13-Po26

LRO Orbit Determination with Laser Ranging Data

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Abstract.

The Laser ranging (LR) experiment on the Lunar Reconnaissance Orbiter (LRO) has been in operation for more than 4 years, since shortly after the arrival of the spacecraft in lunar orbit in June 2009. Led by NASA's Next Generation Satellite Laser Ranging (NGSLR) station at Greenbelt, Maryland, ten laser ranging stations over the world have been participating in the experiment and have collected over 3,400 hours of one-way laser ranging data. These range measurements are used to generate precise orbital solutions for LRO and monitor the behavior of the LRO clock. To achieve high-quality range measurements, the NGSLR and four other ground stations are using Hydrogen-maser clocks as a stable and continuous time reference for the orbit solutions. In January 2013, an All-View GPS receiver was installed at NGSLR, to monitor the H-maser time against the master clock at the United States Naval Observatory (USNO) via GPS satellites. With these improvements, NGSLR established nano-second level epoch time accuracy and 10^{-15} *clock stability.*

By using the LR tracking data alone, together with a high-resolution gravity model from the GRAIL Discovery mission, the LRO orbit solutions have an average total position error of 10 meters, and show the same quality as those generated using conventional radiometric tracking data. With this approach, 2-week long arcs were used with range biases adjusted once per arc. A timing bias was also adjusted to compensate both the ground and spacecraft clock characteristics for each arc. We present the results from both orbit prediction and orbit reconstruction, and an assessment of the quality of the orbital solutions by comparing the results with those from S-band radiometric tracking data.

Introduction

Designed to help meet the position knowledge requirement of the Lunar Reconnaissance Orbiter (LRO), the laser ranging (LR) experiment (Zuber 2010) has been in operation for over 4 years since the launch of the LRO in June 2009. The LR experiment is a system to obtain highly precise one-way, time-of-flight measurements by laser pulses to determine the distance between the transmitting Earth-based satellite laser ranging (SLR) station and the spacecraft orbiting the Moon.

The laser pulses sent from the SLR station are received by the laser ranging telescope (LRT) attached to the LRO high gain antenna (HGA) when the HGA is pointed to the Earth and LRO is in the view of the station. A fiber optic bundle transmits the received pulses from the LRT to one of the five detectors of the Lunar Orbiter Laser Altimeter (LOLA) (Smith 2010). LOLA’s center detector is designed to receive both Earth pulses, captured in an 8ms-long Earth range window, and lunar surface returns within a subsequent receive window during which the 28-Hz laser altimeter operates. The LR pulses are time stamped by the LOLA timing electronics upon arrival.

The laser fire time from the Earth is recorded at the SLR station with event timers connected to stable clocks. Since the beginning of LRO mission, ten SLR stations from the International Laser Ranging Service (ILRS) (Pearlman 2008) have participated in the LR experiment, with NASA's the Next Generation Satellite Laser Ranging (NGSLR) station at Greenbelt, Maryland, serving as the primary LRO LR station. All stations are equipped with oscillators to maintain a stable time base, such as Rubidium (Rb), Cesium (Cs) or Hydrogren-maser clocks (the most stable). NGSLR has recently improved its time base to nanosecond precision and accuracy by employing the hydrogen maser clock of the nearby VLBI site, via optical fibers. Details of this improvement can be found in poster 13-Po54 (Sun 2013). Over 3,400 hours of LRO LR tracking data have been collected in the past 4 years. More information about ground station LR systems and the LR related ground station activities can be found in paper 13-0405 (McGarry 2013).

The laser transmit and receive data from all the SLR stations and LRO are transferred to the LOLA Science Operations Center for processing. The LOLA receive times are paired with corresponding transmit times recorded at ground stations to determine the distances between LRO and SLR stations.

Data processing

To pair up each LOLA-received LR time to the corresponding ground SLR station transmit time, a time of flight is calculated for each out-going laser pulse by using the ground station location, the Earth orientation, and a LRO ephemeris provided by the LRO navigation team at NASA GSFC's Flight Dynamics Facility (FDF).

