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The Lunar Reconnaissance Orbiter Laser Ranging Investigation

Maria T. Zuber · David E. Smith · Ronald S. Zellar · Gregory A. Neumann · Xiaoli Sun · Richard B. Katz · Igor Kleyner · Adam Matuszeski · Jan F. McGarry · Melanie N. Ott · Luis A. Ramos-Izquierdo · David D. Rowlands · Mark H. Torrence · Thomas W. Zagwodzki

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Abstract The objective of the Lunar Reconnaissance Orbiter (LRO) Laser Ranging (LR) system is to collect precise measurements of range that allow the spacecraft to achieve its requirement for precision orbit determination. The LR will make one-way range measurements via laser pulse time-of-flight from Earth to LRO, and will determine the position of the spacecraft at a sub-meter level with respect to ground stations on Earth and the center of mass of the Moon. Ranging will occur whenever LRO is visible in the line of sight from participating Earth ground tracking stations. The LR consists of two primary components, a flight system and ground system. The flight system consists of a small receiver telescope mounted on the LRO high-gain antenna that captures the uplinked laser signal, and a fiber optic cable that routes the signal to the Lunar Orbiter Laser Altimeter (LOLA) instrument on LRO. The LOLA instrument receiver records the time of the laser signal based on an ultrastable crystal oscillator, and provides the information to the onboard LRO data system for storage and/or transmittal to the ground through the spacecraft radio frequency link. The LR ground system consists of a network of satellite laser ranging stations, a data reception and distribution facility, and the LOLA Science Operations Center. LR measurements will enable the determination of a three-dimensional geodetic grid for the Moon based on the precise seleno-location of ground spots from LOLA.

Keywords Moon · Laser ranging · Lunar Reconnaissance Orbiter · Orbit determination

M.T. Zuber (✉)
Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139-4307, USA
e-mail: zuber@mit.edu

D.E. Smith · G.A. Neumann · X. Sun · J.F. McGarry · D.D. Rowlands · T.W. Zagwodzki
Solar System Exploration Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

R.S. Zellar · R.B. Katz · I. Kleyner · A. Matuszeski · M.N. Ott · L.A. Ramos-Izquierdo
Advanced Engineering Technology Directorate, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

M.H. Torrence
Stinger Ghaffarian Technologies, Greenbelt, MD 20770, USA

1 Introduction

1.1 Motivation

The Lunar Reconnaissance Orbiter[1] (LRO) mission (Chin et al. 2007) will perform precise geophysical, geological and geochemical mapping of the Moon in order to provide an observational framework for future orbital, landed and human exploration. The mission represents the first lunar exploration component of the Vision for Space Exploration (Bush 2004). A high-priority component of the mission's exploration objectives is an accurate lunar topography model that will be derived from the Lunar Orbiter Laser Altimeter (LOLA) (Smith et al. 2009). LOLA's lunar topography model will be used to construct a high-accuracy, global geodetic grid that will provide the foundation for positioning data sets from LRO as well as other lunar missions.

1.2 Tracking of LRO

The LOLA instrument has a ranging precision of about 10 cm (Smith et al. 2009), which is considerably better than the orbit determination capability originally baselined for the LRO mission. Uncertainties in spacecraft position represent the limiting error source for both LOLA's topographic model and geodetic grid. The Moon's synchronous rotation presents a special challenge in determination of the spacecraft orbit because the spacecraft cannot be tracked directly while orbiting above the lunar far side as viewed from Earth (cf. Lemoine et al. 1997; Konopliv et al. 1998, 2001). The spacecraft must be tracked as precisely as possible on the near side so that far side errors do not accumulate above the level that would violate the orbit positioning requirement.

The baseline tracking system for LRO is an S-band (2.2–2.3 GHZ) radio frequency link for ∼20 hours per day (Chin et al. 2007). A commercial network, the Universal Space Network (USN), will provide tracking with stations at Dongara, Australia; Kiruna, Sweden; Weilham, Germany; and South Point, Hawaii. The Doppler accuracy of the USN is $\sim 1\ \mathrm{mm\,s^{-1}}$ (1σ) averaged over 10 s, which for the tracking time allocated will permit LRO orbits to be determined to ∼10 m radially and 300 m along-track and across-track. The expected orbit accuracy is based upon simulations (Smith et al. 2008) using the NASA/GSFC GEODYN/Solve orbit analysis software (Pavlis et al. 2001).

Altimetric crossovers from the LOLA instrument will also be used in the LRO orbit determination process (Smith et al. 2009). Crossovers are points on the surface of the target body where spacecraft orbital trajectories cross. For places where surface topography does not change with time (in contrast, for example, to Earth's ocean surface), surface positions reconstructed from a combination of altimetric ranges and orbital tracking on different passes are indicative of orbit error. A global database of crossover mismatches can be minimized in a least square sense to improve orbital knowledge. The use of orbit crossovers has been successfully demonstrated to improve orbits of the Mars Global Surveyor spacecraft (Rowlands et al. 1999), the gravity field of Mars (Lemoine et al. 2001), and the radial accuracy of topography (Neumann et al. 2001) using observations from the Mars Orbiter Laser Altimeter (Zuber et al. 1992; Smith et al. 1999, 2001). Simulations of orbit determination have also been performed for the terrestrial Vegetation Canopy Lidar (VCL) and ICESat missions (Luthcke et al. 2000). The Lunar Reconnaissance Orbiter will be the first to use

[1] All acronyms are defined in the Appendix.

crossovers from a multi-beam altimeter to improve spacecraft orbits for a planetary body with synchronous rotation, where direct tracking of the target body's far side is not possible.

To take maximum advantage of the 10-cm range resolution of LOLA and the 50-cm pixel resolution of the Lunar Reconnaissance Orbiter Camera (LROC) (Robinson et al. 2008), the radial component of the orbit of LRO must be reconstructed to the sub-meter-level. This requirement dictates the need for higher-precision tracking on the lunar near side than is provided by the spacecraft's baselined S-band tracking system, or even by a combination of S-Band tracking and altimetric crossover analysis (Smith et al. 2008). Attainment of the precision tracking requirement on LRO will be achieved by introducing a laser ranging (LR) system in which an Earth-based laser will be used to range to LRO whenever in view.

