13-0407

Numerical Geodesy Experiments for a Phobos Laser Ranging Mission Concept

D.Dirkx (1), L.L.A. Vermeersen (1), R. Noomen (1), P.N.A.M. Visser (1)
(1) Delft University of Technology, the Netherlands
d.dirkx@tudelft.nl

Abstract *We have developed a software framework for simulating interplanetary tracking system performance, with a focus on planetary laser ranging systems. Using this software, we analyze the performance of a Phobos lander equipped with an active laser system conducting two-way asynchronous direct-to-Earth ranging. We assume one 30 min tracking arc per day from 8 SLR stations, providing single two-way range normal points at 1 min intervals with a precision of 1 mm, simulated as Gaussian noise. The analysis focuses on the estimation quality of physical parameters of the Martian system, such as gravity field coefficients, Love numbers and rotational parameters of Mars and Phobos. We present the estimation results, which indicate that significant improvement on knowledge of the interiors of both Phobos and Mars can be achieved, both compared to current knowledge and potential radiometric tracking results. However, assuming purely Gaussian noise yields overly optimistic estimation results. We employ consider covariance analysis to investigate the influence of errors in both range accuracy and SLR station positions (modeled as systematic errors). The results of this analysis indicate that these types of errors will dominate the error introduced by the assumed 1 mm range precision by more than an order of magnitude.*

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 Laser Ranging (PLR) mission (Turyshev et al, 2010), a mission focussed on performing direct-to-Earth interplanetary laser ranging measurements (Degnan, 2002).

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 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.

Here, we present a summary of the results of an analysis of 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.

Simulation models

To assess the capabilities of a PLR concept, simulated two-way (asynchronous) laser range measurements are generated, which are subsequently used as input to an orbit determination and parameter estimation model. From this, formal errors of and correlations between the estimated parameters as a function of time are obtained.

A software package (Dirkx and Vermeersen, 2013) based on the Tudat astrodynamics toolbox is used to perform all simulations. The following models are used for the dynamics of Phobos

- Mutual gravitational attraction between Phobos and Mars. The gravity fields are expressed as spherical harmonics series, with the Mars field expanded to degree and order 12 and the Phobos field expanded to degree and order 2. The gravitational acceleration is modelled after Lainey et al. (2001)
- Third-body attraction due to the Sun, Deimos, Earth's Moon and all planets. All third bodies are considered as point masses

The following environment models are used:

- The static spherical harmonics gravity field of Mars by Lemoine et al. (2008).
- Tidal variations of Mars' gravity field due to Phobos, Deimos and the Sun are included for degrees two and three.
- For Phobos, the gravity field values for C_{20} and C_{22} as estimated by Lainey et al. (2007) are used, with other terms nominally set to zero.
- We use the Phobos libration model by Rambaux et al. (2012), who numerically integrate its rotational equations of motion, using Lainey's ephemeris solution, and perform a frequency decomposition of the results.
- The degree-two Phobos tudal deformation due to the potential of Mars is included

We use 8 SLR stations in our simulations, each of which performs tracking to the Phobos lander according to the following criteria.

- Each ground station performs one 30 minute observation arc per day.
- During each 30 minute arc, a single normal point observation is generated per 60 s.
- Each normal point has a precision σ_{obs} of 1 mm, generated independently from a Gaussian distribution with zero mean and σ_{obs} standard deviation.

And the following constraints

- No observation is possible in case of link occultation by the Moon or Mars.
- No observation is possible for solar separation angles $<5^o$. This constraint is imposed to prevent inclusion of observations for which the stray light would be too intense to separate the signal from the noise photons.
- Local elevation angle both at the lander and at the ground station must be $>10^o$.

Using these settings and constraints, we simulate the dynamics of Phobos and laser range observations over a period of 5 years.

Parameter Estimation

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. Additionally, we estimate the degree two and three static gravity field coeficcients and Mars' rotational preceission. 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, *e.g.* Konopliv et al. (2011).

For Phobos, we simulate the estimation of the libration amplitudes, which are now constrained to only about 0.15^o (Willner et al. 2010), and are related to its relative moments of inertia (MOIs). We also simulate the estimation of Phobos' degree-two gravity field coefficients, the combination of which with the relative MOI can be used to determine Phobos' absolute MOI. Additionally, we investigate the estimation of the tidal deformation of Phobos, placing further constraints on models for its interior structure.

