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Comparative analysis of one- and two-way planetary laser ranging concepts

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ABSTRACT

Laser ranging is an emerging technology for tracking interplanetary missions, offering both range accuracy and precision at the level of several millimeters. The ground segment uses existing Satellite Laser Ranging (SLR) technology, whereas the space segment requires an active system for either one- or two-way ranging. We numerically investigate the performance of one- and two-way active planetary laser ranging systems to quantify the difference in science return from missions employing this technology. In doing so, we assess the added value of the more complicated two-way system compared to its one-way counterpart. We simulate range measurement errors for both types of systems, using clock error time histories generated from Allan variance profiles. We use two test cases: a lunar polar orbiter and a Phobos lander. In the Phobos lander simulations, we include the estimation of Phobos librations and $\bar{C}_{2,2}$ gravity field coefficient. For the lunar orbiter, we include an empirical force-error model in our truth model. We include the estimation of clock parameters over a variety of arc lengths for one-way range data analysis and use a variety of state arc durations for the lunar orbiter simulations. For the lunar orbiter, performance of the one- and two-way system is similar for sufficiently short clock arcs. This indicates that dynamical-model error, not clock noise, is the dominant source of estimation uncertainty. However, correlations between the clock and state parameters cause an exchange between clock and state signal for the one-way system, making these results less robust. The results for the Phobos lander show superior estimation accuracy of the two-way system. However, knowledge of Phobos' interior mass distribution from both the one- or two-way system would currently be limited to the same level by inaccuracies in our knowledge of Phobos' volume. Both the lunar orbiter and Phobos lander simulations show that the use of two-way planetary laser ranging should be accompanied by improvements in associated measurements and models to allow this data type to be exploited to its full potential.

1. Introduction

The determination of the orbits of interplanetary satellites is traditionally done using radiometric tracking techniques (Moyer, 2000; Thornton and Border, 2000; Asmar et al., 2005), in which radio signals, typically in S-, X- and/or Ka-band are transmitted from a ground station to the space segment (and/or *vice versa*). The primary observable used in planetary spacecraft orbit determination is typically a Doppler measurement, which represents a differenced range rate, *i.e.* the change in range, integrated over a certain time, ranging from 1 s *e.g.* (Mazarico et al., 2012) to more than 1000 s *e.g.* (Iess et al., 2009).

Doppler data may be supplemented by range measurements (typical accuracy about 1 m) obtained from a coded radio signal or by ΔDOR (Thornton and Border, 2000) or VLBI (Duev et al., 2012) observations, both of which are angular observables generated by the concurrent observation of the same radiosignals by a (global) set of radio telescopes. Analysis of the tracking data of interplanetary spacecraft and landers has contributed greatly to achieving the scientific objectives of planetary missions, for instance for deducing gravity fields and their temporal variations (Marty et al., 2009; Lemoine et al., 2014), as well as for measuring rotational variations of solar system bodies (Kuchynka et al., 2014) and experimental gravitational physics (Will, 2014).

The use of laser ranging has been proposed for use over interplanetary distances (Degnan, 2002), extending the use of Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) to Interplanetary Laser Ranging (ILR). This will potentially allow an orders-of-magnitude improvement in the accuracy and precision of interplanetary range measurements (compared to traditional

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radiometric tracking data). Single shot measurement accuracy could potentially be at the order of several mm for ILR, with attainable single shot precision at or below the mm-level attainable for moderate integration times of one minute (Turyshev et al., 2010). However, the use of reflectors in SLR and LLR is not feasible at planetary distances due to the inverse fourth-power dependency of received signal strength with distance (Degnan et al., 1993). Instead, an active space segment is required, reducing the signal-strength dependency to inverse square with distance. In a one-way laser range system, only a receiving system is required on the spacecraft and the observable is directly obtained from the uplink light-time. For two-way systems, a transmitter is additionally needed on the space segment, which is used to (asynchronously) fire laser pulses to the ground station(s) (Degnan, 2002; Dirkx et al., 2014). Using such a system, the two-way range observable is realized through pairing of the up- and downlink light-times (Birnbaum et al., 2010).

The primary difference in error budget between the one- and two-way systems stems from the different influence of clock noise on the observables. For the one-way system, clock noise in both the transmitting and the receiving system accumulates over time, in a similar manner that dynamical model errors accumulate in spacecraft orbit determination. For two-way range systems, this clock noise accumulation only occurs over a limited time, specifically the two-way light-time for the ground station clock noise and the retransmission time for the space segment clock noise.