1.3 LR System Overview

As illustrated schematically in Fig. 1, the LR is a one-way, time-of-flight measurement system that uses laser pulses to determine the range between an Earth-based satellite laser ranging station and the LRO spacecraft in orbit around the Moon. The system is an innovative combination of proven flight hardware components and satellite laser ranging technology. Stable clock oscillators on the spacecraft and at Satellite Laser Ranging (SLR) stations on Earth enable a precise time of flight measurement to be obtained whenever the LRO spacecraft is in view from a station. The system is designed to measure centimeter-level orbit perturbations over a few seconds of flying time and meter-level perturbations from pole to pole. The LR system has three main elements: the flight segment, the ground station and the data processing system. Tables 1 and 2 list key parameter values for the flight system and ground system elements.

As illustrated schematically in Fig. 2, the LR flight element includes a laser ranging telescope (LRT) attached to the LRO high-gain antenna (HGA), a fiber optic bundle to transmit the pulses from the LRT to the LOLA detector, and timing electronics on the LOLA instrument to time stamp the pulse arrival times. LOLA's Channel 1 detector assembly is designed to receive the LR signal through wavelength multiplexing, with the LR pulses at 532 nm and the lunar surface returns at 1064 nm. The LOLA timing electronics is designed to time stamp both the LR signal from Earth and the LOLA signal from the lunar surface through time multiplexing.

The LR ground element consists of SLR stations that track the LRO spacecraft as it orbits the Moon and synchronously transmit laser pulses to the spacecraft. The primary ground station for the LR system is NASA's Next Generation Satellite Laser Ranging (NGSLR) station, located at Goddard Space Flight Center in Greenbelt, Maryland, shown in Fig. 3. In addition, stations from the International Laser Ranging Service (ILRS) have been invited to partner with the NGSLR facility and participate in ranging activities. While the single

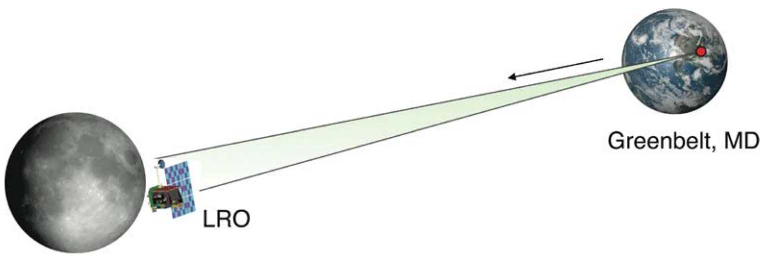


Fig. 1 Schematic illustrating the geometry of the LR uplink

Table 1 LRO LR flight system parameters

Parameter	Unit
Receiver aperture diameter	1.9-cm clear aperture, 3.0-cm outer diameter
Field of view	30 mrad
Fiber optic bundle	400-µrad core diameter, 7 each, 0.22 NA, step index 40% transmission, including fill factor and connector losses
Optical system transmission	27% transmission, including LOLA aft optics
Optical bandwidth	0.3 nm FWHM
Wavelength	532 nm
Detector (LOLA Ch. 1)	
Quantum efficiency	45%
Avalanche gain	120
Dark current	83 pA
Preamp noise	1.5 pA/Hz$^{1/2}$
Impulse response pulse width	5 ns FWHM
Timing electronics	
Timing resolution	<0.2 ns
Clock stability	2×10^{-12} over 1 hour
Pulse energy monitor	10% single shot
Earth window	8 ms

Table 2 NGSLR ground station characteristics

Parameter	Unit
Laser pulse energy	50 mJ
Wavelength	532 nm
Pulse width and rate	<10 ns FWHM, 28 Hz, synchronized to MET
Beam divergence (full angle at $1/e^2$ points)	55 µrad
	(11.3 arcsec)
Pointing uncertainty (3σ)	10 µrad
	(2 arcsec)
Spacecraft position prediction uncertainty	10 µrad
	(2 arcsec)
Laser optics transmission	50%
Transmission through atmosphere	
Minimum elevation	20°
Atmospheric transmission	70% zenith
	35% 20° elevation

NGSLR station is sufficient to meet the LR objectives, the participation from the ILRS will broaden ranging coverage and improve the overall LRO tracking coverage and thus data products.

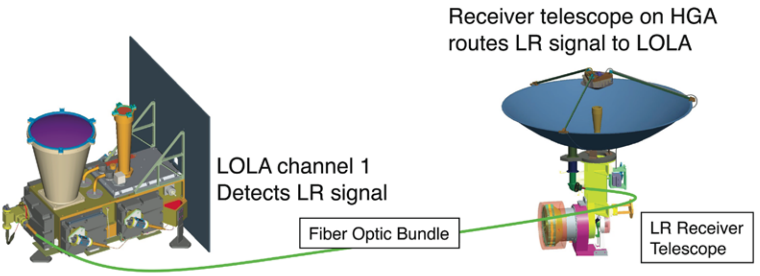
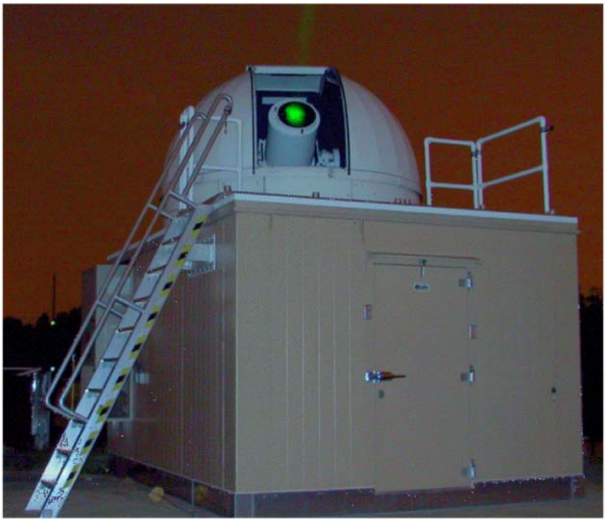


Fig. 2 Schematic showing the LR flight system. The Laser Ranging Telescope (LRT) receives the signal from Earth and transmits it to Channel 1 of the LOLA receiver via the fiber optic bundle (FOB)

Fig. 3 NASA's Next Generation Satellite Laser Ranging System (NGSLR) at NASA/Goddard Space Flight Center, Greenbelt, MD



LR operation is coordinated by the LRO Mission Operations Center (MOC), and the LOLA Science Operations Center (SOC), with the NGSLR facility serving as the single point of contact for ILRS partner stations. The LRO MOC transfers the full set of LOLA science data to the LOLA SOC where the LR pulse transmission and detection times are used to produce ranges to the LRO spacecraft. The ranges are to be archived in the Radio Science Node of the Planetary Data System (PDS).

