Summary of Ground Station Performance in 5 years of Laser Ranging Operation to Lunar Reconnaissance Orbiter

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LRO-LR overview

The Laser ranging (LR) [1] experiment has been set up to make highly precise one-way, time-of-flight measurements by laser pulses to determine the distance between ground based satellite laser ranging (SLR) stations and the Lunar Reconnaissance Orbiter (LRO) circling the Moon to provide high precision orbit solutions of the spacecraft. Green laser pulses of 532 nm wavelength and transmit frequency no higher than 28 Hz are fired and time-stamped at the ground station, and transmitted to LRO. These pulses are received by a 1" telescope mounted on the spacecraft S-band high gain antenna mounted on the spacecraft, then passed on via a fiber optic bundle to the central detector of the Lunar Orbiter Laser Altimeter (LOLA) [2], one of the seven instruments onboard LRO. The pulse arrivals are precisely time-tagged by the LOLA timing electronics, and constitute a novel one-way measurement of the range between the ground station and the LRO spacecraft, at optical wavelength.

LOLA's central detector has a 28Hz dual receive window for the lunar and Earth laser pulses, respectively. LR signals can be either synchronous or a-synchronous with this dual receive window, but only the laser pulses that fall inside of the 8 milli-seconds Earth range gate are considered valid.

Since the beginning of the LRO mission in June 2009, ten SLR stations from the International Laser Ranging Service (ILRS) [3] have participated in the LRO-LR operation. NASA's Next Generation Satellite Laser Ranging (NGSLR) station at Greenbelt, Maryland, serving as the primary LRO-LR station, and 5 other stations with MOBLAS systems are supported by NASA. Eight of the participating stations are located in the northern hemisphere, four in United States and four in Europe, while only two out of these ten stations are in the southern hemisphere, one in Australia and one in South Africa. Of these ten SLR stations, 4 stations use lasers that are synchronous with the 28 Hz LOLA receive window. NGSLR, also known as GO1L, uses a 28 Hz laser, and can thus have a maximum of 28 signals per second received at LRO. The Zimmerwald (ZIML) station in Switzerland and Herstmonceux (HERL) station in Great Britain both use 14 Hz lasers, so only 14 signals can be received at LRO per second at maximum. The Wettzell (WETL) station in Germany adapts its laser firing frequency to 7 Hz when ranging to LRO, in order to be synchronous as well and maximize the number of returns (7 per second). Indeed, the other six stations all use 10 Hz lasers and are asynchronous, which results in a typical 2 to 4 returns per second at LRO.

Table 1. Total minutes of LR data (row 2), and percentage of the total LR dataset (row 3) for

each station over the June 2009 - September 2014 period. A total of 4173.6 hours successful LR data were obtained.

GO1L	**GODL**	**MDOL**	**HERL**	**ZIML**	**WETL**	**HARL**	**YARL**	**MONL**	**GRSM**
81049	19587	26935	3618	3647	290	1878	35299	70793	4694
33%	8%	11%	1%	1%	< 1%	1%	14%	29%	2%

Table 2. Number of 2-way simultaneous ranging passes/segments between June 2009 and September 2014.

Stations	**# 2-way passes**		**Stations**	**#2-way passes**
GO1L, GODL	61		HARL, HERL	1
GO1L, MDOL	139		HARL, ZIML	4
GO1L, MONL	318		GRSM, ZIML	49
GODL, MDOL	58		GRSM, HERL	16
GODL, MONL	93		ZIML, HERL	5
MDOL, MONL	151		HERL, WETL	3
ZIML, GO1L	1		ZIML, WETL	1

Table 3. Number of 3-way and 4-way simultaneous ranging passes/segments between June 2009 and September 2014.

Stations	**# 3-way passes**		**Stations**	**#4-way passes**
GO1L, GODL, MDOL	48		GO1L, GODL, MDOL, MONL	6
GO1L, GODL, MONL	116			
GO1L, MDOL, MONL	257			
GODL, MDOL, MONL	58			
GRSM, HERL, ZIML	2			

LRO-LR operated from the end of June 2009, to the end of September 2014. In the 5+ years of operation, over 4000 hours of successful ranging data to LRO have been obtained, and simultaneous tracking data from 2, 3, or 4 participating stations have been collected routinely. A summary of the contributions from each participating station is shown in table 1, while the number of simultaneous passes/segments from multiple SLR stations are listed in table 2 . Given the line-of-sight nature of LR, and the ~2 hour LRO orbit period, a nominal full-length LR pass from the ground station is typically 50-60 minutes long. However, many simultaneous passes are not full length, as station overlap only exists over shorter segments. Almost all simultaneous passes obtained are from stations in the same continent, either all in the United States, or all in Europe. Cross-continental simultaneous passes were much more difficult to achieve due to various factors. For instance, the different LRO visibility time window for SLR stations from different continents. The only trans-continental simultaneous tracking was obtained between

NGSLR in the United States and Zimmerwald in Switzerland, on September 15, 2014. The duration of this simultaneous tracking pass is only about 2 minutes.

