Icarus 000 (2016) 1–17

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Analysis of one-way laser ranging data to LRO, time transfer and clock characterization

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ARTICLE INFO

Article history:
Received 3 September 2015
Revised 29 July 2016
Accepted 19 September 2016
Available online xxx

Keywords:
Laser ranging
One-way
Lunar Reconnaissance Orbiter
time transfer

ABSTRACT

We processed and analyzed one-way laser ranging data from International Laser Ranging Service ground stations to NASA's Lunar Reconnaissance Orbiter (LRO), obtained from June 13, 2009 until September 30, 2014.

We pair and analyze the one-way range observables from station laser fire and spacecraft laser arrival times by using nominal LRO orbit models based on the GRAIL gravity field. We apply corrections for instrument range walk, as well as for atmospheric and relativistic effects.

In total we derived a tracking data volume of $\approx$ 3000 hours featuring 64 million Full Rate and 1.5 million Normal Point observations. From a statistical analysis of the dataset we evaluate the experiment and the ground station performance. We observe a laser ranging measurement precision of 12.3 cm in case of the Full Rate data which surpasses the LOLA timestamp precision of 15 cm. The averaging to Normal Point data further reduces the measurement precision to 5.6 cm.

We characterized the LRO clock with fits throughout the mission time and estimated the rate to 6.9×10^{-8}, the aging to 1.6×10^{-12} /day and the change of aging to 2.3×10^{-14} /day^2 over all mission phases. The fits also provide referencing of onboard time to the TDB time scale at a precision of 166 ns over two and 256 ns over all mission phases, representing ground to space time transfer. Furthermore we measure ground station clock differences from the fits as well as from simultaneous passes which we use for ground to ground time transfer from common view observations. We observed relative offsets ranging from 33 to 560 ns and relative rates ranging from 2×10^{-13} to 6×10^{-12} between the ground station clocks during selected mission phases. We study the results from the different methods and discuss their applicability for time transfer.

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1. Introduction

NASA's Lunar Reconnaissance Orbiter (LRO) was launched on June 18, 2009 and entered its lunar orbit five days later. The goal of the mission is to carry out a comprehensive geophysical, geological and geochemical mapping campaign to establish an observational framework for future lunar exploration (Zuber et al., 2010).

One of the seven instruments onboard LRO is the Lunar Orbiting Laser Altimeter (LOLA), which was developed at NASA's Goddard Space Flight Center (GSFC), measuring the surface elevation, slope and roughness. From these data a global topographic model and a high-accuracy geodetic grid are derived. LOLA is also capable of detecting laser pulses from Earth ground stations. These one-way range measurements add a new type of tracking data to the mission (Zuber et al., 2010; McGarry et al., 2011 and 2013).

For precise referencing of the orbital remote sensing data, the accuracy and precision of LRO positioning throughout the mission is critical (Zuber et al., 2010). The baseline of the LRO tracking and

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http://dx.doi.org/10.1016/j.icarus.2016.09.026
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orbit determination was realized by radio observations from Earth via NASA's White Sands station and the Universal Space Network (USN) in combination with LOLA's altimetric crossovers. The accuracy of this nominal LRO trajectory which we use in our analysis is reported to be ≈ 9 m overall at the arc overlaps of trajectories consecutive in time (Mazarico et al. 2012 and 2013). Recent solutions of that trajectory used the GRAIL gravity field GRGM900C (Lemoine et al., 2014) up to degree and order 600 (LRO SPICE archive, 2015). The ultimate goal is to combine the various tracking data sets for refined orbit determination to support Lunar precision mapping (Zuber et al., 2010).

Most of the laser ranging experiments beyond an Earth orbit have only been carried out sporadically as for example to Mars Global Surveyor and MESSENGER (Neumann et al., 2006; Smith et al. 2006a). Beside the two-way laser ranging to the mirrors on the lunar surface since the 1970 s (Degnan, 1994), only the one-way ranging to LRO has been carried out routinely between June 30, 2009 and September 30, 2014 (McGarry et al. 2013).

Mao et al. (2014a) demonstrated the application of laser ranging data for analysis of the LRO clock and orbit determination. Trajectories derived from various combinations of different types of tracking data were compared in order to assess their consistency. They found that the application of improved gravity fields from the GRAIL mission supports orbit determination with one-way laser ranging data to a quality comparable to radio data based results. Sun et al. (2013a) also used the same laser uplink for demonstration of data transmission which highlights the versatility of the laser ranging to LRO experiment.

