ELASTIC THICKNESS OF TITAN'S ICE SHELL ESTIMATED FROM A COMBINED STUDY OF GRAVITY AND TOPOGRAPHY.

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Summary: Combined analyses of gravity and topography can yield insights into how surface topography is supported. Here, we examine Titan's degree-2 and degree-3 admittances (ratios of gravity to topography at particular wavelengths) based on recently reported Cassini fly-by results. We obtain significant negative admittances at degree-3, suggesting that Titan's degree-3 topography may be accompanied by anomalously deep roots at the base of the ice shell. We show that such a situation could arise if Titan's ice shell is significantly elastic and if the surface has undergone extensive erosion. Our model predictions match the observed degree-3 admittances when we assume the topographic peaks have experienced ~400 m of erosion since their formation. While the degree-2 case is complicated by Titan's tidal distortion, we can use the degree-3 results to estimate what portion of the degree-2 gravity and topography signals are due to ice shell thickness variations rather than tidal distortion. The analysis suggests that Titan's fluid Love number may be even larger than previously estimated.

Data: Titan's gravity field is represented using spherical harmonic coefficients derived from the potential coefficients of [1]. Titan's topography is represented by coefficients derived from SAR topo and radar altimetry by [2]. Admittance, $Z(l) = \Delta g(l)/h(l)$, and coherence between the gravity (Δg) and topography (h) signals are computed in the frequency domain following [3]. Figure 1 shows admittances computed from each of the three distinct gravity solutions of [1] for each of four different topography solutions from [2]. The distinct topography solutions arise from using different maximum degrees of harmonic expansion to fit the observations. Almost all cases show negative admittance at degree 3, and in the case with greatest coherence, the admittance is -39 ±22 mGal/km. In that case, the degree-3 topography is dominated by the S_{31} term, for which the 1-σ uncertainty is ~26%.

Model: We assume the surface topography is supported through a combination of shell thickness variations and flexure. We allow for loading to occur from the top (e.g., due to sedimentation, erosion, or impacts) and/or the bottom (e.g., by freezing or melting at the base of the ice shell) [4], and we explore the effects of varying both mean ice shell thickness (D) and elastic thickness (T). If both the surface topography (h) and

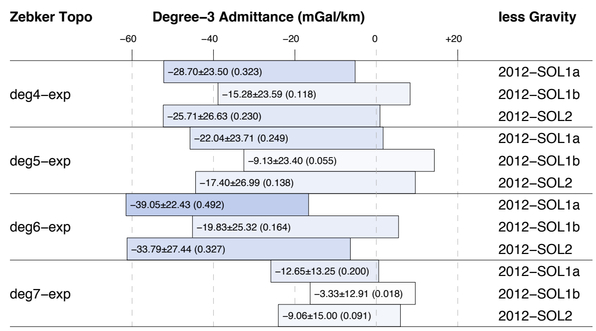

Figure 1: Degree-3 admittances computed for various combinations of gravity and topography data. The bars illustrate the admittance ranges graphically, with each bar shaded according to the coherence between the gravity and topography signals (darker shades indicate stronger coherence). The estimated admittance and uncertainty values are also printed on each bar along with the coherence in parentheses.

the amount of top loading (i.e., positive d_t) or top unloading (i.e., erosion, and therefore negative d_t) are known, then the degree-l admittance, $Z(l)$, can be computed as follows:

$$Z(l) = \frac{(l+1)}{(2l+1)} 4\pi G \rho_c \left[1 - \left(\frac{1 - \frac{d_t}{h}}{C(\rho_c)} + \frac{d_t}{h} \right) \left(1 - \frac{D}{R} \right)^l \right]$$

where R is Titan's mean radius, ρ_c is the crustal (i.e., ice shell) density, and $C(\rho_c)$ is a measure of the degree of compensation, which depends on the wavelength of the load and the elastic properties of the ice shell [5]. When $C = 1$, the topography is fully compensated (isostatic) and admittance is necessarily positive. When $C < 1$, the topography is partly supported by elastic flexure of the ice shell and admittance may be negative for sufficiently negative values of d_t/h (i.e., when erosion has occured in areas of positive topography).