LRO oscillator long-term stability

The LR measurement quality depends on the stability of the clocks both at the ground station and onboard the LRO spacecraft. All stations participating in the LRO-LR operation are equipped with oscillators to maintain a stable time base, such as rubidium (Rb), cesium (Cs) or hydrogen-maser clocks (in increasing order of stability). Since 2013, NGSLR has improved its time base to nanosecond precision and accuracy by employing the hydrogen maser clock of the nearby Very Long Baseline Interferometry (VLBI) site, via optical fibers [4]. Both the epoch time and the frequency of the hydrogen- maser are monitored and referenced to the United States Naval Observatory (USNO) master clock (only ~23 km away) via an All-View GPS receiver. LR data from NGSLR have been used to monitor the mid- to long-term characteristics of the LRO ultra-stable oscillator (USO). This oscillator is used as the clock source for LOLA to time-tag both the LOLA lunar laser pulses and the LR Earth laser pulses. As shown in Figure 1, the absolute value of the USO frequency drift has been decreasing gradually, and its aging rate has steadily decreased as well over the mission, as suggested by pre-launch testing. The oscillator long-term frequency stability shown in Figure 1 is about +/- 2×10^{-12}s per day before applying corrections for temperature-induced frequency variations.

The discontinuities in Figure 1 are caused by the lack of LR data due to either the repairs or upgrades of the NGSLR system (laser and clock; e.g., between days 1000 to 1200), or due to LRO sun-safe events (e.g., around day 400). The LRO anomalies also show obvious impacts on the oscillator frequency aging, because the temporary loss of power affected the temperature of the oven, normally used to keep a stable USO crystal frequency.

After accounting for the oscillator frequency zero-point offset, the frequency, the frequency aging and the frequency aging rate, which are all derived from LR data, as well as applying a light time correction, the range in residual timing error over 5 years is less than 30 micro-seconds for the entire mission (Figure 2). This is significantly better than the 3-ms mission requirement for time reconstruction.

