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LRO-LR: Four Years of History-Making Laser Ranging

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Abstract

The Lunar Reconnaissance Orbiter (LRO) launched in June 2009. The first laser ranging attempted from NASA's Next Generation Satellite Laser Ranging (NGSLR) system was on June 30th, and it was also the first successful ranging to the LRO spacecraft. Since that time ten ILRS systems around the world have participated in ranging to LRO and we have accumulated over 3000 hours of laser ranging data. These data have been used to very accurately determine the clock rate and drift and to produce precision orbits. By using the high-resolution GRAIL gravity models, the LRO orbits determined from LR data alone have a total position error of 10 meters in average, and show the same quality as those generated using conventional radiometric tracking data.

Many LR passes have been taken simultaneously between two, three and four stations and often global tracking achieves close to 24 hour coverage. This has opened up new opportunities for other laser timing and communication technology demonstrations. In 2013 we demonstrated the first uplink lasercom from NGSLR to LRO. We are currently conducting laser time transfer tests between SLR stations using LRO as a common receiver in space.

Overview/Background

The Lunar Reconnaissance Orbiter (LRO) was launched in June 2009. Onboard are seven instruments designed to make cutting-edge measurements of the Moon for science and to determine the best landing site for human exploration. One of the onboard instruments is the Lunar Observer Laser Altimeter (LOLA) built at the Goddard Space Flight Center (Smith et al. 2010). LOLA fires at 28 Hz and uses a diffractive optical element to split the laser beam into five spots. These spots form a cross pattern on the lunar surface. Five detectors each collect return light from their respective spot. The center detector is used for both Lunar and Earth ranging.

Using the LOLA instrument's measurement capability, an uplink-only laser ranging (LR) experiment was designed and implemented (Zuber et al. 2008). LRO's high-gain antenna is used to point the LR telescope to the Earth, and fiber optic cables carry the light to the LOLA receiver electronics. Laser ranging ground stations record their fire times and LOLA measures the receive times and sends this information down in science packets over an S-band communication link. The LOLA Science Team then matches the receive times with the fires to form one-way ranges (Mao et al. 2011).

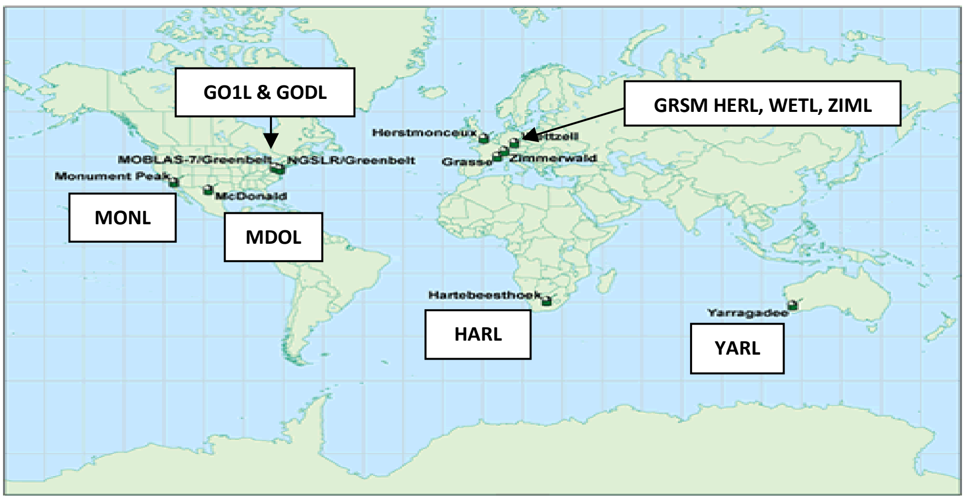
Ground station feedback is provided from LOLA signal processing of the LR pulses. The LR pulses are captured in an 8-millisecond-wide Earth range window that is separate from the LOLA lunar ranging. The signal processing information is sent to the ground in the housekeeping packets which are displayed in a graphical format via a website that is generated by the LOLA Science Operations Center (SOC) and hosted on the Crustal Dynamics Data Information Center (CDDIS) computers (Noll 2010). While this website is delayed by about 10 – 20 seconds from real-time, it nevertheless provides invaluable feedback to the ground stations to optimize their pointing and tracking to LRO. Without the signal processing information from LOLA, the ground stations would be pointing blindly.

