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NASA'S INTERNATIONAL LUNAR NETWORK ANCHOR NODES AND ROBOTIC LUNAR LANDER PROJECT UPDATE

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ABSTRACT

In early 2008, NASA established the Lunar Quest Program, a new lunar science research program within NASA's Science Mission Directorate. The program included the establishment of the anchor nodes of the International Lunar Network (ILN), a network of lunar science stations envisioned to be emplaced by multiple nations. This paper describes the current status of the ILN Anchor Nodes mission development and the lander risk-reduction design and test activities implemented jointly by NASA's Marshall Space Flight Center and The Johns Hopkins University Applied Physics Laboratory. The lunar lander concepts developed by this team are applicable to multiple science missions, and this paper will describe a mission combining the functionality of an ILN node with an investigation of lunar polar volatiles.

INTRODUCTION: NASA ROBOTIC LUNAR LANDER DEVELOPMENT

One of the defining features of the U.S. Vision for Space Exploration, established by the former administration and studied by NASA for the past 4 years, is the goal of a human return to the Moon to live and work for extended periods. Whether that plan will be executed, however, has grown increasingly uncertain. Turbulent economic times, along with the need for the new administration to set its own priorities, have resulted in a complete review of U.S. space policy and NASA's programs. Many months remain before the process will be complete and new plans can be developed. But even in the face of this uncertainty, it is clear that the Moon is of significant scientific importance to NASA and many other nations and is a prime target for low-cost robotic missions that can be undertaken by most of the world's space programs. Thus, it can be expected that lunar robotic missions will remain a high priority while the U.S. human exploration program is restructured; when humans begin to venture beyond low-Earth orbit to the Moon, near-Earth objects, and eventually Mars, the generic technological capabilities developed through lunar robotic missions will serve as important steps toward future achievements.

The Moon contains a wealth of scientific information about planetary formation and the origins of Earth. NASA has a rich portfolio of lunar flight projects, including two payloads on India's Chandrayaan-1; the Lunar Reconnaissance Orbiter (LRO); the Lunar CRater Observation and Sensing Satellite (LCROSS); the Gravity Recovery and Interior Laboratory (GRAIL); the Acceleration, Reconnection, Turbulence and Electrodynamics of Moon's Interaction with the Sun (ARTEMIS) mission; and the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission. Other nations, including China, Japan, and India, also have emergent lunar portfolios. During this exciting time for lunar science, many significant scientific discoveries are just being realized from these flights, including the likely orbital confirmation of trapped water-ice on the lunar surface.

In addition, the U.S. National Research Council (NRC) is in the early stages of its new Decadal Survey for Planetary Science, which establishes priorities to be incorporated into the roadmap for NASA's Planetary Division of the Science Mission Directorate (SMD). The final report will not be ready until January 2011, but the results of many current planetary studies will be publicized along the way, previewing expected planetary (and lunar) priorities for the next 10 years.

Internationally, multiple space-faring nations are concurrently planning robotic missions to the Moon. To maximize the scientific return of these efforts, nine national space agencies signed a statement of intent to establish a set of robotic lunar landers in a geophysical network on the surface of the Moon. This collaborative

initiative is known as the International Lunar Network (ILN). ILN nodes will fly a core set of instruments, plus additional passive, active, in situ resource utilization (ISRU), or engineering experiments, as desired by each space agency. Participants' contributions can be landers, orbiters, instrumentation, or other significant infrastructure contributions, including communications capabilities, which in total will comprise the ILN.

The envisioned U.S. contribution to the ILN was the Anchor Nodes mission to be implemented jointly by NASA's Marshall Space Flight Center (MSFC) and The Johns Hopkins University Applied Physics Laboratory (JHU/APL). The ILN Anchor Nodes mission would develop a broad lander capability and establish surface and embedded elements to better characterize the structure and composition of the lunar interior. The United States originally envisioned launching the first two nodes to the mid-latitude regions in the 2015–2016 time frame, with an option to launch two more nodes shortly thereafter. Alternatively, NASA could launch all four nodes in the 2017–2018 time frame. However, the specific science to be conducted, and the payload suite to carry out these measurements, could change, given the recently published lunar water-ice discoveries and the forthcoming results of the Decadal Survey. Discussions continue with NASA's international partners to provide additional nodes within this time frame to constitute the first lunar scientific network. Regardless of the specific science objectives, the goals of the Anchor Nodes mission will remain technically and programmatically challenging. These goals include the placement of multiple nodes on the near side of the Moon, continuous operations through many years of lunar eclipse, low-mass and low-power subsystems and instruments, and a minimum 6-year lifetime. Future nodes are planned for the far side of the Moon, for which lunar–Earth communication and navigation solutions are under consideration by countries supporting the ILN [1].

After the completion of an extended pre-Phase A study, the implementation of an ILN Anchor Nodes mission was placed on hold pending the resolution of the above-mentioned uncertainties. The MSFC–JHU/APL team was renamed the Robotic Lunar Lander Development Project (RLLDP) with the scope to complete an array of lander technology risk-reduction tasks and to perform studies on other missions that address some of the key science and exploration priorities. One such mission combined the functionality of a single ILN node with instruments to prospect for volatiles in a fixed location within a permanently shadowed lunar polar crater. The latest data from lunar orbiting observatories have further fueled interest in attaining "ground truth" for the presence of volatiles, including water-ice, in permanently shadowed craters. The single-site approach is limited in its ability to fully satisfy key science goals associated either with the ILN mission or with a desire to fully characterize the volatile distribution, but it represents a much more affordable single mission that, combined with other missions, could more fully address these goals. The results of this study and the status of the risk-reduction tasks spanning technologies in propulsion; guidance, navigation, and control; power; avionics; thermal; and structures and mechanisms are documented in this paper.

SCIENCE

The Moon provides an important window into the early history of the Earth, containing information about planetary composition, magmatic evolution, surface bombardment, and exposure to the space environment. Despite more than 4 decades of intensive study, many aspects of the Moon remain to be determined. One of the key motivations for studying the Moon is to better understand the origin of the planets of the inner solar system in general and that of Earth in particular.

The NRC report, New Frontiers in the Solar System: An Integrated Exploration Strategy (the Planetary Science Decadal Survey) [2], is the principal roadmap for solar system exploration, providing a community-based weighting of science priorities across the solar system, including the Earth's Moon. In this document, the Inner Planets Panel asserted that the inner solar system affords the opportunity to address broad objectives for understanding the history, current state, and potential future of habitable planets. Landed missions were recommended by the panel for all of the terrestrial planets—Mars, Venus, Mercury, and the Moon—in order to address multiple key aspects of inner solar system science. The next Planetary Science Decadal Survey for the period 2013–2023 is currently under way. This report will not be ready until January 2011, but the results of many current planetary studies will be publicized along the way, previewing expected planetary (and lunar) priorities for the next 10 years. In support of this activity, the lunar science community articulated and prioritized its science objectives in a set of 35 white papers, painting a coherent and compelling picture of the importance of lunar science to understanding differentiation of planets, the bombardment history of the inner solar system, and processes unique to airless bodies. Two candidate lunar lander missions—a geophysical network and an in situ polar volatile explorer—were studied and presented to the Decadal Survey by this team in order to address multiple key aspects of lunar and planetary science. Lander technology developed for any of these missions will have significant feedforward to other missions to the Moon and indeed, to other airless bodies such as

Mercury, asteroids, and Europa, to which many of the same science objectives are applicable.

Network Science

Because the Moon's geologic engine largely shut down long ago, its deep interior retains information about its initial composition, differentiation, crustal formation, and subsequent magmatic evolution. Data concerning interior structure and dynamics are difficult to obtain but are worth the considerable effort it would take to do so. Geophysical measurements are often the best, and only, way to obtain information about the composition and structure of the deep lunar crust, mantle, and core. The narrow extent and instrumental limitations of the Apollo seismic, magnetometer, heat flow, and laser ranging network resulted in very little information regarding crustal variations, limited resolution of upper-mantle mineralogy, and few details about the lower mantle or the lunar core. Other geophysical methods also had limited coverage and resolution. Therefore, a next-generation lunar geophysical network, acquiring seismic, heat-flow, and magnetic-field data, has been a strong desire of the planetary geophysics community for many decades.

A variety of geophysical and compositional analyses of the Moon will enable researchers to determine the internal structure and composition of a differentiated planetary body. However, the next generation of lunar geophysical measurements has to substantially improve on our current, largely Apollo-based knowledge in order to make significant advances in science. The desires of lunar geophysical science drive severe mission implementation needs, including a sophisticated instrument payload, multiple simultaneously operating nodes, continuous seismometer operations, and a long mission lifetime (2–6 years). Farside placement of geophysical landers is also a strong science desire, but a separate communications satellite would be required to support this. However, all landers in the network mission do not have to be built and flown by a single agency. Geophysical observations of the Moon via a network of stations, such as the envisioned for the ILN, will yield a wealth of knowledge from regions heretofore inaccessible by the Apollo database.

