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The rotational dynamics of Titan from Cassini RADAR images

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ABSTRACT

Between 2004 and 2009 the RADAR instrument of the Cassini mission provided 31 SAR images of Titan. We tracked the position of 160 surface landmarks as a function of time in order to monitor the rotational dynamics of Titan. We generated and processed RADAR observables using a least squares fit to determine the updated values of the rotational parameters. We provide a new rotational model of Titan, which includes updated values for spin pole location, spin rate, precession and nutation terms. The estimated pole location is compatible with the occupancy of a Cassini state 1. We found a synchronous value of the spin rate (22.57693 deg/day), compatible at a 3-σ level with IAU predictions. The estimated obliquity is equal to 0.31°, incompatible with the assumption of a rigid body with fully-damped pole and a moment of inertia factor of 0.34, as determined by gravity measurements.

1. Introduction

The Cassini–Huygens mission has yielded measurements of rotational dynamics, static and dynamic gravity field, and electromagnetic field, which can be used to infer the internal structure of Titan, the largest icy satellite of the Saturnian system. The relatively high axial moment of inertia (MoI = 0.3414 ± 0.0005), estimated from the quadrupole moment (J_2 and C_{22}) of Titan's gravity field using the Radau–Darwin approximation (Iess et al., 2010, 2012), indicates some degree of internal differentiation of Titan with a low density deep interior (~2600 kg m^{-3}). Such a low density value can be explained if Titan is either partially differentiated with a deep interior composed of a mixture of ice and rock or fully differentiated with a deep interior composed mainly of hydrated silicates (Iess et al., 2010; Castillo-Rogez and Lunine, 2010; Fortes, 2012). Iess et al. (2012) measured the tidal Love number k_2 (0.589 ± 0.150), inferred from the time-variation of the quadrupole moment of the gravity field. Mitri et al. (2014) argued that the high value of the measured tidal Love number k_2 indicates the presence of a dense subsurface ocean with an average density of at least 1200 kg m^{-3} underneath an outer ice shell that is at least 50 km thick. Castillo-Rogez and Lunine (2012) have shown that the tidal Love number k_2 value increases as the subsurface ocean density increases up to a value of 0.6 indicating a possible high concentration of salts as expected from interior structure models of Titan in which the silicate core is partially hydrated. The detection of a Schumann-like resonance from the Permittivity, Wave and Altimetry (PWA) instrument on board the Huygens' probe suggests the presence of a conductive subsurface ocean underneath an outer ice shell ~55–80 km thick (Béghin et al., 2010).

The rotational dynamics, specifically the spin rate and obliquity, can provide additional constraints on the interior structure of Titan. Stiles et al. (2008) by tracking surface features using the misregistration between overlapping Cassini SAR images found a significant deviation of Titan's spin rate (~0.36 deg/year) from the expected value of an icy satellite in synchronous rotation. Lorenz et al. (2008) argued that the apparently significant Non-Synchronous Rotation (NSR) of Titan might be produced by the moment exchange between the zonal winds and the outer ice shell, decoupled from the deep interior by a subsurface ocean, as predicted by the General Circulation Model (GCM) of Titan's atmosphere (Tokano and Neubauer, 2005). However, Stiles et al (2010) later corrected this estimate to be 22.57731 deg/day (with a NSR of 0.124 deg/year). Karatekin et al. (2008) demonstrated that the gravitational coupling between the deep interior and the outer ice shell would prevent any deviation from the synchronous rotation larger than 0.02–0.04 deg/year. Van Hoolst et al. (2009, 2013) found a maximal NSR of ~0.013 deg/year. These results are in agreement with the analysis by Goldreich and Mitchell (2010) on the outer icy shell and atmospheric torque, which also predicted a synchronous spin rate for Titan. Goldreich and Mitchell (2010) also have shown that if Titan's surface is spinning faster than the

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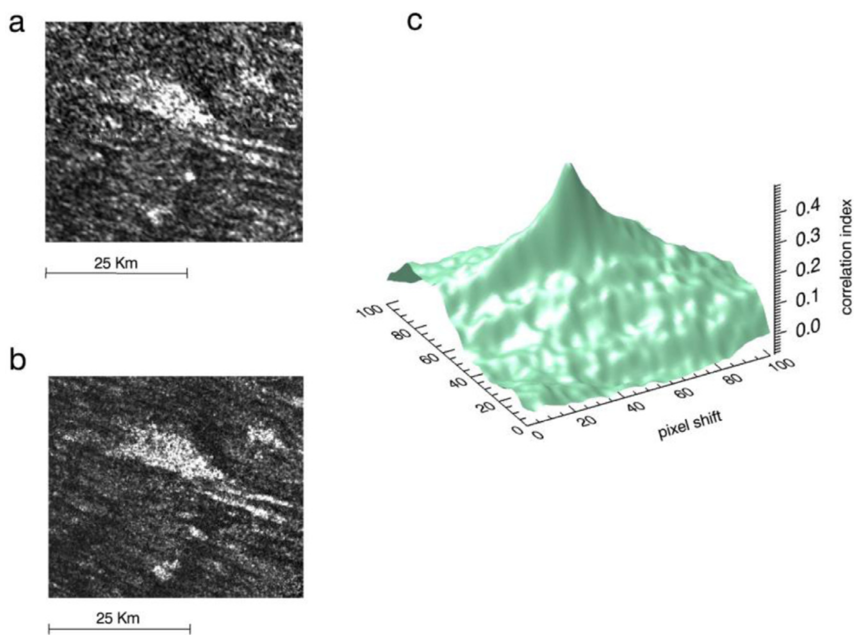

