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Phobos laser ranging: Numerical Geodesy experiments for Martian system science

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ABSTRACT

Laser ranging is emerging as a technology for use over (inter)planetary distances, having the advantage of high (mm-cm) precision and accuracy and low mass and power consumption. We have performed numerical simulations to assess the science return in terms of geodetic observables of a hypothetical Phobos lander performing active two-way laser ranging with Earth-based stations. We focus our analysis on the estimation of Phobos and Mars gravitational, tidal and rotational parameters. We explicitly include systematic error sources in addition to uncorrelated random observation errors. This is achieved through the use of consider covariance parameters, specifically the ground station position and observation biases. Uncertainties for the consider parameters are set at 5 mm and at 1 mm for the Gaussian uncorrelated observation noise (for an observation integration time of 60 s). We perform the analysis for a mission duration up to 5 years.

It is shown that a Phobos Laser Ranging (PLR) can contribute to a better understanding of the Martian system, opening the possibility for improved determination of a variety of physical parameters of Mars and Phobos. The simulations show that the mission concept is especially suited for estimating Mars tidal deformation parameters, estimating degree 2 Love numbers with absolute uncertainties at the 10^{-2} to 10^{-4} level after 1 and 4 years, respectively and providing separate estimates for the Martian quality factors at Sun and Phobos-forced frequencies. The estimation of Phobos libration amplitudes and gravity field coefficients provides an estimate of Phobos' relative equatorial and polar moments of inertia with an absolute uncertainty of 10^{-4} and 10^{-7}, respectively, after 1 year. The observation of Phobos tidal deformation will be able to differentiate between a rubble pile and monolithic interior within 2 years.

For all parameters, systematic errors have a much stronger influence (per unit uncertainty) than the uncorrelated Gaussian observation noise. This indicates the need for the inclusion of systematic errors in simulation studies and special attention to the mitigation of these errors in mission and system design.

1. Introduction

Although there have been various proposed and launched missions targeting Phobos, no *in situ* measurements of it have been performed yet. A number of missions to do so are under investigation such as the Phobos Reconnaissance and International Mars Exploration (PRIME) mission (Lee et al., 2008) consisting of a Phobos lander and orbiter and the Phobos Laser Ranging (PLR) mission (Turyshev et al., 2010), a mission focused on performing direct-to-Earth laser ranging measurements. Current investigations of Phobos employ direct observations by spacecraft such as Mars Express (Witasse et al., 2014), as well as Earth-based tracking of past and current Mars orbiters and astrometric observations (Jacobson and Lainey, 2014; Pascu et al., 2014).

In addition to *in situ* investigations, tracking of a Phobos lander would allow for the direct observation of Phobos libration and deformation (Le Maistre et al., 2013). Modelling of Phobos interior and orbital evolution constrained by available data has not provided an undisputed answer on its origin (Rosenblatt, 2011), making further investigation relevant not only for our understanding of the moon itself, but also planetary system evolution in general. Additionally, Phobos can be used as a drag-free Mars orbiter, allowing potentially improved estimation of Mars physical parameters through tracking of a lander.

Numerical simulations of tracking of spacecraft around and/or landers on Mars, using various mission architectures (*i.e.* direct-to-Earth and lander-orbiter) have been performed, for instance focusing on the estimation of Martian rotational parameters and their relation to its interior structure (Yseboodt et al., 2002; Dehant et al., 2009; Le Maistre et al., 2012) and the seasonal gravity field signal (Karatekin et al., 2005). These studies largely rely on the use of classical radiometric tracking methods, although

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work on new orbit determination methods, such as altimetry crossover (Rosat et al., 2008) and same-beam interferometry (Yseboodt et al., 2012) is also ongoing. Simulations of physical parameter determinations from the combination of Doppler and star tracking observations by a Phobos lander were conducted by Le Maistre et al. (2013), with the goal of constraining Phobos' interior through measurement of its physical librations and tidal deformation.

As an alternative to radiometric methods, interplanetary laser ranging (ILR) is under development as a high-precision tracking technique (mm- to cm-level range) for use on planetary missions (Degnan, 2002). A number of recent mission concepts use this technology, such as the PLR mission (Turyshev et al., 2010) and the Gravity, Einsteins Theory, and Exploration of the Martian Moons Environment (GETEMME) Martian system spacecraft mission (Oberst et al., 2012). The former of these is a Phobos lander that is to perform mm-precise laser range measurements to Earth with the goal of testing general relativity to unprecedented accuracy.

Here, we analyze the capabilities of a Phobos lander similar to the PLR concept to estimate physical parameters of Mars and Phobos. Due to the high range measurement accuracy, as well as the extremely low non-conservative forces acting on Phobos, it is anticipated that significant improvements in their estimation uncertainties can be achieved. From simulated range measurements, we estimate the tidal Love numbers of Mars, as well as the tidal lag at the frequencies of the three main tide-raising bodies. From these parameters, models for the interior structure of Mars can be constrained, in a similar fashion as is now done with tracking data from Martian orbiters (Yoder et al., 2003; Konopliv et al., 2006; Marty et al., 2009; Konopliv et al., 2011).

