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A Phobos geodesy experiment to constrain its bulk interior structure and origin.

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Abstract

The origin of the Martian moons is still an open question [1]. The ill-fated Phobos Soil mission was an ambitious mission devoted to find out an answer to this open issue. Among the suite of instruments dedicated to the interior of Phobos, the radio-science experiment [2] (as well as the libration experiment [3]) were well-suited to provide constraints on the bulk interior structure of Phobos. As such information is one of the key pieces still required to understand the origin of this small body [1], we present here the scientific rationale and the goals of a geodesy experiment, which could easily composed the payload of future missions toward the Martian moon system [4, 5].

1. Scientific rationale

The origin of the Martian moons, Phobos and Deimos, is still an open issue: they may be (a) asteroids captured by Mars, (b) remnants left over from Mars' formation, or (c) formed *in situ* from a circum-Mars debris disk. The premise of the capture scenario is mainly based on the similarities between the physical characteristics of the moons' surfaces, and those of some small-sized low-albedo carbonaceous asteroids. However, this scenario has some weaknesses, for instance, the difficulty to account for the current near-circular and near-equatorial orbits of both moons, and the ambiguity to clearly identify their true composition from the remote sensing observations of their surfaces. On the other hand, the orbits of the Martian moons are consistent with the expected orbits of objects accreted around Mars that led several authors to propose scenarios where both moons formed from material orbiting Mars (e.g. *in situ* formation scenarii). Moreover, the thermal infra-red remote-sensing data of Phobos' surface collected recently by the Mars Express (MEX) spacecraft suggest that Phobos' and Mars' surfaces are composed of similar materials [6], reviving the interest for the *in situ* formation scenarii. However, these scenarii still need to be studied in details and to be confronted with new observations to assess whether they can account for the bulk physical properties of the moons (i.e. size, mass, density [7], viscoelastic properties). Until now, little attention has been paid to the internal structure of those moons. Of particular interest are the mass distribution and the rheological properties of the constituent materials since they influence the dissipation rate of the orbital energy induced by the tidal interactions between Mars and its moons. The MEX data have allowed a precise determination of the density of Phobos (1.85 +/- 0.07 g/cm^3 [1]), which supports heterogeneous composition for Phobos' interior, e.g. porosity and water-ice in addition to rock compounds [1]. On one hand, high porosity fraction inside Phobos supports a formation scenario by re-accretion of debris in Mars' orbit. On the other hand, a water-rich Phobos' interior can significantly increase its tidal dissipation rate, which calls for a fresh look at the capture scenario. Besides the bulk density, the amplitude of the forced libration also provides constraints on the interior structure of the body. Those periodic spin rate variations depend on Phobos moments of inertia and therefore provide insight to its internal structure. A value of 1.2° +/- 0.15° has been obtained from MEX images [8]. Since the error bar includes the expected value of 1.1° obtained from the figure of Phobos in the case of homogeneous mass distribution [8], this measurement is not accurate enough to ensure departures from homogeneity across the satellite. Still, this value within its error bar indicates a slightly heterogeneous internal structure, as suggested by recent models of internal mass distribution [9]. Therefore, the precise determination of Phobos' moments of inertia will provide tighter constraints on its internal structure and the associated dissipation properties. In turn, more realistic constraints will be derived on its post-formation orbital evolution, and hence on its origin.

2. Measurements and goals of a Phobos Geodesy Experiment

The proposed geodesy experiment relies on the ranging and Doppler tracking data acquired by an on-board coherent transponder, providing measurements of radial distance and velocity along the line-of-sight between the spacecraft and Earth-based deep space tracking or VLBI (Very Long Baseline Interferometry) stations. These latter stations afford additional spacecraft position measurements in the plane-of-sky [10]. As foreseen for the Phobos Soil mission, the geodesy experiment will be performed during two important phases of a sample return mission: the orbital and Landing phases. Hereafter, the goals of this experiment are summarized.

Determining the gravity field of Phobos: During the orbital phase, the spacecraft will be in a Quasi-Synchronous-Orbit (QuSyO) with Phobos. It will remain at very close distances to Phobos (45-55 km), and will serve as a sensor of its gravity field. Radio-tracking data will enable precise reconstruction of the orbital perturbations of the spacecraft from which will be estimated the gravity field coefficients, in particular the second-order ones to be used for a precise determination of the principal moments of inertia of Phobos. All deep space and VLBI tracking data will be used in order to separate robustly the gravity field signal from the perturbations induced by the maneuvers required to maintain the QuSyO.

Monitoring the rotational motion of Phobos: Once landed on Phobos, the radio-tracking data of the spacecraft will be used to monitor the rotational motion of Phobos [11]. Numerical simulations have shown that the radio-tracking data will allow determining the amplitude of the short-period librations with a precision of 10^{-3} degrees after a few weeks of data acquisition [12]. Merging the radio tracking data with the star-tracker data will improve the determination of the librations. Along with the gravity field, the libration amplitudes will allow measuring the principal moments of inertia of Phobos at the single-digit percent level, which is required to constrain tightly the internal mass distribution inside the moon [9, 11, 12].

Monitoring the orbital motion of Phobos: The radio-tracking data of the landed spacecraft also contain information on the fine variations of the orbital motion of Phobos. The Doppler measurements are well suited to detect these variations, which could not be measured precisely with astrometry data so far. The gain of precision expected on the reconstructed orbit of Phobos will allow determining the time variations of Mars' even zonal harmonics with a precision of a few percent [4, 13], which have been poorly constrained so far by tracking data of spacecraft orbiting Mars on low-altitude polar orbits (e.g. [14]). It will also lead to an improved determination of the relativistic parameter β by a factor of 2.5 for tracking data acquired over one year [13]. As the radio-tracking data contain information on the full motion of Phobos, the star-tracker measurements will be helpful to decouple the orbital motion from the rotational one.

An "integrated" geodesy experiment: Another important part of the proposed experiment will be based on the merging of the radio-tracking data of both orbiting and landing phases of the mission. The goal of this global inversion of the tracking data is to improve the determination of physical parameters, like the gravity field of Phobos, which influence both spacecraft and Phobos orbital motions [15].

The results of such a Phobos Geodesy Experiment will support the interpretation of other experiments targeting the interior (e.g. using seismometer data) and will complement surface observations, helping to answer the question of the origin of this small body.

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