The LR is required to achieve LRO's precision orbit determination requirement and will allow the production of a precise geodetic grid from LOLA altimetry (Smith et al. 2009) that will enable all LRO and many other archived lunar data to be precisely-located on the lunar surface. In addition, the LR range data along with LRO-supplied S-band ranging data and LOLA altimetry data will also be used to generate a refined gravity model of the Moon on a best-effort basis.

2 Flight Segment

2.1 Laser Ranging Telescope

Laser signals from the ground station are intercepted by the LRT (Ramos-Izquierdo et al. 2008), shown in Fig. 4, which is mounted on and co-bore-sighted with the HGA. Figure 5 shows a schematic model of the spacecraft and points out the location of the LRT, which views the Earth through a 3.81-cm diameter, off-centered hole in the primary reflector of the HGA. This location was chosen for the telescope because the HGA will be constantly pointed toward Earth as LRO orbits the Moon and no additional pointing mechanism(s) or commanding (e.g. spacecraft slewing) are necessary to accommodate the acquisition of LR measurements. The HGA is mounted on two, orthogonal gimbals each capable of rotating 180°, giving the HGA and LRT a hemispherical range of motion. When deployed, the axes

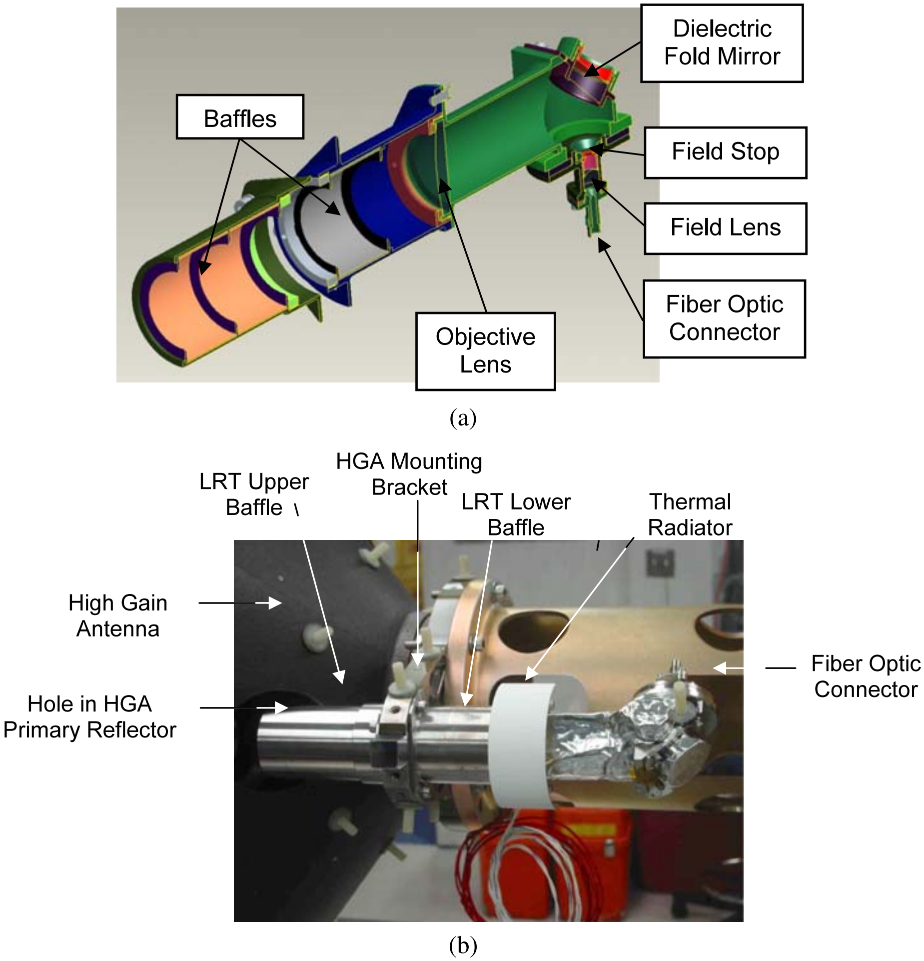


Fig. 4 Laser Ranging Telescope. (**a**) Schematic cutaway. (**b**) Photograph of flight unit. The LRT is attached behind the LRO High Gain Antenna, viewing through a hole in the primary reflector