For Phobos, we simulate the estimation of the libration amplitudes, which are now constrained to only $\sim 0.15^\circ$ (Willner et al., 2010), and are related to its relative moments of inertia. We also simulate the estimation of Phobos' degree-two gravity field coefficients, the combination of which with the relative moments of inertia can be used to determine Phobos' absolute moments of inertia. Additionally, we investigate the estimation of the tidal deformation of Phobos (which is currently unobserved) from simulated tracking data, placing further constraints on models for its interior structure by differentiating between a monolithic and rubble pile structure. The composition of Phobos will provide insight into its origin as well as its orbital evolution, through both long-term propagation of its orbital dynamics and by comparing it to expected compositions from various Phobos origin scenarios.

We first present an overview of the technology and operations of ILR in Section 2, where we also discuss the current state of the technology in terms of experimental implementations and provide some details on the PLR mission concept. Subsequently, the models for the dynamics of Phobos and the observations are presented in Section 3. We discuss the relevance and observation signatures of the estimated geodetic parameters in Section 4 and the estimation procedure in Section 5. The estimation results are discussed in Sections 6 and 7 for Mars and Phobos geodetic parameters, respectively. Finally, we present the main conclusions in Section 8.

2. Planetary laser ranging

Satellite Laser Ranging (SLR) is a space-geodetic technique that is used to directly measure distances from ground stations to Earth-orbiting satellites, *e.g.* Pearlman et al. (2002). It is, along with Global Navigation Satellite Systems (GNSS), Very Long Baseline Interferometry (VLBI) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), one of the fundamental space-geodetic techniques used in the creation of terrestrial reference frames, *e.g.* Altamimi et al. (2011). It has been used for a variety of applications in Earth sciences, summarized by Exertier et al. (2006), such as the determination of Earth rotational parameters, the determination of the behavior of the geocenter and the estimation of low degree and order terms of the Earth's gravity field. Similarly, data from Lunar Laser Ranging (LLR) has been used in the creation of dm-level ephemerides of the Moon (Folkner et al., 2009) and estimation of the lunar libration amplitudes and tidal deformation, leading to an increased understanding of its interior structure (Williams et al., 2006). Additionally, both SLR and LLR have been used in a number of space-based tests of relativity, summarized by Turyshev and Williams (2007).

In this section, the extension of SLR and LLR to interplanetary distances is discussed. Firstly, a general overview of the technique is presented in Section 2.1, followed by its current status of implementation and experimentation in Section 2.2, and its specific conceived implementation for the current study in Section 2.3.

2.1. Overview

The technology of SLR and LLR is based on the reflection of short laser pulses (typically about 10–1000 ps), transmitted from Earth-based stations, by space-based retroreflectors. By measuring the round-trip travel time of the laser pulse and applying corrections for relativistic, tropospheric and hardware effects, the distance to the target can be determined to sub-cm accuracy (Degnan, 1995). Due to the use of retroreflectors, the received laser power falls off with R^{-4}, where R is the distance from the ground station to the target. This aspect puts the Moon near the limit of its feasibility. However, by using active laser transmitters and detectors at both ends of the link (*i.e.* replacing the reflector by an active laser transceiver), the range dependency becomes R^{-2}, allowing sufficient power to be retained when ranging over interplanetary distances (Degnan, 2002).

Also, due to the absence of retroreflectors in such a two-way active configuration, the uncertainty associated with the signature imposed on the laser pulses by reflectors (Otsubo and Appleby, 2003) is absent in ILR. This could potentially increase the attainable measurement accuracy compared to SLR, since the received pulse shape can be predicted better. However, this comes at the expense of the use of active space-based systems (laser transmitter, detector, optics, pointing system, and clock), which complicates both the design and operations of the space segment. Additionally, new types of hardware-induced error sources such as those resulting from the instabilities of the spacecraft clock and optical detector, which are absent in reflector ranging, are introduced.

Using a laser ranging architecture with active systems at both ends of the link, one-, two- and three-way (*i.e.* two-way with different ground stations) interplanetary laser links can be established. In a one-way link, the space segment is typically equipped with only a receiver, which is used to detect laser pulses transmitted from Earth-based ground stations. The transmitted and received signals are then matched and a range measurement is generated. However, since the two measurements are performed by different clocks, the relative behavior of the two clocks during the entire mission needs to be either known from other independent sources or estimated.

In a two- and three-way laser ranging system, laser pulses are typically fired and detected independently from one another by both ends of the link (Degnan, 2002), a technique termed asynchronous ranging. To match transmitted to received laser pulses, the laser pulse transmission time uncertainty (also termed jitter) inherent in transmitters is employed, by matching the jitter pattern as recorded at both ends of the link (Neumann et al., 2008).

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