Space Sci Rev (2010) 150: 7–22
DOI 10.1007/s11214-010-9631-5

Lunar Reconnaissance Orbiter (LRO): Observations for Lunar Exploration and Science

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Received: 12 October 2009 / Accepted: 11 January 2010 / Published online: 23 February 2010

Abstract The Lunar Reconnaissance Orbiter (LRO) was implemented to facilitate scientific and engineering-driven mapping of the lunar surface at new spatial scales and with new remote sensing methods, identify safe landing sites, search for in situ resources, and measure the space radiation environment. After its successful launch on June 18, 2009, the LRO spacecraft and instruments were activated and calibrated in an eccentric polar lunar orbit until September 15, when LRO was moved to a circular polar orbit with a mean altitude of 50 km. LRO will operate for at least one year to support the goals of NASA's Exploration Systems Mission Directorate (ESMD), and for at least two years of extended operations for additional lunar science measurements supported by NASA's Science Mission Directorate (SMD). LRO carries six instruments with associated science and exploration investigations, and a telecommunications/radar technology demonstration. The LRO instruments are: Cosmic Ray Telescope for the Effects of Radiation (CRaTER), Diviner Lunar Radiometer Experiment (DLRE), Lyman-Alpha Mapping Project (LAMP), Lunar Exploration Neutron Detector (LEND), Lunar Orbiter Laser Altimeter (LOLA), and Lunar Reconnaissance Orbiter Camera (LROC). The technology demonstration is a compact, dual-frequency, hybrid polarity synthetic aperture radar instrument (Mini-RF). LRO observations also support the Lunar Crater Observation and Sensing Satellite (LCROSS), the lunar impact mission that was co-manifested with LRO on the Atlas V (401) launch vehicle. This paper describes the LRO objectives and measurements that support exploration of the Moon and that address the science objectives outlined by the National Academy of Science's report on the Scientific Context for Exploration of the Moon (SCEM). We also describe data accessibility by the science and exploration community.

Keywords Moon · Lunar · Remote sensing · Spacecraft

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1 Introduction

The Lunar Reconnaissance Orbiter (LRO) was successfully launched on June 18, 2009 and joined an international fleet of satellites (Japan's SELENE/Kaguya, China's Chang'E, and India's Chandrayaan-1) that have recently orbited the Moon for scientific exploration purposes. LRO is the first step to fulfill the US national space goal to return humans to the Moon's surface, which is a primary objective of NASA's Exploration Systems Mission Directorate (ESMD). The initial LRO mission phase has a one-year duration fully funded under ESMD support. LRO is expected to have an extended phase of operations for at least two additional years to undertake further lunar science measurements that are directly linked to objectives outlined in the National Academy of Science's report on the Scientific Context for Exploration of the Moon (SCEM). All data from LRO will be deposited in the Planetary Data System (PDS) archive so as to be usable for both exploration and science by the widest possible community.

A NASA Announcement of Opportunity (AO) solicited proposals for LRO instruments with associated exploration measurement investigations. A rigorous evaluation process involving scientific peer review, in combination with technical, cost and management risk assessments, recommended six instruments for LRO development and deployment. The competitively selected instruments are: Cosmic Ray Telescope for the Effects of Radiation (CRaTER), Diviner Lunar Radiometer Experiment (DLRE), Lyman-Alpha Mapping Project (LAMP), Lunar Exploration Neutron Detector (LEND), Lunar Orbiter Laser Altimeter (LOLA), and Lunar Reconnaissance Orbiter Camera (LROC). In addition, LRO also accommodates a hybrid-polarity synthetic aperture radar system (Mini-RF) as a technology demonstration supported by NASA's Space Operations Mission Directorate.

The Foreword to this volume provides an overview of the history of lunar robotic exploration since the Apollo program. An early review of LRO exploration mission objectives and instrument description can be found in a recent summary paper (Chin et al. 2007). Other articles in this volume provide detailed descriptions of LRO instrument capabilities, performance, and calibration during ground-based integration and testing. A description of the LRO spacecraft and mission design can also be found in this issue (Tooley et al. 2010).

In this paper, Sect. 2 describes the Exploration Mission objectives. Section 3 summarizes the instrument capabilities and LRO mission implementation. Section 4 describes the options and objectives for the extended Science Mission. Section 5 gives the specific Planetary Data System nodes where each instrument's data will be archived for widespread access and the LRO data deposition schedule.

2 LRO Exploration Objectives

The goal of returning humans to the surface of the Moon is a major objective of the US national space program (National Space Exploration Policy Directive, NSPD 31). LRO is the first mission undertaken by NASA's Exploration Mission Directorate (ESMD) and LRO's primary goal is to provide the critical supporting measurements that will enable cost-effective return of human explorers to the surface of the Moon. Some of the required ESMD measurement data include:

- Knowledge of the radiation environment in lunar orbit and the biological effects caused by exposure to this space radiation environment
- Global geodetic lunar topography tied to an accurate center-of-mass grid at suitable spatial scales (relevant to precision navigation and surface mobility)

