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Enceladus's measured physical libration requires a global subsurface ocean

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ABSTRACT

Several planetary satellites apparently have subsurface seas that are of great interest for, among other reasons, their possible habitability. The geologically diverse saturnian satellite Enceladus vigorously vents liquid water and vapor from fractures within a south polar depression and thus must have a liquid reservoir or active melting. However, the extent and location of any subsurface liquid region is not directly observable. We use measurements of control points across the surface of Enceladus accumulated over seven years of spacecraft observations to determine the satellite's precise rotation state, finding a forced physical libration of $0.120 \pm 0.014°$ (2σ). This value is too large to be consistent with Enceladus's core being rigidly connected to its surface, and thus implies the presence of a global ocean rather than a localized polar sea. The maintenance of a global ocean within Enceladus is problematic according to many thermal models and so may constrain satellite properties or require a surprisingly dissipative Saturn.

1. Introduction

Enceladus is a 500-km-diameter satellite of mean density 1609 ± 5 kg m^{-3} orbiting Saturn every 1.4 days in a slightly eccentric ($e = 0.0047$) orbit (Porco et al., 2006). Much of its surface is covered by tectonic forms that have removed or modified a significant fraction of the impact crater population extant on almost all other icy moons in the outer Solar System (Helfenstein et al., 2010; Bland et al., 2012). Adding to this evidence of geological activity is the discovery (Porco et al., 2006), of ongoing venting of material from fractures at high southern latitudes.

Evidence has accumulated that the jets arise from a liquid reservoir, rather than from active melting, most notably the finding that the particulates in the jets are salty, indicating freezing of droplets that likely originate in a liquid reservoir in contact with a rocky core (Waite et al., 2009; Hansen et al., 2011; Postberg et al., 2011; Porco et al., 2014; Hsu et al., 2015). Tidal heating of Enceladus driven by its elliptical orbit is the favored mechanism to form and maintain a liquid layer in such a small object that has minimal radiogenic contributions (Porco et al., 2006; Travis and Schubert, 2015). The confinement of the jet activity to a ~400-m deep topographic depression poleward of ~60°S has focused attention on the possibility of a lens of liquid beneath the south polar terrain (SPT) (Collins and Goodman, 2007). The stratigraphy of fractures in the south polar terrain has been interpreted as indicating long-term (perhaps on timescales $>10^6$ yr) non-synchronous rotation (Patthoff and Kattenhorn, 2011) that would demand decoupling of the shell from the core and thus a global liquid layer rather than a local sea. Tracking of the Cassini spacecraft during close flybys of Enceladus yielded gravity models consistent with a mass anomaly at high southern latitudes that suggests at least a regional subsurface sea of liquid water (Iess et al., 2014). The gravity data have been reinterpreted (McKinnon, 2015) as allowing for a thin, possibly discontinuous, but perhaps instead global, liquid layer.

One way to attack the problem of the liquid layer's extent is accurate measurement of the satellite's rotation (McKinnon, 2015). Owing to Enceladus's slightly eccentric orbit and somewhat elongated shape (Appendix A), it is subject to periodic torques that force harmonic oscillations (called physical librations) in its orientation, on top of an overall synchronous rotation. The magnitude of this response depends upon the object's moments of inertia and

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the coupling of the surface with the interior (Rambaux et al., 2011). Precise measurements of forced libration can be accomplished by long-term stereogrammetric measurements of surface control-point networks from imaging observations, as reported for Phobos (Oberst et al., 2014), Epimetheus (Tiscareno et al., 2009) and Mimas (Tajeddine et al., 2014). Different techniques such as radar and laser ranging have been used to determine forced librations of Mercury (Margot et al., 2012) and of the Moon (Rambaux and Williams, 2011).

In this paper we next review our methods of control-point calculations, and then in Section 3 we describe the basic rotational elements as related to the physical libration. Subsequently in Section 4 we report the results of the libration measurement and in Section 5 we summarize our estimation of the uncertainty of the libration measurement which is treated in detail in Appendix B. Section 6 discusses some interior models consistent with the physical libration amplitude of Enceladus and Section 7 summarizes our results and their implications.

2. Methods

Control points are surface features, usually craters, whose locations are manually digitized. Image coordinates of four or more points on crater rims are marked, and the line and sample of the center of an ellipse fit to those points (Fig. 1a) are recorded as the control-point's image coordinates. These coordinates are then rotated with the camera's inertial orientation (C-matrix), scaled by the camera's optical parameters in combination with the relative positions of target and spacecraft, to provide body-centered (3-D) vectors. The array of these observed (2-D) image coordinates can then be fit to predicted coordinates in the target body's coordinate frame (Davies et al., 1998). Most of the software used in this work was developed for the NEAR mission by J. Joseph (Thomas et al., 2002) with subsequent modifications by B. Carcich and J. Joseph. The processes of recording and analyzing control point data are common to most stereogrammetric measurements of planetary bodies using spacecraft imaging.