Lunar Polar Volatiles

The discovery of water at the poles of the Moon has captured the interest of both scientists and the general public. The hydrogen anomalies detected by Lunar Prospector, Earth-based radar data, and the LCROSS impactor all indicate that deposits of water-ice and other volatile compounds (e.g., CO, CO_2, HN_3, etc.) are widespread and abundant within the lunar polar regolith. Volatile compounds at the Moon's poles may come from many sources—comets, asteroids, interplanetary dust particles, interstellar molecular clouds, solar wind, lunar volcanic and radiogenic gases, etc.—all of which are important in NASA's strategic plans for understanding habitable environments and useful resources in the solar system. The inventory and isotopic compositions of lunar polar volatiles (LPVs) represent a record of the solar system over the time they have been accumulating, some 2 billion years or more. Understanding the distribution (vertical and lateral) and state (bound or free, blocky, etc.) of the volatiles is also crucial for determining both how these molecules interact with the lunar surface and their potential as strategic or economic resources.

Surface-based in situ measurements will still be needed for a detailed understanding of volatile compounds in the lunar polar regions. Once we definitively know the full composition and abundance of the volatiles, we can begin to evaluate them as a resource for further scientific inquiry as well as human exploration. Current information on the location of deposits of water-ice (and other volatiles) suggests that the ice is concentrated in permanently shadowed craters near the poles. These data also suggest that the ice is concentrated in the topmost 1 m of regolith but not exposed at the regolith surface. The best fit models suggest that ice-rich regolith is overlain by 20–30 cm of desiccated regolith, a result that is consistent with interpretations of Earth-based radar data. Meeting important science objectives in this environment therefore presented its own set of demands, including requiring subsurface access and working in the cold and dark of a permanently shadowed lunar crater.

LUNAR POLAR VOLATILES MISSION

Introduction

The joint MSFC–JHU/APL robotic lander team has completed a mission design concept to sample for volatiles in a permanently shadowed lunar polar region. This LPV mission concept leverages the previously matured ILN Solar-Array Battery (SAB) lander as the design point of departure [1]. The resulting mission concept provides a lander capability with significant design maturity and further demonstrates the broad applicability of the ILN core lander capability for multiple science and exploration missions.

Mission Objectives and Science Instruments

The primary LPV mission goal is to conduct a detailed inventory of volatile species and provide sufficient analysis to determine or greatly constrain the sources of polar volatiles and their nature. Specific science objectives are to:

1. Determine the chemical composition, abundance, and isotopic ratios of volatiles cold-trapped in permanently shadowed regions (PSRs) of the lunar poles
2. Determine the near-surface vertical profile of the lunar polar deposits
3. Monitor the time-sensitive magnitude and variability of current volatile deposition from the exosphere and the environmental conditions that control this process

The instruments for an LPV mission would likely be chosen through a competitive Announcement of Opportunity process; however, to perform a meaningful design study, it was necessary to identify a notional instrument suite. Table 1 shows the instruments used for this mission concept and their associated mass and power.

As a secondary scientific objective, a seismometer was also included in the instrument suite. This allows the Advanced Stirling Radioisotope Generator (ASRG)-powered lander to also function as an anchor node for a future geophysical network. The seismometer would be deployed after completion of the primary volatiles sampling mission objective.

Mission Design and System Overview

The mission concept will emplace a single stationary polar lander in a permanently shadowed lunar crater. Specific landing site selection will be optimized for science return. The landing will occur at a predetermined and relatively obstacle free location and will make use of optical terrain-relative navigation for a safe landing.

Communication opportunities within a PSR are particularly challenging and will pose the primary landing site constraint. Because there is no available lunar orbiting communications asset, direct line of sight between the lander and Earth is required in order to provide data communication. A direct communication path can only be obtained in a PSR when the landing site is permanently shadowed from the Sun but visible from Earth, resulting in "earthshine" conditions. The earthshine present in this scenario is also sufficient to support optical terrain-relative navigation. Figure 1 shows representative lunar south pole images from Earth-based radar illuminations and the Lunar Orbiter program illustrating areas that are shadowed from the Sun but visible from Earth.

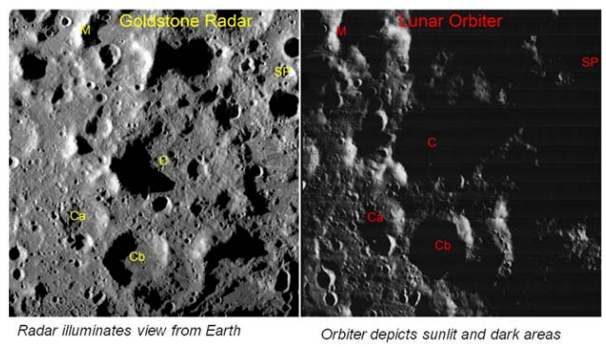


Fig. 1: Areas shadowed from the Sun but visible from Earth.

Based on initial assessment of candidate landing sites, the study team devised a surface operations scenario for 24-hour drilling cycles based on 15 hours of transmit and receive communication opportunities per day for 7 days per month.

Lander Payload	Objective	Mass (kg)	Power (W)
Drill and Deployment Mechanism	Recover regolith samples from depths of 1 m	39.0	108.3–520
Sample Camera	Imaging of drill sample, particle size, and shape distribution	2.3	14
Sample Delivery System	Process core material for analysis	6.5	26
Mass Spectrometer	Determine the various volatile compounds present and their isotopic composition	19.5	24 (48 peak)
Neutron Spectrometer	Determine the flux and energies of neutrons to determine H content of regolith	1.3	2.3
Ground-Penetrating Radar	Determine the depth profile of regolith to tens of meters	5.0	6.5
Seismometer	Long-term monitoring of seismic activity, background levels, and lunar normal modes	6.5	3.4

Table 1: Notional Science Instruments.

The notional LPV mission instrument suite is significantly heavier and more power demanding than the ILN mission instruments. For the instruments assumed in the design study, the LPV mission will need to accommodate a total mass on the order of 80 kg and peak power consumption during drill operations of >600 W, including growth margin. For comparison,

the ILN mission instrument mass per lander is ~12.5 kg, and power consumption is ~20 W [3]. To accommodate this extra mass, the larger ILN SAB lander structure is used for the LPV mission concept, but the solar arrays and most of the massive secondary batteries required for the 6-year SAB ILN mission were removed. Because solar arrays would be of no use in a PSR, an ASRG is used to provide power for surface operations. Replacing the ILN solar arrays and batteries with the much lighter but power-rich ASRG allows mass and power capacity to accommodate the LPV instrument package. Only a relatively small mass allocation for rechargeable batteries remains for the LPV lander to handle surface peak power needs that exceed the ASRG's instantaneously available output.

The LPV lander is shown in cruise phase and landed surface operations configuration in Figures 2 and 3, respectively. The total lander dry mass is ~275 kg, including growth margin. Table 2 provides a comparison of key LPV and ILN SAB lander system attributes. In addition to the science instrument and power system changes noted above, other key changes from the ILN SAB lander configuration include the use of terrain-relative navigation and the addition of thrust vector control to the solid braking motor. Both of these features have been added to support the precision landing required to effectively target the crucial Earth-lighted but Sun-shaded landing location.

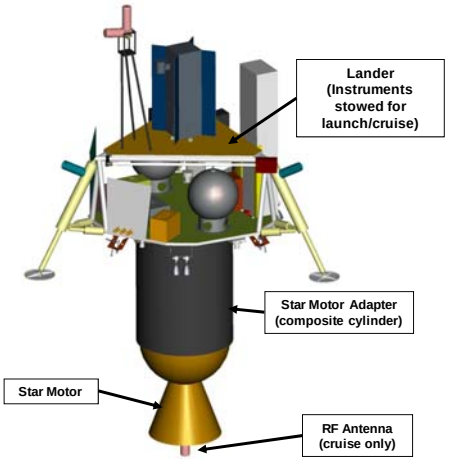


Fig. 2: LPV lander in cruise configuration.

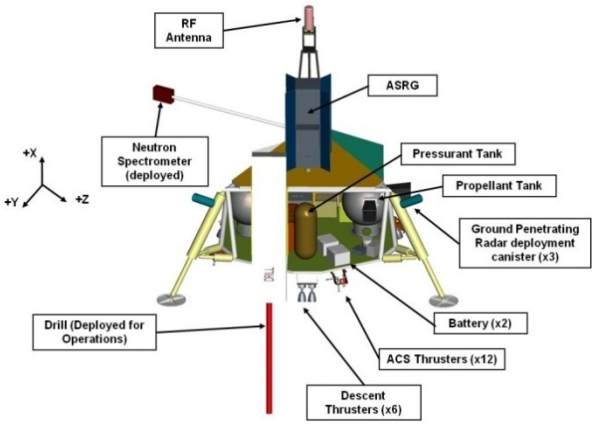


Fig. 3: LPV lander in surface operations configuration.