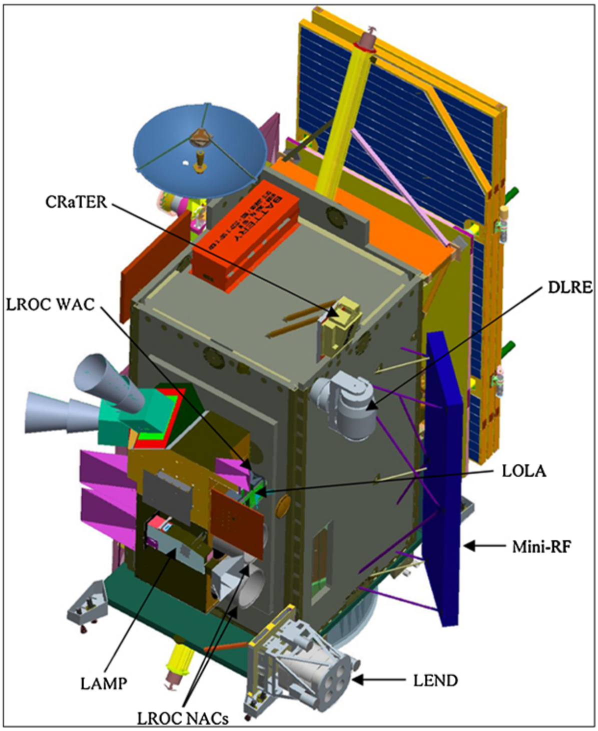

Fig. 1 Placement of the instruments on the LRO spacecraft

- High spatial resolution maps of enhanced hydrogen deposits in the Moon's regolith
- Temperature maps of the Moon's polar permanently shadowed regions (PSR's)
- Landform-scale images of lunar surfaces in permanently shadowed regions
- Identification of putative deposits of appreciable near-surface water ice in the Moon's polar permanently shadowed regions (PSR's) or evidence that they do not exist
- Images at meter and smaller scales to assess the safety of potential lunar landing sites (with definitive meter-scale feature identification)
- Characterization of the illumination in the Moon's polar regions at relevant spatial and temporal scales (i.e., in terms of hours)

NASA released an Announcement of Opportunity (AO) that called for a suite of instruments to provide measurements that will fulfill Exploration requirements on the basis of an independent assessment of measurement objectives essential for human lunar exploration. After a rigorous evaluation process of scientific peer review, as well as technical, cost and management risk assessments, six instruments were selected for LRO. The selected instruments are: Cosmic Ray Telescope for the Effects of Radiation (CRaTER), Diviner Lunar Radiometer Experiment (DLRE), Lyman-Alpha Mapping Project (LAMP), Lunar Exploration Neutron Detector (LEND), Lunar Orbiter Laser Altimeter (LOLA), and Lunar Reconnaissance Orbiter Camera (LROC). In addition, LRO also accommodates a compact, hybrid-polarity, dual-wavelength synthetic aperture radar system (Mini-RF) as a technology demonstration focused on advanced telecommunications and polarimetric SAR imaging, supported by NASA's Space Operations Mission Directorate. Figure 1 shows the mounting of the instruments on the LRO spacecraft flight system.

Table 1 Key LRO Data Products Advance ESMD Exploration Goals

Instrument	Key LRO Data Products	Examples of Exploration Benefits
CRaTER: Cosmic Ray Tele-scope for the Effects of Radiation PI: Harlan Spence, University of New Hampshire	Lunar and deep space radiation environment and tissue equivalent plastic response to radiation	Safe, lighter weight space vehicles. Determination of the radiation environment for human presence at the Moon and journeys to Mars and beyond
DLRE: Diviner Lunar Radiometer Experiment PI: David Paige, UCLA	500 m scale maps of surface temperature, albedo, rock abundance, and ice stability	Measures thermal environment in permanent shadow and permanent light, ice depth map
LAMP: Lyman Alpha Mapping Project PI: Randall Gladstone, SWRI	Maps of frosts and landforms in permanently shadowed regions (PSRs)	Locate potential water-ice on the surface, image shadowed areas, and map potential landing areas in PSRs
LEND: Lunar Exploration Neutron Detector PI: Igor Mitrofanov, IKI	Maps of hydrogen in upper 1 m of Moon at 10-km scales using neutron albedo	Locate potential water-ice in lunar soil or concentrations of implanted hydrogen
LOLA: Lunar Orbiter Laser Altimeter PI: David Smith, GSFC	$\sim$25 m scale polar topography at $<$10 cm vertical, global topography, surface slopes and roughness	Identify safe landing sites, image shadowed regions, map potential surface ice, improve gravity field model
LROC: Lunar Reconnaissance Orbiter Camera PI: Mark Robinson, ASU	Thousands of 50 cm/pixel images, and entire Moon at 100 m in UV, Visible. Illumination conditions of the poles	Surface landing hazards and some resource identification, including locations of near constant solar illumination
Mini-Rf Technology Demonstration PI: Ben Bussey, APL/JHU	X and S-band radar imaging and repeat-pass interferometric SAR	Demonstrate lightweight SAR and communication technologies, locate potential water-ice using radar scattering

Table 1 provides the list of LRO instruments, the Principal Investigator, key data the instrument plans to provide, and the benefits to the Exploration program. The instrument performance parameters are summarized in Table 2, and the wavelength coverage and spectral resolving power of the LRO instruments is shown in Fig. 2.

Except for calibration activities, the LRO spacecraft is generally pointed in a nadir direction to allow mapping of the lunar surface by the remote sensing instruments. The LRO spacecraft capabilities are summarized in the companion paper by Tooley et al. (2010). A unique feature of the LRO spacecraft is the precision orbit determination that is provided by one-way laser tracking of LRO from Earth-based laser ranging facilities, which is enabled by the Lunar Orbiter Laser Altimeter (Zuber et al. 2010, this issue).

