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Space Administration

LUNAR CRATER OBSERVATION AND SENSING SATELLITE (LCROSS)
SCIENCE PLAN

DRAFT B
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DRAFT C
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DRAFT D
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SCOPE

This document describes the derivation of science and measurement requirements for the Lunar Crater Observation and Sensing Satellite (LCROSS).

The science goals are derived from ESMD-RQ-0014 and the "Secondary Payload Mission Center Call" from ESMD. Measurement requirements (level 2 and 3) are described in the PRD and MRD with their justifications provided here. The goals described here are to support the mission design, instrument selection, and impact target selection.

MISSION OBJECTIVE

The primary objective of the LCROSS mission is to advance the Vision for Space Exploration by investigating the presence of water ice at the lunar poles. The mission will impact a permanently shadowed region at a lunar polar latitude to create and measure the characteristics of an ejecta cloud of regolith and possibly ice and water vapor. The LCROSS Project will solicit input from the scientific community through a Site Selection Workshop regarding sites with a high probability of ice detection that are also in compliance with the engineering and logistics capabilities of the mission. The LCROSS Project will establish a Site Selection Committee to evaluate the impact sites suggested by the community and evaluate these sites compared with the baseline impact site of Shackleton Crater. The Site Selection Committee will then recommend to the Program Office and ESMD either one of two options:

1) The Site Selection Committee may recommend that LCROSS impact at the baseline site of Shackleton Crater.

2) If sufficient information exists such that a impact site other than Shackleton Crater both satisfies the engineering constraints and also will provide a higher probability of harboring water ice, the Site Selection Committee may recommend that LCROSS impact at this alternate site. Such a recommendation must take into account any perceived impacts to the LCROSS Project and must be outweighed by the increased benefits of impacting in this particular location.

ADDITIONAL INVESTIGATIONS

NASA may solicit additional participation in the LCROSS mission to view, measure, process, record, and analyze the ejecta plume. This may include the services of lunar orbiting spacecraft, space-based systems, and/or Earth-based systems.

APPLICABLE DOCUMENTS

Document No.	Document Title
SA-0001	Level 0 Exploration Requirements for the National Aeronautics and Space Administration, Baseline Version, May 4, 2004
NPSD31	President's Space Exploration Policy Directive (Goal and Objectives)
ESMD-RQ-0010	Exploration System of Systems Requirements
ESMD-RQ-0014	Robotic Lunar Exploration Program (RLEP) Requirements
	Secondary Payload Mission Center Call (SPMCC)

SCIENCE GOALS

Each of the science goals traces back to the Program Level 1 requirements.

The LCROSS mission science goals, in order of priority, are:

1. Confirm the presence or absence of water ice in a permanently shadowed region on the Moon

2. Identify the form/state of hydrogen observed by Lunar Prospector at the lunar poles

3. Quantify, if present, the amount of water in the lunar regolith, with respect to hydrogen concentrations observed by Lunar Prospector

4. Characterize the lunar regolith within a permanently shadowed crater on the Moon

MEASUREMENT GOALS

Measurement goals trace back to each of the science goals. Measurement goals do not yet specify a technique, accuracy or precision, but do identify the quantity to be measured.

The LCROSS Measurement goals are:

1. Measure the total concentration of water in the sunlit ejecta cloud.

2. Detect any possible hydrogen bearing compounds including water, hydrated minerals, and organics, including hydrocarbons in the sunlit ejecta cloud.

3. Constrain the sunlit ejecta cloud particle physical properties, including composition and particle size.

4. Constrain the mechanical properties of the impact site, including minimum regolith depth and strength.

MEASUREMENT SPECIFICATIONS

Measurement specifications trace back to each of the measurement goals. Measurement specifications do not yet specify a technique but do identify a required accuracy and precision. Measurement requirements are captured in the Project Level 3 Requirements.

LCROSS measurement specifications:

1. Detect possible hydrogen bearing compounds including water, hydrated minerals, and organics, including hydrocarbons in the sunlit ejecta cloud.