A sub-network of the International Laser Ranging Service (ILRS) (Pearlman et al. 2002), which is shown in Figure 1, provides global coverage of laser ranging to LRO. Some of the stations use knowledge of the spacecraft Mission Elapsed Time (MET) with respect to UTC to time their fires so that their laser pulses arrive at LRO when the LOLA Earth window is open. This is synchronous ranging. Other stations fire their lasers asynchronously to LOLA, at their normal 10-Hz frequency. Asynchronous ranging at 10 Hz puts at most four fires per second into the LOLA Earth Window. Table 1 below gives the characteristics of each LRO-LR ground station.

Table 1. LRO-LR ground station characteristics

Station	Location	Synchronous?	First successful LRO ranging
NGSLR (GO1L)	Greenbelt, Maryland, US	Yes – 28 Hz	30-Jun-2009
MLRS (MDOL)	McDonald Obs., Texas, US	No – 10 Hz	02-Jul-2009
MOBLAS-7 (GODL)	Greenbelt, Maryland, US	No – 10 Hz	02-Jul-2009
Herstmonceux (HERL)	Great Britain	Yes – 14 Hz	13-Jul2009
Zimmerwald (ZIML)	Switzerland	Yes – 14 Hz	20-Jul2009
Wettzell (WETL)	Germany	Yes – 7 Hz	30-Oct-2009
MOBLAS-6 (HARL)	Hartebeesthoek, South Africa	No – 10 Hz	05-Dec-2009
MOBLAS-5 (YARL)	Yarragadee, Australia	No – 10 Hz	25-Jan-2010
MOBLAS-4 (MONL)	Monument Peak, California, US	No – 10 Hz	03-Feb-2010
Grasse/MEO (GRSM)	France	No – 10 Hz	18-May-2010

Figure 1. LRO-LR ground stations



Laser Ranging Results

The first attempt at laser ranging to LRO was from NASA's Next Generation Satellite Laser Ranging Station (NGSLR) on 30 June 2009, less than two weeks after launch. This first attempt was successful and set the stage for the next four years of laser ranging to LRO. Early into the mission it was determined that the Science Team could separate laser ranging pulses coming from two or more stations at the same time. The LOLA onboard signal processing was designed to be able to handle multiple stations ranging simultaneously, and it was found that the ground stations could distinguish their returns on the real-time website from other stations ranging at the same time. Simultaneous ranging provides the Science Team with the additional information needed to more easily determine biases. It also provides the ability to perform geometric solutions of LRO position, and to enable calculation of time transfer. The LRO-LR firsts are given in Table 2 below.

Table 2. LR Network First Successes

	Date	**Station(s)**
Ranging to LRO	30-Jun-2009	GO1L
2-way simultaneous	28-Jul 2009	GO1L, GODL
3-way simultaneous	01-Nov-2010	GO1L, MDOL, MONL
4- way simultaneous	11-Mar-2011	GO1L, GODL, MDOL, MONL
Lasercom over LR	10-May-2011	GO1L

Summaries of LRO ranging statistics are compiled weekly. From June 2009 through September 2013 there were 3489 hours of successful laser ranging data recorded at LOLA. The LR data as seen in the LOLA Earth window are shown in Figure 2 below. The number of minutes and the percentage of total data for each station are given in Table 3. Simultaneous ranging statistics for this same 4+ year period are given in Tables 4 and 5. This global network of stations has demonstrated that it can provide close to 24 hour coverage for LRO-LR. In each year from 2011 through 2013 there were over 100 days with ranging at or over 16 hours per day.

Table 3. Total minutes of data in row 2 with percentage of total LR data for each station for the period June 2009 through September 2013

GO1L	**GODL**	**MDOL**	**HERL**	**ZIML**	**WETL**	**HARL**	**YARL**	**MONL**	**GRSM**
68605	18771	21926	2290	2249	216	1849	30513	57646	2820
33%	9%	11%	1%	1%	< 1%	1%	15%	28%	1%

