Laser Ranging Experiment on Lunar Reconnaissance Orbiter: Timing Determination and Orbit Constraints

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Abstract

Accurate ranges from Earth to the Lunar Reconnaissance Orbiter (LRO) spacecraft Laser Ranging (LR) system supplement the precision orbit determination (POD) of LRO. LRO is tracked by ten LR stations from the International Laser Ranging Service (ILRS), using H-maser, GPS-steered Rb, and Cs oscillators as reference clocks. The LR system routinely makes one-way range measurements via laser time-of-flight from Earth to LRO. Uplink laser pulses are received by a telescope mounted on the high-gain antenna of LRO, transferred through a fiber optic cable to a Lunar Orbiter Laser Altimeter (LOLA) detector, and time-tagged with respect to the spacecraft clock. The range from the LR Earth stations to LRO is derived from paired outgoing and receive times. Accurate ranges can only be obtained after solving for both the spacecraft and ground station clock errors and removing temperature effects. The drift rate and aging rate of the LRO clock are calculated from data provided by the primary LR station, NASA's Next-Generation Satellite Laser Ranging System (NGSLR) in Greenbelt, Maryland. The results confirm the LRO clock oscillator mid- to long- term stability measured during ground testing. These rates also agree well with those determined through POD. Ten-cm level LR observations are used in the POD procedure to form strong orbit constraints. We have processed the entire LRO mission with the radiometric and LR data, and estimated the impact of the LR data on the orbit reconstruction and accuracy. The orbit residual fits of the LR data over 14 days are less than 10 meters, nominally smaller than the 15-meter residuals of the S-band data. The difference between the orbit results determined with and without LR contribution is up to 10 meters.

1. Introduction

The laser ranging (LR) system has been set up to track the Lunar Reconnaissance Orbiter (LRO) (*Chin, G., et al.,* 2007) in order to supplement the precision orbit determination (*Zuber, M., et al.,* 2010) since June, 2009. The system includes two primary components: a flight system and ground system. The ground system consists of 10 participating Earth-based satellite laser ranging (SLR) stations, which regularly transmit laser pulses to LRO. These laser pulses give one-way time-of-flight measurements of the range between the ground station and LRO in orbit around the Moon. The flight system includes a telescope attached to the LRO high-gain antenna (HGA), which receives the laser pulses and sends them to the detector on the Lunar Orbiter Laser Altimeter (LOLA) instrument (*Smith, D.E., et al.,* 2009) through a fiber optic cable bundle. The LOLA timing electronics then time-tag the pulse for later processing. These time-tags are synchronized with the LRO Mission Elapsed Time (MET), based on an oven-controlled quartz ultra-stable oscillator (USO) which is stable to several nano-seconds per hour. The USO and the accurate ground station clocks collectively enable the LR to achieve sub-meter level measurements. The precision of LOLA time stamps is about 0.5 ns in standard deviation depending on receive pulse width and energy, which is equivalent to 15 cm precision of one-way ranging measurement. To obtain the one-way range, ground station laser transmitted times are paired with corresponding LOLA receive times using predicted one-way time-of-flight in the consolidated prediction format (CPF) if the predicted receive time and the LOLA time stamp differ by less than 200 ns.

Detailed laser properties of all ten participating SLR stations are listed in *McGarry, J., et al.* (2011). The nominal precision of received pulses from the primary ground station, NASA's Next-Generation Satellite Laser Ranging System (NGSLR), is about 15 cm root mean square (RMS), and 10 cm to 30 cm for other stations. Analysis figures for all SLR stations can be found in *McGarry, J., et al.* (2011b). In the current precision analysis, a range walk correction based on the NGSLR pulse shape has been applied to the LOLA receive times for all ground stations. The laser properties, such as the energy, the wavelength, and the pulse shape, are station-dependent. Hence the range walk correction, which minimizes NGSLR's RMS, is not necessarily optimal for data from other stations. New range walk corrections will be derived in the future for each ground station and applied to the analysis in order to improve the ranging precision from non-NGSLR stations.