2. Measure total water concentration (by mass) in the sunlit ejecta cloud to within a factor of three (3).

3. Measure the total sunlit ejecta cloud mass to within a factor of two (2).

4. Measure the mean grain size of the sunlit ejecta cloud for particles sizes between 10 and 100 microns.

5. Measure the sunlit ejecta cloud temperature to an accuracy of 10 K at 200 K.

6. Measure the total impact flash luminescence to an accuracy of 20% assuming a luminescence efficiency of 10^{-4}.

7. Measure the impact flash light curve as a function of time at a resolution of 10^{-2} sec.

8. Resolve the morphological evolution of the ejecta cloud for at least three minutes following the time of when the ejecta cloud becomes sunlit with spatial resolutions <500 m per pixel at all times.

9. Resolve the thermal evolution of the ejecta cloud for at least three minutes following the time of when the ejecta cloud becomes sunlit with spatial resolutions <500 m per pixel at all times.

MEASUREMENT TECHNIQUES

Multiple measurement techniques will be utilized by the LCROSS S-S/C and include some measurement goal overlap. By addressing each measurement goal with overlapping techniques a level of robustness against misinterpretation can be achieved and the mission susceptibility to false positive / negative results minimized. Ground or orbital based measurements other than those performed from the S-S/C are not described here, however, the LCROSS science team, specifically the Observation Coordinator, will work with these other platforms to maximize their utility in achieving the LCROS science goals. It is anticipated that the LCROSS S-C/C measurements will provide the measurements with a greater resolution and sensitivity than any other known ground based, or earth or lunar orbiting platforms. Therefore, the S-S/C measurements should be of higher priority than those from other platforms. Table 1 shows the trace between measurement goals and the various measurement techniques that have been identified for the LCROSS S-S/C. Each measurement technique is summarized below.

Flash Photometry – At impact, the kinetic energy of the projectile is transferred to the kinetic (ejecta) and internal energy the target (compaction, heating). A portion of the internal energy may induce vapor resulting in vibrational and rotational emission lines that will evolve with space and time. The intensity and decay of the initial flash are related to the physical structure of the target (porosity, strength, volatile content, composition). Consequently, characterization of the initial flash provides a complementary tool to understand initial coupling and the nature of the target.

Visible Spectroscopy – Here visible spectroscopy refers to the measurement of spectra between 0.25 µm and 0.8 µm with a resolving power of $\lambda/d\lambda > 100$. The LCROSS S-S/C will observe the pre- and post-EDUS-impacted lunar regolith in and outside the targeted region at a spatial resolution and viewing angle unobtainable from Earth. The visible spectrometer shall record the sunlit plume evolution, and track the evolution of OH^- radicals from sunlight-dissociated water vapor molecules. The visible spectrometer will measure the OH^- (308 nm) and H2O+ (619 nm) transitions simultaneous which shall assess the water vapor production.

NIR (Near Infrared) Spectroscopy – Here NIR spectroscopy refers to the measurement of spectra between 1.0 µm and 4.0 µm with a resolving power of $\lambda/d\lambda > 100$. The LCROSS S-S/C will monitor spectral bands associated with water vapor, ice, and hydrated minerals covering the first overtones of the symmetric and asymmetric stretches of water; this

Table 1. Measurement to Technique Trace

Measurement	Flash Photometry	Visible Spectroscopy	NIR Spectroscopy	NIR Imaging	MIR Imaging	Visible Imaging
Total Water	X	X	XXX		X	
Water Ice		X	XXX	XX	XX	X
Water Vapor		XX	XXX		XX	
Organics		XX	X			
Hydrated Minerals			XX			
Target Properties	XXX	XX		X	X	X
Cloud Morphology				XXX	XXX	XXX
Thermal Evolution	X			X	XXX	
Mineralogy		XX	XX			
Particle Size and Shape		XX	XX	X		X

Addresses: XXX = Very Direct, XX = Direct, X = Indirect

band, relatively free from interferences, is more brightly illuminated by sunlight than the fundamentals near 3 microns, more than compensating the weaker absorption of the overtones. The regions near 1.4 and 1.9 microns, normally obscured by terrestrial atmospheric background in spectra from icy surfaces, will provide a sensitive indication of water vapor from ice or hydrates. The remainder of the spectral band will reveal the nature of ice crystals and mineral hydrates.

