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Prediction of Saturn's gravity harmonics and ring mass sensitivity for the proximal orbits of the Cassini Solstice mission

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Abstract

The Cassini-Huygens spacecraft continues to explore the Saturn system in the extended mission named "Solstice". This 7-year extension will culminate with 22 proximal orbits that have periapses located between the innermost D-ring and the upper layers of Saturn's atmosphere. Six of these orbits will most likely be used for the gravity field mapping and ring mass measurements. Our current study shows that the data obtained during these flybys will result in ~25% accuracy for the B-ring mass. Furthermore, we will be able to measure the even zonal harmonics to at least 12th degree. The Solstice mission ends with a Titan flyby that sets the spacecraft on the final impact trajectory with Saturn.

1. Introduction

The Saturn system was previously surveyed by three spacecraft; Pioneer 11, Voyager 1 and 2. Its most recent visitor is Cassini, in residence since 2004. Despite our growing knowledge about Saturn and its prominent rings, there are some important physical parameters that are yet to be estimated. For example, mass of the rings is only known to an order-of-magnitude. We need to refine this value in order to better understand ring dynamics and to establish their origin and age. We also need to learn more about the gravity field of Saturn. The higher degree gravitational harmonics ($n \geq 8$) are currently largely unconstrained and these parameters provide a direct clue about the planet's interior structure and possibly even the deep wind patterns [1]. We look to the proximal orbits of the Solstice mission to provide this highly valuable science data.

2. Methods

Proximal orbits are designed so that the spacecraft serves as a "test" particle in the Saturn gravitational field. It is likely that the ring mass will also perturb the spacecraft trajectory. We selected 6 non-consecutive orbits for our gravity measurements. These are the only orbits for which we will have the continuous (except when occulted by the rings) radio-tracking of the spacecraft from Earth as it is going though the periapses and through the ring plane. Table 1 shows the approximate ring mass values [2], [3], [4] that are based on the optical depths of the rings. The Cassini trajectory will primarily be perturbed by the B-ring which has the largest mass. Our orbital model assumes that D-ring mass is negligible, and that the total ring mass is distributed among the A, B, and C rings. We use a weighted-least squares fit to estimate the dynamical parameters of the equations of motion for the spacecraft. We solve for the state vector, radioisotope thermoelectric generator (RTG) accelerations, small forces acting on the spacecraft due to daily angular momentum management of the Reaction Wheel Assembly (RWAs), GM of Saturn, pole of Saturn, GM of the B-ring, and gravity harmonics J_2, J_3, J_4, J_6, J_8, J_{10}, and J_{12}. In order to produce more conservative estimates of the data sensitivity with respect to the ring mass and gravitational harmonics, our study includes various sources of non-gravitational perturbations on the spacecraft, variations in tracking stations coverage, 100% uncertainty on the C and A ring masses (see Table 1), as well as varying data weights for two-way Doppler.

3. Results

Based on the data from 6 proximal orbits we expect to estimate the B-ring GM at a level of ~0.4 km^3s^{-2}, which could be within 25% of the B-ring mass assuming GM = 1.5 km^3s^{-2} (Table 1). Our study also shows that the data have good sensitivity to the higher degree gravitational harmonics. Table 2 summarizes the measurement accuracy for the gravitational field coefficients. Predicted values of the zonal harmonics with degree ten and higher fall into the 10^{-6} to 10^{-7} range [5]. Table 2 shows that our data allow for at least 10% accuracy. We do however have a considerable correlation between the higher degree harmonics. We are very interested in these zonal harmonics because a recent modeling study of Jupiter's gravitational field [4] found that the gravity harmonics beyond tenth-degree originate from the atmospheric dynamics (e.g. density anomalies due to wind) as opposed to gravitational effects that are induced by the planet's rotation. The Cassini Solstice mission will be able to provide experimental evidence if such a phenomenon also occurs at Saturn.

4. Tables

Table 1: Saturn's rings GMs calculated based on [2], [3], [4] and assuming Saturn's GM=3.8×10^7 km^3 s^{-2}

Ring	km^3 s^{-2}
C	0.06
B	1.3-1.9
A	0.22-0.32

Table 2: Measurement uncertainties for Saturn's gravitational harmonics

Coefficient	$\times$ 10^{-9}
δ J_2	1
δ J_3	1
δ J_4	3
δ J_6	6
δ J_8	10
δ J_{10}	10
δ J_{12}	7

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