Each LRO instrument has strong individual capabilities for providing both scientific and engineering-enabling measurements of the lunar surface and environment. In concert, the LRO instrument suite addresses LRO measurement goals in a robust and resilient manner by using several complementary remote sensing methods that reinforce the discoveries made by an individual instrument. Table 4 summarizes the LRO measurement objectives for ESMD and the complementary nature of their investigations. Figure 3 illustrates the role that each instrument plays to contribute to the success of the LRO ESMD mission, as stated by the mission's Level 1 requirements, and the required performances to reach minimum and full mission success.

Table 2 Instrument Performance Parameters

Instrument	Instrument Classification	Characteristic Range	Characteristic Resolution	Spatial Resolution (from 50 km)	Spatial Coverage	Data Rate Gbits/day
LOLA	Laser Altimeter	Range Window 20–70 km	10 cm vertical	Five 5 m laser spots 25 m spacing	Polar Grid 0.001° latitude 0.04° longitude	1.4
LROC NAC	High Resolution Camera	Broadband Centered at 550 nm	±150 nm	50 cm/pixel	Targeted >10% Lunar Surface 100% >85.5° lat.	515
LROC WAC	MultiSpectral Camera	315–680 nm	Spectral filters centered at 315 nm 360 nm, 415 nm, 560 nm, 600 nm, 640 nm, 680 nm	100 m/pixel visible; 400 m/pixel UV	Full lunar surface at each wave-length and various lighting angles	41
LEND	Neutron Detector	Thermal to 15 MeV	*Four Bands* Thermal <0.4 eV Epithermal 0.4 eV–10 keV Fast 10 keV–1 MeV Energetic 1 MeV–15 MeV	Epithermal 10 km FWHM (see text for other bands)	Full lunar surface and deep space	0.26
DLRE	Radiometer	20 K to 400 K	5 K	400 m	Full Lunar Surface Day/Night Temperatures	3.5
LAMP	UV Imaging Spectrograph	52 to 187 nm	3.5 nm	260 m	Full Lunar Surface	2
CRaTER	Primary and albedo cosmic ray sensor	LET spectra 0.2 keV/μm to 7 MeV/μm	<3%	77 km	Full lunar surface and deep space	7.8 (peak)
Mini-RF	X- and S-band Synthetic Aperture Radar	4 cm (X-band) 12 cm (S-band)	Sensitivity (NES0): −30 dB (S-band) −25 dB (X-band)	150 m 15 × 30 m (zoom)	Limited during the nominal mission	7.7*

*mini-RF 7.7 Gbits for 4 min. data collection interval

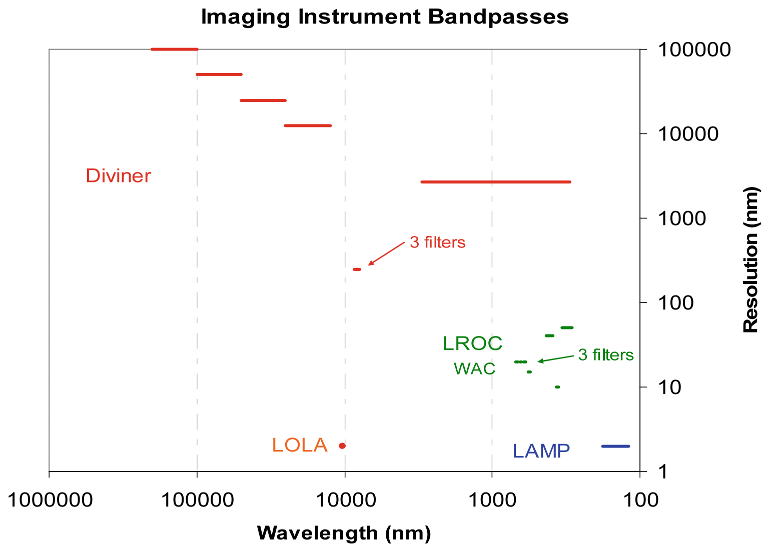

Fig. 2 Instrument bandpasses. LOLA instrument included for completeness, but not scaled to resolution

	Objectives	LRO Requirements	CRaTER	DLRE	LAMP	LEND	LOLA	LROC	Mini-RF
1	Find Safe Landing Sites	M30 M40 – Global geodetic grid 10 cm vertical, and at the poles, 50 m horizontal resolution					▲	▲	●
		M80 – Identify surface features & hazards		▲			▲	▲	●
2	Locate Potential Resources	M90 – Characterize the polar region illumination environment		▲			▲	▲	
		M50 – Provide lunar temperature map from 40 - 300K, 5 K precision over full diurnal cycle.		▲					
		M60 – Image the permanently shadowed regions.			▲		▲	●	
		M70 - Identify putative deposits of water-ice			▲	▲	▲		●
		M100 - Characterize lunar mineralogy		▲	●	●	●	▲	●
		M110 - Hydrogen mapping				▲		●	
3	Life in the Space Environment	M10 - Characterize the deep space radiation environment at energies in excess of 10 MeV	▲			▲			
		M20 - measure the deposition of deep space radiation on human equivalent tissue.	▲						
4	New Technology	P160 - Technology demo	●				●		▲

Minimum Success (M30 M40, M80, M90)

Full Success (all requirements)

▲ Level 1 Requirements
● Contributions– may require additional analysis to exploit

Fig. 3 LRO level 1 Requirements and Criteria for Minimum and Full Mission Success of the ESMD Mission

3 Exploration Mission Implementation

After LRO payload selection in December, 2004, the LRO development was begun early in 2005. A summary of key dates in the development of the LRO spacecraft flight system is given in Table 3.

