Launch Vehicle & Services (08)	Decadal Survey Ground Rules (LV, NEPA compliance)	Estimate covers LV I/F engineering support based on engineering estimate
Ground Data Systems (08)	Engineering estimate	Originally developed for ILN
Integration & Test (10)	Analogy based on STEREO cost data& engineering analyses	Adjusted for Rover I&T effort
DSN Charges	Pricing based on DSN rates	

Appendix D – Presentation Materials