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Phobos interior from librations determination using Doppler and star tracker measurements

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ABSTRACT

Numerical simulations have been performed to assess the precision that can be obtained on Phobos libration angles by using two types of data acquired by a probe landed on the Martian moon: (1) Direct-To-Earth (DTE) Doppler data and (2) Star-Tracker (ST) data. Compared to independent estimates, combination of DTE and ST data provides the more precise estimates of Phobos libration angles at the 10^{-3}–10^{-5} degree level. Short period libration amplitudes are functions of the relative moments of inertia. Thus their determination would provide constraints on mass distributions inside Phobos. We show that the longitudinal libration amplitude at the orbital period, while being clearly distinct from the resonance period, is the most interesting signal for that purpose, because it leads to the best precision on $(B-A)/C$ (10^{-5} after only 10 weeks of operation). Nevertheless, we showed that inferring the individual moments of inertia A, B and C with a precision sufficient ($<1\%$) to distinguish the rotational behavior of an homogenous from that of an heterogenous body requires the determination of one of the degree-two gravity field coefficient at the percent level.

In addition, we stress that ST and DTE data combination allows de-correlating librational motion from orbital motion since ST measurements are sensitive to the moon's rotation and do not depend on its ephemeris, whereas DTE Doppler data are sensitive to both motions as well as to Phobos' surface displacement due to the tides raised by Mars. Furthermore, the ephemeris of Phobos has to be known at the centimeter level to allow measuring the tidal surface displacement with enough precision to conclude on the nature of Phobos' interior (rubble pile versus monolithic) as one step toward constraining its origin and evolution.

1. Introduction

Recent technological developments for close proximity and in situ operations are opening the door to a new generation of lander-based missions. Owing to its singular place in the Martian system, Phobos is a favored target for these missions in the frame of prospective human exploration and for better constraining the origin of the Martian system. For the past decade, several mission concepts for the in situ exploration[1] of Phobos have been proposed: *Mars Moon Sample Return* mission (Michel et al., 2011) or *Gravity, Einstein's Theory, and Exploration of the Martian Moons' Environment* also known as GETEMME (Oberst et al., 2012) on the European side and *Hall* (Lee et al., 2010), *Phobos Laser Ranging* or PLR (Turyshev et al., 2010), *Phobos Reconnaissance and International Mars Exploration* or PRIME (Lee et al., 2008), and *Mars Moons Multiple-landings Mission* (Lee et al., 2011) on the US side. Also, a Russian mission named *Phobos-Soil* (Korablev, 2009) was launched in November 2011 but failed shortly after launch, falling down into the Pacific ocean in January 2012.

Phobos is in synchronous spin-orbit resonance around Mars, showing on average the same hemisphere to Mars. This uniform rotational motion is superimposed by oscillations, called physical librations, that result from the time-varying gravitational torque exerted by Mars on the dynamical figure of Phobos. In 2010, by analyzing Phobos images obtained by the SRC (Super Resolution Channel) of the HRSC (High Resolution Stereo Camera) on the European *Mars Express* (MEX) spacecraft, Willner et al. (2010) observed a libration in longitude of amplitude $1.2 \pm 0.15°$. This physical libration of about 500 m peak-to-peak at the surface is one of the largest among all known synchronously orbiting, natural satellites of the solar system. The amplitudes of libration are linked to the mass repartition inside the body and so are an elegant way to obtain information on the interior. Taking as a

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[1] By "in situ" we refer to landed missions.

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reference the payload onboard *Phobos-Soil*, including a star tracker and an X-band coherent transponder, we assess the precision that could be achieved on the determination of Phobos' libration amplitudes using both Direct-To-Earth (DTE) Doppler (as done in Le Maistre et al., 2012 for Mars) and Star Tracker (ST) measurements.

In addition, the tidal deformation of Phobos is evaluated and compared against the estimated precision that could be obtained on the surface displacement by using DTE Doppler data. Phobos' ability to deform depends on its bulk interior, rigidity and composition. Knowing these properties would provide crucial information on its origin and evolution (Rosenblatt, 2011).

To reach these objectives, we perform numerical simulations based on a least-squares techniques. Results from that study stress the value of geodetic measurements for constraining Phobos' interior.

The paper is divided in 13 parts. The model of rotation of Phobos used in this study is presented first in Section 2. Then we describe the data simulation method in Section 3. The precisions that can be achieved on the determination of the libration of Phobos are shown in Section 4 and the lander coordinates estimates, determined using DTE Doppler data simultaneously with rotational parameters, are presented in Section 5. The Phobos ephemeris issue is discussed in Section 6 and the rotation mismodeling impact on libration amplitude estimates is pointed out in Section 7. We assess then the constraints that can be obtained on the proper frequency (Section 8) and moments of inertia (Section 9) of the Martian moon from the determination of its librations. We shortly discuss in Section 10 about what can be learned on Phobos gravity field and Mars oblateness from a precise measurement of the librations. Finally, we characterize in Section 11 the tides raised by Mars on Phobos' surface as a function of its interior structure and composition and we compare the theoretical radial motion of the lander with the precisions that can be obtained on the tidal displacement determination using radio science measurements. A brief discussion on Phobos dissipation is carried out in Section 12 and key results are summarized in Section 13.

Table 1
Direction of the North pole of rotation and the prime meridian of Phobos at J2000 derived from the Rambaux et al. (2012) rotational model. Linear and quadratic terms are from Seidelmann et al. (2002).