As reported in Ref. 1, the basic lander bus studied for the ILN and LPV missions could be easily adapted to perform a number of different lunar science and exploration missions in varying environments. Reusing this bus design would offer significant nonrecurring cost savings. Figure 4 illustrates the range of available payload power versus payload mass for some of the scenarios that have been considered by the joint MSFC–JHU/APL team using the two primary ILN lander bus concepts. The LPV mission lander, which has been the focus of this section of the paper, has been added for comparison (Fig. 4, item 8, circled).

RISK-REDUCTION ACTIVITIES

During the pre-phase A studies for the ILN mission, lander subsystem technology risks were identified and prioritized based on technology readiness level (TRL) and commonality to the multi-missions. The mass and power constraints of the lander system are key drivers for the risks. Risk-mitigation activities to increase the TRL of a technology or reduce the development risk were instigated, and many of the activities are ongoing, with their status presented below.

Propulsion

High Thrust to Weight Bipropellant Thrusters Qualification

The ILN mission concepts and all small lander (landers with <150-kg payload capacity) concepts recently studied by this team use pulsed, high thrust to weight thrusters. Thrusters of this class have flight heritage in Department of Defense (DoD) applications, but the ILN and LPV missions will require longer burn times for trajectory correction maneuvers (TCMs) and landing with the use of MON-25 propellant to assist the propulsion system thermal management. Risk-reduction testing has recently been performed over a full ILN and LPV mission duty cycle spanning 995 s

Subsystem	LPV Mission	ILN SAB Mission
Power	• ASRG primary power source • Small compliment of rechargeable batteries to address surface operations peak power • Power system electronics	• Solar array power for cruise and lunar day • Secondary batteries for lunar night • Power system electronics
Propulsion	• Bipropellant • 100-lbf descent divert and attitude control system (DACS) engines (6) • 6-lbf ACS DACS engines (12) • Two custom metal diaphragm tanks	• Bipropellant • 100-lbf descent DACS engines (6) • 6-lbf ACS DACS engines (12) • Two custom metal diaphragm tanks
Avionics	• Integrated flight computer and power distribution	• Integrated flight computer and power distribution
Communications	• S-band • 1-W radio frequency transmit power • 2-kbps uplink, 100-kbps downlink capable on surface	• S-band • 1-W radio frequency transmit power • 2-kbps uplink, 100-kbps downlink capable on surface • Antenna coverage for nearside or farside operations
Guidance, Navigation, and Control (GN&C)	• Star Tracker (dual) • Inertial measurement unit (IMU) • Radar altimeter • Landing cameras (2) • Terrain-relative navigation for precision landing in earthshine • Increased thruster vector control accuracy on solid braking motor	• Star Tracker (dual) • IMU • Radar altimeter • Landing cameras (2)
Structure	• Composite primary structure	• Composite primary structure

Table 2: Comparison of ILN and LPV lander attributes.

for a 445 N DoD flight heritage descent thruster. Figure 5 shows the test setup for the high thrust to weight thrusters and a size comparison between a conventional thruster and the DoD flight heritage thruster. Test results demonstrated good thermal control and combustion stability with MON-25. Planning for testing of a 30 N DoD flight heritage attitude control system (ACS) thruster is in progress, with testing planned for July 2010.

Helium Pressure Regulator for High-Pressure Blow-Down Ratio

The ILN mission concept uses a high thrust to weight propellant system that requires a pressurant blow-down ratio of up to 10:1 with the upstream pressure starting at 69,000 kPa. Available high TRL regulators may not be capable of performing as required at a 10:1 blow-down ratio. The test facility at NASA/MSFC has been characterized for testing an existing flight heritage pressure regulator to validate its suitability for this application. Risks to be mitigated by this testing are:

- Regulation pressure band – outlet band may fluctuate, causing erratic thruster performance
- Internal media (helium) temperature – rapid expulsion of the pressurant results in cold helium and impacts regulator performance

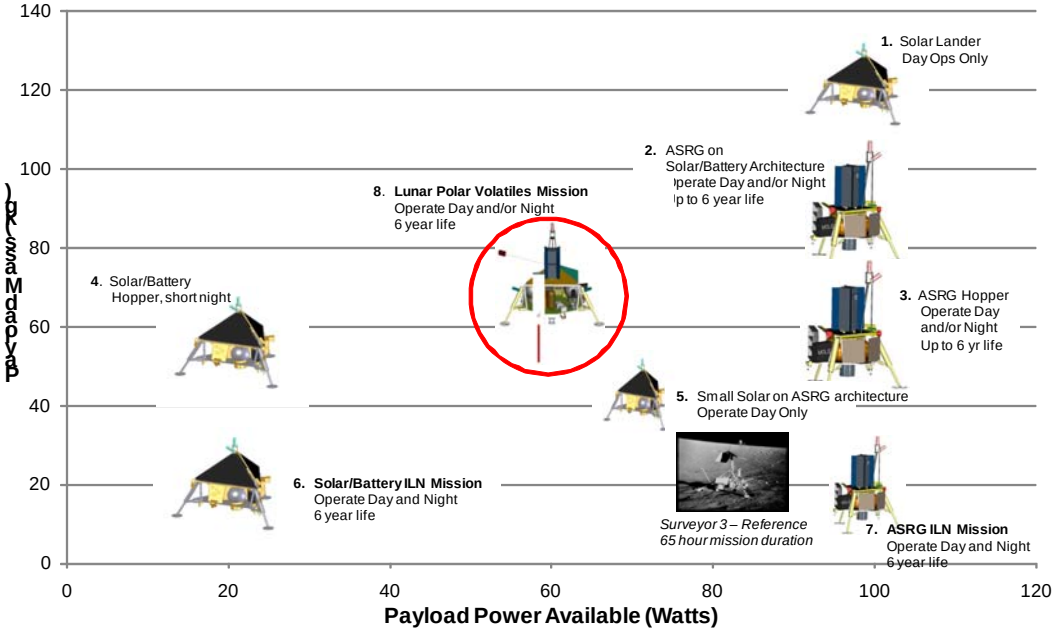
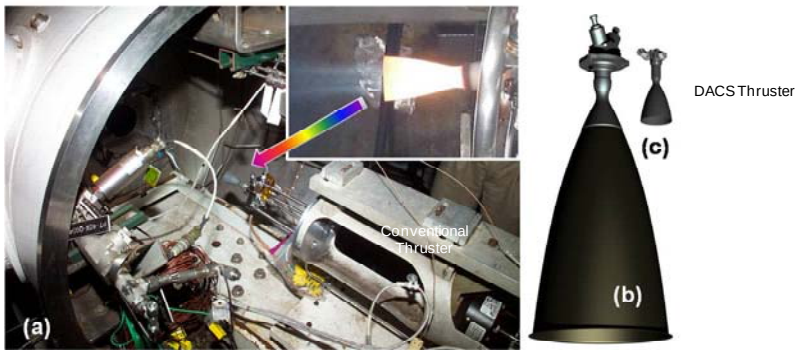


Fig. 4: Generic lander payload mass versus power.

- Slam start – changes in regulator performance attributable to filter damage and/or stress on internal components
- Outlet pressure stability – interaction between propulsion system and regulator can cause fluctuation
- Internal leakage – internal leakage during cruise can cause pressure fluctuations in the regulator outlet pressure
- External leakage – overboard pressurant leakage resulting in loss of pressure

Mitigation tests include:

- Blow down – rapid blow down from 69,000 kPa to 6,900 kPa inlet pressure
- Lock-up – blow down from 69,000 kPa to 6,900 kPa in increments of 6,900 kPa
- Mission duty cycle – pulsing performance due to thruster operation
- Slam-start – regulator operation during and after pyro valve simulation



a) Test Setup in Vacuum Chamber at WSTF for DACS Thruster Hot-Firing and Comparison of Engine Envelope
(b) Conventional Thruster and (c) DACS Thruster

Fig. 5: Thruster testing.

Guidance, Navigation, and Control

The planned landing concept, which will make use of optical cameras and lit landing sites for control of lateral velocities, has not been used for a lunar landing. A least-squares optical flow (LSOF) algorithm, which takes images of the lunar surface during the descent phase and compares the sequential images to determine the lateral velocity, has been completed, and bench testing is under way. A navigation filter with inputs from a radar altimeter and LSOF has started. The terminal descent phase is completely autonomous, and the vertical and lateral velocities are reduced to <1 m/s to allow a soft landing. High-fidelity end-to-end simulation, field testing, and testing in an Earth-based hover/descent lander test bed are planned to demonstrate the technique and reduce the landing risk. The first test bed lander has been constructed, and initial checkout of the closed-loop control algorithms from descent and landing is under way. This first test bed lander, known as the "cold gas" test article (CGTA) uses compressed air as the propellant and has a flight time of ~10 s because of the low specific impulse. A second test bed lander called the "warm gas" test article (WGTA) uses hydrogen peroxide as a mono-propellant. The WGTA has completed critical design and will begin system hot-fire testing in summer 2010 followed by demonstrations of the flight-like control algorithms during free flights of the vehicle. The WGTA is designed to achieve flight times nearing 1 min and to allow for validation of control algorithms in a flight-like software environment, using a processor and sensor suite representative of that which would be used on a flight mission to the lunar surface. The test article avionics box is capable of hosting multiple processor cards that are candidates for a flight mission. The sensor suite includes an inertial measurement unit, a radar altimeter, and optical cameras. Like the CGTA, the WGTA uses a center-line-mounted throttleable thruster that offsets a portion of the vehicle's weight to simulate a lower gravity environment. This gravity-canceling thruster is throttled over the duration of the flight to account for decreasing vehicle mass due to expended propellant. The test goals for this article culminate in a controlled descent from a 30-m altitude, control to a preferred orientation, and null out lateral translations. The WGTA is shown in Figure 6.