As described in Tooley et al. (2010), LRO was a rapid development project. The launch date was moved from the fourth quarter 2008 to 2009 due to delays in availability of the launch vehicle and due to conflicts with the Atlas V launch facilities at Cape Canaveral.

Table 3 Summary of key events in LRO development

Event	Date
Preliminary Design Review	2/7/2006
Confirmation Review	5/17/2006
Comprehensive Design Review	11/10/2006
Pre-Ship Review	2/9/2009
Orbiter delivered to the Cape	2/12/2009
Launch Readiness Review	6/15/2009
Spacecraft Launch	6/18/2009
Lunar Orbit Insertion	6/23/2009
Begin Instrument Activation and Calibration	6/30/2009
Insert into Mission Orbit (50 ± 15 km circular)	9/15/2009

LRO was launched from the Cape Canaveral Air Station in Florida on June 18, 2009 and was inserted directly into lunar orbit on June 23. LRO entered into an initial polar-inclination (89.7) elliptical orbit (30×216 km) with the periselene over the southern hemisphere. After reaching this initial orbit, a commissioning phase began during which the spacecraft and instruments were tested and calibrated. This phase was planned to last for approximately 60 days.

During the commissioning phase the spacecraft systems were activated and tested. Each of the instruments was activated and numerous calibrations were successfully conducted. Data were collected in the nominal operating configuration with the instruments nadir pointing to verify that they were functioning properly and to calibrate against well known lunar features, as well as with deep space. Also, there were specific star calibrations where the LRO orbiter was pointed or rastered across selected stars to verify the pointing accuracy of the instruments and to determine the sensitivity. The LRO spacecraft was reoriented to point at the Earth to calibrate the Laser Ranging instrument and the Mini-RF Technology Demonstration Experiment with Earth based assets, such as the radar at the National Astronomy and Ionosphere Center Arecibo Observatory for the Mini-RF instrument and one-way laser ranging from LOLA to a receiver on the Earth, and from an Earth based laser to the LOLA receivers. Finally a number of roll, yaw and pitch maneuvers were undertaken to assess light scattering in the instruments and relative inter-pixel sensitivity (flat field).

Because of the MiniSAR S-band polarimetric radar on the ISRO Chandrayaan-1, there was a unique opportunity for bistatic radar measurements during the commissioning period when the LRO and Chandrayaan-1 spacecraft were at approximately the same altitude. A dual orbiter spacecraft bistatic experiment was attempted on August 19, 2009, but was not successful due to operational difficulties with the pointing of the ISRO Chandrayaan-1 spacecraft. Another dual-spacecraft bistatic radar scattering experiment attempt was planned for the following week, but was canceled due to the loss of communications with the Chandrayaan-1 spacecraft on August 25, 2009. These coordinated operations resulted in an extension of the LRO commissioning activities for an additional two weeks, relative to the original baseline plan.

On September 15, 2009 the LRO orbiter spacecraft was moved into a polar-inclination (89.7 degrees) circular 50-km mean altitude orbit for a planned one-year duration to execute its baseline ESMD mission phase ("the Exploration Mission"). The orbital period is typically 113 minutes. This polar orbit allows repetitive measurements at high latitudes, producing a dense net of measurements as illustrated in Fig. 4, where the polar groundtrack is shown for a one month period. Since the Moon rotates once each sidereal month, successive

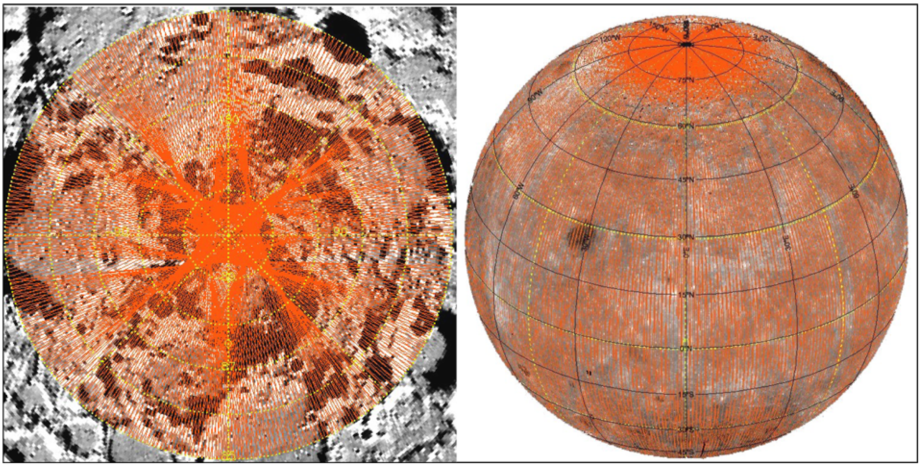

Fig. 4 LRO groundtrack emphasizes remote sensing of the Lunar Poles

groundtracks are separated by about 31 km at the equator. Because most instruments make measurements over a narrow swath, at lower latitudes there will be inter-orbit ground track gaps or gores in the mapping during one lunation. However, measurements accumulated during the one-year Exploration Mission result in complete global coverage.

An important consideration in selecting the launch date was the variation of the LRO orbital plane during the course of the primary mission. Even though the tilt of the lunar spin axis with respect to the ecliptic plane is very small, only 1.557 degrees, there will be some seasonal variation of illumination and resulting surface physical temperature in the lunar polar regions. To measure this effect, it is desirable to have the LRO ground track be very near the noon-midnight meridian at the solstices. As shown in Fig. 5, at the first solstice on October 22, which corresponds to midsummer at the South Pole and midwinter at the North Pole, the LRO ground track will be very close to local noon/midnight at that time.