Fig. 1. Surface feature observed during the T13 (A) and T55 (B) Cassini RADAR flybys, and the relative correlation matrix (C). The correlation peak value is equal to 0.50. The images have the same resolution (256 pxl/deg) but only T55 is corrected for the thermal noise.

synchronous spin rate, then tides raised by Saturn on Titan would provide an additional torque tending to restore synchronous spin.

Stiles et al. (2008) also estimated that the obliquity of Titan is 0.3°. Such a value is not in agreement with the 0.15° value inferred from gravity measurements (Iess et al., 2010). Bills and Nimmo (2008, 2011) sought to explain the measured value of the obliquity obtained by Stiles et al. by suggesting that Titan possessed a partial decoupling between the deep interior and the outer shell, or a partial spin pole damping. Subsequently Baland et al. (2011) defined the Cassini state for a model of Titan with a liquid ocean and determined a theoretical prediction for the obliquity of the shell equal to 0.32°. In agreement with Mitri et al. (2014), Baland et al. (2014) have shown that Titan's obliquity measurements by Stiles et al. (2008) can be explained only if a subsurface ocean with a mean density between 1275 and 1350 kg m^{-3} is present. Furthermore, Baland et al. (2014) have shown that the measured value of the obliquity of Titan (Stiles et al., 2008) and the tidal Love number (Iess et al., 2012) indicates that the outer ice shell is at least 40 km thick and the subsurface ocean density ranges between 1300–1350 kg m^{-3}.

We analyze the rotational dynamics of Titan by tracking surface landmark features in time using Cassini SAR images acquired from both the Cassini Prime and Extended Mission up until 2009. We provide a new estimate of spin rate and obliquity of Titan, and we present a rotational model, including precession and nutation effects. In addition, we discuss the implications of the rotational dynamics for the internal structure of this icy satellite.

2. Method

2.1. SAR data analysis

The rotational dynamics of a celestial body can be determined by tracking its surface landmarks along time (e.g. Davies et al., 1992). We determined the rotational state of Titan using Cassini RADAR observations of 160 surface landmarks, obtained from 31 flybys of Titan during the Prime and Extended Mission (2004 – 2009). Previous analysis by Stiles et al. (2008) used two years of data (from 2004 to 2006). Landmark tracking is a comparison between two (at least) SAR images observing the same surface feature (e.g. lakes, channels, ridges). Fig. 1 shows an example of a surface landmark observed during the Cassini RADAR T25 flyby of February 22, 2007 (Panel A) and subsequently monitored on the T28 flyby on April 10, 2007 (Panel B). Since SAR images are geo-referenced it is possible to compare the registered position of each landmark at two different epochs. The difference between the registered positions is called *registration error*. Registration errors are due to a difference between the true rotation of the body and the rotational model used to geo-reference the images. We minimized the misregistration resulting from the rotational model using a least squares fit, correcting the pole location and spin rate. The uncertainties of these rotational parameters were calibrated by considering the errors on the spacecraft (S/C) ephemeris and attitude reconstruction, as well as data calibration.

From 2004 to 2009 the Cassini RADAR instrument provided 2000 km long by 200 km wide SAR image swaths during 31 flybys of Titan, with a total coverage to 2009 > 30 % of the surface. Images reporting the normalized backscatter cross-section value were registered at a closest approach altitude between 950 and 1900 km. The large strip width is due to the multiple antenna Ku-band array structure used to generate five SAR beams, put together to form the image. Each of these beams is characterized by a different pointing angle, relative to antenna reflector's focal axis (Elachi et al., 2005).

We used a 2D cross-correlation method, largely applied to remote sensing field (Brown, 1992), to register the SAR image pairs. This approach is significantly different with respect to previous analysis (Stiles et al., 2008) where a visual detection was used, a method that does not allow one to quantify the accuracy of the image matching. A 2D cross-correlation algorithm is based on the identification of the position of the maximum of the cross-correlation function between the two images (I). If we indicate with A the N×M matrix registered at first observation and with B the N×M matrix registered at the second observation, the bidimensional cross-correlation function f_c is expressed as:

$$f_c(k,q) = \frac{\sum_{i=1}^{N}\sum_{j=1}^{M}[A(i,j)-\bar{a}]\left[B(i-k,j-q)-\bar{b}\right]}{\sqrt{\sum_{i=1}^{N}\sum_{j=1}^{M}[A(i,j)-\bar{a}]^2\sum_{i=1}^{N}\sum_{j=1}^{M}\left[B(i-k,j-q)-\bar{b}\right]^2}} \quad (1)$$