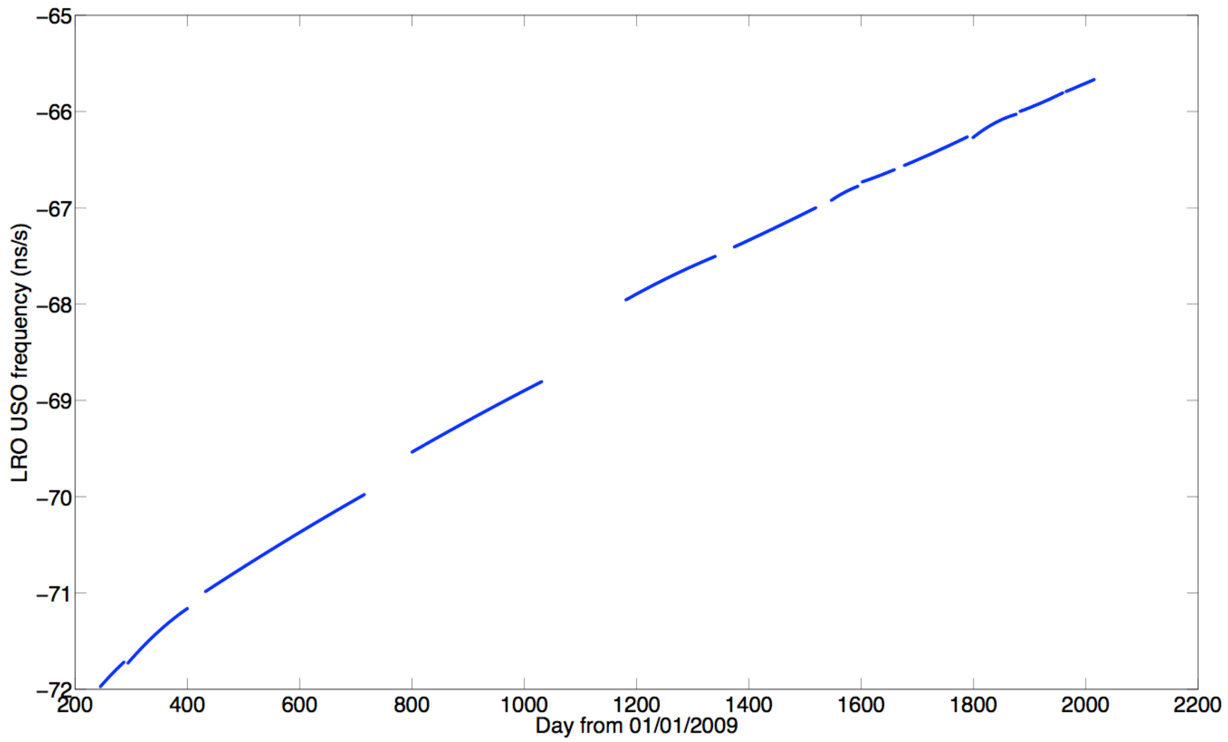

Figure 1. LRO USO frequency drift estimated from NGSLR LR data between September 2009 and September 2014, before applying temperature corrections.

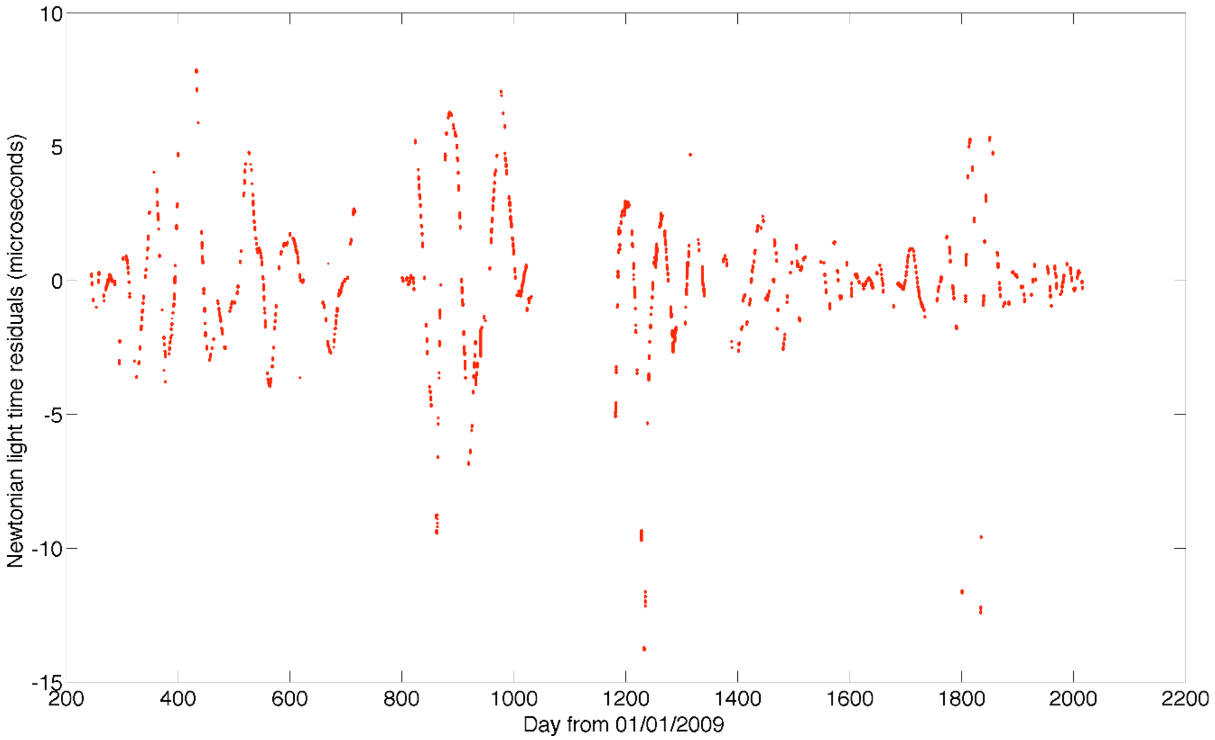

Figure 2. LRO USO light time residuals derived from NGSLR LR data between September 2009 and September 2014.