The LRO mission played a major role in the support of the Oct. 9, 2009 LCROSS impact experiment. When LRO was manifested on an Atlas V (401) rocket, NASA took advantage of the additional payload capacity to select the Lunar Crater Observation and Sensing Satellite (LCROSS), a lunar impactor mission to launch simultaneously with LRO. LCROSS consists of the Centaur stage as a primary impactor, accompanied by a shepherding remote sensing satellite for post-impact observations.

The role of LRO is to make detailed observations before, during, and after the LCROSS impact in a permanently shadowed crater near the lunar South Pole. The impact will occur within the highlands impact crater Cabeus on October 9, 2009. LRO has made detailed observations to support the LCROSS selection of this crater for the impact. The LRO team used laser altimetry data from both the LRO LOLA and JAXA Kaguya laser altimeters to determine regions of permanent shadows that would be the most likely regions to harbor frozen volatiles, if any are preserved in significant concentrations. The topography measurements also identified regions within the polar impact craters where the local slope is sufficiently small to maximize the transfer of kinetic energy from LCROSS impact into the lunar regolith target. LRO's LEND neutron spectrometer provided maps of enhanced hydrogen concentrations that could indicate water ice embedded in the upper meter of the lunar regolith. LRO Diviner temperature measurements of the South Polar region were used to reveal the extremely low temperatures of cold traps that can potentially preserve volatiles

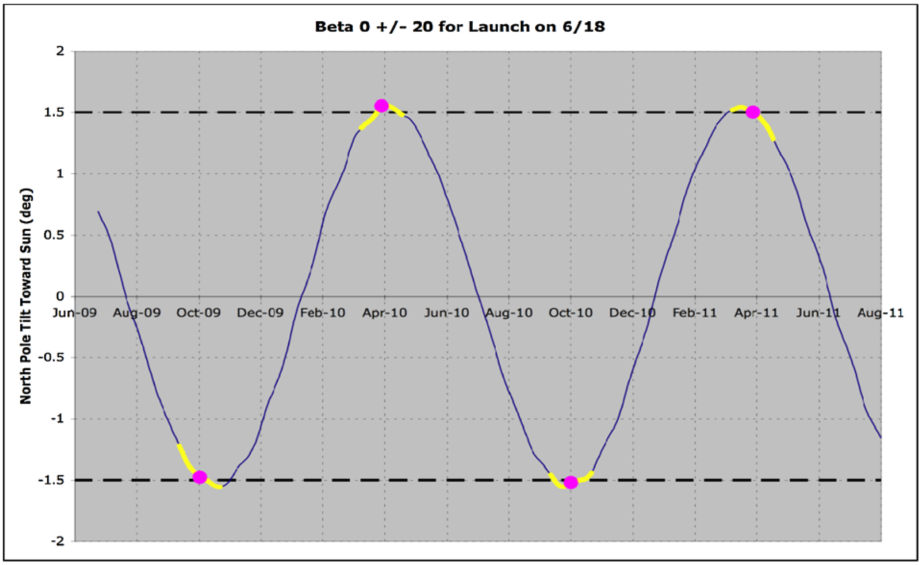

Fig. 5 Variation of the angle between the LRO orbit and the direction of the sun. South Pole summer occurs on October 22

in ice form. Mini-RF dual-frequency radar polarization imaging provided information that indicates the blockiness of the impact site and which can be used to further test for the presence of significant water ice on the basis of anomalous scattering behavior. These combinations of LRO measurements as well as other factors led the LCROSS team to choose the south polar crater Cabeus for its impact target. Before the impact occurs the Cabeus target area will be exhaustively observed by the LRO LROC, LOLA, and Mini-RF instruments in detail to characterize the pre-impact geology.

The LRO spacecraft orbit will be adjusted to pass at closest approach to the Cabeus target site approximately 90 seconds after the LCROSS Centaur impact. At impact and after the impact the LRO LAMP far UV spectrometer will search for evidence of significant volatile species and how they evolve in the Moon's tenuous atmosphere. LRO's Diviner radiometer will peer into the impact site to measure the heating effects of the impact and how it changes over time. The LRO mission plans to undertake a campaign of extensive observations of the post-impact surface geological effects by all instruments over the course of the days and weeks following the LCROSS impact event. Such LRO-based observations will provide important measurements in support of the LCROSS' team analysis of the physics of the impact and how volatile materials may have been mobilized.

An important objective during the primary LRO Exploration Mission is intensive measurements of specific sites, chosen by NASA's Constellation program, as representative of a broad distribution of lunar geological features important for both their value to human exploration as well as for scientific objectives. An LRO Science Targeting Meeting was held at Arizona State University on June 9–11, 2009 to solicit ideas and priorities from the scientific community for LRO targeting, both in terms of focused science themes and specific features on the Moon. Additional areas for intensive measurements will be identified during the LRO mission.