Power

One of the biggest challenges facing a lunar platform designer is the electrical power subsystem (EPS). The length of the lunar night (372 h) and the severe thermal environment, whether in sunlight or shadow (+200°C to –110°C), necessitate unique engineering accommodations. Mission length and the presence or absence of

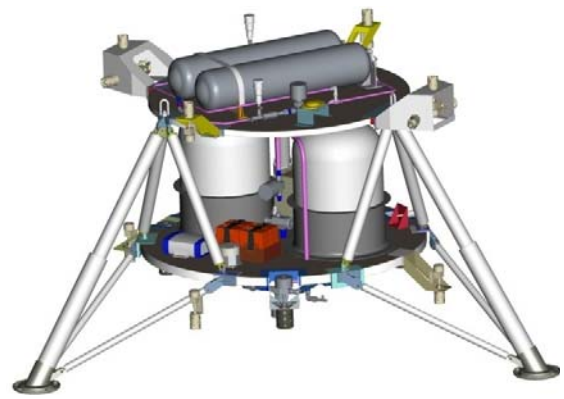


Fig. 6: WGTA.

solar illumination must be considered when choosing a power source for lunar use. Long-duration missions on the lunar surface usually use solar arrays or radioisotopes as power sources. Secondary (rechargeable) chemical storage batteries are commonly used in conjunction with solar arrays to provide power through the night or in conjunction with nuclear sources to provide supplementary or peak power. Chemical storage batteries are typically the weakest component in an EPS. Secondary chemical storage batteries in EPSs for lunar platform conceptual missions currently under consideration are challenged by the lunar thermal environment, the length of the mission, and the depth of discharge required. Mission designers typically require lifetimes measured in multiple years, tolerance for the thermal environment (+200°C to –110°C), and the ability to achieve depths of discharge approaching 80% for the mission duration. EPSs are usually designed so that batteries are not stressed by each of these three variables at the same time. Long-duration lunar surface missions typically require battery performance that causes stress from all three of these variables at the same time.

The Robotic Lunar Lander Design Team (RLLDT) is studying conceptual missions that would have long lifetimes on the lunar surface and require batteries to meet performance requirements when subjected to severe thermal environments and high depths of discharge. To reduce the risks associated with the use of secondary chemical storage batteries for the conceptual long-duration lunar surface missions, a body of planned testing is being undertaken by the RLLDT. This testing will reduce the risk associated with performance and lifetime uncertainties of lithium-ion battery cells at elevated temperatures (50°C) for a 6-year mission life requirement. The planned testing also incorporates testing to reduce the risks posed by batteries

on a notional ASRG-powered lander platform. An ASRG-powered platform could be used for an ILN mission with seismometers or an LPV mission in a permanently shadowed crater. For an ASRG mission, the batteries are needed during peak power demands, typically for high current such as during the operation of the propulsion system valves or, in the case of the LPV mission, during the operation of a drill or an ISRU experiment. The battery cells have been procured and will be tested in summer 2010.

Avionics

Power requirements from the avionics have a twofold effect on the system. Because of the long lunar night, slight increases in power requirements of the avionics during night operations result in additional secondary battery mass. Based on the battery chemistry baselined for the 6-year geophysical mission, 1 additional watt of power required for continuous operations at night requires ~4.5 kg of battery mass. Low-power/lightweight avionics are desired to reduce the lander dry mass. A leading candidate for the low-power single board computer with solid state recorder and high-speed communications is based on the Aeroflex LEON processor. The operating modes are software controlled and range from 2 W to 8 W. The board design, design peer review, and initial board layout are complete. The engineering board testing and evaluation are planned for summer 2010. The propulsion interface electronics, which will provide the commands to the propulsion system valves, will have the critical design, development, and evaluation completed in July 2010.

Thermal

The ILN mission concept requires thermal management for continuous operation over the wide range of environmental extremes for lunar night and day and a potentially large range of latitudes. Efforts are under way to assess and refine available thermal management systems for this application. This includes detailed design studies of compact radiator geometries to parametrically assess the sensitivities to latitude and landing slopes that impact the view factors to lunar regolith and sun during the lunar day. During the hot lunar day, the radiator will serve to reject as much heat as possible, whereas during the cold lunar night, heat loss through the radiator should be minimized. Design studies, fabrication, and hardware testing of variable-conductance heat-transport capabilities that couple and decouple the main electronics compartment and the heat-rejection radiators are under way.

Another risk that is common to all landers studied by this team is the solid rocket motor (SRM) thermal control. Typically, the thermal control of the SRM can be managed by slowly spinning the spacecraft during the cruise phase. However, during TCM and the braking burn, the descent thrusters will be operated, and the plume of the descent thrusters will impact the SRM casing. An analysis was performed to determine the impact of the plume impingement, and it was determined that the temperature gradient of the SRM would exceed tolerances and that a thermal shield is required on the SRM. The descent thruster plume impingement on the multi-layer insulation (MLI) causes the temperature on the outside surface of the blanket to exceed the typical MLI allowance. A coating will be needed on the MLI used on the SRM. Design and fabrication are under way, and testing of the thermal blanket is planned for summer 2010. A thermal profile on the outer surface of the SRM blanket is shown in Figure 7.

Structures and Mechanisms

The overall structure and many of the mechanisms are similar for the several mission concepts studied by this team. Three key areas of risk reduction for the structures and mechanisms technology are discussed below.

Lander Leg Stability

Because the descent and ACS propulsion systems use pulsed thrusters, the vertical touchdown velocity and the tilt angle and rates may not be completely nulled at touchdown. In addition, the lunar surface is highly variable, with terrain features such as slopes, rocks, and craters that the landing legs must accommodate. Nonlinear kinematic math models have been produced for the flight lander in order to predict the behavior of the lander at landing and optimize the design. A test

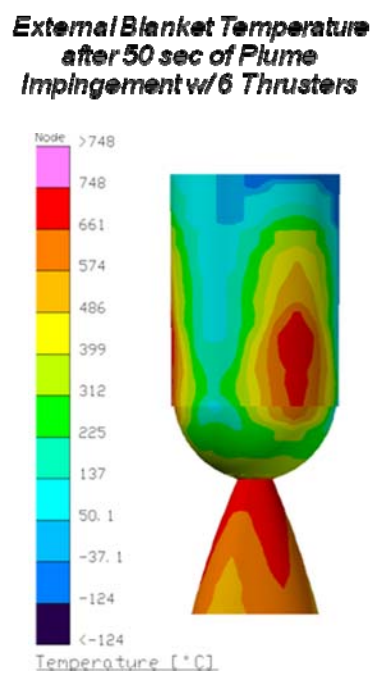


Fig. 7: Thermal profile of the outer surface of the SRM blanket.

program is under way to validate these models. The testing is in three phases: (1) a simple rigid block lander; (2) a ½-scale lander model of a flight lander with elastic deformation; and (3) the same ½-scale model with inelastic energy absorption systems. Math models were developed for each of these configurations, and test data will be compared to the analytic results. To date, the first phase (rigid block) of testing has been completed. The test results agreed very well with the analytic predictions. The ½-scale model and the associated test equipment are in final assembly, and testing will begin soon.

Star Motor Adapter

The star motor adapter (SMA) is a large composite cylinder designed to connect the SRM to the lander. This is a large highly loaded structure with high stiffness requirements. To optimize the design, a full-size model is being built using flight-like materials and processes. Test data will be used to validate the model and aid in minimizing structural mass. Of particular interest is the three-point structural attachment to the lander. This discrete attachment approach minimizes lander mass and separation system mass at the expense of inefficiency in the adapter load paths. This is believed to be a good trade-off because of the higher staging factors on landed mass, but the effect on the adapter must be fully understood. This adapter will be subjected to static loads, vibration, and separation tests. Figure 8 shows the separation test setup.

Lander Structural Design and Fabrication Processes

The structures and mechanisms team for the lunar flight unit has executed the design and fabrication of the structure for the WGTA using the same composite material expected to be used in the lunar flight system. This allowed the opportunity to prove out processes and interactions of the diverse and distributed team and optimize the methodologies in anticipation of a flight vehicle build. This is applicable to refining design and fabrication processes as well as communication and management approaches.