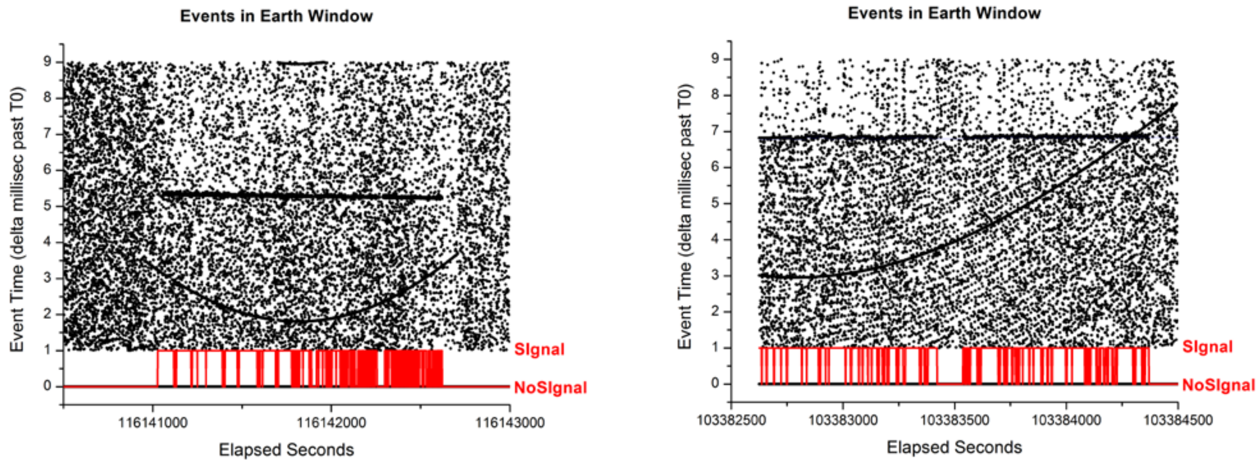
Table 4. Number of 2-way simultaneous ranging passes between June 2009 and September 2013

Stations	**# 2-way passes**		**Stations**	**#2-way passes**
GO1L, GODL	48		HARL, HERL	1
GO1L, MDOL	111		HARL, ZIML	4
GO1L, MONL	241		GRSM, ZIML	26
GODL, MDOL	58		GRSM, HERL	1
GODL, MONL	92		ZIML, HERL	1
MDOL, MONL	105		HERL, WETL	2

Table 5. Number of 3-way and 4-way simultaneous ranging passes between June 2009 and September 2013

Stations	# 3-way passes		Stations	#4-way passes
GO1L, GODL, MDOL	48		GO1L, GODL, MDOL, MONL	6
GO1L, GODL, MONL	111			
GO1L, MDOL, MONL	241			
GODL, MDOL, MONL	58			

Figure 2. The left hand plot shows simultaneous ranging to LRO between HERL and GRSM as seen in the LOLA Earth Window on 16 Oct 2013 21:20 UTC. Black dots represent LOLA received events. Most are background noise. Receive events from HERL show up as a straight line in this plot and those from GRSM appear as a curved line. The right hand plot shows simultaneous ranging to LRO between GO1L, MONL and MDOL on 22 May 2013 05:20 UTC. Received events from GO1L show up as a straight line, those from MONL as a single curved line, and those from MDOL as multiple lighter curves (MDOL's laser fire rate is not exactly 10 Hz). The curved lines from the asynchronous stations are due to fire times not compensating for changes in spacecraft range over the half orbit that LRO is visible.



Data processing

To pair up the LOLA received LR times to corresponding ground SLR station transmit times, a time of flight is calculated for each out-going laser pulse by using the ground station location and a definitive LRO ephemeris provided by GSFC's Flight Dynamics Facility (FDF). After removing this calculated light time and a polynomial function modeling the LRO orbit from the difference of LOLA receive time and the ground laser fire time, the residuals of a successfully matched LR pass usually yield a RMS value ranging from 10 to 50 cm, depend on the laser properties of the ground station. To further reduce the residual RMS and data quantity, normal points were formed every 5 seconds from the full rate data based on the ILRS normal point algorithm. The RMS value of the light time residual normal points is nominally 1 to 5 cm. A plot of NGSLR full rate and normal point light time residuals from a matched 60-minute long pass is shown here as an example. Similar plots for all other stations can be found in poster 13-Po26 (Mao et al. 2013).