One-way laser ranging has been used for tracking the Lunar Reconnaissance Orbiter (LRO) spacecraft (Zuber et al., 2010), which used a novel link between receiver optics mounted on the high-gain antenna and its laser altimeter. However, orbit determination of LRO was initially performed using classical radio tracking and altimeter crossovers only, due to the difficulties in processing the one-way laser ranging measurements, as well as the unexpectedly high quality of the radio-science data (Mazarico et al., 2012). Recent progress in including the laser ranging data into LRO orbit determination, as well as efforts to produce laser-only orbits, has shown the feasibility of using this data type for producing high-quality spacecraft trajectories (Mao et al., 2013; Bauer et al., 2014). The concept of two-way laser ranging has been demonstrated by the MESSENGER spacecraft en route to Mercury (Smith et al., 2006) using its laser altimeter system to both detect laser pulses from Earth and transmit pulses to a ground station from a distance of 24 M km.

The use of two-way laser ranging has been proposed for ultra-precise tracking in a number of mission concepts, such as Phobos Laser Ranging (PLR) (Turyshev et al., 2010) and GETEMME (Oberst et al., 2012). Analyses of the attainable parameter estimation quality of the PLR mission for relativistic parameters (Turyshev et al., 2010) and geophysical parameters of the Martian system (Dirkx et al., 2014) indicate that substantial gains in science return can be made by using this technology, compared to results from radiometric methods.

However, detailed analyses of the error budgets of ILR systems have not been performed to date, whereas such analyses are crucial for understanding the limitations in its applicability, the required technology development for its implementation and its expected science return. Due to the absence of retroreflectors in ILR, and the inclusion of active space segment hardware, the relative contributions of the various sources of range errors will be different for SLR and LLR. Although mm-level precision over one minute integration-times (Turyshev et al., 2010) is likely feasible, attaining a measurement accuracy at this level will prove to be more difficult. For instance, Dirkx et al. (2014a) showed that atmospheric turbulence and variable detection energy can already result in accuracy degradations of several mm. It has been shown by Dirkx et al. (2014) that systematic range errors (accuracy degradation) at or even well below the mm-level can result in a much reduced attainable estimation accuracy, compared to perfectly accurate mm-precise range measurements. That is, range measurements with 0 mm precision and 1 mm systematic error will result in substantially larger estimation uncertainties than measurements with 1 mm precision and 0 mm systematic error. This difference between attainable true error and formal error is well acknowledged in the literature on tracking data processing of current planetary missions *e.g.* Marty et al. (2009). To obtain realistic insight into the potential of planetary laser ranging systems, it is crucial to properly include non-Gaussian errors in both observation models and dynamical models.

In this paper, we investigate the influence of signal timing errors on the performance of both one- and two-way laser ranging systems by quantifying the mapping of uncertainties in the clock stability to parameter estimation accuracy. Using these results, we compare the performance of one- and two-way laser ranging systems, for which the primary difference is in how clock errors accumulate in the range measurements. For our simulations we use both a lunar orbiter and a Phobos lander as test cases. In Section 2, we present models for simulating the timing of the transmission and reception of laser pulses, with a specific emphasis on modeling the influence of stochastic clock noise. Methods for modeling and measuring one- and two-way range measurements are given in Section 3. The settings and assumptions for our simulations of both the lunar orbiter and the Phobos lander are presented in Section 4, and results for the performance of both the one- and two-way range systems are presented in Sections 5 and 6 for the lunar orbiter and the Phobos lander, respectively. Finally, Section 7 will summarize the main conclusions of this study. Mathematical details of the method we use to generate colored noise time series are provided in Appendix A.

2. Signal timing

Both one- and two-way range measurements are obtained directly from time tags of signal transmission and reception on the space and ground segments. By processing and combining these time tags, the observables are formed, as will be described in more detail in Section 3.2. Here, we will discuss the model we use for the clocks registering the time tags, from which we can (statistically) quantify the difference between actual and observed measurement times and observables. First, we briefly review the conversion between observable (proper) time and global (coordinate) time in Section 2.1. Subsequently, we present the models we use to quantify clock errors in Section 2.2 and our method to generate stochastic clock noise in Section 2.3. Finally, we discuss the use of estimated arc-wise clock parameters to mitigate clock noise in Section 2.4.

2.1. Time scales

The clocks carried by the observers ideally register their local proper time, which is the relativistic concept of time experienced by an observer. The rate at which an observer's proper time passes, compared to a global (coordinate) time is different for observers at different relative potentials and velocities due to relativistic effects *e.g.* Soffel et al. (2003) and Kopeikin et al. (2011).

For generating range observables, measured proper times need to be converted to a global time scale, such as Dynamical Barycentric Time (TDB) or Barycentric Coordinate Time (TCB), which are independent variables in which planetary ephemerides are typically expressed *e.g.* Moyer (2000); Fienga et al. (2009). It should be noted that although TDB is typically used as a global time, it is *not* a coordinate time, leading to a rescaling of for

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