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Resonant Rotation states of Saturnian satellites

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Abstract

The planet Saturn hosts over sixty known satellites. While most of the large satellites move in the near-equatorial plane of Saturn in near-circular orbits, others move in higher-eccentricity or inclined orbits. Most of the satellites (15) are known - and others are believed (4) - to be tidally locked, i.e., their mean orbital and rotational periods are identical. Rotational parameters of the satellites - when combined with shape information - offer unique insights into the interior structures of these bodies. The resonant rotation parameters are a prerequisite for the interpretation of the measurements and form a basic framework especially for parameters associated with long-period terms.

1. Method

The resonant rotation states are derived from the ephemerides of the satellites. In fact, we are using the osculating orbital elements of a satellite in an inertial reference frame, i.e., International Celestial Reference Frame (ICRF). The time series of orbital elements is decomposed in a secular part and a sum of periodic terms

$$x(t) = \sum_{i=0}^{n_s} x_i t^i + \sum_{i=1}^{n_p} x_i^p \begin{matrix} \sin(\omega_i t + \varphi_i) \\ \cos(\omega_i t + \varphi_i) \end{matrix}, \qquad (1)$$

where $x(t)$ is the signal, t the ephemeris time (TDB), x_i are the parameters of the secular part and $x_i^p, \omega_i, \varphi_i$ are the amplitude, frequency, and phase of the periodic part, respectively. n_s and n_p denote the number of terms in the secular and periodic part, respectively.

The parameters are obtained by an iterative algorithm. Using a Fast Fourier transformation (FFT) we identify the frequency and phase of the highest amplitude in the power spectrum. The derived values are then used as initial values within a least-squares fit of the secular and periodic parts. The obtained fit parameters are used to extract the identified component from the original signal and the iteration cycle starts again with the residuals as input signal. When a threshold in the residuals RMS is reached or the requested number of periodic terms n_p is obtained the iteration stops. More details on the frequency mapping approach can be found in [1,2].

2. Rotation axis

For the resonant rotation state we assume that the satellite occupies Cassini state 1 with zero obliquity. Furthermore, we assume that the free precession period is much smaller than any periods in the orbit orientation variations. With these assumptions the satellite's rotation axis is precisely following the instantaneous orientation of the orbital plane. This assumption is supported by the fact that amplitudes of very short variations of the orbital orientation are typically very small and can be neglected in practice. In some cases where the free precession period is considered to be close to some period of significant orientation variation the derived values can be used as forcing terms in the computation of the satellite's response. Hence, we derive the resonant rotation axis parameters by mapping them to the parameters of the osculating orbital elements. We use the parameters obtained from the decomposition of the time series of the orbital inclination i and the longitude of the ascending node Ω

$$\begin{aligned} \alpha_0 &= \Omega_0 + \frac{\pi}{2}, \qquad \alpha_i = \Omega_i\,, \qquad \alpha_i^p = \Omega_i^p \\ \delta_0 &= \frac{\pi}{2} - i_0, \qquad \delta_i = -i_i\,, \qquad \delta_i^p = -i_i^p\,. \end{aligned} \qquad (2)$$

The trigonometric functions $\sin(\omega_i t + \varphi_i)$ and $\cos(\omega_i t + \varphi_i)$ can be directly inferred from the orbital elements.

3. Physical librations

With the resonant rotation axis we can now compute the longitudinal libration forcing terms. For that we compute the angle λ measured between the direction to the central body and the x-axis of the frame aligned with the rotation axis in z-direction. By construction of this frame, the vector pointing from the satellite to the central body lies always in the same plane, i.e., the orbital plane. The derived angle λ is comparable to the mean longitude in case the rotation axis is close to the z-axis of the inertial frame. The decomposition of λ gives the dynamical prime meridian constant λ_0, resonant rotation rate λ_1, and the forcing amplitudes of the longitudinal libration λ_i^{p}.

The physical libration in longitude γ of a satellite is its response to the forcing (e.g. [3])

$$\gamma = \sum_i \frac{\lambda_i^{\mathrm{p}}}{1 - (\omega_i / \omega_0)^2} \sin(\omega_i\, t + \varphi_i)\,. \tag{3}$$

The free libration frequency ω_0 is critical, as it is linked to the interior structure. For a solid body and expanded up to first order in the eccentricity it is given by

$$\omega_0 = n \sqrt{3 \frac{B - A}{C}}\,, \tag{4}$$

where n is the mean motion and $A < B < C$ are the satellite's principal moments of inertia.

We may distinguish between two regimes in the librational response spectrum. For $\omega_0 \ll \omega_i$ the libration amplitude approaches

$$\frac{\lambda_i^{\mathrm{p}}}{1 - (\omega_i / \omega_0)^2} \rightarrow 0\,. \tag{5}$$

For $\omega_0 \gg \omega_i$, however, the libration amplitude approaches

$$\frac{\lambda_i^{\mathrm{p}}}{1 - (\omega_i / \omega_0)^2} \rightarrow \lambda_i^{\mathrm{p}}\,, \tag{6}$$

For the resonant rotation model, we assume that the free libration period is vanishing, i.e. $\omega_0 \rightarrow \infty$, and report all forcing terms which are above a specified threshold, e.g., 10 arc sec. Once the amplitude of the physical librations is measured it can be interpreted in terms of the moments of inertia with the help of the forcing terms in the resonant rotation model.

4. Results - Enceladus

Using Cassini Imaging Science Subsystem (ISS) images the Enceladus' physical libration amplitude of about 500 m (at the equator) has been measured [4]. Besides the annual libration (at 1.37 days) the authors have also considered long-period libration terms with periods of 3.88 and 11.05 years, respectively [5]. Our analysis of the libration forcing λ reveals that there are two additional terms with periods of 2.36 and 4.99 years, which have amplitudes of about 100 m (at the equator) [6]. This value is larger than the 2σ uncertainty for the annual libration amplitude of 60 m [4]. We argue that these long-period terms can bias the annual libration measurement especially in the case when observations from different epochs are combined in the analysis.

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