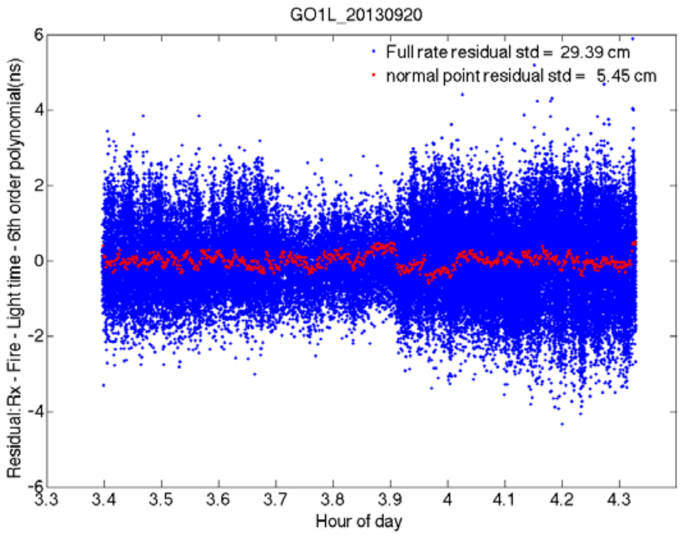


Figure 3. Newtonian light time residuals of full rate and normal point data from a 60-min-long NGSLR pass taken on 09/20/2013.

LRO clock long-term characteristics monitored by LR

LRO clock is a Project-supplied ultra stable oscillator (USO), which provides the LR receive times. The LR data have been used to monitor the long-term characteristics behavior since launch. Pre-launch ground test suggested the clock had a frequency of approximately 1.00000007659 seconds per 1-s clock tick. The results from LR showed that the clock has been slowing down gradually and steadily. Presently, long term frequency stability is about ±1.95e-12 seconds per day before removing the temperature effect, and the frequency is about 1.00000006754 seconds per 1-s clock tick. After removing a constant time offset, a linear time drift, a quadratic frequency aging, a cubic frequency aging rate, and a calculated light time, the residuals are less than 0.1 ms for the entire mission (shown in Figure 4), which is ~30 times better than the 3-ms mission requirement.

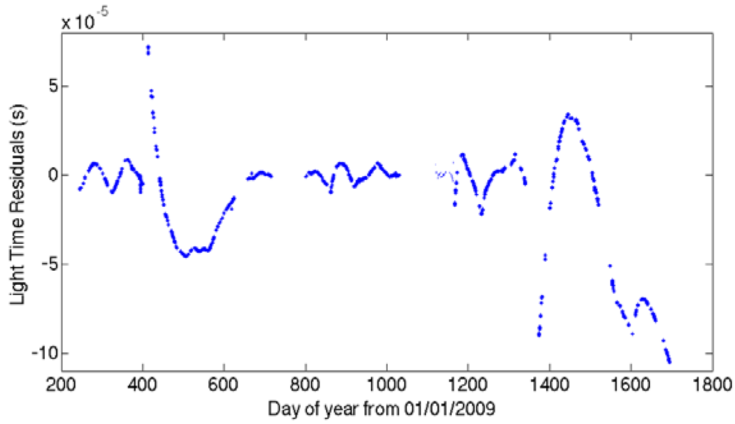


Figure 4. Newtonian light time residuals of LRO USO long-term behavior from September, 2009 to August, 2013.

LRO precise orbit determination with LR

LR data have been used independently and with S-band radio tracking data in the LRO POD process to provide orbit solution using NASA/GSFC GEODYN orbit analysis software (Pavlis

2001). These orbits are then used to locate LOLA altimetry returns, which are compared to the "truth", chosen to be a most recent LOLA grid, in order to determine the quality of these orbital solutions. Table 6 shows the comparison results for two continuous two-week arcs in June, 2010 with a time span of 28 days. The use of the high resolution GRAIL gravity field model GL0420 (Zuber et al. 2013) yielded much smaller RMS of altimetry difference in all directions than the gravity field model LLGM-1 constructed from LRO data. With GL0420 gravity model, the RMS values of the altimetry difference between results from LR-only orbits and the LOLA grid are similar to those from orbits generated by S-band data only. This suggests that LR data can independently generate orbital solutions with comparable quality with respect to those from S-band data with a high resolution gravity field model, such as GRAIL models.

Table 6. Orbital results in comparison with the most recent LOLA grid

	rms horizontal (m)	**rms radial (m)**	**rms total (m)**
LR only - grid GL0420	18.17	2.57	18.35
S-band only - grid GL0420	17.43	0.85	17.45
LR + S-band - grid GL0420	17.45	0.85	17.44
LR + S-band - grid LLGM-1	27.37	2.31	27.47

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