NIR Imaging – Imaging provides spatial resolution of the observed target. Two NIR imaging schemes are possible for LCROSS. The baseline includes two imagers, both with bandpass filters, one inside a water absorption line (e.g. at 1.6 μm) and one outside the line (e.g. at 1.4 μm), allowing the creation of water absorption band depth maps. The second scheme utilizes only a single broad band NIR imager to provide scene context for the NIR spectroscopy.

MIR (Mid Infrared) Imaging – For LCROSS, MIR imaging refers to imaging at thermal wavelengths between 6 and 15 μm. The same two NIR imaging schemes apply to MIR imaging. Pre- and post- impact thermal images of the impact terrain will be obtained from MIR cameras on the S-S/C to characterize the surface material (rock vs. regolith), obtain the thermal evolution of the plume (which is dependent on the water content), and observe the ejecta blanket and freshly exposed regolith.

Visible Imaging – Visible imaging for LCROSS refers to imaging at wavelengths between 0.4 and 0.8 μm with broad bandpass filtering for color.

IMPACT CHARACTERIZATION

The LCROSS mission uses the impact of the Atlas V Centaur upper stage to excavate ad eject lunar surface material to where it can be observed by both the LCROSS S-S/C and other lunar orbiting, earth orbiting and ground based assets. It is necessary to model the expected results of the impact in order to plan and deploy the most effective observational campaign.

For this reason, it is necessary to rely not only (or even primarily) on numerical modeling, but also experimental results and analytical models based on them. All approaches have their uses and contribute information to the task of guiding the design of the LCROSS mission. Given that the present goal is mission design, such a variety of approaches and the corresponding range of results will very likely prove more useful in bracketing the expected outcomes, rather than a highly focused prediction that would undoubtedly miss the mark due to unanticipated factors. Methods used to model the impact event include semi-empirical scaling relations as well as numerical hydrodynamic code. Semi-empirical scaling relations include those developed by Holsapple, Housen, Schmidt and Schultz. The hydrodynamic codes available to us include RAGE, developed at Los Alamos National Laboratories, ZEUSMP, a three-dimensional hydrocode developed by Michael Norman and others, and an SPH (”Smooth Particle Hydrodyanmics”) calculation kindly performed by Martin Jutzi (of Zurich ETH). In addition, CTH calculations are being done by Schultz and his students. A more complete description of the impact modeling efforts will be made available in time for CDR.

To aid in the formulation of the LCROSS mission and measurement design a compilation of model results was built that summarized the current best estimate for the impact event. This summary, called the Current Best Estimate Impact Model (CBEIM), includes both high and low values for a variety of relevant physical quantities including crater dimensions and ejecta velocities. The CBEIM summary is included in Table 2. In most cases the "current best estimate" was used for design purposes, however, on a case-by-case bases additional "margin" was allowed for by using the model results between the best estimate and the modeled low estimate (e.g., often the values closer to the low-end expectation for the total ejected mass above 2 km were used in order to build in margin).

Table 2 – CBEIM

NOTE: Assumes an impactor density of ~0.03g/cc and target density (regolith) of 1.5 g/cc, 70 deg impact angle,