Ground station clock long-term behavior

Although all stations participating in the LRO-LR operation have been working to maintain a stable time base, different references can result in different timing biases. Using the LRO USO as a common clock, Figure 3 shows the long-term behavior of each ground station clock with respect to NGSLR over the 5 years of LRO-LR operation. The ground clock behavior is re-evaluated every 3 or 4 months due to interruptions by ground clock or spacecraft USO anomalies. Time at NGSLR has been monitored to sub-nanosecond with an absolute accuracy of about 1 nano-second and a stability mainly governed by the station clock, which is $4x10^{-15}$ second for the hydrogen maser from January, 2013 on, and 10^{-13} second for the cesium clock source beforehand. As shown in Figure 3, the clock frequency drift differences from the 7 ground stations all agree well over most of 5-year LR experiment (especially since year 2013, i.e., day 1100 on Figure 3) to less than $5x10^{-12}$ s/s. The frequency drift differences in some time periods have obvious parabola trends. This may be caused by the lack of LR data from that station in the given time period, or data not distributed well over the entire time interval, which usually yield poorly constrained clock fitting functions. For that reason, the behavior of clocks from Herstmonceux (Great Britain), Hartebeesthoek (South Africa), and Wettzell (Germany) are not included in the comparison due to the lack of data or data distribution. Some of the drift differences are larger than 0.02 ns/s, which may suggest anomalies of the station ground clock with respect to NGSLR (e.g., before day 400).

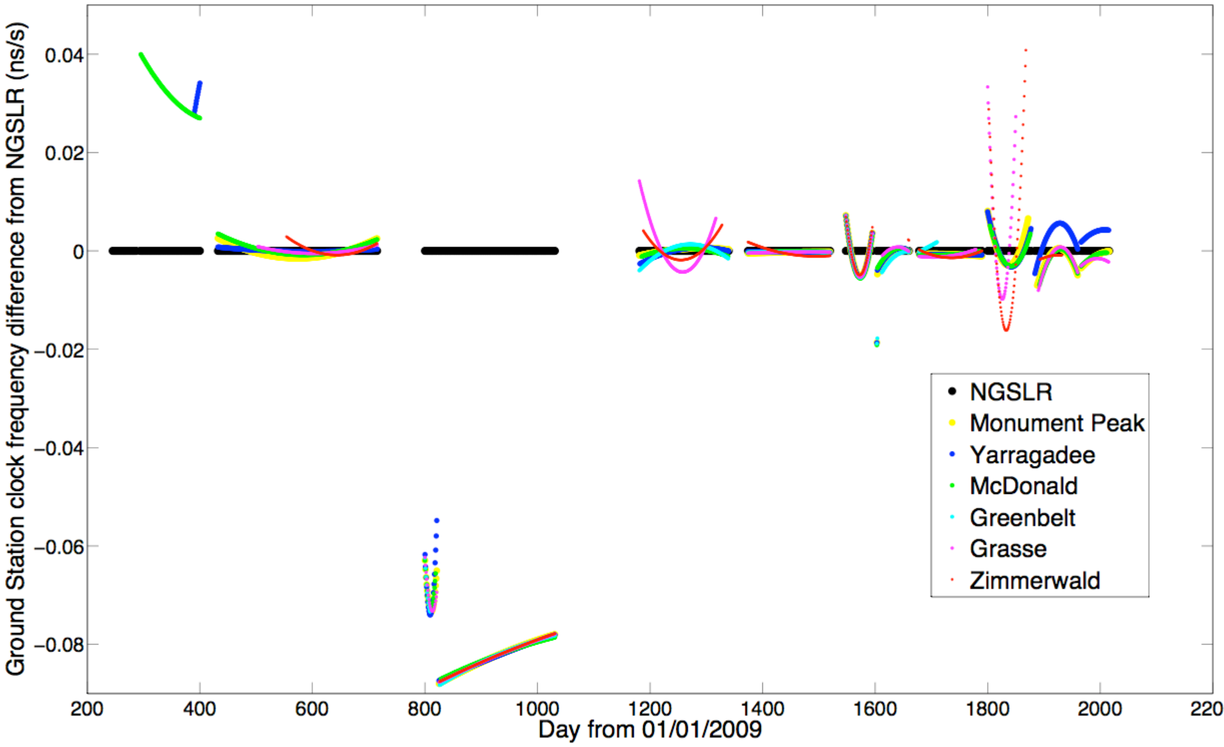

Figure 3. Ground station clock frequency difference with respect to NGSLR clock from September, 2009 to September, 2014.

Summary

During the 5 years of LRO-LR operation, ten SLR stations from the ILRS have obtained over 4000 hours of successful LR data, including regular simultaneous ranging data from 2 or more stations. All participating stations are using various types of time sources to maintain a stable and accurate timing, which is essential to achieve high-precision one-way range measurement to LRO. The LR data, especially those from NGSLR, have been used to monitor the long-term behavior of the LRO USO, and have resulted in less than 30 micro-second accuracy over the entire LR operation. Using the LRO USO as a common clock, the behavior of the ground station clocks can be compared with one another, and the results showed good agreements among the clocks. The complete LRO-LR dataset is archived at the NASA Planetary Data System[5].

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