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Reduction, analysis and application of one-way laser ranging data from ILRS ground stations to LRO

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Abstract

One-way Laser Ranging is being performed routinely from International Laser Ranging Service ground stations to the Lunar Orbiter Laser Altimeter, an instrument onboard NASA's Lunar Reconnaissance Orbiter. We developed software to process this novel type of tracking data and gathered information e.g. on characteristics and distribution in a preliminary analysis. By incorporating the high accuracy spacecraft range measurements into orbit determination, one expects the positioning and thereby the accuracy of further derived data products to improve. We used the one-way Laser Ranging measurements within the estimation software TUDAT for carrying out an orbit determination for the Lunar Reconnaissance Orbiter. To select a certain timeframe we considered the size of the jumps at the Lunar Reconnaissance Orbiter Spacecraft Positioning Kernel merge points and the tracking data coverage, quality and quantity. The results from the preliminary analysis were used for various inputs into the estimation.

Background

The one-way LR (Laser Ranging) experiment provides high-accuracy range measurements over interplanetary distances between ILRS (International Laser Ranging Service) ground stations and the LOLA (Lunar Orbiter Laser Altimeter) instrument onboard NASA's LRO (Lunar Reconnaissance Orbiter). Furthermore, this data can be used for characterizing the LRO clock and monitoring the long-term behavior as well as referencing the MET (Mission Elapsed Time) to TDB (Barycentric Coordinated Time). Unlike ranging experiments to reflectors or transponders, LR to LRO is a one-way measurement (Figure 1). A ground station fires a laser pulse to LRO at a certain time and the received pulse is time stamped by the satellite. An optical receiver is attached to LRO's HGA (High Gain Antenna), which is always pointed towards Earth, and incoming Laser pulses are transmitted into the LOLA laser detector by a fiber optic cable.

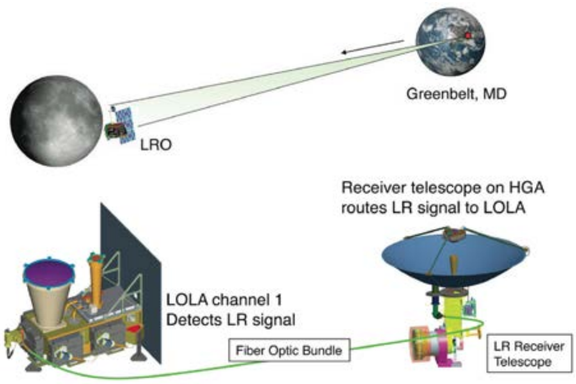

Figure 1: LR to LRO - basic principle [1]

This permits ranging measurements to LRO simultaneously while LOLA is ranging to the lunar surface [1]. By calculating the light travel time between the receiving and the firing time, a high precision range measurement with a typical RMS of 10 to 30 cm in case of this experiment is derived [3]. Currently the OD (Orbit Determination) for LRO is based on radio as well as altimetric crossover data and is provided in the form of the LRO SPK's (Spacecraft Positioning Kernels) with an accuracy of ≈ 14 m in total spacecraft positioning [2]. This, as well as the quality of Lunar remote sensing data products, is expected to improve with a successful incorporation of the LR data to the LRO nominal navigation data [1].

Data processing

Beginning with data obtained during a LR to LRO campaign from the ILRS station in Wettzell Germany, we have developed an independent matching program at DLR Berlin. This software relates the separated station laser fire times to the LOLA laser receive times and has been extended to process a large number of passes automatically. Beginning with the LRO commissioning phase, we now have processed and analyzed data until the end of ES03 mission phase (~July 2009 until December 2012). From that preliminary analysis we derived information on the LRO clock as well as tracking data coverage, quantity and quality. Thereby the mean measurement RMS value of 13.4 cm estimated from this analysis, agrees with the LOLA instrument accuracy.

Application

In order to make use of the high accuracy measurements in an OD, we used the one-way laser ranging data within the estimation software TUDAT [4]. We selected a certain timeframe for a first estimation by investigating the magnitude of the jumps at the LRO SPK merge points. Since the orbit in the SPK's consists of many partial trajectories, one can see jumps of the position and the velocity at the times where they are merged together. Throughout the analyzed timeframe we saw a mean jump size of ~ 83 m. While looking for timeframes with small jumps we also took into account the tracking data coverage, quality and quantity. Since the tracking data is not evenly distributed due to station characteristics, we used this information to develop station specific weights. Likewise, we also developed and provided *a priori* covariance to the estimation, in order to stabilize the solution.