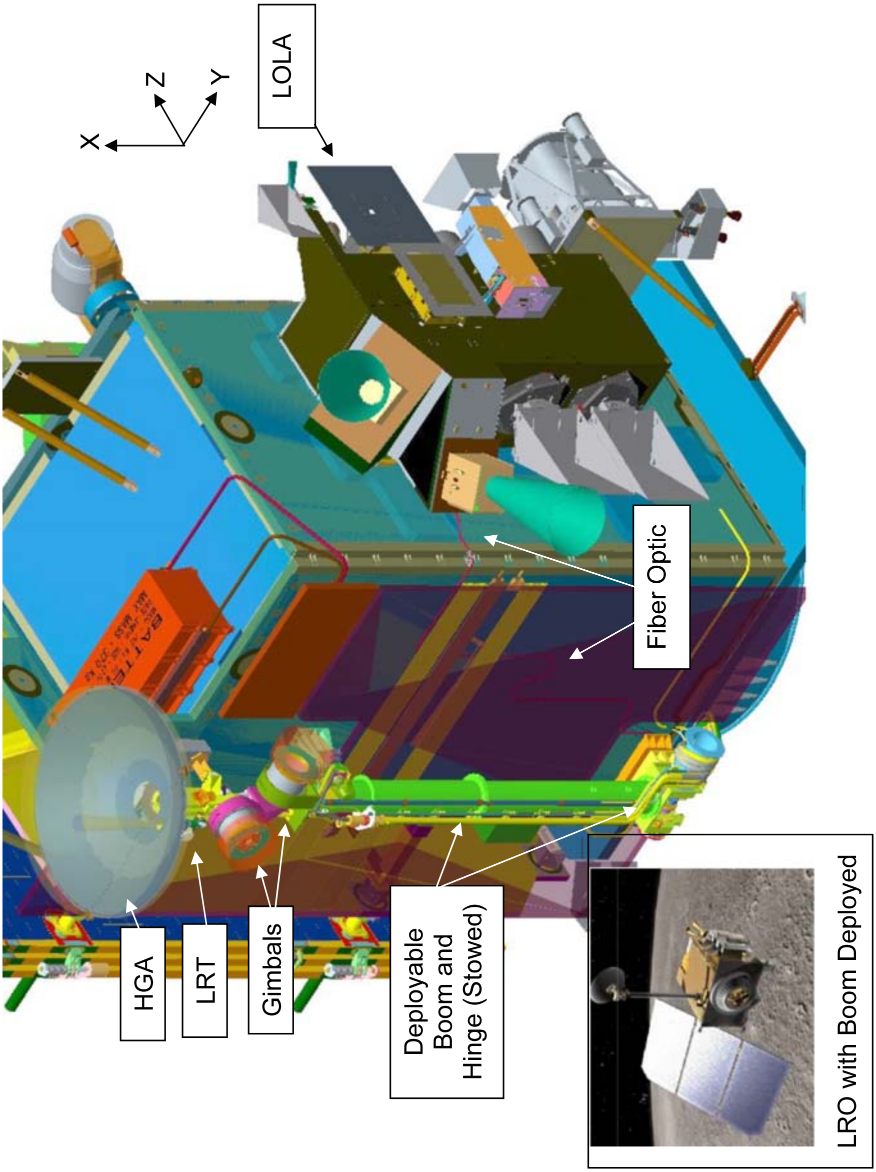


Fig. 5 Schematic showing positions of various components involved in laser ranging on the LRO spacecraft

of the gimbals are oriented parallel to the Y and X spacecraft axes, and are attached to the end of a deployable boom mounted to the $-Z$ side of the LRO spacecraft.

LRO will utilize the HGA Ka-band transceiver to downlink telemetry by pointing the HGA at the White Sands Missile Range, White Sands, NM, whenever it is in view. As observed from LRO, the position of the NGSLR Ground Station at Greenbelt with respect to White Sands will change depending on the orientation of the spacecraft, the position of the HGA gimbals, and the rotation of the Earth. In order to maximize LR ranging opportunities without impacting LRO HGA operations, the LRT field of view (FOV) was designed to cover nearly the entire Earth while centered on White Sands.

The LR telescope is boresighted to the HGA to within 0.01° (cf. Fig. 5). The HGA beam has a divergence of 0.9° and the pointing stability is 0.1° RMS. The telescope has a 30-mrad ($\sim$1.7°) field of view with a 19-mm clear aperture, and consists of a sapphire objective lens, a 45° angle of incidence dielectric fold mirror with maximum reflectivity at 532 nm, a 2.74-mm (30-mrad) diameter field stop, and a molded aspheric field lens. A baffle tube assembly limits the telescope's optical acceptance angle.

2.2 Fiber Optic Bundle

A multiple fiber-optic cable (Ramos-Izquierdo et al. 2008) is used to transmit signals received at the LRT to the LOLA channel 1 detector housing. This cable, shown schematically in Figs. 2 and 5, is referred to as the Fiber Optic Bundle (FOB). The FOB is a parallel set of seven individual 400-µm-diameter, 0.22-NA step index fibers. The FOB has three segments, one attached to the antenna, one to the gimbal assembly and boom, and one to the spacecraft body.

As shown schematically in Fig. 5, the fiber optic route passes through each gimbal, down the spacecraft boom, around the deployment hinge and across the spacecraft deck, requiring the fiber to be approximately 10 m in length. The gimbal assemblies contain special channels for FOB and other electrical cables to control the movement and bend curvature when the HGA is in motion. The FOB also has to survive the one time deployment of the boom.

2.3 LOLA Receiver

LOLA is mounted on the LRO Instrument Module attached to the $+Y$ side of the spacecraft. The LOLA instrument Channel 1 aft optic assembly contains a dichoric beam splitter to combine the LR signal and the LOLA signal onto the detector. The LOLA Channel 1 aft optic assembly re-images the light from the FOB into a 600-µm diameter image at the surface of the detector. The aft optic includes a 532-nm bandpass filter with 0.3-nm FWHM to limit the effects of the background light from the sunlit Earth.

To improve the receiver sensitivity and reduce the false detections, the LOLA receiver utilizes range windows. Only signals within the range windows are detected and processed. There are two separate range windows within the LOLA timing electronics. The first, referred to as the Earth window, is 8 ms wide and opened before each LOLA laser pulse emission. The second, referred to as the lunar window, is less than 5 ms wide, and opened after a small delay from the laser pulse emission. The LOLA laser operates at 28 Hz, and the laser emission times and consequently the range windows are synchronized with the LRO Mission Elapse Time (MET). The ground stations will synchronize the laser emission time with the predicted MET for the optimal LR measurement rate.

The LRO MET is based on a ultrastable, oven-controlled crystal oscillator (OCXO). The OCXO is stable to 1 part in 10^{-12} over an hour to enable the measurement of small spacecraft orbit perturbations from pole to pole. The long-term stability of the OCXO is expected to be better than 1 part in 2×10^{-11} per day, which allows estimation of the spacecraft MET to $\ll$1 ms with respect to coordinated universal time (UTC). Together with the orbit prediction, ground stations will synchronize pulse arrival to well within the LR's Earth window.

The LR time stamp precision from the LOLA instrument is about 0.5 ns in standard deviation and depends on the signal pulse energy and pulse width. The equivalent ranging precision for the one-way laser ranging is about 15 cm.