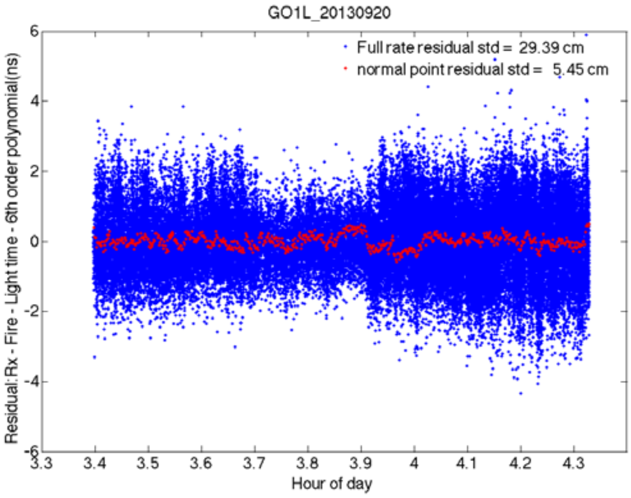

Figure 1. Newtonian light time residuals of full rate (blue) and normal point (red) data from a 60-minute-long NGSLR pass taken on 09/20/2013.

After accounting for the calculated light time, a low-degree polynomial is used to model the difference of LOLA receive time and the ground laser fire time arising mainly from orbit error. The residuals of a successfully-matched LR pass usually have 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, 5-second normal points were formed from the full-rate data according to the ILRS normal point algorithm. The RMS value of the normal point residuals is nominally 1 to 5 cm. Figure 1 shows an example of NGSLR full-rate and normal point residuals from a 60-minute pass. The LR full-rate and normal point data products are delivered regularly to NASA's Planetary Data System Radio Science archive (http://pds-geosciences.wustl.edu/missions/lro/rss.htm) for public access.

LRO clock long-term characteristics monitored by LR

The stability of the clocks both on the spacecraft and on the ground is important for the quality of the one-way time-of-flight measurement. The ground clocks at each participating SLR station were carefully calibrated and monitored. The LRO clock behavior, especially the long-term behavior, can also be characterized by using LR data from a closely-monitored ground station clock as a reference, such as the clock at NGSLR where most of the LR data are collected.

The LOLA time stamps of the received LR pulses are derived from the ultra stable oscillator (USO) of the LRO spacecraft. The LR data from NGSLR have been used to monitor its long-term behavior since launch. After removing a light time correction calculated from the ground station location and FDF reconstructed ephemeris (as described above), we perform a cubic polynomial fit. This degree-3 polynomial describes the constant time offset between LOLA USO and the NGSLR clock and the USO frequency, the rate of frequency change, and its derivative at the reference epoch.

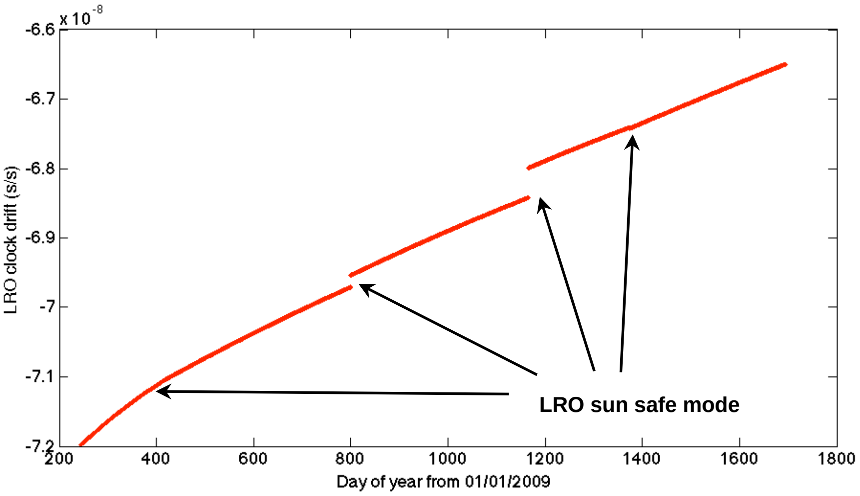

Figure 2. LRO USO long-term frequency behavior from September, 2009 to August, 2013.

Pre-launch ground testing determined a frequency offset of approximately 76.59 parts per billion. Our results from NGSLR's LR data showed that the clock has been speeding up gradually and steadily (Figure 2). Long-term frequency stability is about +/-0.68e-12 seconds per day (with no temperature correction), and the inverse frequency was about 1.00000006650 seconds per clock count on September 18, 2013. In addition to slowly changing frequency, we have to account for sudden discontinuities in the USO frequency and frequency aging, as shown in Figure 2, which are the result of spacecraft safe mode events, during which the USO oven temperature undergoes large excursions.

