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Demonstration of orbit determination for the Lunar Reconnaissance Orbiter using one-way laser ranging data

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ABSTRACT

We used one-way laser ranging data from International Laser Ranging Service (ILRS) ground stations to NASA's Lunar Reconnaissance Orbiter (LRO) for a demonstration of orbit determination.

In the one-way setup, the state of LRO and the parameters of the spacecraft and all involved ground station clocks must be estimated simultaneously. This setup introduces many correlated parameters that are resolved by using a priori constraints. Moreover the observation data coverage and errors accumulating from the dynamical and the clock modeling limit the maximum arc length.

The objective of this paper is to investigate the effect of the arc length, the dynamical and modeling accuracy and the observation data coverage on the accuracy of the results.

We analyzed multiple arcs using lengths of 2 and 7 days during a one-week period in Science Mission phase 02 (SM02, November 2010) and compared the trajectories, the post-fit measurement residuals and the estimated clock parameters. We further incorporated simultaneous passes from multiple stations within the observation data to investigate the expected improvement in positioning. The estimated trajectories were compared to the nominal LRO trajectory and the clock parameters (offset, rate and aging) to the results found in the literature.

Arcs estimated with one-way ranging data had differences of 5–30 m compared to the nominal LRO trajectory. While the estimated LRO clock rates agreed closely with the a priori constraints, the aging parameters absorbed clock modeling errors with increasing clock arc length. Because of high correlations between the different ground station clocks and due to limited clock modeling accuracy, their differences only agreed at the order of magnitude with the literature. We found that the incorporation of simultaneous passes requires improved modeling in particular to enable the expected improvement in positioning. We found that gaps in the observation data coverage over 12 h ($\approx$ 6 successive LRO orbits) prevented the successful estimation of arcs with lengths shorter or longer than 2 or 7 days with our given modeling.

1. Introduction

NASA's Lunar Reconnaissance Orbiter (LRO) was launched on June 18th, 2009 and reached its lunar orbit five days later. A comprehensive geophysical, geological and geochemical mapping of the Moon is carried out by the spacecraft in order to establish an observational framework for future lunar exploration (Zuber et al., 2010).

The Lunar Orbiting Laser Altimeter (LOLA) is one of the seven instruments onboard LRO. Its main science objectives are the derivation of a global topographic model and a high-accuracy geodetic grid. LOLA is also able to receive laser pulses from

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Earth-based International Laser Ranging Service (ILRS) ground stations (Pearlman et al. 2002) at a single-shot precision of 15 cm. This precision is further reduced to <6 cm with an averaging of the Full Rate to Normal Point data (Bauer et al., 2016). The ranging to LRO as illustrated in Sun et al. (2013) 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. A fiber optic cable is forwarding incoming laser pulses into the LOLA instrument for detection. LOLA is designed so that the Earth and the Lunar return pulses can be detected concurrently with the same instrument. Further details about the ground station characteristics, the spacecraft setup including LOLA's hardware extension and the data setup can be found in Bauer et al. (2016). Both LOLA's altimetry data and the one-way range measurements provide additional observational data that complement the regular radio tracking data for orbit determination (Zuber et al., 2010; McGarry et al., 2011, 2013).

The accuracy and precision of the LRO positioning throughout the mission is critical to enable a precise referencing of the remote sensing data. From the combination of the various tracking data sets the orbit determination of LRO shall be improved in order to support Lunar precision mapping (Zuber et al., 2010).

Most of the interplanetary laser ranging experiments have been carried out only occasionally as for example to Mars Global Surveyor, MESSENGER (Neumann et al., 2006; Smith et al. 2006) and LADEE (D'Ortenzio et al., 2015). Only the ranging to LRO and the retroreflectors on the lunar surface has been done on a routine basis. While the one-way laser ranging experiment has been carried out between June 30, 2009 and September 30, 2014 (McGarry et al. 2013), two-way Lunar Laser Ranging is done since the 1970s already (Degnan, 1994). While usually one ground station is ranging to LRO at a time, other stations can join for simultaneous observations.

The LRO spacecraft is regularly tracked by NASA's radio station White Sands in New Mexico as well as by the commercial Universal Space Network (USN). From the radio tracking data the LOLA team estimates the nominal LRO trajectory via orbit determination (Mazarico et al., 2012). Within early updates of the orbit they further used LOLA's altimetric crossover data for improved solutions. Derived from the differences at the arc overlaps of trajectories consecutive in time, this nominal LRO trajectory had an overall accuracy of 23 m for the radio only and 14 m for the radio and crossover solutions (Mazarico et al., 2012). The individual arcs had a length of 2.5 days, which is typical for the orbit determination of lunar orbiters (Konopliv et al., 2001; Mazarico et al., 2010, 2012, 2013).

