ROBOTIC LUNAR LANDERS FOR SCIENCE AND EXPLORATION.

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Introduction: 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. Robotic lunar landers to achieve science goals and to provide precursor technology development and site characterization are an important part of program balance within NASA's Science Mission Directorate (SMD) and Exploration Systems Mission Directorate (ESMD). A Robotic Lunar Lander mission complements SMD's initiatives to build a robust lunar science community through R&A lines and increases international participation in NASA's robotic exploration of the Moon.

Robotic Lunar Lander project history (2005-2009): As a result of an intra-NASA competitive call, in 2005 ESMD selected an MSFC/APL/Goddard team to implement the Robotic Lunar Exploration Program Mission #2 (RLEP-2) as a precursor robotic lunar lander mission to demonstrate precision landing and definitively determine if there was water ice at the lunar poles. The RLEP-2 mission was put on hold by ESMD in 2006 due to funding shortfalls. In 2008, the MSFC/APL team received redirection by SMD to develop the International Lunar Network (ILN) Anchor Nodes Mission, as part of a lunar geophysical network. Development activities continued through 2009, culminating with a midsummer Office of Program Analysis and Evaluation review. The review found that the ILN Anchor Nodes Mission engineering to be past pre-Phase A development and the mission cost and schedule estimates to be conservative and within family. In fiscal year 2010, the ILN Anchor Nodes mission was put on hold by SMD due to funding shortfalls and the spinup of the Planetary Science Decadal Survey, which will prioritize mission concepts for development. The team was directed to focus on risk reduction activities as the Robotic Lunar Lander development office. Table 1 shows a summary of the Robotic Lunar Lander capabilities developed by this team to date.

Mission Science: In the last decade, the lunar science community has articulated and prioritized its science objectives in multiple documents [1-4], most recently in a set of 35 white papers submitted to the 2011 Decadal Survey. Remarkably, all these documents paint 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. Landed lunar missions, including in situ explorers, geophysical networks, and sample-return missions, address multiple key aspects of lunar and planetary science. The SCEM report provided an independently formulated "Candidate Lunar Research Strategy for the Near Term," in order to balance the highest integrated science priorities with the feasibility of implementing them during the time interval 2010–2022. Three of the recommended mission candidates for the Moon are based on lander architectures: an atmosphere and polar volatile explorer, a geophysical network, and sample-return missions. Each of these missions could be accomplished using one or more of the point designs in Table 1.

Polar Volatiles: The polar regions of near-airless bodies represent special regions where volatiles can collect within cold traps. Observational evidence supports the existence of volatiles in the extremely cold, permanently shaded regions near the poles of the Moon (Ground-based radar, Clementine, Lunar Prospector, LRO, LCROSS). At the successful conclusion of these missions, however, surface-based, in situ measurements will still be needed to extensively characterize the chemical and molecular forms of the volatiles in the lunar polar regions, their distribution (including both lateral and vertical variability), and their physical properties. Some of these measurements might be made in regions that receive limited sunlight; others may require landers that can sustain permanent shadow. Some measurements could be made from a stationary platform, or a highly capable lander could carry a small rover for lateral exploration, as conceived for RLEP-2 (Table 1).

Network Science: Because the Moon's internal thermal engine largely shut down long ago, its deep interior reflects its initial composition, differentiation, crustal formation, and subsequent magmatic evolution. 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. 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. In situ geophysical observations of the Moon can be conducted aboard small but long-lived landers such as those designed for the ILN Anchor Nodes, using either solar or nuclear power (Table 1).

Sample Return: Answering many current questions of lunar science will require analyses of samples distant from the Apollo-Luna region, informed by remote sensing and subjected to mineralogical, lithologic, geochemical, and geochronological analyses with precision and accuracy achieved only in terrestrial laboratories. For example, dating impact-derived samples from the South Pole-Aitken Basin will allow determination of the chronology of the basin and tests of models for impact bombardment of the inner Solar System during the first ~600 million years following accretion. Sampling different styles and expressions of lunar volcanism, including the youngest and oldest basalts, pyroclastic deposits, and nonmare domes, will provide vital information about the thermal history of the Moon, which informs our understanding of terrestrial planet formation. Several lander designs in Table 1 could be adapted to accommodate sample-return architectures; all are currently designed for global access including the lunar farside and a wide range of latitudes where samples are desired.

