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Modeling the polar motion of Titan

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ABSTRACT

The angular momentum of the atmosphere and of the hydrocarbon lakes of Titan have a large equatorial component that can excite polar motion, a variable orientation of the rotation axis of Titan with respect to its surface. We here use the angular momentum obtained from a General Circulation Model of the atmosphere of Titan and from an Ocean Circulation Model for Titan's polar lakes to model the polar motion of Titan as a function of the interior structure. Besides the gravitational torque exerted by Saturn on Titan's aspherical mass distribution, the rotational model also includes torques arising due to the presence of an ocean under a thin ice shell as well as the influence of the elasticity of the different layers.

The Chandler wobble period of a solid and rigid Titan without its atmosphere is about 279 years. The period of the Chandler wobble is mainly influenced by the atmosphere of Titan (−166 years) and the presence of an internal global ocean (+135 to 295 years depending on the internal model) and to a lesser extent by the elastic deformations (+3.7 years).

The forced polar motion of a solid and rigid Titan is elliptical with an amplitude of about 50 m and a main period equal to the orbital period of Saturn. It is mainly forced by the atmosphere of Titan while the lakes of Titan are at the origin of a displacement of the mean polar motion, or polar offset. The subsurface ocean can largely increase the polar motion amplitude due to resonant amplification with a wobble free mode of Titan. The amplitudes as well as the main periods of the polar motion depend on whether and which forcing period is close to the period of a free mode. For a thick ice shell, the polar motion mainly has an annual period and an amplitude of about 1 km. For thinner ice shells, the polar motion amplitude can reach several tens of km and shorter periods become dominant. We demonstrate that for thick ice shells, the ice shell rigidity weakly influences the amplitude of the polar motion. For thin ice shells, the level of the resonant amplification of the polar motion amplitude depends on the ice shell rigidity. Future observations of the polar motion of Titan could help constraining some properties of its interior structure as the ice shell thickness and ocean density.

1. Introduction

Titan is one of the large icy satellites of the Solar System together with Europa, Callisto and Ganymede, which are thought to have a global ocean beneath their surface. There is ample evidence for the presence of such a subsurface ocean. The measured tidal Love number of Titan is much larger than expected for a entirely solid satellite and compatible with a dense subsurface ocean (Iess et al., 2012). The measured obliquity of Titan is also larger than expected for a solid satellite while a global subsurface ocean allows deriving realistic values for the mean moment of inertia from the measured obliquity (Baland et al., 2011, 2014; Noyelles and Nimmo, 2014). Moreover, measurements of extremely low frequency electromagnetic waves and of the conductivity in the atmosphere of Titan by the Huygens probe indicate the presence of a subsurface conducting layer (Béghin et al., 2010, 2012).

Due to the presence of a fluid layer between two solid layers, an upper ice shell and a solid interior, the rotation of the interior of Titan can differ from the rotation of the ice shell. Titan rotates almost synchronously with its orbital motion, but small variations with respect to the synchronous state are possible due to the gravitational forcing of Saturn and exchange of angular momentum with the atmosphere and hydrocarbon lakes. The rotation variations of the different internal layers of the satellite are coupled through various coupling mechanisms, and the surface rotation

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variations could be different from those for a solid satellite. Rotation variations include the spin precession, the variations in the rotation rate and the polar motion.

The deviation from a synchronous rotation of the ice shell was estimated as 0.36°/year by Lorenz et al. (2008), a value so high that it was suggested that the shell of Titan was decoupled from its interior. However, a reprocessing of the data led to a smaller value of 0.11°/year (Stiles et al., 2010) and recent data even indicate a value as small as 0.02°/year (Meriggiola and Iess, 2012). Theoretical estimates of the influence of a subsurface ocean on the rotation rate variations of Titan showed that the amplitude of the gravitationally forced variations (librations) is strongly influenced by the thickness of the ice shell for a high rigidity shell although tidal deformations of the different layers of the satellite for realistic rigidities reduce the libration amplitude to values close to that of an entirely solid satellite (Van Hoolst et al., 2009, 2013; Richard et al., 2014; Jara-Orué and Vermeersen, 2014). Length-of-day variations forced by exchanges of angular momentum between the atmosphere and the surface of Titan increase substantially by elasticity when a subsurface ocean is present (Van Hoolst et al., 2013). These seasonal changes in the rotation rate could potentially be observed and inform on the properties of the ice shell and ocean.

Here, instead of considering variations in the rotation rate or the spin axis precession, we study the changes in the orientation of the rotation axis with respect to the solid surface, or polar motion. For the Earth, polar motion is mainly excited by the atmosphere and the oceans. Besides seasonal polar motion, the polar motion of the Earth has also an important component with a period equal to the period of the Chandler wobble, the free mode of polar motion. The Chandler wobble period is strongly influenced by the elastic deformations, the presence of a liquid core and of the oceans (Smith and Dahlen, 1981). It can be expected that periodic exchanges of angular momentum between the dense atmosphere of Titan and the surface will also excite polar motion of Titan and that the presence of an internal ocean and elasticity will affect the Chandler wobble period and therefore polar motion. The influence of the atmospheric forcing on the polar motion has already been studied by Tokano et al. (2011) for a rigid Titan. They showed that the amplitude of the polar motion of Titan is of the order of a few meters and increases by an order of magnitude for solid layers fully decoupled in the presence of a subsurface ocean. For small ice shell thicknesses, a resonance with the Chandler wobble could further increase the polar motion amplitude. The possibility of a resonance of the wobble of Titan triggered by the orbital node precession has been investigated in Noyelles et al. (2008) and Noyelles (2008). We here do not take the slow variations of the orbit orientation into account and we focus on periods shorter than the annual period of Saturn (29.42 years).