Table 4 Objectives are met by LRO instrument investigations, some with complementary data products

LRO Measurement Objective	LRO Instrument	Data Product
The LRO shall characterize the deep space radiation environment at energies in excess of 10 MeV in lunar orbit, including neutron albedo	LEND	Radiation Data Product for global distribution of neutrons at Moon's orbit with spatial resolution of 50 km at different energy ranges from thermal energy up to $>$15 MeV separately for periods of quiet Sun and for periods of Solar Particle Events
	CRaTER	Provide Linear Energy Transfer (LET) spectra of cosmic rays (particularly above 10 MeV), most critically important to the engineering and modeling communities to assure safe, long-term, human presence in space
The LRO shall measure the deposition of deep space radiation on human equivalent tissue while in the lunar orbit environment	CRaTER	Provide LET spectra behind different amounts and types of areal density, including tissue-equivalent plastic
The LRO shall measure lunar terrain altitude to a resolution of 10 cm and an accuracy of 1 m for an average grid density of approximately 0.001 degrees latitude by 0.04 degrees longitude	LOLA	Provide a global digital elevation model of the Moon with 10 cm vertical resolution, 1 m vertical accuracy and 50–100 m horizontal resolution with 1 km average cross track sampling at the equator
The LRO shall determine the horizontal position of altitude measurements to an accuracy of 100 m	LOLA	Provide global topography of the Moon with 10 cm vertical resolution, 1 m vertical accuracy and 50–100 m horizonal resolution with 1 km average cross track sampling at the equator
	LROC	For areas of high interest (targets), collect multi-look NAC data reducible to 2 m scale Digital Elevation Models for 25 km^2 areas
	LROC	Acquire 100 m/pixel global stereo imaging reducible to 1 km/pixel global topography in EDR format
The LRO shall obtain temperature mapping from 40–300 K in the Moon's polar regions to better than 500 m spatial resolution and 5 K precision for a full diurnal cycle	Diviner	Temperature maps at better than 500 m spatial resolution from 40–300 K over an entire diurnal cycle to enable the detection and characterization of cold traps in polar shadowed regions
The LRO shall obtain landform-scale imaging of lunar surfaces in permanently shadowed regions at better than 100 m spatial resolution	LOLA	Provide global topography with 10 cm vertical resolution, 1 m vertical accuracy and 50–100 m horizontal resolution with 1 km average cross track sampling at the equator
	LAMP	Albedo maps of all permanently shadowed regions with resolutions down to 300 m
The LRO shall identify putative deposits of water-ice in the Moon's polar cold traps at a spatial resolution of better than 500 m on the surface and 10 km subsurface (up to 2 m deep)	LOLA	Provide Reflectance data from the permanently shadowed regions to identify surface ice signatures at a limit of 4% ice surface coverage by area
	LEND	Develop maps of putative water-ice column density on polar regions of the moon with spatial resolution of 10 km
	LAMP	Develop water-frost concentration maps of the lunar polar regions Mapping resolutions as good as 3 km for frost abundances down to 1.5%

Table 4 (*Continued*)

LRO Measurement Objective	LRO Instrument	Data Product
The LRO shall assess meter-scale features of the lunar surface to enable safety analysis for potential lunar landing sites over targeted areas of 100 km^2	LROC	Provide up to 50 Mosaics of selected potential landing sites with one meter scale resolution
	LROC	Provide crater size density and size distribution maps of up to 10 potential landing sites (100 km^2/site)
	Diviner	Provide rock ($\leq$0.5 m diam) abundance percentages for up to 50 selected potential landing sites by measuring the ratio of high thermal to low thermal inertia material
	LOLA	Provide topography, surface slopes, and surface roughness at 25-m spacing over a 70 m wide FOV swath at up to 50 selected potential landing sites
The LRO shall characterize the Moon's polar region illumination environment to a 100 m spatial resolution and 5 Earth hour average temporal resolution	LROC	Provide uncontrolled illumination movies, 1 each of North and South Lunar Poles over the course of 1 lunar year at an average time resolution of 5 hours or better (Wide Angle Camera)
	LROC	Provide meter scale resolution summer (uncontrolled) mosaics of the lunar poles ($\pm$4 degrees). (Narrow Angle Camera). Some gores in the data beyond the polar regions are acceptable
	LOLA	Polar region maps of latitudes 86°–90° with a vertical resolution of 10 cm and a spatial resolution of 25 to 35 m after one year. This will help to identify potential sites of optimal solar power generation
	Diviner	Provide polar illumination map at better than 500 m spatial scales over a full diurnal cycle
The LRO shall characterize lunar mineralogy by mapping the thermal properties of regolith and characterizing UV, visible, and infrared spectral differences and variations at km scales globally	LROC	Global imaging 400 m/pixel in the ultraviolet bands and 100 m/pixel in the visible bands, ten uncontrolled demonstration multi-spectral mosaics for high priority targets
	Diviner	Global fine-component thermal inertia, silicate mineralogy and Lambert albedo from thermal emission, solar reflectance and topography measurements with greater than 50% spatial coverage at the equator
The LRO shall perform hydrogen mapping of the Moon's surface with a sensitivity of 100 ppm or better, a SNR of 3, and 10 km resolution in the polar regions	LEND	Determine hydrogen content of the subsurface at the polar regions with spatial resolution of 10 km and with sensitivity to concentration variations of 100 parts per million at the poles

4 LRO Science Mission Objectives

Although LRO was conceived and designed to be an Exploration Mission of primary benefit to ESMD (i.e., for providing boundary conditions in support of engineering decisions pertaining to the return of human explorers to the Moon), the science value of the LRO observations was recognized by NASA's Science Mission Directorate (SMD) from the outset (i.e. the Announcement of Opportunity was issued jointly by ESMD and SMD, and SMD was jointly responsible for the selection of LRO instruments). Most of the competitively-selected instruments have a significant heritage in remote sensing devices that have been flown to other planetary objects for scientific purposes. In order to fully realize the scientific potential expected from the wealth of LRO data, NASA's SMD in partnership with ESMD competitively selected in 2007 a team of Participating Scientists (PS) to work closely with the LRO instrument teams and their Principal Investigators (PIs). The Participating Scientists help plan observations during the LRO Exploration Mission and the extended Science Mission and aid in the analysis of LRO data, especially correlating results from multiple instruments to develop improved models of the lunar surface and geological evolution.