Parameter	Low	High	Average or CBE	Units / Notes / Comments
Crater Diameter	13	21.6	17.9	m
Crater Rim Diameter	17	25	21	m
Crater Depth	3.6	4.2	3.875	m
Ejected Mass	250,000	1,000,000	494,500	kg
Crater Formation Time	1.3	3.5	1.975	sec
Impact Visible Flash	1.00E-06	1.00E-03	1.00E-04	luminance efficiency
Impact NIR Flash	0.001	0.5	0.01	luminance efficiency
Impact mid-IR Flash	0.001	0.5	0.01	luminance efficiency
NOTE: Analytical approximations break down due to non-uniform growth of the crater, initial compression, and downward displacement (rather than ejection). This is exacerbated by the low-density of the projectile. This values for velocities greater than ~300 m/s and masses above ~10 km contain greater uncertainty. Areas of greater uncertainty are highlighted in RED.				
% Ejecta velocity >100 m/sec	0.81	1.3	0.976666667	%
% Ejecta velocity >250 m/sec	0.2	0.44	0.286666667	%
% Ejecta velocity >450 m/sec	1.30E-03	0.22	0.098433333	%
% Ejecta velocity >1800 m/sec	2.00E-04	0.04	0.0146	%
Maximum Ejecta Mass at 2 km	2800	10265	6532.5	kg, The maximum ejecta cloud/curtain mass at 2 km for any time after impact
Maximum Ejecta Mass at 5 km	1600	6330	3965	
Maximum Ejecta Mass at 10 km	1000	4041	2520.5	
Maximum Ejecta Mass at 15 km	820	3187	2003.5	
Maximum Ejecta Mass at 25 km	600	1981	1290.5	
Maximum Ejecta Mass at 35 km	490	1126	808	
Time after impact of Maximum Ejecta Mass at 2 km	50	52	51	sec, The time corresponding to maximum ejecta mass at specified altitude
Time after impact of Maximum Ejecta Mass at 5 km	78	84	81	
Time after impact of Maximum Ejecta Mass at 10 km	111	114	112.5	
Time after impact of Maximum Ejecta Mass at 15 km	136	139	137.5	
Time after impact of Maximum Ejecta Mass at 25 km	175	184	179.5	
Time after impact of Maximum Ejecta Mass at 35 km	207	214	210.5	
Maximum Ejecta Curtain Radius (Time = Max Mass @ 2 km)	7.6	8.1		The maximum ejecta curtain Radius at specified time
Maximum Ejecta Curtain Radius (Time = Max Mass @ 5 km)	10.8	20		Blue indicates the maximum "mass weighted" extent
Maximum Ejecta Curtain Radius (Time = Max Mass @ 10 km)	11.7	40		
Maximum Ejecta Curtain Radius (Time = Max Mass @ 15 km)	12.1	60		

IMPACT CONTAMINATION CONTROL AND MITIGATION

After launch the Centaur stage of the Atlas V rocket contains some water or hydrogen and oxygen bearing compounds that may constitute contamination to the actual hydrogen signal trying to be measured. This contamination on the Centaur stage is in the form of liquid hydrogen and oxygen, hydrazine, and water, in batteries and as part of adhesives, potting materials, etc. (It must be noted that the presence of hydrogen does not necessarily translate to a contaminant. The measurement techniques to be employed by the LCROSS S-S/C are not sensitive to hydrogen by itself, but rather compounds that contain hydrogen.) To minimize the effect of water contamination that may be present in the impacting Centaur several measures will be taken:

1. Liquid hydrogen and oxygen fuel remaining after the lunar transit burn will be vented.

2. Remaining hydrazine fuel will be vented.

3. The launch vehicle provider will make an estimate of all water or water/hydrogen bearing materials.

4. The total combined hydrogen and oxygen mass be kept to below 100 kg (corresponding the maximum amount allowed to keep the contamination level to 0.1% within the ejecta curtain, assuming a total ejected mass of 200,000 kg).

The LCROSS Project does not require the S-S/C contamination to be controlled.

IMPACT SITE SELECTION

The LCROSS mission will target a region on the Moon with the highest probability of harboring water ice in the near surface (first several meters) environment. The target location must also be consistent with several engineering constraints. To achieve this objective of selecting a target with high probability of ice detection and compliance with engineering and logistics capabilities, the LCROSS Project has thus developed a formal process for target selection. The LCROSS Site Selection Workshop will assume Shackleton Crater as the baseline impact site and any other proposed sites will be compared with this baseline location.

LCROSS Site Selection Workshop

Overview

The LCROSS Site Selection Workshop will be held at NASA Ames Research Center on October 16, 2006. All members of the scientific community are invited to present their recommendations for potential LCROSS impact sites. Researchers are encouraged to present their recommendations at the LCROSS Site Selection Workshop (15 minute talks followed by Q&A, although print-only abstracts can be accepted). Each proposed site will be discussed at the Workshop in an open forum. The LCROSS Site Selection Committee will then recommend optimal sites to NASA Headquarters / ESMD and to the Lunar Precursor and Robotic Program (LPRP) at Marshall Space Flight Center for use in their final target selection. The LCROSS Site Selection Committee will evaluate all proposed impact sites against the baseline site of Shackleton Crater. The Site Selection Committee may recommend that LCROSS impact at either Shackleton Crater or at an alternate site. A recommendation of an alternate site must take into account any perceived impacts to the LCROSS Project (which must remain minimal to none), and the perceived impacts to the LCROSS Project must be outweighed by the increased benefits of impacting in this particular location.