3 The NGSLR Ground Station

3.1 Introduction/Overview

The primary ground station for LRO laser ranging is NASA's NGSLR station. NGSLR is the prototype for NASA's next generation of eye-safe, automated SLR stations. NASA's current SLR Network provides two-way ranging to Earth-orbiting satellites that are equipped with retro-reflector arrays. The NGSLR has recently been modified for dual use of LRO LR and satellite ranging.

The NGSLR was designed as a prototype to replace the current NASA stations with a more automated, less hazardous, easier to maintain system (McGarry and Zagwodzki 2006). Operational capabilities of NGSLR include the traditional two-way laser ranging to retro-reflector equipped satellites, and also the ability to perform one-way and two-way transponder laser ranging. During the LRO mission the NGSLR will be used to track the spacecraft when possible and it will track Earth satellites at other times. Routine satellite tracking observations not only provide data to the SLR data system but also verify the system's pointing accuracy for LR.

NGSLR points its telescope at LRO using ILRS predictions in Consolidated Prediction Format, referred to as CPFs. These are Earth-centered, Earth-rotating vectors spaced at intervals depending upon the orbit. The software interpolates and translates these vectors to the site location and transforms them to the local azimuth and elevation required to drive the mount. The local mount angles are corrected for refraction and mount pointing errors. Measurements taken at the ground station of barometric pressure, temperature and humidity are used in the calculation of the elevation and range refraction. The mount pointing errors are determined by pointing to stars.

3.2 NGSLR Modifications for LRO LR

In order to support the LR experiment, several modifications to the basic NGSLR design were made. Figure 6 shows a block diagram of NGSLR as configured for LRO operations. Modifications included: (1) the addition of a higher power, 28-Hz laser, (2) installation of an aircraft avoidance radar, with a range of 20 km, in support of the higher power laser, and (3) control of the laser fire time by the software.

The laser is a diode-pumped, frequency-doubled (532 nm) Nd:YAG built by Northrop Grumman Space Technology Cutting Edge Optronics of St. Charles, Missouri. The laser pulse width is 5.5 ns (FWHM) and the energy is nominally 50 mJ per pulse. The laser is mounted on an upper level breadboard above the NGSLR host system and is coupled into the telescope with a removable aperture share mirror. Final laser beam divergence is controlled with an external beam expander mounted on the upper breadboard The removable mirror allows for easy switching back and forth between NGSLR operations and LRO

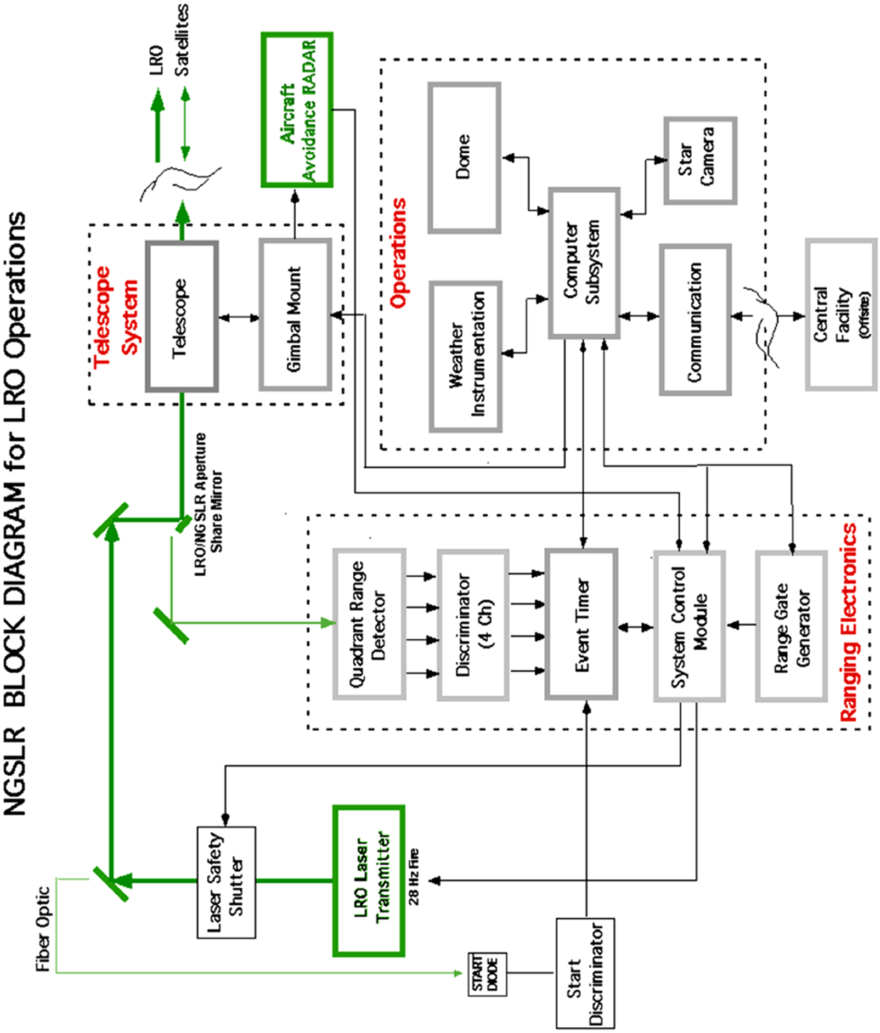


Fig. 6 LRO block diagram utilizing the NGSLR as the host tracking system

tracking and permits SLR tracking utilizing the LRO laser for system check out and verification. In testing, the LOLA LR filter was tilt-tuned to the NGSLR LR laser to optimize its transmission.

The Laser Hazard Reduction System (LHRS) provides a means of detecting aircraft before they intersect the transmitted laser beam out to a range greater than the nominal ocular hazard distance. This function is accomplished by the use of a pedestal-mounted radar that is bore-sighted to the laser-transmitting telescope. Upon detection of an aircraft by the radar, the LHRS provides a signal to activate a laser beam block. The X-band radar is based on a commercial marine radar that is interfaced with several redundant safety systems that constantly monitor system parameters to ensure proper radar operation and pointing along the laser beam axis.