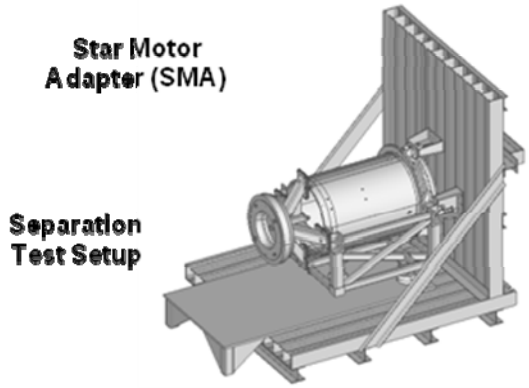


Fig. 8: SMA in test fixture.

CONCLUSIONS

For almost five years now, the MSFC and JHU/APL team have developed the flexible architecture of the robotic lunar lander to envelope multiple missions, to include both the ILN and LPV. This architecture has both nuclear and solar array battery powered versions that interface-well to multiple launch vehicles depending on the number of landers desired and commensurate to, available funding. The basic lander bus constitutes a transportation system that could be easily adapted to perform a number of different lunar science missions for NASA's SMD or lunar exploration missions for ESMD. The U.S. lunar science missions of the next decade, and their priority, will be determined by the in-progress Planetary Science Decadal Survey, and the lunar exploration missions are currently under study as defined by President Obama's new space policy and vision. For lunar robotic missions in general there is a rather clear intersection between science and exploration, and this robotic lander will satisfy requirements of the first of several surface missions envisioned to be implemented over the next five years. The risk-reduction activities continue to advance with significant progress to date. The single site LPV mission provides a cost effective approach toward advancing our knowledge of the state of volatiles at the lunar poles while contributing to the key objective of establishing a global lunar geophysical network. Combining missions in this way would constitute prudent use of NASA funds in an exciting partnership of two key Directorates (SMD and ESMD), and still provide the U.S. contribution to international ILN collaboration. Equally important, many of the robotic lander technologies to be demonstrated also have extended application to future robotic missions of other inner planet airless bodies, destinations of both SMD and ESMD.

ACKNOWLEDGMENTS

We thank NASA's Planetary Division, Science Mission Directorate Headquarters, the Lunar Quest Program Office, the ILN Science Definition Team, the Robotic Lunar Lander Development Project Office, and our entire ILN science and design team at Marshall Space Flight Center and The Johns Hopkins University Applied Physics Laboratory for their support and contributions herein.

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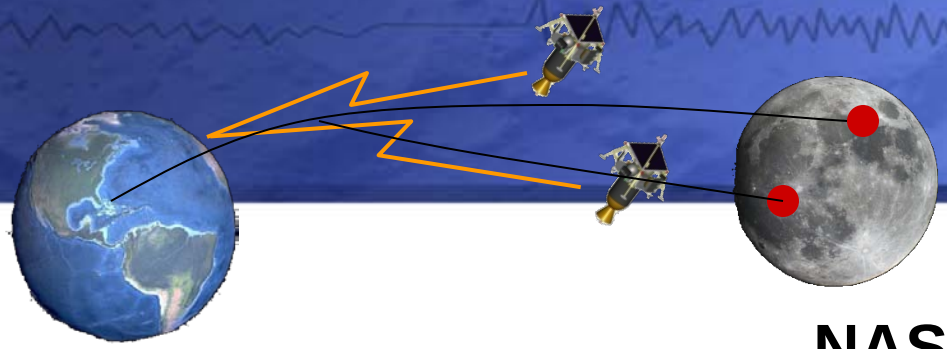

NASA ILN Anchor Nodes and Robotic Lunar Lander Project

GLUC-2010.1.5.B.3

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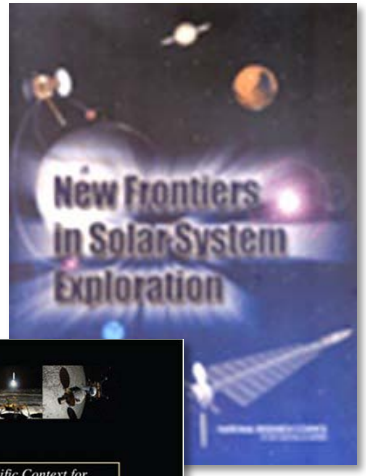
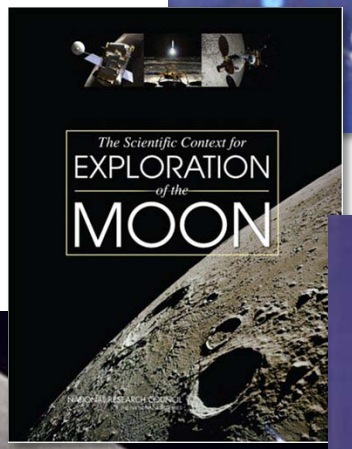
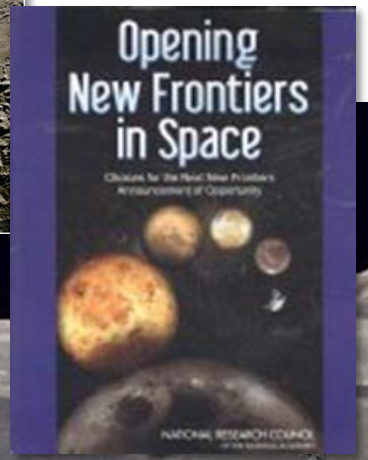






Contents

- ILN/Robotic Lunar lander history
- Robotic Lander Project Activities Status
- Single Site Lunar Polar Volatiles Mission Study
- Risk Reduction Status
- Summary

History

- **International Lunar Network (ILN)**
  - A series of US and International Partner provided Lunar Landers which act as common science nodes in a lunar geophysical network
  - Letter of intent signed with eight other space agencies: Canada, Britain, Germany, France, Italy, Japan, India and Korea
- **NASA ILN anchor node mission**
  - In pre-phase A study with a technology risk reduction program since Spring 2008
  - A technical and costing review was conducted by NASA HQ in June 2009
  - Mission on hold awaiting Decadal Survey prioritization
- **Robotic Lunar Lander project team continuing with Risk Reduction technology development and examining lander bus applications to other lunar science missions**

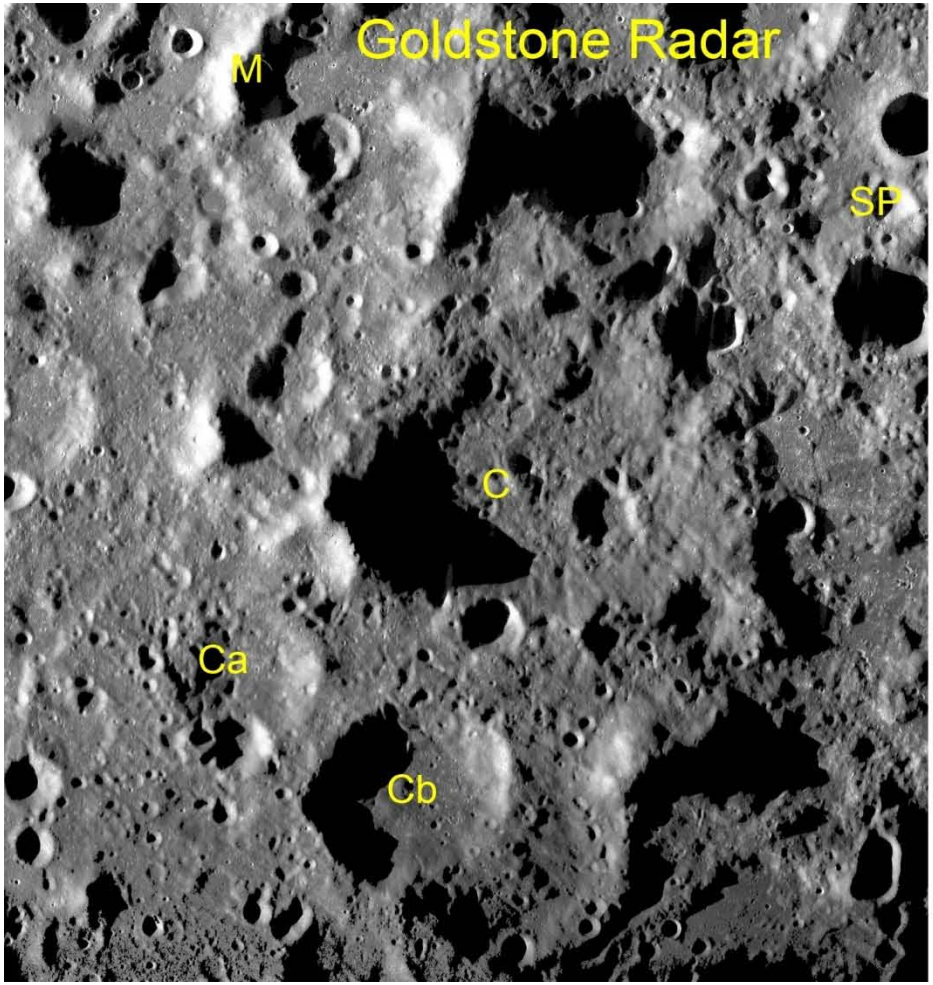
Robotic Lander Project Activities Status