When processing tracking data to planetary satellites, the true error is typically roughly one order of magnitude larger than the formal error, *e.g.* Konopliv et al. (2011), due to among others differences between the estimation model and the actual dynamical and observation model. To mitigate this problem, we use consider covariance analysis (Montenbruck and Gill, 2000). In consider covariance analysis, extra parameters are added to the estimation procedure, which are not themselves estimated, but the uncertainty of which is included when determining the covariance matrix. We use a 5 mm consider paramater uncertainty for the ground station position and observation biases to capture the systematic measurement errors and non-Gaussian observation error power spectrum.

Estimation results

Here, we provide a brief overview of the main estimation results that are derived from the simulations. For a deeper interpretation of the results and their relation to Mars and Phobos interior models and the Martian system evolution, the reader is referred to Dirkx et al. (2014). We present example of formal errors with and without the consider parameters in Fig. 1. Discussion of esttimated values assume the inclusion of the consider parameters unless otherwise stated.

Mars gravity and rotation

For the estimation of the precession rate of Mars, roughly 1.5 years of tracking are required for the estimation to reach the *a priori* uncertainty of 10 mas/year with the applied systematic errors. This improves to about 0.1 mas/year after about 3 years, highlighting the strength of the Phobos orbital stability in the parameter estimation. Little improvement in the estimation of Mars' static gravity field is obtained during the mission.

Mars tides

The mission architecture and tracking allows for separate determination of degree-two Love numbers of different orders (see Fig. 1, left panel). The Love numbers at different orders at degree two can be distinguished to the 10^{-2} to 10^{-3} level after 2 years. However, due to the combined effect of degree-two and higher-order Love numbers on the orbit of Phobos, the Love numbers at different degrees cannot be decoupled. Mars quality factors at degree two can be decoupled for the Sun- and

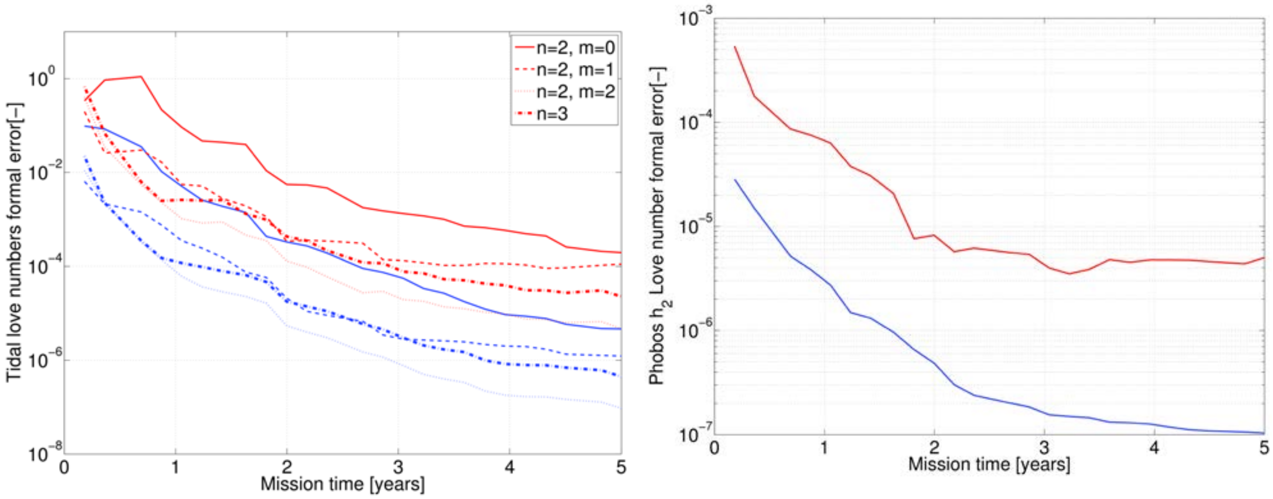

Figure 1 Estimation result of (left) Mars tidal Love numbers (right) Phobos h_2 deformation Love number. Blue: without consider parame- ters. Red: with consider parameters.

Phobos-forced frequency. The delay of the Sun-raised tide takes several years to be decoupled from the systematic errors, though, requiring 3 years to attain an uncertainty on the order of 1. The uncertainty at the Phobos-raised tide frequency reaches 0.01 after 2 years. The effect of the Deimos raised tidal lag is unobservable from the Phobos orbiter, though, preventing the testing of a specific functional form relating quality factor to forcing frequency.