2. Timing Determination

The LRO MET time can be related to Coordinated Universal Time (UTC) through space clock kernel corrections, provided weekly by NASA flight dynamics facility (FDF) to an accuracy of better than 3 ms. Using Hydrogen-maser or Cesium/Rubidium oscillators as reference at the ground stations, LR has the ability to more accurately cross reference LOLA MET time tags to UTC time within a couple milliseconds over several months by pairing up outgoing laser time and LOLA receive time, given the precise locations of the ground stations and preliminary knowledge of the LRO satellite. The long-term stability of the LRO clock was characterized using 10 months of NGSLR ranging data from February 2010 to December 2010. A time drift rate of 71.05 ns/s and a frequency aging rate of 2.044e-8 ns/s^2 were derived by fitting the outgoing and receive time pair differences with a quadratic polynomial without correcting for relativistic effects. The Newtonian residuals after removing the fitting polynomial remain less than ±0.25 milliseconds over 10 months with an obvious monthly behavior as expected (shown in Fig. 1). The drift and aging rates are in agreement with the pre-launch test in 2009, which found a drift of 76.59 ns/s and aging rate of 2.89e-9 ns/s^2. The LRO clock has also been characterized bi-weekly by the GEODYN software (*Pavlis, D.E., et al.,* 2001) which applies relativistic corrections to the ground station clock and the satellite clock, accounting for gravitational potential and motion with respect to a solar system barycentric reference frame. The results are plotted in Fig. 2. Both the drift and aging rates estimated by GEODYN agree with those from LR analysis. The largest difference between the drift rates is about 0.066 ns/s due to relativistic effects.

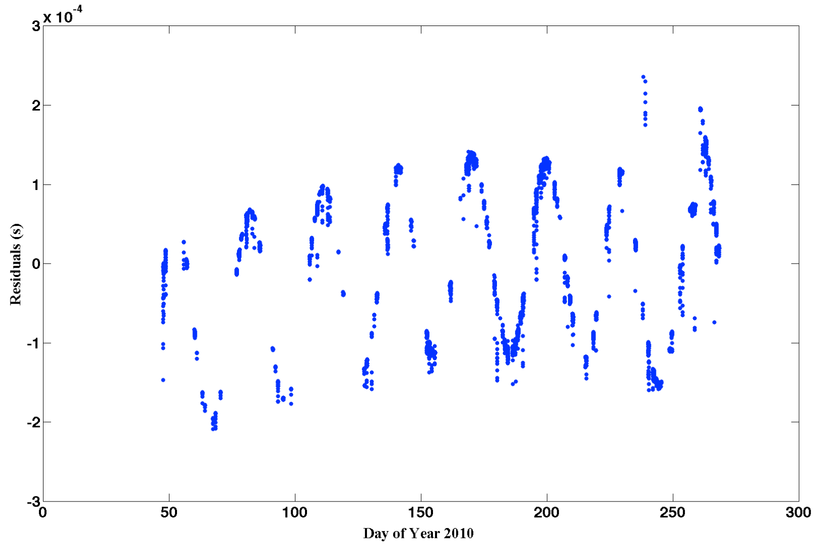

Figure 1 Newtonian light time residuals with LRO clock drift and aging removed.

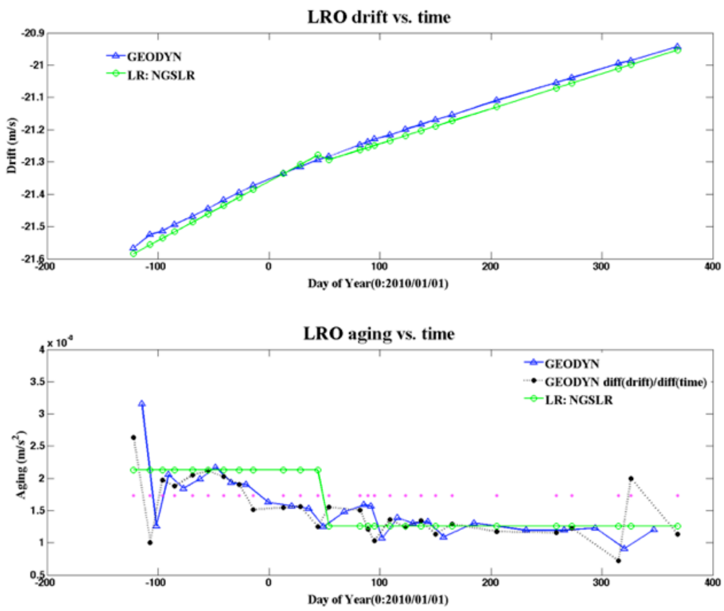

Figure 2 Long-term LRO clock stability derived from LR data (green) and GEODYN estimation (blue), and the aging rate from pre-launch testing (magenta) plotted as a constant.