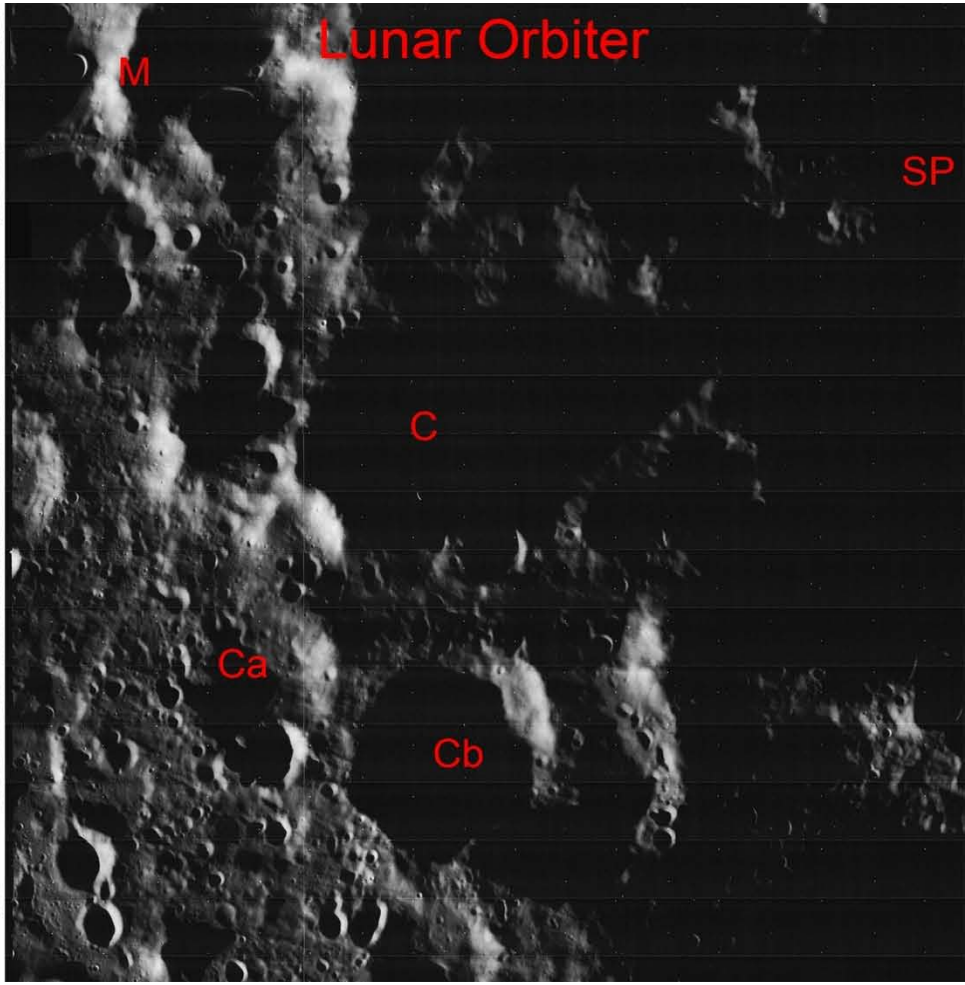
- **Conducted a Single Site Lunar Polar Volatiles mission study – Summarized here**
- **Conducted Studies under the direction of the Inner Planets Panel of the Decadal Survey**
  - Lunar Geophysical Network Mission
  - Multisite (Mobile) Lunar Polar Volatiles Mission
  - Decadal Study results not yet public
- **Continued to fly Cold Gas Test Article with GN&C algorithms of increasing fidelity**
- **Continued Risk Reduction analysis and test for robotic lunar landers**
  - Propulsion, Power Thermal, Structures, Avionics, GN&C

Lunar Polar Volatiles Mission Goals

- **Mission Goal: Conduct a detailed inventory of volatile species and provide sufficient analysis to determine or greatly constrain the sources of polar volatiles and their nature**
- **Unique new science objectives:**
  - Determine the chemical composition, abundance and isotopic ratios (i.e. D/H) of volatiles cold-trapped in permanently shadowed regions of the lunar poles
  - Determine the near-surface vertical profile of the lunar polar deposits
  - Monitor the time-sensitive magnitude and variability of current volatile deposition from the exosphere and the environmental conditions that control this process
- **Mission overview**
  - **Single stationary polar lander to permanently shadowed lunar crater.**
  - **ASRG powered and launched via Atlas V EELV. (Co-manifest compatible)**
  - **Land at a predetermined obstacle free site with 200m accuracy using TRN, no HDA**
  - **Payload to include drill (to 1-m in lunar surface) and sample analysis, spectrometry, ground penetrating radar and EM sounding.**
  - **Also provide seismometer to act as a single node of an ILN seismometry network.**
  - **Mission life provides 3 months of active drilling and 6 years seismometry.**
  - **Site selected to provide seven days per month communication direct to earth**

Shadowed from Sun but Visible from Earth





Radar illuminates view from earth

Orbiter depicts sunlit and dark areas

Notional Science Payload

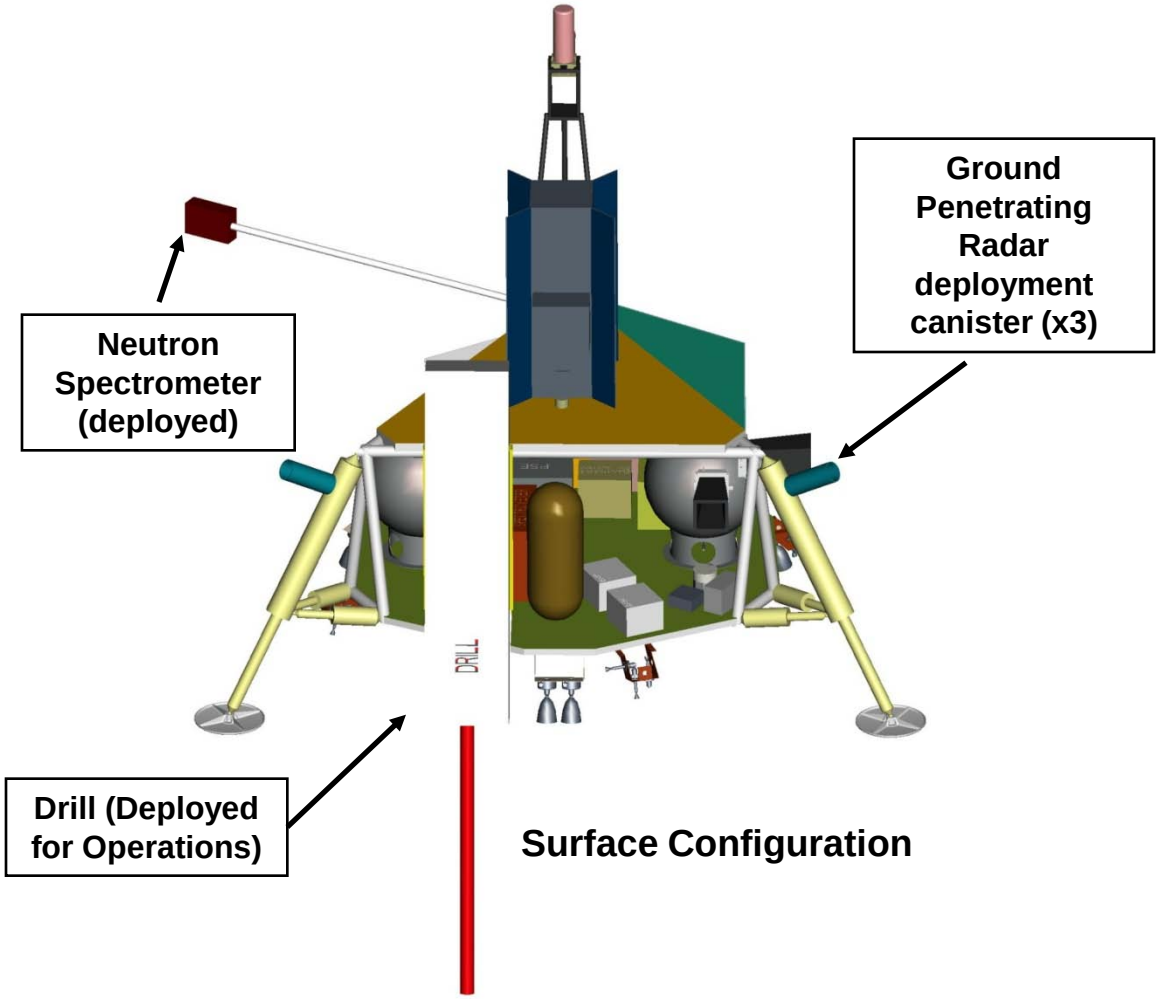
Lander Payload Element	Objective	Mass +30% (kg)	Power +30% (W)	Cost ($M)	Reserve ($M)	Heritage/TRL	Notes
Drill and drill deployment mechanism	Recover regolith samples from depths of 1 m	39.0	108.3 to 520	25.0	12.5 (50%)	Current TRL 5	Dimensions: 1.3m x 30cm x 20cm. Keep actuators warm, drill shaft/head cold. 1 DoF movement. 100N force over drill. Pwr driven by 2 actuator solution, 14A/30V. Operate 3 min for 2 cm. Tlm rate 5-10 kbps.
Sample Cam	Imaging of drill sample, particle size & shape distribution	2.3	14	10.0	3.0 (30%)	MAHLI or MER MI	Dimensions: Camera 4cm x 4cm x 12 cm; Electronics box 8 cm x 12 cm x 4 cm. Can achieve 5 um resolution. 500KB thumbnail down realtime before Mass Spec. 4 Images/sample run, 2 MB/image, down before "hold period".
Sample delivery system	Process core material for analysis	6.5	26.0	7.0	2.1 (30%)	MSL delivery system	Dimensions dependent on Honeybee drill implementation, lander packaging. Deliver drill material to sample cam/mass spectrometer.
Mass Spectrometer	Determine the various volatile compounds present and their isotopic composition	19.5	24, peak of 48 (pyro)	20.0	10.0 (50%)	MS flown on CONTOUR, CASSINI, MSL (TRL 8-9); MSL (TRL 7); VaPOR	Dimensions: 11" x 7" x 15". 2 Mb per sample @ 4 kbps. GSFC MS identifies masses from 2-300 amu; volatiles (H2O, CO2, etc.) at the part per million level. Operate 1 hr at nom power, 1 hr at peak pwr per sample run.
Neutron Spectrometer	Determine the flux and energies of neutrons to determine H content of regolith	1.3	2.3	5.0	1.5 (30%)	LP, Messenger, etc.	Dimensions: 18x12x6 cm. APL design based on Los Alamos HYDRA. Sensitivity to 0.5 wt% H2O under 50 cm dry regolith. Deployed on boom to side (common with ILN).
Ground Penetrating Radar / EM	Determine the depth profile of regolith to 10's of m	5.0	6.5	13.0	6.5 (50%)	WISDOM on ExoMars	Dimensions TBD. NOTE that mass/power for sensor-imbedded wires deployment mechanism, wires, and deployment control are not included in stated mass & power numbers. Needs more development; potential for international contribution
Seismometer	Long-term monitoring of seismic activity, background levels, lunar normal modes	6.5	3.4	--	--	SEIS on ExoMars	Use applicable assumptions from ILN. International Contribution.
Totals		80.1	*208.5 to 655.2*	80.0	35.6		When profiled by Ops concept, peak power driven by drill operation (520W). Non-drilling peak is during Mass Spec Pyrolysis (48W)