While using the GRAIL gravity field within the estimation, Mazarico et al. (2013) derived updated solutions that had a total average difference of ≈ 9 m at the arc overlaps over all mission phases. The GRAIL mission enabled a global estimation of the lunar gravity field to unprecedented precision from the inter-distance measurement of two co-orbiting spacecraft (Zuber et al., 2013). The most recent solutions of the nominal LRO trajectory that we use within this work incorporates the GRAIL gravity field GRGM900C (Lemoine et al., 2014) up to degree and order 600 (LRO SPICE archive, December 2015).

The application of laser ranging data for both LRO clock analysis and orbit determination was first reported by Mao et al. (2014a). Their 2-week laser-ranging-data-only arcs had differences in total of 5–30 m with respect to the nominal LRO trajectory being thus comparable in accuracy with the radio-based result. Löcher et al. (2015) and Buccino et al. (2016) also estimated orbits comparable to the radio-based results while using laser data. Except for Mao et al. (2014), the authors could not derive an improvement in positioning when using both radio and laser data within the LRO orbit determination. Since the reasons have not been reported yet, one aspect of this work is the analysis of the inherent issues of the one-way laser data application in particular.

Sun et al. (2013) and Mao et al. (2014b) reported results from simultaneous passes by multiple stations and utilized them for ground to ground time transfer with one-way data. Furthermore the positioning was expected to improve with simultaneous passes due to the geometry and the additional observations (Neumann et al., 2014). Other optical time transfer experiments like the time transfer by laser link (T2L2) and the European Laser Timing (ELT) have a two-way setup from which they derive ground to space and ground to ground time transfer (Exertier et al., 2013; Schreiber et al., 2009).

Bauer et al. (2016) characterized the LRO and the ground station clocks from single, multiple as well as simultaneous passes. They estimated the parameters offset, rate, aging and change of aging for the LRO and relative offsets and rates for the ground station clocks (ground to ground time transfer) while keeping the orbit fixed by using the nominal LRO trajectory. Within this work we also use the terms offset, rate, aging and change of aging which are equivalent to phase, frequency, frequency drift and change of frequency drift respectively as used within the time and frequency community.

This work extends the former demonstration of orbit determination based on one-way laser ranging data only by Bauer et al. (2014) from a timeframe of 5 to 7 days. Furthermore variations in the length of the trajectory and the LRO clock arc were used to research the requirements of the one-way data application within orbit determination.

In Section 2 we discuss the errors arising from the ranging measurement and the involved clocks on ground and in space. Section 3 provides a comparison of optical one- and two-way time transfer experiments and their measurement accuracy. In Section 4 we provide the theoretical background of the observation model, the estimation software with its dynamical modeling as well as the a priori constraints we apply to the state and all clocks. Further we describe the timeframe we selected for demonstration of orbit determination including the observation data coverage, characteristics of the LRO orbit, the detailed setup of the various arcs we estimated and how we analyze the estimated results. Section 5 presents our estimated trajectories with their post-fit measurement residuals, the LRO clock parameters and the ground station clock differences that we estimated and compares them to the literature. Section 6 will discuss the results and draw conclusions.

2. Measurement and clock errors

Compared to the nominal timestamp precision of 15 cm (0.5 ns) of the Full Rate LOLA data, Exertier et al. (2006) reported random errors below that within SLR. They found a 7–12 mm random error for Full Rate and 1–3 mm for Normal Point data. The errors are thereby coming from the ground station laser, detector, timer, clock and other dependencies as well as from the atmosphere and the target signature. The calibration of the station hardware, the atmosphere itself as well as the target signature introduce a systematic error of 8–19 mm.

With the ranging to LRO the LOLA time stamp accuracy is above the random error reported within SLR. With the one-way setup the systematic errors are larger than the random errors. The errors are thereby coming from the LRO onboard and the ground station clocks, the orbit that is used to complete the one-way observable as well as the modeling accuracy (see Section 4.2). Since only an uplink is used, target signature errors are not present.

The one-way observable is affected by the ground station and LRO clock stability, since their errors affect their time tags