The long-term behavior of the LRO clock can be monitored not only by the data from NGSLR, but also by the data from other participating ground stations. Using the spacecraft clock as the common reference, the difference among clocks at Earth-based stations can be obtained. The LRO clock drift rates derived from the LR data collected by NGSLR and six other stations are presented in Fig. 3 with respect to the NGSLR estimation. The slope of each station in Fig. 3 shows that the clocks at different ground stations have slightly different frequencies. Although this analysis provides information about the difference in long-term behavior among the ground station clocks, it doesn't give the relative time difference in a short time period. This short-term relative timing can be obtained by having more than one station range to LRO at the same time.

Simultaneous ranging experiments have been performed successfully among two, three, and four participating stations from the same continent many times in the past two years, and simultaneous ranging shows the possibility to perform time transfer among ground stations.

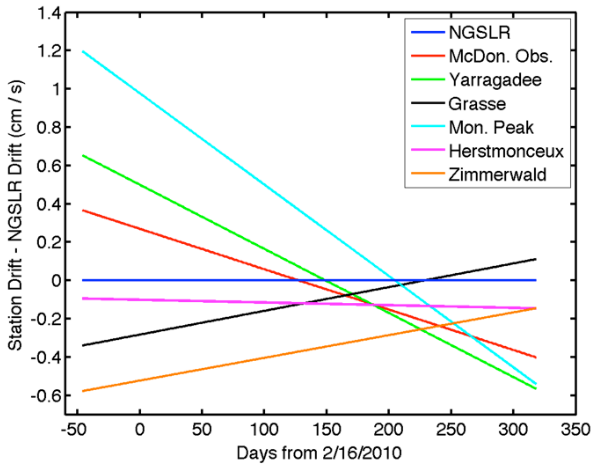

Figure 3 LRO clock drift rate for different LR stations relative to NGSLR.

3. Orbit Constraints

LR data were used in GEODYN to provide additional constraints to POD. *Mazarico, E., et al.,* 2011 relied on another tracking data type, the S-band radiometric tracking, which is supported by NASA's White Sand station and stations from the Universal Space Network (USN) for the LRO mission. The line-of-sight measurements taken with S-band tracking yielded a precision of 0.5 – 1 meter in the range observations, and two-way Doppler observations better than of 1 mm/s. Using GEODYN, we fit the tracking observations by integrating the LRO trajectory over 2-week time intervals. To achieve the

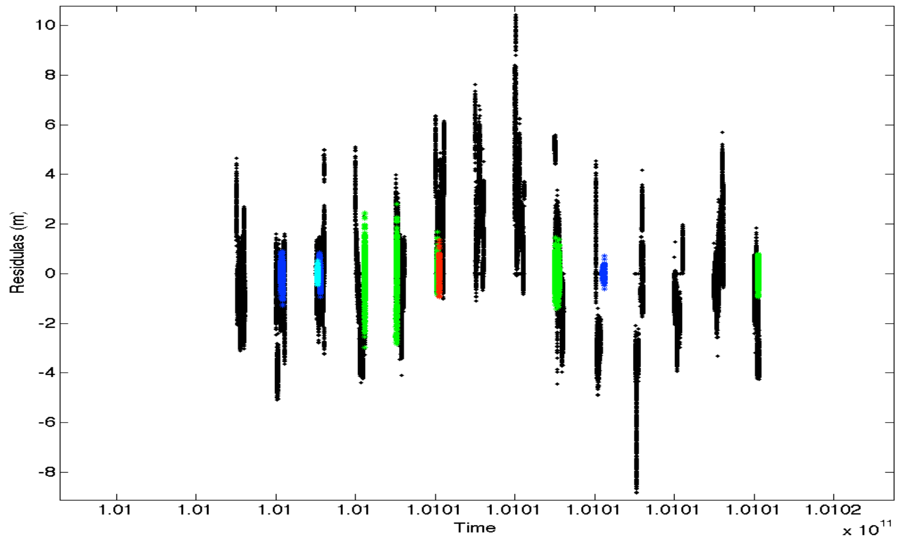

Figure 4 Orbit residuals of S-band data (black) and LR data from Yarragadee (green), McDonald (blue), Hartebeesthoek (red), and Zimmerwald (cyan).