Logistics

The meeting logistics are being handled by the Lunar and Planetary Institute (LPI) in Houston, TX. LPI contributions include:

- providing and maintaining a web page for announcements, hotel information, abstract submission, schedule of sessions with abstracts, and final report
- sending out an email exploder to a broad planetary listing, pointing to the web site for additional information
- providing a printed program and abstract book plus meeting nametags for participants

The LCROSS Site Selection Workshop was announced to the planetary science community on July 20, 2006. Abstracts are due to LPI by August 15, 2006. The final announcement with program, abstracts, and registration forms will be posted on the LPI website on September 15, 2006. Preregistration deadline is October 2, 2006.

Site Selection Criteria

The following criteria have been disseminated to the planetary science community regarding the LCROSS site selection. All proposed impact sites must meet these criteria to receive full consideration.

Site Selection Criteria:

• a 3-km-radius impact area at 3 sigma (LCROSS aims for 3-km-radius impact area but final accuracy may be as high as 10 km; targeting accuracy will be refined in upcoming weeks)
• poleward of 70° latitude at either lunar pole
• a region of permanent shadow
• a region on the lunar nearside such that the impact plume is observable to groundbased observatories

Science Organizing Committee

The following personnel are serving on the Science Organizing Committee (SOC). Primary duties of the SOC include review of abstracts and organization of abstracts into the program agenda for the Site Selection Workshop.

SOC Members:
Dr. Jennifer Heldmann (NASA Ames Research Center / SETI Institute)
Dr. Pete Schultz (Brown University)
Dr. Don Korycanksy (University of California, Santa Cruz)
Dr. Geoffrey Briggs (NASA Ames Research Center)
Dr. Tony Colaprete (NASA Ames Research Center)

Site Selection Committee

The following personnel are serving on the Site Selection Committee (SSC). Primary duties of the SSC include review of suggested target locations that have been suggested as potential LCROSS targets via the LCROSS Site Selection Workshop abstract submission process, synthesis of this information based on the Workshop, and delivery of recommendations regarding targets to the LPRP and HQ/ESMD. In addition, the SSC will review and provide further recommendations (if applicable) on impact target selection or science implementation based on the acquisition of additional lunar data prior to the LCROSS impact (e.g. LRO data, Chandraayan data).

SSC Members:
Dr. Ben Bussey (APL, LPRP Program Office)
Dr. Pete Schultz (Brown University, LCROSS Project)
Dr. David Paige (UCLA, LRO Diviner PI)
Dr. Jeffrey Moore (NASA Ames Research Center)
Dr. Christopher McKay (NASA Ames Research Center, Constellation representative)
Dr. Richard Elphic (Los Alamos National Laboratory)

Timeline

The following timeline represents major milestones in the LCROSS Site Selection process.

• October 16, 2006: LCROSS Site Selection Workshop, acquisition of community input regarding potential impact sites
• November 22, 2006: Delivery of target selection recommendations to NASA HQ / ESMD and LPRP from LCROSS Site Selection Committee (SSC), inputs based on Site Selection Workshop
• February 2007: Decision from NASA HQ / ESMD and LPRP regarding which lunar hemisphere to impact (north vs. south), prior to LCROS Critical Design Review (CDR).
• January 2009: Review of Chandrayaan data by SSC, refinement of site selection recommendations to NASA HQ / ESMD and LPRP (if applicable and warranted given new Chandrayaan data)

• October 2008-January 2009: Review of LRO data by SSC, refinement of site selection recommendations to NASA HQ / ESMD and LPRP (if applicable and warranted given the new LRO data)
• January 2009 (30 days before impact): Final decision from NASA HQ / ESMD and LPRP regarding LCROSS impact site
• January 2009: LCROSS impact