We defined several cases, to check our approaches, simulation setups and validity of the results. We did that by assessing the impact of changes of the setups, the used models (e.g. clock), the effect of the weights and *a priori* covariance on the estimated parameters and their attainable accuracy. To verify whether the results were reasonable, we first looked at the RMS of the measurements with respect to the derived trajectory. In addition, the results from the preliminary analysis were used as a reference to check on the total value and the variation of the estimated parameters.

Results and Outlook

The results for the various defined cases 1 to 6 are listed in Table 1. For the very first cases 1&2 we did only estimate the clock parameters and varied the length of this approximation between per single pass and per day. In both cases the *a priori* information on the initial state of LRO was taken from the LRO SPK's. While the result for the estimation of the clock parameters per pass (case 1) has a very good RMS of only 0.3 m, the estimated values did show large deviations and variation with respect to the preliminary results. Changing the length of the approximation to per day (case 2) caused the RMS to increase significantly to 75 m, but the estimated values had better agreement and less variation with respect to the reference.

This is, because some of the models that are currently implemented in the software are too simplistic, for example a ‘cannonball mode’ that is used for the solar radiation pressure and therefore the estimated parameters are affected by those errors. So if the clock is estimated per pass, the RMS is good, but the corresponding values are off with respect to the reference due to the mismodeling. If the clock is estimated per day, the RMS increases because the model is too coarse and it does not describe the changes over the longer time span well enough. But the estimated values are closer to the reference and show less variation because they are not changing from pass to pass and therefore reflect the behavior on average.
For the next step we also included the estimation of the initial state (case 3&4) and regarding the change of the clock approximation length, we observed the same behavior for the RMS and the estimated values as before (case 1&2). When changing the length from per pass to per day the RMS is increasing, but the values are closer to the reference. In addition, overall the RMS for case 3&4 was higher than for case 1&2, which is due to correlations between the estimated clock parameters and the initial state.
When we further tried to estimate empirical accelerations along with the clock parameters and the initial state (case 5&6), we were yet not able to retrieve a converging solution for both clock approximation lengths. Still the application of empirical accelerations helped to lower the correlations, but overall the used models were too simplistic and the numbers of parameters too large to enable an uncorrelated estimation of them. Since we think that the mismodelling is currently the main reason for the errors that we observe, one of the next steps is to make the models more realistic and improve their accuracy.

Table 1: Estimation results for the various setups

Estimation of \ **Clock parameters**	**Clock parameters**	**Clock parameters** **Initial state of LRO**	**Clock parameters** **Initial State of LRO** **Empirical accelerations**
Estimated per pass	**Case 1**	**Case 3**	**Case 5**
RMS	RMS = 0.3 m	RMS = 5 m	Estimation was diverging
Comments	estimated values of the clock parameters show large deviation and variation with respect to the reference	estimated values of the clock parameters show large deviation and variation with respect to the reference	Diverging due to too many parameters, empirical accelerations help to reduce the correlations
Estimated per day	**Case 2**	**Case 4**	**Case 6**
RMS	RMS = 75 m	RMS = 100 m	Estimation was diverging
Comments	estimated values of the clock parameters show small deviation and variation with respect to the reference	estimated values of the clock parameters show small deviation and variation with respect to the reference	Diverging even faster due to too many parameters and too long time span for the clock approximation, empirical accelerations help to reduce the correlations

In the results for the cases 3 to 6, we saw high correlations between the clock and the initial state, which are caused by the setup of the one-way experiment. The application of *a priori* covariance and weights to the estimation helps to lower the correlations, but cannot remove them completely. By providing a further reference, we intend to compensate the issues of the one-way setup and overcome the contradictions between the RMS and the estimated values in our current results, in order to use LR data for the positioning of LRO. Whether we can perform that referencing, for example, by the incorporation of radio tracking data or whether we have to develop other approaches is currently under consideration.

Summary

Beginning with the participation in an observation campaign at the Fundamentalstation Wettzell, we developed software to process one-way LR data from ground stations to LRO and carried out a preliminary analysis. We derived information on the LRO clock behavior as well as tracking data coverage, quality and quantity over a timeframe from beginning of CO until the end of ES03 mission phase (~ July 2009 until December 2012).

By incorporating the processed data into the estimation software TUDAT, we made an attempt to use the high accuracy LR data for the estimation of the LRO position. We compared, validated and improved the incorporated models as well as the results coming from the respective software systems. The results from the preliminary analysis were used to develop station specific weights for balancing the tracking data and *a priori* covariance in order to stabilize the estimation solution.

We identified critical issues of the application of the one-way measurements within an OD and furthered our understanding of this novel type of tracking data. By improving the incorporated models and introducing further referencing, we intend to overcome the issues that are associated with this type of data and the experimental setup.

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