At the end of the ESMD Exploration Mission phase, LRO will undertake a minimum two-year Science Mission sponsored by the Science Mission Directorate (SMD). The science objectives of this extended mission will reflect the themes outlined by the National Academy of Science's report on the Scientific Context for Exploration of the Moon (SCEM). Table 5 lists the SCEM themes and an initial formulation of the LRO science objectives that might comprise the core investigations during the Science Mission. This initial formulation will be refined and a proposal for the Science Mission will be submitted to SMD early in 2010.

LRO has several orbital configurations to consider in executing the extended Science Mission, depending on the amount of fuel left at the end of the 1-year baseline mission. Figure 6 shows the fuel required for several types of orbits, expressed in terms of velocity change (m/s) from the 50-km circular orbit. It is expected that about 220 m/s of velocity change capability will remain at the end of the Exploration Mission.

The most compelling options for the LRO Science Mission include:

- continue the 50-km altitude orbit (MO, or Exploration Mission Orbit) for an additional to-be-determined number of months depending on available station-keeping fuel,
- return to the 30×216 km commissioning orbit (FO, or Frozen Orbit) with a periselene at the southern hemisphere for several additional years—this orbit requires minimum fuel to maintain,
- move first to a transition mission orbit (TMO) with mean altitude of 110 km (20×220 km elliptical), with the periselene initially at 40 degrees south of the equator (argument of periapse $\sim$220 degrees) moving north towards the equator, and over the north pole (with a 90×150 km altitude), and returning to an altitude range of 20×220 km at 40 degrees south of the equator after a total of about 350 days, and finally, to the commissioning orbit (30×216 km, periapse over the southern hemisphere) for remainder of mission life.

Table 6 summarizes these various orbits and required propulsion fuel capacity. They are organized according to Science Mission duration (Short, Medium, Long). In early 2010 a decision will be made as to the orbital strategy for the Science Mission.

5 Data Accessibility

To make the LRO observations accessible to both human exploration planners as well as the science community, calibrated LRO data will be rapidly deposited into the Planetary Data

Table 5 LRO measurement capabilities can accomplish many NRC SCEM science objectives

SCEM Theme	LRO Approach/SCM Objective	Measurements	Contributing Instruments
Bombardment History of the Inner Solar System	Characterize Recent Impact Flux Crater age studies Role of volatiles on crater morphology Basin formation and modification	Topography, High Resolution & Multispectral Imagery Reimaging of Apollo era sites	LROC, DLRE, LAMP, LOLA
Lunar Interior	Thickness of the Lunar Crust Stratification of the Mantle Heat Flow Tidal Deformation	Global Geodetic Grid Multispectral Imagery Temperature Measurements of PSRs	LROC, DLRE, LOLA
Compositional Diversity of the Lunar Crust	Determine the extent of planetary differentiation, the age, distribution, and origin of lunar rock types, and the composition of the lower crust both globally and regionally	Topography, High Resolution & Multispectral Imagery Neutron albedo Radar images and polar	LROC, DLRE, Mini-RF, LOLA, LEND
Polar Volatiles	Sources, composition, physical properties of locations	Neutron albedo maps Temperature maps of PSRs Reflectance data Surface UV spectra	DLRE, Mini-RF, LOLA, LEND, LAMP, LOLA
Lunar volcanism	Origin, compositional variability, age of mare basalts and pyroclastic deposits	High resolution topography Dual band radar imaging High-resolution and multispectral imaging Day/night thermal emission	DLRE, LOLA, LROC, LEND, Mini-RF

System (PDS) by each instrument Science Operations Center (SOC). Figure 7 illustrates the locations where the various LRO observational data and data products will be located.

Each instrument team is required to submit to the PDS several types of data products. Typically Level 0 data products are raw data in the form of counts accumulated during specific time intervals of measurements, with orbital information and engineering parameters. Higher level data products consist generally of count rates converted into physical units and projected onto the lunar surface as maps of geophysical quantities.

Each instrument SOC is required to deliver validated and calibrated data to the PDS every three months, starting six months after the beginning of the primary Exploration Mission (i.e., March 15, 2010). The initial delivery will include all measurements made from the time of launch through the first three months of the primary orbit (e.g., June 18 to December 15, 2009). Subsequent deliveries will be made every three months after the first delivery and will include all data that is no more than three months old. After the Exploration Mission ends, some investigations plan to reprocess data and develop higher level composite data products. These will be delivered to the PDS no later than six months after end of the Exploration Mission.