At J2000	Linear terms	Quadratic terms
$\alpha_0 = 317.65171^\circ$	$\dot{\alpha} = -0.108^\circ$/century	–
$\delta_0 = 52.875277^\circ$	$\dot{\delta} = -0.061^\circ$/century	–
$W_0 = 34.78084^\circ$	$\dot{W} = 1128.844585^\circ$/day	$\ddot{W} = 8.864^\circ$/century^2

Table 2
Periodic variations of the rotation axis direction and prime meridian of Phobos' figure expressed in amplitudes of sine and cosine derived from the Rambaux et al. (2012) rotational model. The series are truncated at 10^{-4} degree, hence considering only variations greater than 2 cm at the surface of Phobos.

Period (**day**) T_α	**Cosine amplitude** (**deg.**) $\alpha^c_{T_\alpha}$	**Sine amplitude** (**deg.**) $\alpha^s_{T_\alpha}$
Libration in α		
826.2093	0.325245	1.758464
686.9689	3.7879×10^{-3}	-9.9870×10^{-3}
413.1034	8.0360×10^{-3}	2.0727×10^{-2}
0.8430	-5.0099×10^{-3}	1.5865×10^{-2}
0.5133	-1.3858×10^{-2}	-2.6599×10^{-2}
0.2313	-3.0986×10^{-2}	-3.4267×10^{-2}
T_δ	$\delta^c_{T_\delta}$	$\delta^s_{T_\delta}$
Librations in δ		
826.2098	1.059273	−0.200688
686.9603	-5.8509×10^{-3}	-3.1664×10^{-3}
413.0996	6.2752×10^{-3}	-2.3877×10^{-3}
0.8430	9.5540×10^{-3}	3.2837×10^{-3}
0.5133	1.6049×10^{-2}	-8.3571×10^{-3}
0.2313	2.0673×10^{-2}	-1.8695×10^{-2}
T_W	$W^c_{T_w}$	$W^s_{T_w}$
Librations in W		
826.2082	−0.260555	−1.403236
413.1050	-8.1901×10^{-3}	-2.1305×10^{-2}
0.8430	3.9954×10^{-3}	-1.2650×10^{-2}
0.5133	1.1051×10^{-2}	2.1210×10^{-2}
0.3190	0.177178	1.085406
0.2313	2.4709×10^{-2}	2.7324×10^{-2}
0.1595	-2.7638×10^{-3}	-8.2309×10^{-3}

2. Phobos rotational model

In the simulations presented in this paper, we use the most recent model of rotation of Phobos from Rambaux et al. (2012). This model expresses the transformation between Mars' mean equatorial plane at the date and the reference frame tied to Phobos. In the present paper dealing with the observation of Phobos from the Earth, we use the Earth mean equator of J2000 epoch (i.e., the 1st January 2000 at 12 h) as reference frame. Thus, the librational angles expressed in Mars' mean equatorial plane at the date are expressed in the Earth mean equator of J2000 (inertial frame denoted hereafter as EME2000) and the rotation is described through three angles (α, δ, W). The right ascension, α, and the declination, δ, specify the direction of the figure axis of the body. The angle W describes the location of the prime meridian of the body in its equatorial plane. We express these angles as

$$\alpha = \alpha_0 + \dot{\alpha} t + \sum_{T_\alpha} \left(\alpha^c_{T_\alpha} \cos\left(\frac{2\pi}{T_\alpha} t\right) + \alpha^s_{T_\alpha} \sin\left(\frac{2\pi}{T_\alpha} t\right) \right), \tag{1}$$

$$\delta = \delta_0 + \dot{\delta} t + \sum_{T_\delta} \left(\delta^c_{T_\delta} \cos\left(\frac{2\pi}{T_\delta} t\right) + \delta^s_{T_\delta} \sin\left(\frac{2\pi}{T_\delta} t\right) \right), \tag{2}$$

$$\begin{aligned} W = {} & W_0 + \dot{W} t + \ddot{W} t^2 \\ & + \sum_{T_w} \left(W^c_{T_w} \cos\left(\frac{2\pi}{T_W} t\right) + W^s_{T_w} \sin\left(\frac{2\pi}{T_W} t\right) \right) - \Delta\alpha \sin\delta. \end{aligned} \tag{3}$$

where the sine (cosine) amplitudes are labeled with a superscript "s" ("c"). T_α, T_δ and T_W are the periods of the librational signals. The values of the coefficients are listed in Tables 1 and 2.

These angles are expressed as functions of constant, linear, quadratic, and periodic terms. The α_0, δ_0 represent the position of the rotation axis at J2000, and W_0 describes the location of the prime meridian at J2000. The linear term in W represents the uniform rotational motion of Phobos and the quadratic term is related to the secular acceleration of the orbital motion that is transferred to the rotation through the spin-orbit resonance (Rambaux et al., 2012). The linear term in α and δ and the periodic terms represent the precessional motion of the polar axis of Phobos and its librational motion, respectively.

We introduce the last term in Eq. (3) for the reduction process. In this equation $\Delta\alpha$ is the deviation of the $\alpha-$libration from its a priori value, i.e., the correction in the orientation of the equatorial plane of Phobos and differs from zero only when $\alpha^c_{T_\alpha}$ and $\alpha^s_{T_\alpha}$ are estimated.

All the periodic terms are called hereafter "Phobos rotation and Orientation Parameters" (POP) or "libration parameters". In the following, the longitudinal librations refer to the W series and latitudinal librations refer to the series in α and δ. Their coefficients and periods are listed in Table 2. The amplitudes reported in that