3.3 NGSLR Timing System

The NGSLR station controls the laser pulse fire times to synchronize the pulse arrival with the LOLA Earth window, compensating for spacecraft movement and Earth rotation. Outgoing laser pulses from Earth are time-stamped with <0.1-ns precision for individual laser shots. The ground-based timing system has a drift rate less than 1 part in 10^{-12} per hour and has an absolute time bias of <1 µsec with respect to UTC. The station time is tied to UTC via the TrueTime XL-DC GPS-steered Rubidium oscillator that provides a 1 pulse per second input to the system. A Cesium frequency standard (Symmetricom model 4310), provides the 10-MHz external input to the Event Timer.

3.4 Telescope Pointing

LRO position predictions will be generated by the Goddard Flight Dynamics Facility. These predictions are expected have an accuracy requirement of 4 km. Laser ground stations must be able to open loop point their systems to provide between 1 and 10 fJ cm^{-2} of laser energy density on LRO, while ensuring less than 0.07 mW of peak power on the LOLA detector to avoid damage. NGSLR's peak power will be less than 0.001 mW.

The absolute accuracy of the laser fire measurement must be within 100 ns of UTC with a laser fire inter-arrival time average measurement error of 200 ps or less over a 10-s period. NGSLR's station timing satisfies both of these requirements with the use of the TrueTime Rb Station Timing, the unstirred cesium external source, and the Honeywell Event Timer.

3.5 ILRS Participation

Several ILRS stations (Pearlman et al. 2008) will also be participating in the LR investigation as ground stations. The addition of ILRS stations provides global coverage for LR and increases the laser ranging data set. A few of the participating ILRS stations are also synchronizing their laser fires to the LOLA Earth window in a similar manner to NGSLR, while several others are firing asynchronously at 5 or 10 Hz. At 10 Hz only 2 to 4 pulses per second will fall in the LOLA Earth window. The remaining 6–8 pulses will be treated as noise by LOLA, but these are not enough to cause significant disruptions to the LOLA measurements.

3.6 Feedback to Ground Stations

Since this is an uplink-only ranging measurement, there is no real-time feedback of spacecraft tracking as in normal SLR operations. Instead, LOLA's real-time housekeeping telemetry will be used to provide needed feedback to the stations. LOLA's onboard signal processing indicates whether the Earth pulses are arriving at LRO, and in addition tracks the time at which these pulses occur within the Earth window. The LOLA Earth energy monitor also provides an integrated energy over each Earth window. This information is posted in graphical form to a password protected website that will provide feedback to all participating stations. The delay between spacecraft event and webpage plot should be less than 30 s. NGSLR will be able to bias its fire times from this information to: (1) search for the Earth window if no signal is seen in the LOLA housekeeping telemetry, and/or (2) ensure that its laser pulses are arriving as early as possible in the single-stop Earth window.

3.7 Operations, Data Flow and Scheduling

LRO is visible to Earth for approximately one hour during its two-hour orbit period when the Moon is above the horizon. Laser ranging can only occur at NGSLR above 20° elevation due to regulations by the Federal Aviation Administration and radar viewing limitations. After approximately each pass, the laser emission times and associated information are written to a file that is ultimately transmitted to a computer at the Crustal Dynamics Data Information System (CDDIS) (Noll et al. 2006) at NASA/GSFC, where it is transferred to the LOLA SOC for analysis.

The global network of participating stations will be scheduled from a central facility. Laser stations will be scheduled to range during periods when nearby S-band stations have been scheduled for downlink. This will ensure that the real-time feedback to the stations can occur. Initially only one station will be scheduled to range to LRO at a time, however, as the mission progresses, we anticipate two or possibly three ground stations ranging at overlapping times. In addition to providing redundancy, multiple observations can slightly reduce the error in the observations.

4 Link Margin

The LR receiver uses the same Silicon avalanche photodiode detector as LOLA, but at 532-nm wavelength. Under sunlit Earth background, the detector sensitivity is about

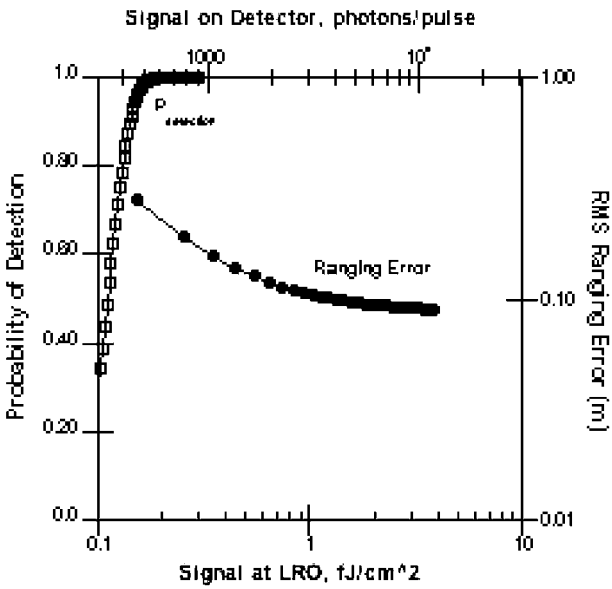


Fig. 7 Link analysis for the LR system. The plot displays the probability of detection and associated range error for signal levels expected during the LRO mapping mission

400 photons pulse^{-1} at 95% detection probability. The optical transmission from the LR telescope to the detector is about 40%, which gives a minimum detectable signal level of about 0.2 fJ cm^{-2} at the entrance of the LR telescope. The ranging error improves with the signal level. Figure 7 shows the receiver probability of detection and the root mean square (RMS) ranging error as a function of input signal level in both cm^{-2} at the entrance of the LRT and photons/pulse on the detector. The desired signal level is 1–5 fJ cm^{-2}, where the ranging error approaches the noise floor of the LOLA receiver timing electronics. The laser pulse width is assumed to be 8 ns at FWHM points. The ranging error generally improves as the laser pulse width gets shorter but is dominated by the receiver electronics to about 20 cm (0.67 ns) from each laser shot. The receiver also measures the pulse energy which can be used to correct any range-walk associated with the pulse amplitude. The mid- to long-term timing accuracy is governed by the OCXO, which is stable to better than 3 ns peak-to-peak over a period of several hours after removing a linear frequency drift rate.