LPV Lander Concept comparison

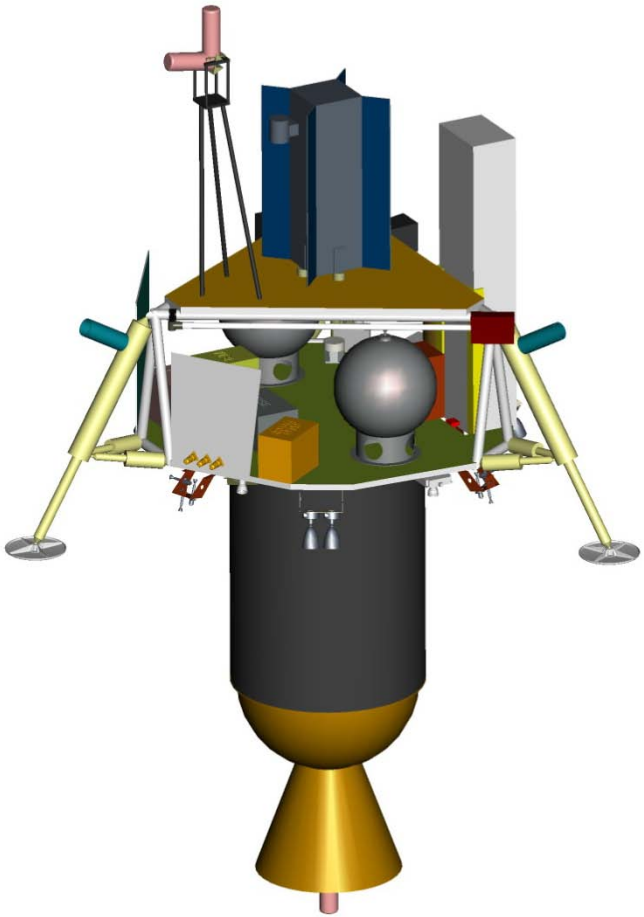
	ILN Design Approach	Polar Volatiles Mission
Structures	• Composite Primary Structure	• Composite Primary Structure
Deployments	• Seismometer, EM booms, Mole	• Seismometer, NS boom, drill and sample collection
Power	• ASRG Primary Power Source • Power System Electronics • Primary Batteries	• ASRG • Secondary Batteries to support Drill and landing • Power System Electronics
Thermal	• Isolated WEB, variable link to Radiator	• Isolated inner structure, variable link to Radiator
Propulsion	• Bi-Propellant, custom tanks • 100 lbf Descent DACS Engines (6) • 6 lbf ACS DACS Engines (6)	• Bi-Propellant, custom tanks • 100 lbf Descent DACS Engines (6) • 6 lbf ACS DACS Engines (12) – precision landing
Avionics	• Integrated Flight Computer and PDU	• Upgrade to faster Maxwell 750 processor for precision landing TRN • Separate PDU
RF	• S-band • 1 W transmit power • 2 kbps uplink, 100 kbps downlink capable on surface	• S-band • 1 W transmit power • 2 kbps uplink, 100 kbps downlink capable on surface
GN&C	• Star Trackers (Dual head), Landing Cameras (2) • IMU, Radar Altimeter	• Star Trackers (Dual head), Landing Cameras (2) • IMU, Radar Altimeter • TRN added to meet precision landing in earth shine • Increased TVC accuracy on SRM
Software	• ILN Baseline	• More complex autonomy for drill, TRN processing for precision landing
Msn Ops	• Long duration autonomous ops	• Shorter duration, complex tasks
Launch Vehicle	• 1-4 landers on Falcon 9 or Atlas V 401 -511	• Single lander on Atlas V 401 (ASRG mission)

Deltas highlighted

Lander Configuration



Surface Configuration



Cruise Configuration

Cost: Approximately $500M ($FY10) excluding LV. In

Risk Reduction

Incremental Development Approach for Flight Robotic Lander Design: Phase 1 (Cold Gas)

Robotic Lander Testbed - Cold Gas Test Article (Operational)

- Completed in 9 months
- Demonstrates autonomous, controlled descent and landing on airless bodies
- Emulates robotic f**light** lander design for thruster configuration in 1/6th gravity
- Incorporates **flight** algorithms, software environment, heritage avionics, and sensors
- Gravity cancelling thruster provides for reduced gravity operations that can vary with throttling
- Flight time of 10 seconds and descends from 3 meters altitude
- Utilizes 3000psi compressed air for safety, operational simplicity, and multiple tests per day
- 3 primary and 6 ACS thrusters

Accomplishments

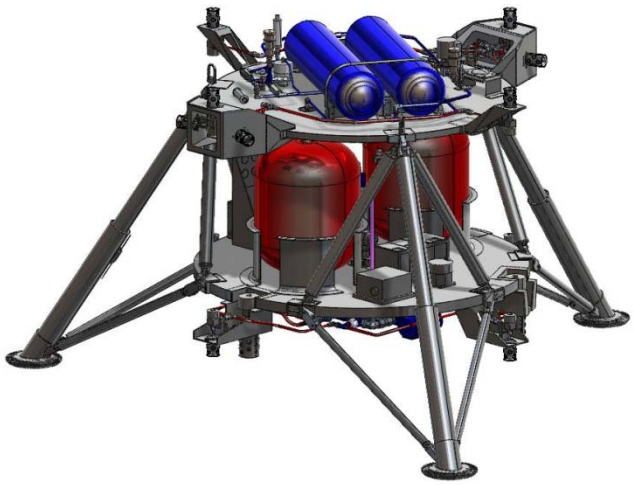
Fully Functional, Flown >150 times

Upgraded with flight-like algorithms

Incremental Development Approach for Flight Robotic Lander Design: Phase 2 (Warm Gas)

Warm Gas Test Article (Summer 2010) adds to Cold Gas Test Article Functionality:

- Demonstrates terminal descent phase autonomous controlled
- Began WGTA September 2009 ; Critical Design Review March 2010
- Designed to emulate Robotic **Flight** Lander design sensor suite, software environment, avionics processors, GN&C algorithms, ground control software, composite decks and landing legs
- Longer flight duration (approx. 1 min) and descends from 30 meters to support more complex testing
- Can accommodate 3U or 6U size processor boards.
- Incorporates Core Flight Executive (cFE) which allows for modular software applications
- 12 thruster ACS configuration. Option to only fire 6 ACS thrusters. Provides capability to support testing of hazard avoidance or precision landing algorithms. Emulates pulse or throttle system.
- G-thruster can be set to different g levels between 1 g to zero g for descent. Therefore, can be used to emulate any airless body for descent.



