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Librational response of a deformed 3-layer Titan perturbed by non-Keplerian orbit and atmospheric couplings

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ABSTRACT

The analyses of Titan's gravity field obtained by Cassini space mission suggest the presence of an internal ocean beneath its icy surface. The characterization of the geophysical parameters of the icy shell and the ocean is important to constrain the evolution models of Titan. The knowledge of the librations, that are periodic oscillations around a uniform rotational motion, can bring a piece of information on the interior parameters.

The objective of this paper is to study the librational response in longitude from an analytical approach for Titan composed of a deep atmosphere, an elastic icy shell, an internal ocean, and an elastic rocky core perturbed by the gravitational interactions with Saturn. We start from the librational equations developed for a rigid satellite in synchronous spin–orbit resonance. We introduce explicitly the atmospheric torque acting on the surface computed from the Titan IPSL GCM (*Institut Pierre Simon Laplace General Circulation Model*) and the periodic deformations of elastic solid layers due to the tides. We investigate the librational response for various interior models in order to compare and to identify the influence of the geophysical parameters and the impact of the elasticity.

The main librations arise at two well-separated forcing frequency ranges: low forcing frequencies dominated by the Saturnian annual and semi-annual frequencies, and a high forcing frequency regime dominated by Titan's orbital frequency around Saturn. At low forcing frequency, the librational response is dominated by the Saturnian gravitational torque and the atmospheric torque has a small effect. In addition, the libration amplitude in that case is almost equal to the magnitude of the perturbation. The modulation of the gravitational torque amplitude at the orbital frequency with periodic deformation induces long-period terms in the librational response which contain information on the internal structure. At high forcing frequency the libration depends on the inertia of the layers and the elasticity can strongly reduce its amplitude at orbital frequency. For example, the amplitude of diurnal libration for oceanic models goes from about 320–390 m if the icy shell is purely rigid to 60–85 m when the elasticity is included, *i.e.* a reduction of about 80%. For models without ocean, diurnal libration goes from 52 m in a rigid case to 50 m for an elastic case, a very low reduction due to the weak deformation of an entirely solid satellite compared to the deformation of a thin icy shell. Oceanic models with elastic solid layers have the same order of libration amplitude than the oceanless models, which makes more challenging to differentiate them by the interpretation of librational motion.

1. Introduction

Titan exhibits a rich interior structure due to its large mean radius of 2575 km. The recent measurements of the gravity field by Iess et al. (2010, 2012) reveal that Titan's moment of inertia (MoI) is as low as 0.33–0.34 MR^2. A large panel of internal structures, made of a low density core surrounded by icy layers, is consistent with this range of MoI and the mean density value of 1881 kg m^{-3} deduced by Iess et al. (2010). In addition, the presence of a global internal ocean has been suggested from several techniques. First, Lorenz et al. (2008) deduced the putative internal ocean through the response of the rotational motion of the surface to the atmospheric coupling. A second piece of evidence has been obtained from the determination of the non-zero obliquity by Stiles et al. (2008) from the radar images of Cassini. They determined an obliquity equal to 0.3° that is larger

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than 0.1° obtained for a rigid Titan in a Cassini state (*e.g.* Bills and Nimmo, 2008). Then Bills and Nimmo (2008) and Baland et al. (2011) suggested that this deviation is related to the influence of an internal ocean on the obliquity. Additional arguments in favor of this internal ocean have been obtained by electrical (Béghin et al., 2012), topographical (Nimmo and Bills, 2010) and gravitational (Iess et al., 2012) analyses of Titan from Cassini–Huygens data.

Titan's rotational motion has been measured by Stiles et al. (2008, 2010) that used the Cassini spacecraft's radar images in order to follow landmarks at the surface. They obtained a near-synchronous rotation for Titan with a drift rate of 0.00033 degree per day, *i.e.* 0.12 degree per year (Stiles et al., 2010). This approach has been recently revisited by Meriggiola and Iess (2012) that determined a synchronous spin–orbit motion within a residual of about 0.02 degree per year. The main advantage of their approach is the introduction of Titan's librational motion in the reduction process. The librations describe the oscillations around the uniform rotational motion. Here we focus on the librations in longitude that correspond to the oscillations of the body principal axis projected onto the equatorial plane of the satellite. In the case of Titan, they have two distinct origins. The first one comes from the gravitational torque exerted by Saturn on the dynamical figure of Titan. The second one results from the atmospheric torque, i.e. the coupling between the surface and the dense atmosphere of Titan. Their amplitudes are modified by the interior parameters of Titan. However, Goldreich and Mitchell (2010) suggested that the elastic behavior of the icy shell is not negligible and may strongly reduce the librational motion. Such a prediction has been confirmed by Van Hoolst et al. (2013) that computed the libration in longitude at the orbital frequency of Titan. In that case, Titan's surface will deform instead of rotating since the ocean figure should always point toward the planet and exert an elastic torque on the icy shell.