Furthermore Sun et al. (2013b) and Mao et al. (2014b) reported about simultaneous passes from multiple stations. They demonstrated the measurement of differences between and the synchronization of remote ground station clocks with the one-way data thus performing ground to ground time transfer. Other optical time transfer experiments like the time transfer by laser link (T2L2) and the European Laser Timing (ELT) have a two-way setup. They derive ground to space and ground to ground time transfer by using an onboard retro-reflector and a detector which provides an active uplink (Exertier et al., 2013; Schreiber et al., 2009).

While previous data analyses have been carried out in the early stages of the experiment (Bauer et al., 2013), we now use all data obtained between July 16, 2009 and September 10, 2014. This report describes the application of the nominal LRO trajectory for the pairing, processing and the analysis of the one-way range measurements as well as the characterization of the onboard clock and the ground station clock differences by time transfer.

We analyze the derived dataset regarding criteria such as pass length, ratio of successfully paired to actually fired shots and measurement precision. From the averaging of these values either over all or all passes of a certain station, we derive the overall and the ground station performance.

Furthermore we use approaches based on the analysis of single and multiple passes in order to characterize the LRO clock by estimating its parameters offset, rate, aging and its change and derive a referencing of onboard to ground time (ground to space time transfer). While we use these terms for the clock parameters they are equivalent to the terms phase, frequency, frequency drift and change of frequency drift respectively, which are used within the time and frequency community. By comparing the parameters derived from the single- and the multiple-pass analysis, we get estimates of their accuracy and precision. We further use the multiple-pass analysis and simultaneous passes to characterize the timing differences between ground station clocks (ground to ground time transfer). Measuring their relative offsets and rates enables the monitoring of their timing.

Section 2 describes the setup and the features of the ground stations that are ranging to LRO along with their timing system stabilities. Section 3 provides the setup of the spacecraft and the laser ranging data and discusses the LRO clock stability. Section 4 compares optical two-way time transfer experiments regarding their performance and difference to the time transfer experiment done with the one-way laser ranging data to LRO. Section 5 explains our data processing methods for the pairing, processing and the formation of the Normal Point data as well as the corrections that we apply. In Section 6 we introduce our data analysis methods that utilize either single, multiple or simultaneous passes. The results on the dataset statistics, the characterization of the LRO clock and the ground station clock differences are presented in Section 7. In Section 8 we discuss these results and draw conclusion from our work.

2. Ground stations

LRO is tracked by selected ground stations of the International Laser Ranging Service (ILRS – Pearlman et al., 2002), which differ in their equipment and characteristics as listed in Table 1. Table 2 shows the corresponding stability values of their timing systems. For completion the stability of the LRO onboard clock is added as well, while it is discussed in Section 3 with more detail. With stations in the US, Europe, South Africa (HARL) and Australia (YARL) a global coverage of LRO is basically provided.

Contrary to other established stations, the stations YARL, GODL, MONL and HARL are trailer-based Mobile Laser Ranging Station (MOBLAS). These stations were deployed by NASA in the 1970′s for a global tracking of the SEASAT mission (Husson et al., 1992) and have similar hardware and performance characteristics.

3. Spacecraft and data setup

The ranging to LRO as illustrated in Sun et al. (2013a) is done from either one or multiple stations at a time. In order to receive laser shots from Earth ground stations, an optical receiver, the Laser Ranging Telescope was added to the high gain communication antenna which is always pointing towards Earth - in particular, to the White Sands radio station, New Mexico, US, when it is in view. A fiber optic cable is forwarding incoming laser pulses into the LOLA instrument for detection.

From a distance of 381,000 km the Laser Ranging Telescope field of view of 30 mrad covers a circular surface segment with a diameter of ≈ 11,433 km. With this field of view all US stations to range to LRO simultaneously while the LRO antenna is pointed at White Sands (Ramos et al., 2009).

LOLA has five channels which are designed to receive and detect the 1064 nm lunar return pulses from the laser beams, resulting in five altimetry measurements at a time ideally. The Silicon Avalanche Photodiode (SiAPD) is also able to detect signals at a wavelength of 532 nm (Ramos-Izquierdo et al., 2009), which is commonly used by ILRS ground stations for the ranging to Earth orbiting satellites (Smith et al., 2006b). It is shown in Ramos-Izquierdo et al. (2009) how the signals at both wavelengths are merged. With this setup the regular signals from ILRS Earth ground stations and the returns from the lunar surface can be detected concurrently with the same instrument. Since the LOLA time stamp precision is 0.5 ns, the precision of derived range measurements is ≈ 15 cm.

While the stations record their fire times in UTC, LOLA measures the arrival of laser shots in Mission Elapsed Time (MET), which is the internal timing system of the LRO onboard clock. Within our work we use the Barycentric Dynamical Time (TDB) time scale because it is commonly used for ephemerides and interplanetary orbit determination. Fig. 1 illustrates the relation of these timing systems and their conversion along with the corresponding accuracies. The officially provided data product for the conversion

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