best possible fit to the tracking observations, we adopted the latest lunar gravity field from LRO data, LLGM-1 (*Mazarico, E., et al.,* 2011), and iteratively adjusted several input parameters, such as timing and ranging biases. Weekly empirical constant along-track and once per revolution cross-track accelerations were also adjusted in the calculations. For comparison, the calculations were carried out, first, using radio-tracking data only and, second, with radio-tracking and LR data.
The orbit residuals resulting from a well-converged two-week arc, with S-band and LR data from 09/30/2010 to 10/13/2010, are shown in Fig. 4. The residuals of the LR passes are nominally less than 10 meters, while those of the S-band ranging passes are generally less than 15 meters. The RMS values of the arc by arc LRO orbit differences from the calculations are

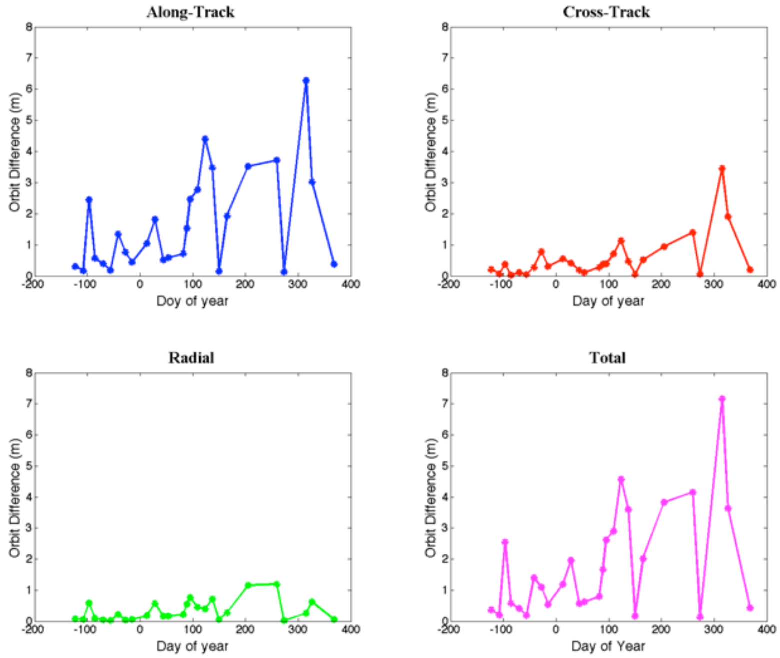

Figure 5 Orbit difference between GEODYN calculations with and without LR data in three directions, along track (blue), cross track (red), radial (green), as well as the total orbit difference (magenta).

plotted in Fig. 5, covering the time period from the start of the LRO mission, 07/02/2009, to 01/31/2011. The along-track direction shows the largest orbit difference of up to 7 meters, while the difference along the radial direction is the smallest, no larger than 2 meters. The total orbit difference is less than 10 meters. In addition, only 10% to 15% of the data used in the orbit determination process is contributed by LR. Such a low percentage might weaken the constraints of the LR constraints on the orbit, but optimal data weighting could mitigate this issue. The POD results with LR data is are expected to be further improved by better calibrating the ground and LRO clock using other telemetry data, such as temperature.

4. Summary

The one-way LR experiment has been performing daily from July, 2009 to the present with contributions from NGSLR and nine other participating ground stations from the ILRS network. LR proved its ability to obtain time information from the LRO clock oscillator accurate to 0.25 ms over ten months, and showed the possibility for future time transfer between a ground station and a satellite as well as among different ground stations. In addition to timing determination, LR data were also used to form constraints on the LRO orbit determination calculations. Meter-level changes were observed in orbit solutions after adding LR data to S-band tracking data in the GEODYN analysis. Further calculations will be carried out to examine the quality of the new orbits due to the contribution of LR observations.

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