Current Activities: To continue to support development of Robotic Lunar Landers, risk-reduction tests and activities are ongoing in areas that are common to all lander concepts. Engineering tasks include propulsion thruster testing in collaboration with the Missile Defense Agency; propulsion thermal control testing and demonstration; composite coupon testing and evaluation; landing leg stability and vibration; demonstration of landing algorithms in a lander testbed; and understanding how candidate experiments might be deployed from the lander. Some of these activities will take place in the MSFC Lunar Lander Robotic Exploration Testbed, which was established in support of risk reduction testing to demonstrate robotic lander capabilities. The MSFC test facility is currently operational and contains test vehicle using an Anchor Nodes-like design that allows demonstration of control software. The current vehicle utilizes a compressed air propulsion system, but a second version of the MSFC vehicle is planned that will utilize an alternate propulsion system for longer duration flight and descent testing. The upgraded test vehicle will also integrate flight-like components for risk reduction testing, such as landing sensors (cameras, altimeters), instruments, and structural features (landing legs, deployment mechanisms).

In summary, many high-priority lunar science objectives are uniquely met with landed missions to the Moon. Such missions will allow significant progress in our understanding of the Moon as well as our Earth, our Sun, and our solar system. Robotic Lunar Lander design and development for any of these missions will have significant feed-forward to other missions to the Moon and, indeed, to other airless bodies such as Mercury, asteroids, and Europa, to which similar science objectives are applicable.

References: [1] *New Frontiers in the Solar System: An Integrated Exploration Strategy*, NRC Space Studies Board, 2003. [2] *The Scientific Context for Exploration of the Moon*, NRC Space Studies Board, 2007. [3] *Workshop on Science Associated with the Lunar Exploration Architecture*, Tempe, Arizona, 2007. [4] *Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity*, NRC Space Studies Board, 2008.

Table 1: MSFC/APL Robotic Lunar Lander capabilities.

Class	**Mini**	**Small**	**Small**	**Small**	**Small**	**Medium**	**Medium**	**Large**	**Large**	**Large**
Dry Mass [1]	116	179	299	315	466	1132	1186	1756	2013	3169
LV Sizing	Minotaur V	Taurus/ Falcon	Taurus/ Falcon	Taurus/ Falcon	Taurus/ Falcon	Atlas (401)	Atlas (401)	Atlas (551)	Atlas (551)	Delta IV Heavy
Landers per LV	1	2	2	2	1	1	1	1	1	1
Trajectory	Direct	Direct	Direct	Direct	Direct	Orbit First	Direct	Direct	Orbit First	Orbit First
Design Life	6 years	6 years	6 years	6 years	90 days	1 year	1 Year	1 year	1 year	1 year
Payload Mass [1]	5	26	22	53	130	296	530	1100	729	1491
First / Unit Cost [2]	130 / 45	170 / 50	160/ 45	200 / 70	240/80	280/80	235/50	345/105	350/105	675/130
Propulsion	Bi-Prop w/Stage MMH/ NTO	Bi-Prop w/ Stage MMH/ NTO	Bi-Prop w/ Stage MMH/ NTO	Bi-Prop w/ Stage MMH/ NTO	Mono-Prop w/ Stage	Bi-Prop MMH/ NTO	Bi-Prop w/ Solid N_2H_4/ NTO	Bi-prop w/ Solid MMH/ NTO	Bi-Prop MMH/ NTO	Cryo LH_2/ LOX
Power	Sm-RPS	ASRG	Solar	ASRG	Solar	Solar	Solar	Solar	Solar	Solar
Basis	ILN	ILN	ILN	Polar Volatiles	RLEP-2	RLEP-2	RLEP-2	RLEP-2	RLEP-2	RLEP-2

[1]Mass in kg, including 30% margin
[2]FY10 $M for cost of first lander (including NRE) and for each additional identical unit, including 30% reserve, exclusive of launch vehicle