Accomplishments

Mechanical Design Complete, Fabricating elements

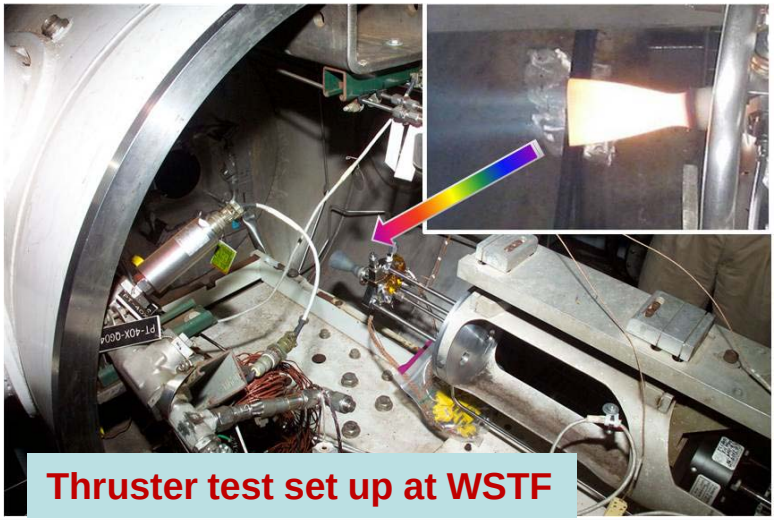
GN&C Framework S/W delivered, 2nd build in test

Testing begins Summer 2010

Flight Propulsion System Risk Reduction Status

Light-Weight Thruster Hot-Fire Tests for Robotic Lunar Lander

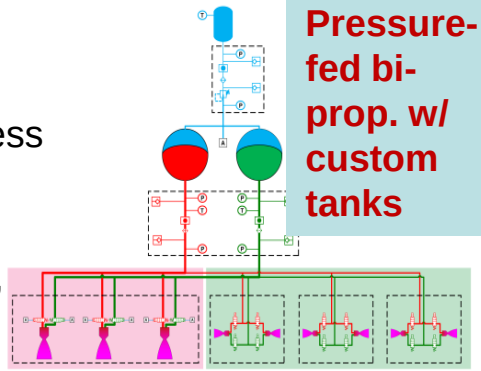
- **Objective:** **a**) Leveraging DOD thruster technology; **b)** Test both 100-lbf descent and 6.7-lbf ACS thrusters in vacuum to assess performance, thermal, and combustion stability.
- **Accomplishment:**
  - Successfully completed a matrix of 12 hot-fire tests on 100-lbf thruster in Sept., 2009 at WSTF
  - Evaluated 100-lbf thruster characteristics in relevant environment with a representative full mission flight profile spanned 995 seconds.
  - Test plan for 7-lbf ACS thruster to be conducted in July, 2010.



Thruster test set up at WSTF

Propulsion Concept Assessment

- **Objective:** **a**) Evaluate propulsion design concept; **b)** Independent assessment on propulsion technology maturity, work schedule, and ROM.
- **Accomplishment:**
  - Verified propulsion design concept, technology readiness level, and cost in July, 2009
  - Wide participation of propulsion industry (Aerojet, AMPAC, Orion Propulsion, and PWR) in concept study.



Pressure-fed bi-prop. w/ custom tanks

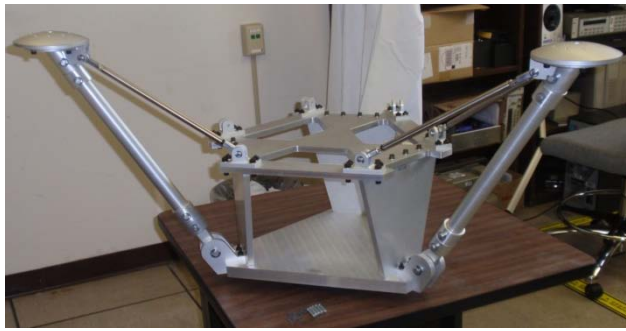
High-Pressure Regulator Characterization

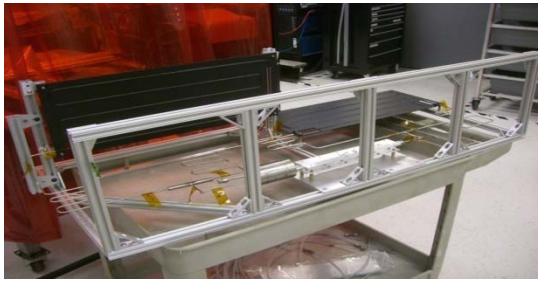
- **Objective:** MSFC in-house evaluation and characterization of pressure regulator operated at high blow down ratio for light-weight propulsion system
- **Accomplishment:**
  - Received the regulator test article.
  - Obtained all components and instrumentation for test setup.
  - Completed test plan & documentation

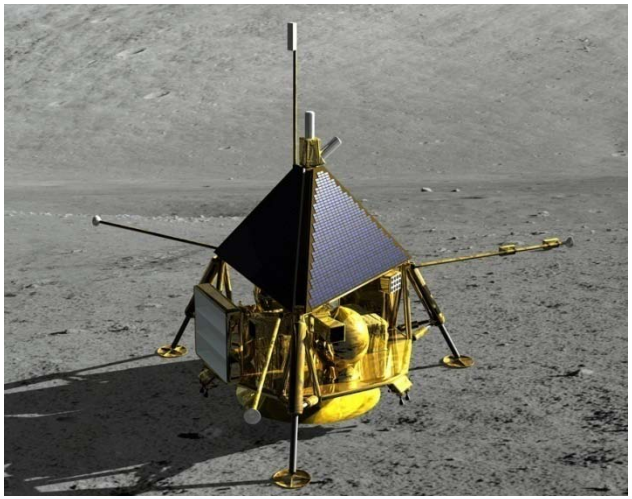
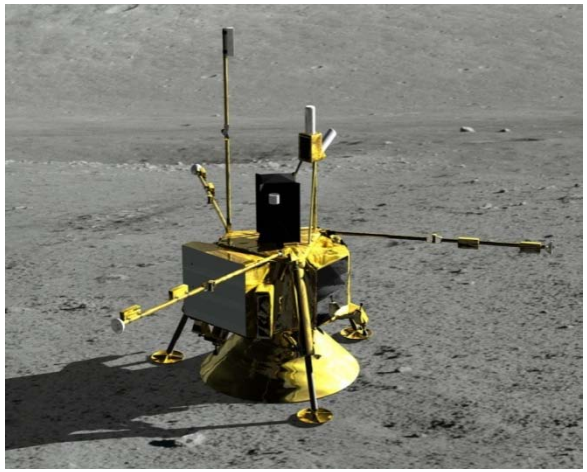
10K psi regulator

Other Risk Reduction Status

- **GN&C**: Validation of landing algorithms with simulations and HWIL
  - Testing Optical velocity estimater
  - Running Monte Carlo simulations
- **Structures**: Composite panel fabrication and testing, lander leg stability testing, star motor vibe test
  - Coupon testing complete
  - Starting WGTA Panel fabrication
  - Rigid body stability testing complete – Good correlation with analysis
  - Flexible/nonlinear test article and fixtures in assembly
  - Star motor adapter design complete, finalizing fabrication subcontract
- **Thermal**: Variable heat transport and lunar heat rejection testing
  - Completed fabrication of Loop Heat Pipe assembly Finalizing test Plans
- **Power**: Thermal and life battery testing
  - Batteries on order
- **Avionics:** Testing a low power, high speed communications, and large data storage processor
  - Design Complete. Printed wiring boards in fabrication
- **Ground Systems:** Portable Mission operations Centers **(**mini-MOCs) for control of WGTA
  - Mini-MOCs assembled. Working Screens and networking configurations





Summary

- **ILN mission on hold awaiting Decadal Survey results**
- **Lander bus design has been refined and is suitable for multiple mission scenarios**
- **A comprehensive risk reduction effort is underway and is producing results**
- **NASA's new direction in space exploration may present an opportunity for a robotic lunar lander to support exploration objectives**