5 Data Processing

LOLA science data and Earth ranges are collected at the SOC following each downlink. Transmit times from each participating Earth station are provided in UTC seconds-of-day, in a common ILRS Consolidated Ranging Data (CRD) format (Ricklefs 2006). The LR range signals are calibrated to pulse centroid time with corrections for fixed system biases in the predicted MET. The LRO timing system (LRO 2006) provides a Spacecraft Time Correction Factor (STCF) that converts the MET counter content to time in UTC. This number of seconds is then used to calculate an approximate UTC arrival time for each range measurement. The difference between the Earth-based laser transmit times and the received time at the spacecraft, times the speed of light, is the nominal one-way range. The STCF, which provides the common time system for LRO instruments, has a 3-ms accuracy requirement, which is sufficient for the initial LR acquisition. Once acquired, the LRO clock frequency and drift rate can be much better predicted from LR data by trending the time bias between the predicted and actual MET.

The production process consists of matching ground fires with Earth ranges using a predicted one-way time-of-flight. Production requires predictions of the spacecraft ephemeris, the exported lunar ephemerides with respect to Earth, and the current station positions and Earth orientation parameters. The light-time-corrected distance between the ground station and LRO, divided by the speed of light, is added to the fire time. LOLA- Earth ranges within an 8-ms window are matched to these predicted times. If the number of matched differences fills a given 200-ns histogram bin to a significant level, the Earth range times in seconds from midnight are merged with the full-rate CRD data.

Normal points consisting of 5-s fits to the valid transmit and receive times in their respective time systems, are provided to the Flight Dynamics Facility and archived with the full-rate data in the ILRS data system.

An example of the value of pulse averaging to produce normal points is given in Fig. 8, which shows observations from the Mercury Laser Altimeter (Cavanaugh et al. 2007). In spite of considerable noise background from sunlit Earth (Fig. 8a, black dots), the signal (red dots) in a 200-ns bin, shown at smaller scale in Fig. 8b, can, after removing three outliers, be fit to a linear function to produce a normal point.

The raw laser ranges consist of pairs of times that will be recorded by separate clocks, and represent only approximate one-way times. The ground station biases and spacecraft clock drift will be solved for in the course of tracking solutions within the GEODYN/Solve orbit

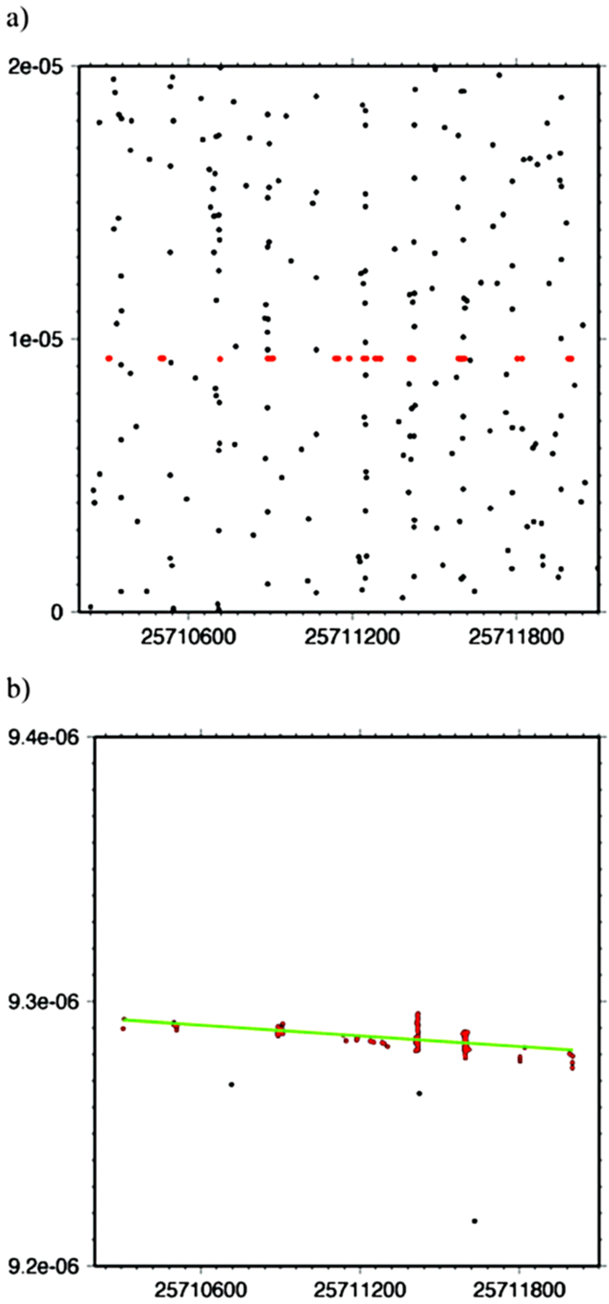


Fig. 8 (**a**) Triggers recorded by the Mercury Laser Altimeter on May 27, 2005 versus time, with laser ranges from Earth in *red*. Ordinates indicate residual times (s) with respect to predicted range. (**b**) Linear fit (in *green*) to residuals (in *red*) in a 200-ns-wide bin, excluding three outliers (in *blue*)

determination software system (Pavlis et al. 2001), applying corrections for time delays due to general relativity. To minimize the range error due to drift inherent in the OCXO, clock drift will be monitored and correlated with variations in temperature and supply voltage from spacecraft housekeeping. These parameters will be monitored from the ground, and their effects will be modeled and calibrated. After the initial calibration period, the long-term frequency drift will also be monitored and modeled. A byproduct of this analysis will be a much more precise clock correction factor for station fire time prediction and altimetry analysis.

The baseline for calibration of the LR measurement is via the process of precision orbit determination. As the LRO spacecraft orbits the Moon the LR measurement will be characterized as a biased range and a range rate coming from the drift of both the spacecraft and ground oscillators. The bias, and perhaps in addition the drift rate of the spacecraft oscillator, should be estimable from the data during orbit analysis.