After removing the fitted cubic polynomial function and the light time correction, the residuals over 4 years are less than 0.1 ms for the entire mission (shown in Figure 3.), which is more than 30 times better than the 3-ms mission requirement (Zuber 2010) for USO time precision.

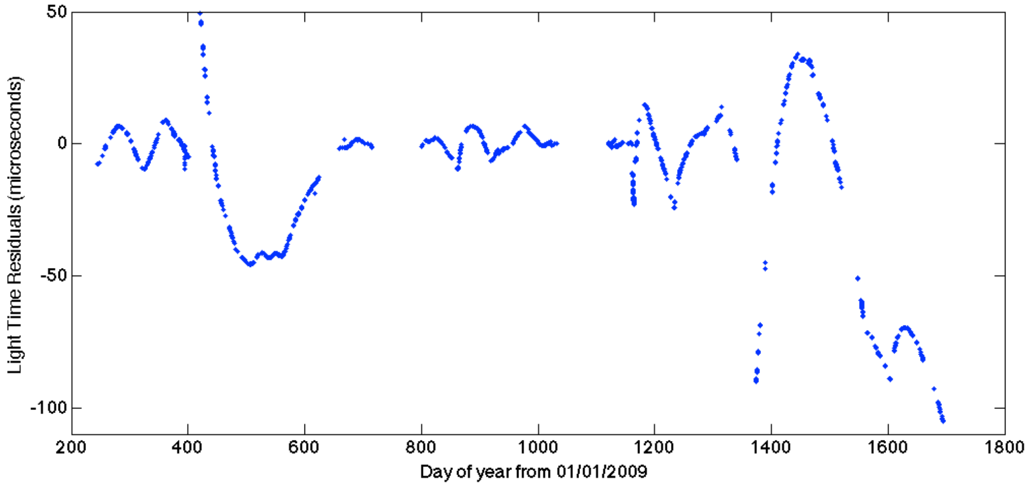

Figure 3. Newtonian light time residuals of LRO USO long-term behavior from September, 2009 to August, 2013.

LRO precise orbit determination with LR

The baseline LRO tracking system is a S-band radio frequency link (Chin 2007). The original goal of LR was to improve the S-band LRO orbit solutions, and even those from the combination of S-band tracking and altimetric crossover analysis (Smith 2008).

We processed the LR data to determine LRO orbits either independently or with S-band radio tracking data. We used the NASA/GSFC GEODYN orbit analysis software (Pavlis 2001) to perform the LRO precise orbit determination (POD). Here we present preliminary results of both LRO orbit prediction and orbit reconstruction, obtained with a high-resolution gravity model from the GRAIL mission (Zuber 2013).

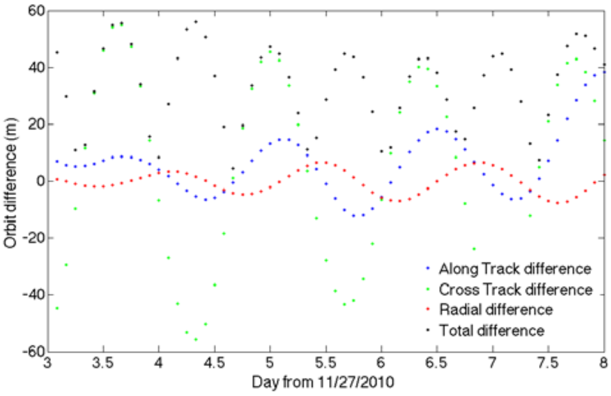

Figure 4. Orbit differences in along track (in blue), cross track (green), radial directions (red) as well as total orbit differences (black) between the predicted orbit from LR data and reconstructed orbit from S-band data.