The objective of this paper is to determine the librational response of an elastic Titan at various forcing frequencies resulting from its orbital motion. By including the atmospheric coupling, we want to decorrelate surface forcing from the internal geophysical properties related to the internal ocean and perturbation of Titan's orbit. We investigate the wide spectrum of Titan's librations in contrast to Van Hoolst et al. (2009, 2013) that focused on the diurnal frequency (Titan's orbital frequency) and its harmonics, and on the Saturnian semi-annual frequency (twice Saturn's orbital frequency) for the atmospheric coupling. The main interest is that in the orbital motion, there are librations at the Saturnian semi-annual frequency that comes from the interaction of Saturn with the Sun. Such librations have the same frequency than the main component of the atmospheric torque. In addition, the orbital frequency spectrum can be in, or close to, resonance with some proper frequencies as shown for the Galilean satellites (Rambaux et al., 2011). Finally, the periodic variation of the gravitational torque amplitude at orbital frequency provides long-period terms in the libration with amplitudes dependent on the interior model.

In this paper, the recent interior models of Titan are also used (*e.g.* Castillo-Rogez and Lunine, 2010; Fortes, 2012; McKinnon and Bland, 2011) in order to compute the values of the proper frequencies and to discuss the differences in the amplitude of librations. The elasticity is investigated by computing the radial deformations of surfaces due to the tides and responsible for the gravitational torques amplitude variations.

Finally, we use the 3D atmospheric model from Lebonnois et al. (2012) that predicts an atmospheric torque smaller than in the Tokano and Neubauer (2005) paper used in all previous studies (Goldreich and Mitchell, 2010; Karatekin et al., 2008; Lorenz et al., 2008; Van Hoolst et al., 2009, 2013).

In the first part of the paper, the internal structure models selected for the librational computation are described. The properties of these models depend on the history and energy sources of Titan (*e.g.* Tobie et al., 2012). We selected a broad range of possible internal scenarios for Titan in order to characterize the impact of the geophysical parameters on the librations. The atmospheric torques of Charnay and Lebonnois (2012) (called here CH12) and of Tokano and Neubauer (2005) (called here TO05) are described and discussed in Section 3. The orbit of Titan is then analyzed in Section 4 by using the frequency analysis method providing the spectrum of the orbital motion. In Section 5 the elasticity is introduced in the librational equations through periodic torques amplitudes and the librations are analytically determined for the rigid and elastic cases. Finally, the behavior of the libration angle at different forcing frequency ranges is analyzed and the influence of the geophysical parameters of the different interior models is discussed in Section 6.

2. Interior models

Titan's internal structure has been revealed by accurately tracking the trajectory of Cassini spacecraft approaching Titan during six flybys (Iess et al., 2010, 2012). They measured the gravity field and its variations allowing one to infer information on the density profile of the satellite. Since the inversion between the gravity field and the density profile is not unique, only a range of models can be determined. The add-on assumption that Titan is close to the hydrostatic equilibrium led Iess et al. (2010) to obtain an estimation of the moment of inertia (MoI) I of Titan between 0.33 and 0.34 MR^2 (where M and R are the mass and mean radius of Titan, respectively). Such a small MoI implies an increase of density towards Titan's center and requires a low-density core to match the mean density of 1881 kg m^{-3} (Iess et al., 2010).

In parallel to these gravity measurements, two categories of thermal and chemical models have been developed to determine Titan's internal structure (*e.g.* Castillo-Rogez and Lunine, 2010, 2012; Fortes, 2012; McKinnon and Bland, 2011 and see the review of Tobie et al., 2012). In the first category, as developed by Fortes (2012), the models described essentially the upper layers (dense and light ocean, comparison of solid models with pure water ice or methane clathrate layers), while in the second category the models focused on the inner core composition assuming the presence of a global ocean layer (*e.g.* Castillo-Rogez and Lunine, 2012; McKinnon and Bland, 2011).

Castillo-Rogez and Lunine (2012) built interior models made of an anhydrous silicate core surrounded by hydrated rock and water ice, while McKinnon and Bland (2011) focused on hydrated silicates surrounded by mixture of rock and ice. These models of inner core allow the presence of a small iron core, and are compatible with an internal ocean as deduced by Iess et al. (2012).

Six different models reported in Table 1 have been selected, coming from Fortes (2012) (the models called F1, F2 and the solid model F3), Castillo-Rogez and Lunine (2010) (models CA10 and FE10) and McKinnon and Bland (2011) (model MC11). The FE10 model is similar to the CA10 model with an additional small inner iron core as suggested by Castillo-Rogez and Lunine (2010). The icy shell thickness has been taken equal to 100 km for each model. Such a value corresponds to the upper bound obtained by the topographical model of Nimmo and Bills (2010). The lower bound has been obtained by Béghin et al. (2012) by using Schumann's resonance in Titan's atmosphere. The icy shell thickness is an essential parameter for Titan's models with a rigid shell (Van Hoolst et al., 2009) but the elasticity strongly diminishes its influence (see Section 6). Fortes (2012) used oceans with a bottom mean radius of 2225 km (models F1 and F2). To be able to compare the influence of the ocean density and the inner core structure on the libration, the same ocean bottom mean radius is used for the CA10, MC11 and FE10 models. For a given set of solid layers' sizes