In a demonstration experiment, a ground-based laser at the Apache Point Observatory in Sunspot, NM plans to range every two weeks to a laser retroreflector array on LRO. The array is comprised of twelve 37.7-mm-diameter solid Surprisil (quartz) cubes, mounted on the $+Y$ panel of the spacecraft. These ranges will be obtained in cooperation with the APOLLO lunar laser ranging experiment (Murphy et al. 2000). Ranging will occur over one or two days during each two-week period, for about 15 minutes per orbit. Although relatively infrequent, and not required for the LR investigation to achieve its objectives, these two-way measurements will provide centimeter-level ranges to the LRO spacecraft that are expected be useful in further calibrating LR ranges. In addition, retroreflector measurements can be used to calibrate the spacecraft oscillator and can conceivably improve the timing for LRO instruments.

6 LRO Orbit Improvement

LR normal points represent a data type in the determination of precision spacecraft orbits using the GEODYN program (Pavlis et al. 2001). The combination of radio tracking combined with orbit crossovers from the LOLA instrument (Smith et al. 2009) and optical tracking from the LR, will be used in a best effort basis to improve the gravity field of the Moon to contribute towards selenocentric location of LOLA altimetric shots and the production of a global geodetic grid. The LR observations are particularly useful in improving orbital knowledge on the Moon's far side that lacks direct tracking. The LR observations limit time drift to <3 ns hour^{-1}, and then provide an additional "anchor point" for timing when the spacecraft re-emerges from the far side.

Orbit determination for the LRO mission (Chin et al. 2007) for the current lunar gravity field (Konopliv et al. 2001) has been studied via simulations (Smith et al. 2008; Rowlands et al. 2008). Table 3 summarizes the various contributions from S-band tracking, LOLA and the LR, to precision orbit determination of LRO on the basis of the analysis by Smith et al. (2008). Unlike the analysis by Smith et al., the analysis by Rowlands et al. (2008) treats the case of multi-beam rather than single beam altimetry, the former of which is better for orbit improvement from crossover analysis than the latter. However, the analysis of Smith et al. incorporates experience from orbit and gravity field improvement in tracking of Mars Global Surveyor and in particular exploits the power of altimetry in orbit improvement. LOLA's five beams and 10-cm ranging precision along with the LR are expected to ultimately result in a radial RMS of order 0.5 m, including orbit and instrument errors, and horizontal errors should approach 10 m. Improvements due to the addition of the LR system are thus significant and will greatly improve knowledge of global and polar topography, footprint-scale surface slopes, and surface roughness. Knowledge of surface slopes improves from about 2° to 0.3°. The LR, however, does not contribute notably to knowledge of surface roughness within the footprint (5-m-scale). Radial and spatial improvements of altimetric footprints map directly into the global geodetic grid.

Table 3 Contributions to LRO orbit improvement and implications for LOLA data products

LOLA data products	S-band tracking alone	S-band + LOLA	S-band + LOLA + LR
Global topography			
Accuracy/ Resolution	R: 10 m; H: ∼300 m	R: 10 m; H: ∼200 m	R: 1 m; H: 50 m
Polar topography			
Accuracy/ Resolution	R: 10 m; H: ∼ 300 m	R: 5 m; H: 200 m	R: 0.1 m; H: 25 m
Surface slopes			
Accuracy	2°	1.5°	0.3°
Resolution	300 m	200 m	25 m
Surface roughness			
Accuracy	35 cm	35 cm	35 cm
Resolution	∼5 m	∼5 m	∼5 m

7 LR Archive

The deliverable product to the NASA Planetary Data System (PDS) are precision orbits. There is no explicit requirement to deliver the various radio tracking data sets, though the matter is currently under discussion.

While the LR uses LOLA as its data interface and the LOLA SOC as its pipeline, LR data are not part of the LOLA archive. The LR full-rate and normal point data will be processed and delivered into the ILRS, using CDDIS/ILRS services as its hosts. Any improved lunar gravity fields that result as a byproduct from the optical tracking of LRO will be archived on a best efforts basis with other planetary gravity fields in the Geoscience Node of the PDS.

8 Summary

Key objectives in the LRO mission include determination of a precise global topography model and a precise geodetic grid that will serve as a reference for LOLA, other LRO data sets, and, we anticipate, many other lunar data sets. Orbit determination is the limiting error source in the LOLA instrument's ability to measure lunar topography, as well as in the determination of the geodetic grid. The Laser Ranging system was added to the LRO spacecraft to enable the mission's precision orbit requirement to be achieved. The LR will allow LRO orbits to be determined at the meter scale radially and 50 m spatially, and these accuracies will approximately define the accuracy of LOLA and the resulting geodetic grid. LRO's LR experiment represents the first time that optical ranging will be used to track a planetary spacecraft, either experimentally or in an operational sense, and will demonstrate technology and analysis methods that will enable more sophisticated applications in future exploration of the planets.

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Appendix: Acronym List

Acronym	Definition
CDDIS	Crustal Dynamics Data and Information System
CPF	Consolidated Prediction Format
CRD	Consolidate laser Ranging Data
fJ	femtoJoule = 10^{-15} Joule
FOB	Fiber Optic Bundle
FOV	Field of View
FWHM	Full Width at Half the Maximum amplitude
GEODYN	GSFC processing code for orbit determination
GHz	Gigahertz
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HGA	High-Gain Antenna
ILRS	International Laser Ranging Service
LHRS	Laser Hazard Reduction System
LOLA	Lunar Orbiter Laser Altimeter
LR	Laser Ranger
LRO	Lunar Reconnaissance Orbiter
LROC	Lunar Reconnaissance Orbiter Camera
LRT	Laser Ranging Telescope
MET	Mission Elapsed Time
NASA	National Aeronautics and Space Administration
Nd:YAG	Neodymium-doped, Yttrium, Aluminum, Garnet
NGSLR	Next Generation Satellite Laser Ranging
nm	nanometer = 10^{-9} m
ns	nanosecond = 10^{-9} s
OCXO	Oven-Controlled Crystal Oscillator
POD	Precision Orbit Determination
ps	picosecond = 10^{-12} s
RF	Radio Frequency
RGG	Range Gate Generator
SCLK	Spacecraft CLocK
SLR	Satellite Laser Ranging
SOC	Science Operations Center
STCF	Spacecraft Time Correction Factor
TOF	Time of Flight
USN	Universal Space Network
USO	UltraStable Oscillator
UTC	Coordinated Universal Time
VCL	Vegetation Canopy Lidar

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