We used LR data to predict LRO orbits independently from S-band tracking data over two-week periods with GRAIL GL0420 model by propagating the orbit solutions reconstructed based on 2.5 days of LR data alone. The maximum 2-week time span is a constraint from the regular LRO maneuvers. Comparing with orbits reconstructed over 2.5-day spans with only radio tracking data and a higher degree GRAIL model GRGM900B (Lemoine 2013) truncated at degree 270, we find that LR-predicted orbits are consistent to less than 6 m radially, and less than 60 m in total position over the two weeks (Figure 4). These differences are well within the FDF orbit prediction requirement of 800 m along-track difference over 84 hours, suggesting that the LR data alone are capable to provide good LRO orbit predictions.

To assess the quality of reconstructed orbits generated with LR data, we constructed 3 sets of 2-week arc solutions covering the time period from September, 2009 to December 2012: with LR data only, with S-band data only, and with both LR with S-band data. The orbit solutions from these 3 sets of arcs are each compared with the orbits obtained with 2.5-day reconstructions with radio tracking data only. Those are used as baseline as they are considered the best definitive orbit results at present, since the 2.5 day time span for S-band data balances the defining of the orbit and minimizing the modeling errors. On the other hand, since the one-way LR measurements require knowledge of both ground and spacecraft clocks, longer arcs, such as 2-week ones, are preferred to allow recovery of clock and orbit parameter. The GL0420 gravity model was used for all orbit solutions. Figure 5 shows orbit differences less than 6 m radially and less than 35 m in total position have been achieved using LR data only. Total orbit differences are comparable between LR only orbit solutions (~15 m on average) and S-band only solutions (12 m on average).

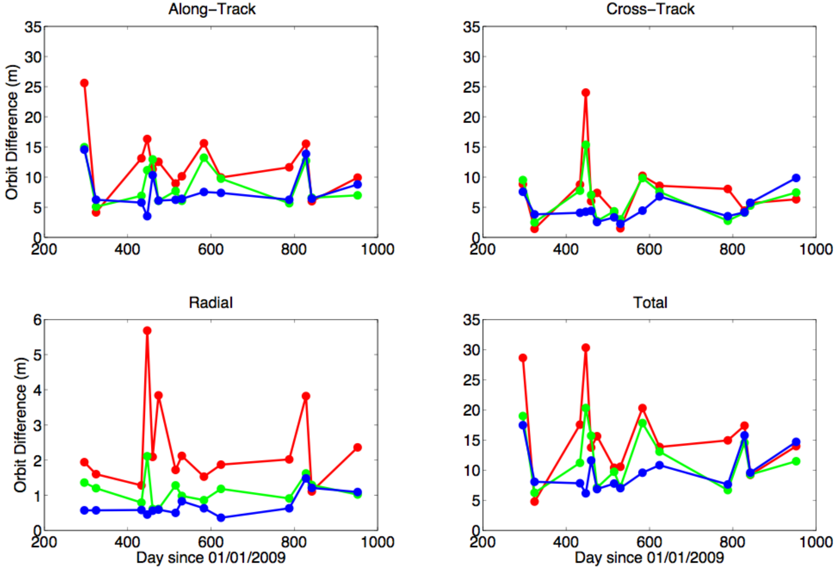

Figure 5. Obit differences in along track, cross tack, radial directions and total orbit difference between 2-week LR only arcs (red), 2-week S-band only arcs (green), and 2-week LR + S-band arcs (blue) with respect to 2.5-day S-band only orbits. GL0420 gravity model used for all solutions.

The three sets of orbits described above are then used to locate LOLA altimetry returns, which are compared to a well-registered LOLA south pole topographic map, in order to determine the consistency and quality of these orbital solutions. Table 1 shows the results for 2 continuous 2-week arcs in June 2010. The use of the high-resolution GRAIL gravity field model GL0420 yielded much smaller RMS of position differences in all directions than the gravity field model LLGM-1 based on pre-GRAIL data (Mazarico et al. 2012). With GL0420, the RMS values of the position adjustments to the LR-only orbits and the S-band orbits are similar. The results from both a direct orbit comparison and a compairons with LOLA altimetry suggest that LR data can independently generate reconstructed 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 1. Comparison between positions of 170 altimetry passes generated from different orbit solutions and the LOLA definitive 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

Summary

LRO LR data have been used to monitor the LRO clock long term behavior through the entire LRO mission to help maintain the high precision of the range measurements. LR has also shown its ability to independently produce both predicted and reconstructed orbit solutions at comparable quality to conventional radiometric tracking data with the help of high resolution gravity models from the GRAIL mission.

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