Project Review Board Approved Site Selection Recommendation

The success of the LCROSS mission depends, in part, on the selection of the Lunar impact site (see "Project Impact Site Position"). Due to the nature of the LCROSS impact experiment, specifically the need for the impact ejecta cloud to reach sunlight, the optimum site varies with launch date due to changes in solar illumination and impact angles. An optimal impact site is defined by three criteria:

1) Instrument sensitivity to water within the cloud
2) Understanding of the target properties
3) Target association with enhanced hydrogen

Therefore, the LCROSS Project recommends the following with respect to impact site selection:

A) A target will be selected for each possible LRO launch date;
B) Future data sets or analysis should be used to refine targeting up until 30 days prior to Centaur separation.

The Project's target selection will have minimal impact to the LCROSS Project, in terms of spacecraft consumables (specifically propellant), targeting accuracy, cost, and schedule.

Each target selection has no impact on the current launch vehicle requirements.

The LCROSS Project Review Board shall approve the list of targets for each LRO launch date and any future changes to these targets. Approved impact crater targets will then get elevated to the Program Office / ESMD for concurrence/approval.

DATA ANALYSIS AND REPORTING

The LCROSS mission has three months (funded) following impact to reduce the S-S/C instrument data to Level 2 (calibrated with physical units). Within 24 hours Level 1 data will be delivered from the Mission Operations Center (MOC) to the Payload Scientist who will lead the processing of the Level 1 data to Level 2 data. To insure that this Level 1 data can be processed in the short amount of time allotted all analysis routines will be developed prior to launch and tested against the output from the instrument Engineering Test Units (ETU) and the pre-flight instrument calibration data.

At the end of three months following impact a report will be submitted to LPRP and HQ (ESMD) that details the findings from the LCROSS S-S/C instruments. Specifically the report will describe those findings that address primary mission goals #1 through #3. At the end of six months following impact the S-S/C Level 2 data, in the appropriate format, will be delivered to the Planetary Data System (PDS). The handover mechanisms and formats of data to the PDS will be specified in a Data ICD between the Project and the PDS.

OBSERVATION SUPPORT

Ground-based and orbital observatories will observe the dust and water vapor plume caused by the two impacts into the lunar surface. Compared to the Deep Impact (DI) Mission encounter with comet 9P/Tempel, LCROSS's EDUS impact plume will have 100 times less mass at 360 times closer range, so the surface brightness will be higher. However, the dust-to-ice ratio for Shakleton Crater regolith is expected to be 100 in comparison to ~0.5 for Deep Impact. Therefore, ground-based telescopes will observe the thermal evolution of and the properties of the dust in the ejecta plume, and 8-10 m class telescopes, e.g., NASA-Keck+NIRSPEC, will be required to search for water vapor using the non-resonant fluorescent lines at ~3 μm. The longer time scale evolution of the OH exosphere will be followed by telescopes in Spain (Calar Alto), the Canary Islands (Mount Teide), and Australia (Siding Springs, Mt. Stromlo). The timing of the two impacts should allow for simultaneous observations from Hawaii (NASA-IRTF, NASA-Keck, Gemini-N, Subaru, CFHT), the Continental US (Kitt Peak), and from South America (Gemini-S, VLT-ESO in Chile).

Orbital assets such as NASA's Hubble Space Telescope (HST) and the European Space Agency (ESA) Odin spacecraft may be used to observe the impact plume. In a similar manor as what was done for DI, LCROSS will ask NASA management to leverage NASA–Keck and NASA-IRTF time as well as encourage NSF-operated telescopes to assign Directors Discretionary time for LCROSS observations. The Observation Campaign Manager will be responsible for the coordination of the ground-based observing campaign. Only minimal funding is included in the LCROSS budget to support the Observation Campaign Manager and their efforts. No funding is carried to support the observatories or the reduction of data from these observatories.

To maximize the effectiveness of the observation support, the LCROSS project requires that:

- the impacts occur at least 30 degrees away from full or new moon
- the impact occur at least two (2) hours after dusk and two (2) hours prior to dawn
- the moon is at least 45 degrees above the horizon (air mass less than 2) at either Hawaii or Chile assets