Phobos gravity field, librations and moments of inertia

By a combined estimation of the degree two gravity field coefficients and the libration amplitudes of Phobos, we put constraints on first the relative and then the absolute MOI of Phobos. The determination of the ratio of the polar MOI, denoted γ, at 10^{-8} after 2 years, is consistently about two orders of magnitude more precise than the other two ratios. This is due to the higher precision of the longitude librations, which determines this ratio,. The precision that is reached on the MOI will allow for the determination of the degree of heterogeneity of Phobos' interior. For instance, local unsymmetrical voids or other mass anomalies will be manifested in the relative MOI values. It was found that for the entire mission duration, the libration uncertainties dominate the MOI error budget.

Phobos deformation

The estimation of Phobos' h_2 deformation Love number converges to the 10^{-5} level, with little improvement after 2 years of observation time (see Fig. 1, right panel). The expected lower h_2 values for a rubble-pile Phobos are at the 10^{-4} level (Le Maistre et al. 2013). As a result, a Phobos laser ranging mission will be able to distinguish between a Phobos rubble-pile and a monolithic Phobos after about two years of observation time. Additionally, in the case of a rubble pile Phobos, the mean rigidity can be well constrained. By making this distinction, it will be possible to constrain origin theories of Phobos.

Discussion & Conclusions

We find a substantial difference between results based on simulated data with Gaussian noise only and with additional systematic errors. Due to the very precise nature of the laser ranging measurements, both observational biases and errors resulting from ground station position and calibration mismodelling are much more influential than what is typically the case for planetary tracking data analysis. We find that the inclusion of systematic errors has a strong damping effect on the decrease of the formal estimation error with time, especially for parameters estimated from periodic effects. Only moderate improvement in parameter uncertainties is obtained after 2-3 years for most parameters. This indicates that, firstly, the reduction or mitigation of systematic errors due to ground station errors will be crucial for future planetary laser ranging mission. Secondly, it shows the need to include them in simulation studies, to prevent averaging out of Gaussian noise from providing overly optimistic simulation results.

Since a Phobos lander is relatively insensitive to small Martian rotational variations, combined data analysis of a Phobos and Mars lander (including non-geodetic observations) would provide strong synergy for investigations relating to the Martian interior, as well as precise modelling of Phobos' dynamics. Also, the comparison of modelled and measured internal Phobos composition will be limited by the uncertainty of Phobos' exact volume and shape, which cannot be improved using the PLR mission. Currently, the uncertainty in the volume of Phobos (Willner et al. 2010) will propagate onto a 2% uncertainty in the modelled moments of inertia of a homogeneous Phobos (Le Maistre et al. 2013). Both these points show the need for combining the highly precise laser tracking data with other future high precision measurement types, in both geodetic and non-geodetic studies.

Finally, we conclude from our simulation results that interplanetary laser ranging will be able to strongly improve the science return of a Phobos lander mission, providing orders of magnitude improvements of geodetic measurements of both Mars and Phobos. From these measurements, we will be able to better constrain the origin of the Martian moons and the evolution of the Martian system.

References

Degnan, J., 2002. Asynchronous laser transponders for precise interplanetary ranging and time transfer, J. Geo., 34, p. 551-594.
Dirkx and Vermeersen, Simulation of Interplanetary Laser Links, 2013, EPSC Abstracts, Vol. 8, EPSC2013-481
Dirkx et al., 2014, Phobos Laser Ranging: Numerical Geodesy Experiments for Martian System Science, PSS (submit.)
Konopliv, A. S. et al., Mars high resolution gravity elds from MRO, Mars seasonal gravity, and other dynamical parameters, 2011, Icarus 211, p.401-428.
Lainey, V. et al., 2007, First numerical ephemerides of the Martian moons, A&A 465, p. 1075-84.
Lainey, V. et al., 2001, New estimation of usually neglected forces acting on Galilean system, Celest. Mech. Dyn. Astron. 81, p. 115-122.
Le Maistre, S. et al., 2013, Phobos interior from librations determination using Doppler and star tracker measurements, PSS 85, p. 106-122.
Montenbruck, O. and Gill, E., 2000. Satellite Orbits: Models, Methods, and Applications. Springer Verlag.
Rambaux, N. et al., 2012, Rotational motion of Phobos, A&A 548, A14.
Rosenblatt, P. 2011, The origin of the Martian moons revisited, The A&A Rev. 19, 44.
Turyshev, S. G. et al., 2010, Advancing tests of relativistic gravity via laser ranging to Phobos, Exp. Ast. 28, p. 209-249.
Willner, K. et al, 2010, Phobos control point network, rotation, and shape, EPSL 294, p. 541-546.