Interpretation: In order to obtain a net negative gravity anomaly over positive surface topography (i.e., a negative admittance), the negative gravity anomaly caused by the roots must overwhelm the positive gravity anomaly caused by the surface topography. Hence, the roots beneath the observed positive topography must be anomalously large compared with the isostatic case. This situation could arise if the ice shell is substantially elastic, and thus able to support large, buoy-

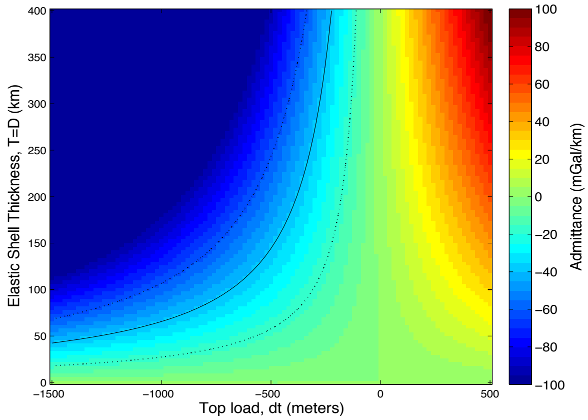

Figure 2: Degree-3 admittance as a function of elastic shell thickness ($T = D$) and top loading (d_t, where negative d_t indicates erosion) computed assuming h=66 m. The solid black line shows the contour corresponding to the admittance computed from the degree-6 expansion topography [2] and the SOL1a gravity [1]. Dotted lines indicate the uncertainty range on the computed admittance.

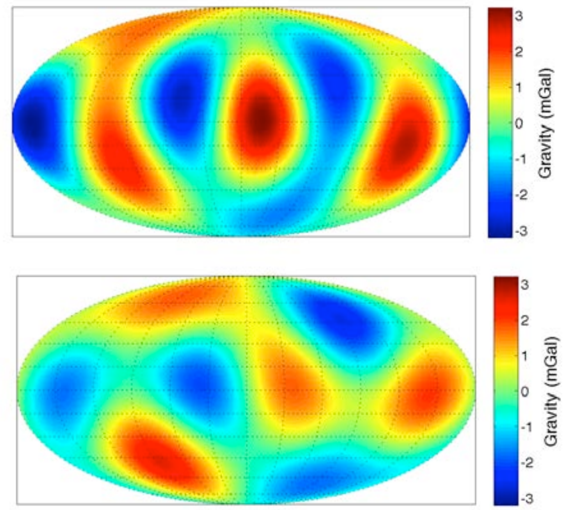

Figure 3: Degree-3 gravity from: [1] SOL1a (top) and our model prediction (bottom), based on the observed degree-3 topography.

ant roots through upward flexure, and if the resulting surface topography has been subdued due to erosion.

If we assume $T = D$, we can plot admittance as a function of D and d_t. Figure 2 shows that the observed admittance requires that several hundred meters of surface erosion has occurred at the current topographic highs and that the amount of erosion required to give rise to the observed admittance increases rapidly with decreasing elastic thickness.

Assuming the ice shell is fully elastic, with a mean thickness of 200 km, and that 383 m of erosion has taken place at the topographic peaks (and therefore 383 m of deposition in the valleys), we can use the observed topography to calculate the implied root thickness everywhere over the body. The bottom part of Figure 3 shows the resulting gravity anomaly, which resembles the observed gravity field as reported by [1].

Discussion: Our model results suggest that the bulk of Titan's ice shell is rigid. This could be the case if the ice shell is clathrate-rich and/or the shell and subsurface ocean are extremely cold [6] and the interior is depleted in radioactive elements, which would also help to explain the maintenance of lateral ice shell thickness variations over time [4]. Our model suggests that the degree-3 topography is the result of uplift due to spatially non-uniform basal freezing, but the reason for the observed pattern is unclear. The estimated magnitude of erosion (~400 m) requires on the order of 1 mm of vertical erosion per 10,000 years and horizontal transport of just ~1 mm per year, values consistent with [7,8].

The degree-2 gravity signal is dominated by Titan's internal (tidally distorted) mass distribution with any ice shell thickness variations, of the kind described for degree 3, having only a relatively minor influence. If we assume that basal freezing, uplift and erosion processes act similarly at degrees 2 and 3, we can expect that degree-2 ice shell thickness variations will produce a gravity anomaly (Δg_D) with negative amplitude. This suggests that the gravity anomaly due to tidal distortion ($\Delta g_{tidal} = \Delta g_{total} - \Delta g_D$) is actually larger than the observed total gravity anomaly (Δg_{total}). This, in turn, suggests that Titan's fluid Love number is in fact larger than the value estimated directly from Δg_{total}. A rigid outer shell will also impact Titan's tidal Love number, reducing k_2 by ~10% if the shell is 100 km thick and ~20% if the shell is 200 km thick.

Assuming similar processes are working at degree 4, we can predict the gravity anomaly associated with ice shell thickness variations at degree 4. The result is a gravity anomaly with amplitude ~1.6 mGal. Current estimates of the degree-4 gravity signal have similar amplitude but are spatially unlike our prediction. However, the degree-4 gravity observations are not well constrained at this time [1].

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