ENCELADUS GRAVITY AND TITAN GRAVITY AND TIDES FROM CASSINI TRACKING DATA.

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Introduction: For more than a decade the Cassini mission [1] explored Saturn and its icy moons. Among its many instruments, Cassini carried a Radio Science Subsystem that provided Earth-based Doppler tracking of the spacecraft using the Deep Space Network (DSN). These radiometric tracking data were used to determine the gravity fields and, consequently, the interior structure of some of Saturn's moons [*e.g.*, 2,3,4], and of Saturn itself [5]. Here, we reanalyze Cassini radiometric tracking data with an independent analysis strategy and different tools from previous efforts. Our analysis focuses on the flybys of the moons Enceladus and Titan. We determine Enceladus' gravity field to spherical harmonics degree two, including the zonal term J_3 as well. For Titan, following previous efforts [6], we determine its gravity field up to degree and order 5, as well as its tidal Love number k_2 [6,7]. Our results are in agreement with earlier efforts for Enceladus [3]. For Titan, our results for the degree two coefficients are in general agreement, but we find higher power for the other terms. We also find a Love number k_2 that is more in agreement with pre-Cassini studies [8].

Data Analysis: We processed DSN radiometric X-band tracking data in continuous spans of time called arcs, using the NASA GSFC GEODYN II software [9]. We use 10 seconds averaged data for the flybys of both bodies. We numerically integrate the equations of motion for both the central body (Enceladus or Titan) and the spacecraft, using high-fidelity models for the forces. The forces include the following: the central body's gravity field (and tides, for Titan); third body perturbations by Saturn, seven of its largest moons, and the solar system bodies; Saturn's zonal harmonics gravity; solar radiation and drag; and accelerations induced by the radioisotope thermoelectric generators (RTG). We model the measurements using highly accurate and state-of-the art models, including but not limited to effects from the troposphere and ionosphere, and effects from ocean loading on the DSN sites. We then compare the modeled measurements with the actual observations (their differences are the residuals) and adjust parameters for both forces and measurements in a batch least-squares sense [*e.g.*, 10].

We divide the set of estimated parameters into two groups: local parameters that only affect measurements in one arc, and global parameters that affect measurements for all arcs. The local parameters are the following: the state (position and velocity) at initial epoch for both the spacecraft and central body, a scaling coefficient for solar radiation pressure, scaling coefficients in the spacecraft frame for the RTG accelerations, and a measurement bias for 3-way Doppler data (different transmitting and receiving stations) to account for differences in reference frequency at the stations. We only used 3-way data if they were collected during closest approach. We also estimate a drag scaling coefficient for each Titan flyby, and velocity adjustments at closest approach for two of the three Enceladus flybys [3]. The global parameters are the coefficients of a spherical harmonics expansion of the gravity field, the body's gravitational parameter *GM*, and for Titan its Love number k_2.

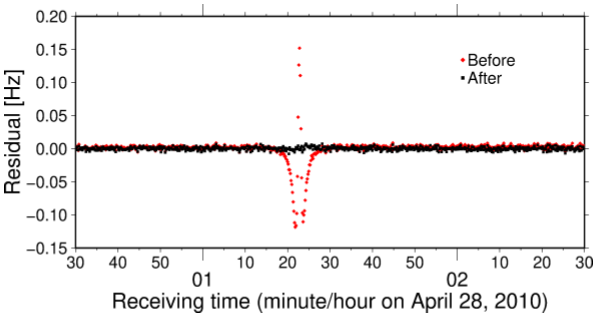

Figure 1: Tracking data residuals from DSN-55 before and after gravity field estimation for the Enceladus flyby E009. The closest approach signal is clearly visible before gravity estimation. After gravity estimation, the residuals resemble measurement noise.

For Enceladus, there were three flybys dedicated to gravity. We processed these data in arcs with durations slightly over one day. For the ten flybys dedicated to Titan gravity we processed the data in arcs with an average length of slightly more than two days. We apply relatively weak constraints on the state parameters of the central body, but all other parameters are unconstrained. We iterate this process many times, initially estimating only a degree and order two field, and gradually increasing the number of spherical harmonic coefficients (in the case of Titan; for Enceladus we included J_3 after several iterations). We consider the iterations converged when the residuals fit at noise level and do not change between iterations. In Figure 1 we show an example of residuals for Enceladus flyby E009, before and after gravity estimation.