Table 5 (*Continued*)

SCEM Theme	LRO Approach/SCM Objective	Measurements	Contributing Instruments
Impact processes	Melt sheet differentiation Multi-ring basin structure Lateral and vertical mixing of compositional units	Regional and high resolution topography of craters and basins Spectral reflectance and thermal emission properties of multi-ring basins	LROC, DLRE, Mini-RF, LOLA
Regolith processes and weathering	Identify ancient regolith Modification processes Rare earth minerals (Gd and Sm)	High resolution slope characterization Physical properties High-resolution and multispectral imaging Day/Night thermal emission S and X band synthetic aperture radar	DLRE, Mini-RF, LOLA. LEND, LAMP, LOLA
Atmosphere and dust environment	Density and composition of exospheric species Size, charge and distribution of electrostatically levitated dust	Fluorescence and light scattering in exosphere from atomic species and dust	LAMP, LROC
Other Lunar and non-Lunar Science	Novel heliophysics and astrophysics studies Solar cycle dependence of the lunar radiation environment	Galactic cosmic rays and solar energetic particles Earth's aurora, plasma-sphere, and astronomical objects in the UV	CRaTER, LEND

Table 6 Options for orbits during the science mission

	Option	Mission Orbit (MO) + Transition Orbit (TO) Duration (Months)	50×50 km Nominal Mission Orbit ΔV (m/s)	20×140 km Transition Orbit ΔV (m/s)	16×200 Maintain Frozen Orbit (FO) ΔV (m/s)	Total ΔV (m/s)
L	6-months MO 2×350-days TMO about 4-years FO	30	75	118	19	212
M	10-months MO 350-days TMO 4-years FO	22	125	67	20	212
S	11-months MO MO to FO (costs 50 m/s) About 5-years-FO	11	138		24 + 50 (MO to FO)	212

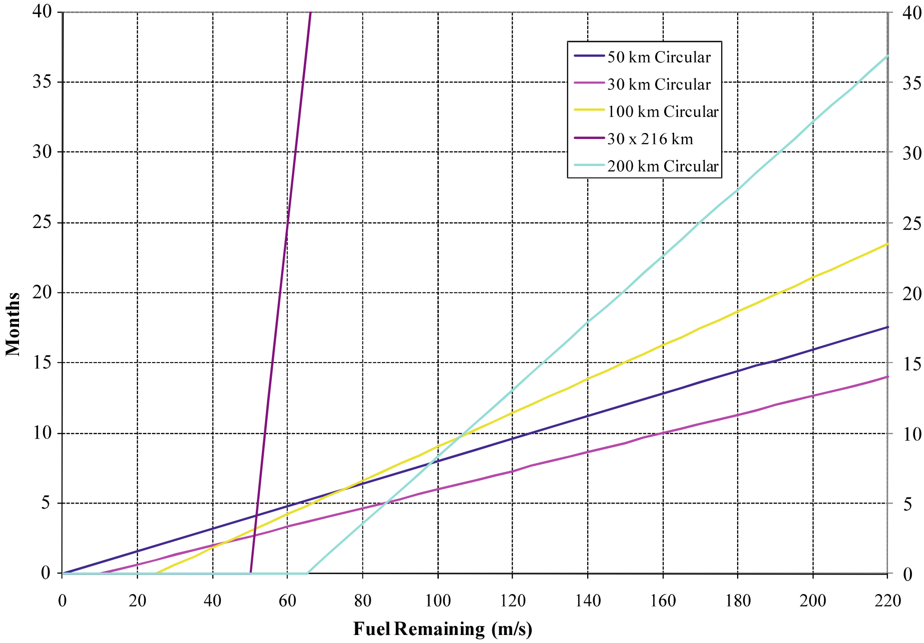

Fig. 6 LRO Extended Science Mission Options: Lifetime vs. Fuel Available at the Start of the Extended Mission for Various Orbits

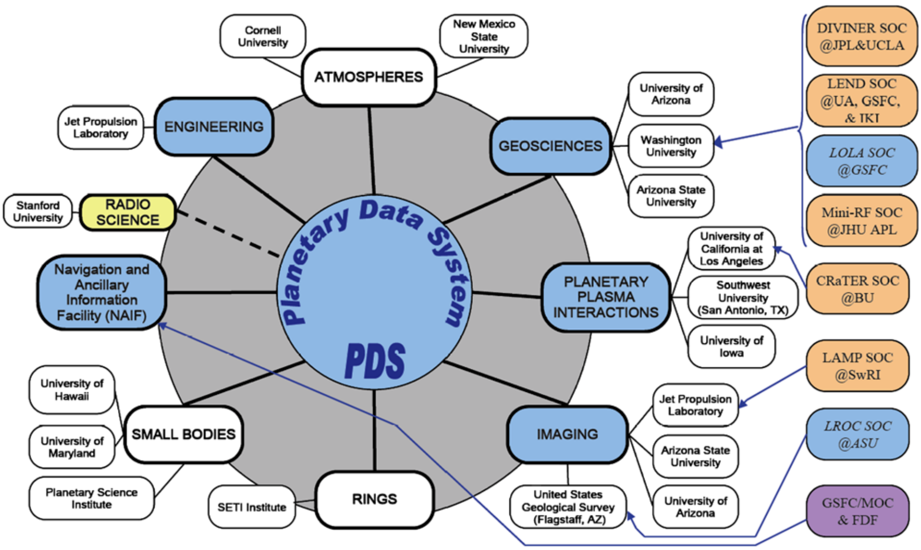

Fig. 7 LRO SOCs and PDS Nodes and Data Nodes

6 Conclusions

LRO is in orbit around the Moon, has successfully completed its commissioning phase and has been inserted into the 50 km mission orbit. The spacecraft and instruments are performing well and there appears to be no barrier toward fulfilling the objectives of the mission. After the one year ESMD mission and especially after an extended mission LRO will have provided a comprehensive data set that will guide future exploration and scientific discoveries. LRO is the first dual-purpose mission conducted by NASA, with a unique capability to accomplish both paradigm-shifting science observations together with critical engineering measurements necessary for cost-effective and safe return of human explorers to the lunar surface.

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