The aim of this article is to develop a model for the polar motion of Titan that includes the effects of a subsurface ocean, various interlayer couplings and elasticity. We not only consider polar motion due to the atmosphere but also caused by exchanges of angular momentum with the hydrocarbon lakes. We model the polar motion for a large set of interior models of Titan to assess if essential properties of the ice shell of Titan (as its thickness and its density) could be deduced from future observations of the polar motion of Titan.

The plan of the paper is as follows. In Section 2, we develop the angular momentum equations that will be used to obtain the polar motion of an entirely solid Titan. We describe the torques due to Saturn, the atmosphere and the lakes and show that Titan has a rotational normal mode like the Chandler wobble for the Earth. The study for an entirely solid Titan sets the stage and introduces the main methods to be used in Section 3, where we develop the angular momentum equations for a model of Titan including a subsurface ocean. We develop expressions for various interlayer torques and model the influence of tidal deformations. Numerical results for polar motion are calculated for a large set of interior models of Titan in Section 4 and compared with the case of an entirely solid Titan. We end with a discussion of the results in Section 5.

2. Chandler wobble and polar motion of a solid Titan

2.1. Governing equations

The polar motion of Titan describes the motion of the axis of rotation with respect to the surface. It is the combination of the free wobble of the body due to the misalignment between its rotation axis and its figure axis and wobbles forced by Saturn, by the atmosphere and the hydrocarbon lakes of Titan. We first describe the changes in the angular momentum of Titan due to the torques and next derive expressions for the three different torques.

2.1.1. Angular momentum equations

We first consider the rotation of an entirely solid and rigid Titan. In a frame related to the mean principal axes of inertia of Titan (called Body Frame or BF) with equatorial axes X and Y and polar axis Z corresponding to the principal moments of inertia A, B and C, respectively ($A < B < C$), and with the origin at the mass center of Titan, we write the rotation vector as $\vec{\omega} = (\omega_X, \omega_Y, \omega_Z)$ where (ω_X, ω_Y) expresses the polar motion and $\omega_Z = n + \dot{\gamma}$ the rotation rate where n is the mean motion of the synchronous Titan and γ is the libration angle. In order to model the polar motion, we use the basic physical principle that, in an inertial reference frame, the time-derivative of the angular momentum $\vec{H}$ of the system, here Titan, is equal to the applied torque $\vec{\Gamma}$ on the system. This angular momentum equation, or Euler–Liouville equation, can be expressed in the BF of the satellite as

$$\frac{d}{dt}\begin{pmatrix} H_X \\ H_Y \\ H_Z \end{pmatrix} + \begin{pmatrix} \omega_X \\ \omega_Y \\ \omega_Z \end{pmatrix} \times \begin{pmatrix} H_X \\ H_Y \\ H_Z \end{pmatrix} = \begin{pmatrix} \Gamma_X \\ \Gamma_Y \\ \Gamma_Z \end{pmatrix} \tag{1}$$

since the body frame is rotating with respect to an inertial frame with the rotation vector $\vec{\omega}$ of the satellite. The total torque $\vec{\Gamma} = (\Gamma_X, \Gamma_Y, \Gamma_Z)$ acting on a solid Titan is the sum of the gravitational torque $\vec{\Gamma}_e$ exerted by Saturn, the atmospheric torque $\vec{\Gamma}_{\rm Atm}$ and the torque due to the hydrocarbon lakes of Titan $\vec{\Gamma}_l$.

In the BF, the angular momentum $\vec{H} = (H_X, H_Y, H_Z)$ is equal to the product of the inertia tensor and the rotation vector. $\vec{H}$ can be written as

$$\begin{pmatrix} H_X \\ H_Y \\ H_Z \end{pmatrix} = \begin{pmatrix} A + c_{11} & c_{12} & c_{13} \\ c_{12} & B + c_{22} & c_{23} \\ c_{13} & c_{23} & C + c_{33} \end{pmatrix} \begin{pmatrix} \omega_X \\ \omega_Y \\ \omega_Z \end{pmatrix}, \tag{2}$$

where the incremental inertia c_{ij} are due to elastic rotational an tidal deformations of Titan (see Section 2.1.2.2). Correct up to the first order in $\omega_X,\ \omega_Y$ and in the incremental inertia c_{ij}, we have

$$\begin{pmatrix} H_X \\ H_Y \\ H_Z \end{pmatrix} = \begin{pmatrix} A\omega_X + nc_{13} \\ B\omega_Y + nc_{23} \\ C\omega_Z + nc_{33} \end{pmatrix}, \tag{3}$$

so that we need to derive an expression for $c_{13},\ c_{23}$ and c_{33} in order to study the angular momentum equations of Titan.

2.1.2. Gravitational torque

2.1.2.1. Rigid Titan. The gravitational torque exerted by Saturn on Titan is defined by

$$\vec{\Gamma}_e = -\int_V \vec{r} \times \rho(\vec{r}) \nabla W(\vec{r}) dV, \tag{4}$$