The Cassini camera's optical parameters (focal length, distortion) are sufficiently accurate that they introduce errors of well under 0.1 pixels across the detector. Geometric calibration of the ISS Narrow and Wide-Angle cameras (NAC, WAC), based on in-flight stellar images is described in Owen (2003). The NAC provides scales of 6 μrad/pixel (6 km/pixel at 10^6 km range), and the WAC 60 μrad/pixel (60 km/pixel at 10^6 km range). Fields of view of the two cameras are 0.35° and 3.5°.

Because achievable precision in the measurements is far better than the camera pointing information, all images require pointing corrections. In this operation, the target body's center is shifted in line and sample (X, Y). We do not generally allow the twist (rotation about the optical axis) to vary if the solution has any rotational outcome of interest. In a libration study using images obtained from high latitude, allowing the twist to vary would directly affect the inferred rotational orientation.

Images spanning all longitudes allow closure of the control network such that relative positions of all points around the object are constrained. In our solution we require at least three different measurements of a point, with minimal angular separation of 10°. Nearly all our data far exceed the minimal angular and number requirements.

Because image pointing is allowed to change, the residuals in the images are determined by the relative spacing of the projections of the points in the image, rather than by total rotational offsets. Thus, for each solution, all the body-centered positions in each image are recalculated, and a change of any input data or assumed spacecraft position (including the rotation model) can affect all computed body-centered x, y, z positions. We have held the body center fixed in image coordinates for three images only, to have the coordinate origin conform to the centers found by limb-fitting (Thomas, 2010). For the overall solution, this is largely a convenience, as once the coordinate origin is reset and a best solution found with all other image pointings reset, allowing all the image centers (that is, camera-pointing) to vary did not change the average best-fit residuals (to 0.0001 pixels).

Binary kernels were developed to encode different physical libration amplitudes at increments of 0.01° over a wide range of values and with finer increments (0.001°) close to the best solution. The entire data set was then used in solutions for each assumed libration amplitude.

3. Rotation models

Previous observations have confirmed that Enceladus rotates synchronously to within 1.5° (Porco et al., 2014); by definition, this rate matches Enceladus's mean motion (its average angular orbital velocity) as specified by the orbit's semimajor axis via Kepler's Third Law. However, as with other bodies in the complex saturnian

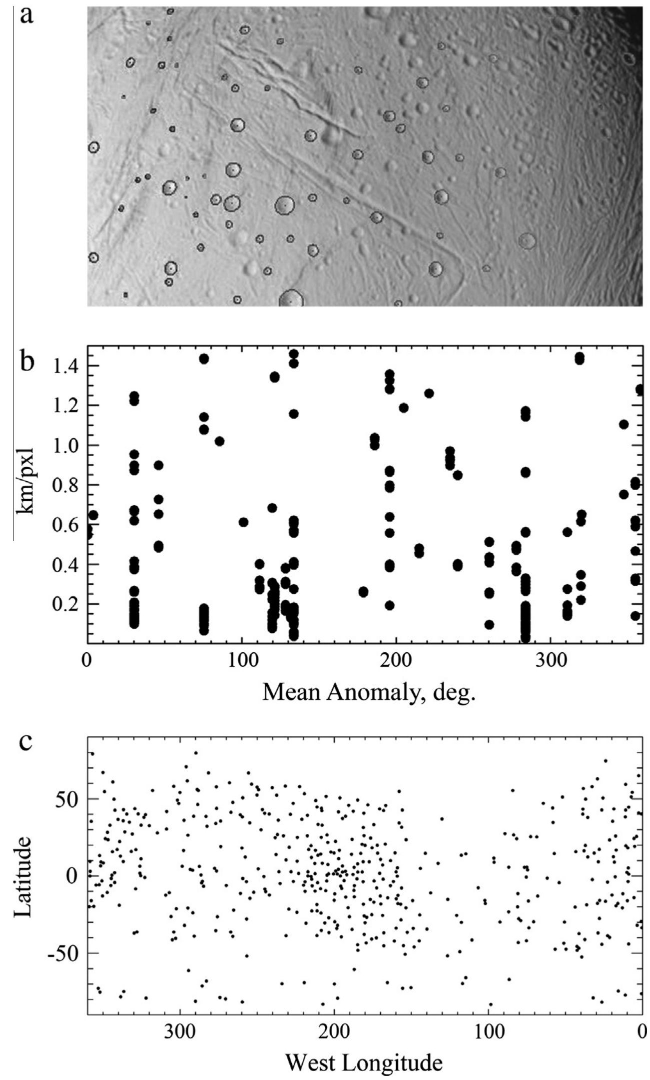

Fig. 1. Measurement of the libration amplitude. (a) Example of marked control points in a Cassini image. Image panel width 260 km. (b) The pixel scale of images used vs. mean anomaly, the angular distance from periapse. (c) Distribution of control points over the surface of Enceladus.