Results: For Enceladus, we find that the coefficients that are determined best are J_2 and C_{22}; J_3 has a formal error just below its estimated value, and the remaining degree 2 coefficients have errors larger than their values (we use unnormalized coefficients unless stated otherwise). We find a ratio of J_2/C_{22}=3.30±0.27, which is consistent with hydrostatic equilibrium within the given error bars. Our results compare well to those from an earlier analysis [3]. Our J_2/C_{22} ratio is somewhat smaller, and our J_3 somewhat larger. Our remaining degree 2 coefficients are considerably larger (but as indicated, in principle statistically insignificant), but we also find our results for the other coefficients are not very sensitive to them. Forcing them to be small in our solution does not significantly change the other coefficients. We use variance component estimation (VCE; [11]) in our analysis to determine the data weights per flyby. Our formal errors are larger than those from [3]. We show the results for Enceladus' gravity field in Figure 2.

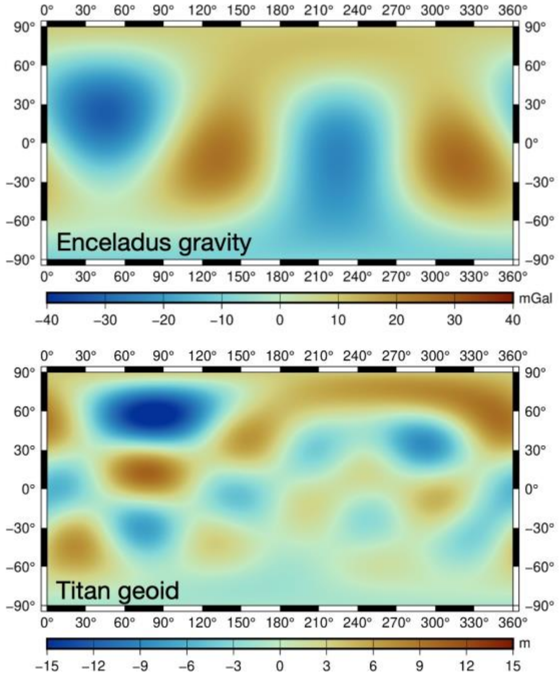

Figure 2: Enceladus radial gravity (top) and Titan geoid (bottom). The coefficients C_{20} and C_{22} were set to zero as they dominate the solutions.

For Titan we find results that agree with earlier analysis [2] when we do not estimate Titan's Love number. Our ratio of J_2 and C_{22} is 3.44±0.79, though our errors are again larger. We show Titan's geoid in Figure 2. We also find a higher power in our solution for Titan than earlier work [6]; see Figure 3. This could indicate a need for constraints, although the actual power at the very low degrees is unknown.

When we include the estimation of the Love number k_2, our results differ. Our ratio J_2/C_{22} is 3.21±0.72, close to that of earlier analysis with again a larger error. Our values for k_2 however are generally between 0.3 and 0.4, in line with pre-Cassini predictions [8]. This has implications for the density of the ocean and rigidity of the interior, among others [6].

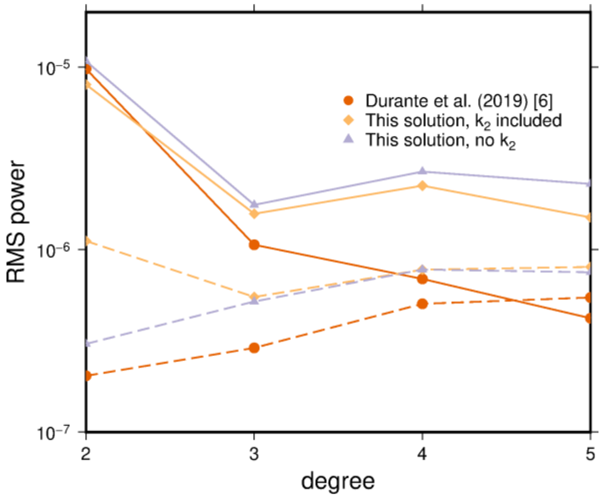

Figure 3: Root mean square of the power (using normalized coefficients) for various solutions for Titan's gravity field. Dashed lines indicate the formal errors.

Acknowledgments: Cassini radiometric tracking data and ancillary information can be found at the Planetary Data System, Atmospheres Node: https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/Cassini/inst-rss.html.

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