**Table 5**
SatStress run IDs for figures in this paper.

| Fig. | Run ID |
|---|---|
| 3a | 20080121182229_4795536555ce9 |
| 3b | 20080121183751_479556ff3edfa |
| 3c | 20080121183841_4795573178a18 |
| 3d | 20080121183921_479557592a9dc |
| 4a | 20080122145730_479674da20bc2 |
| 4b | 20080122145857_4796753191483 |
| 4c | 20080122150014_4796757e38a13 |
| 4d | 20080122150135_479675cfe6ef0 |
| 5b | 20080123194857_47980aa9b37a4 |
| 5d | 20080123191023_4798019f7b218 |

to keep track of every parameter involved in a calculation, and we hope it will facilitate future collaboration.


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## Appendix A. Tidal potential

Let ($r$, $\theta$, $\phi$) be the spherical coordinates ($r=$ radius, $\theta=$ co-latitude, $\phi=$ longitude) of a point in the satellite. The general form of the tidal potential at ($r$, $\theta$, $\phi$) caused by an external point mass (the parent planet), is given in Eq. (1) of Kaula (1964) (changing some of the variable names):

$$\begin{aligned} V_T(r,\theta,\phi) = {} & \frac{Gm^*}{a^*}\sum_{l=2}^{\infty}\left(\frac{r}{a^*}\right)^l\sum_{m=0}^{l}\frac{(l-m)!}{(l+m)!}(2-\delta_{0m}) \\ & \times P_{lm}(\cos\theta)\sum_{p,q}F_{lmp}(i^*)G_{lpq}(\epsilon) \\ & \times\left[\cos(m\phi)\begin{Bmatrix}\cos\\ \sin\end{Bmatrix}_{l-m=\mathrm{odd}}^{l-m=\mathrm{even}}\{(l-2p)\omega^* \right. \\ & + (l-2p+q)M^* + m(\Omega^*-\Theta^*)\} \\ & + \sin(m\phi)\begin{Bmatrix}\sin\\ -\cos\end{Bmatrix}_{l-m=\mathrm{odd}}^{l-m=\mathrm{even}}\{(l-2p)\omega^* \\ & \left. + (l-2p+q)M^* + m(\Omega^*-\Theta^*)\}\right], \end{aligned} \tag{A.1}$$

where the six Keplerian elements that describe the parent planet's apparent motion are $\Omega^*$ (longitude of the ascending node), $M^*$ (mean anomaly), $i^*$ (inclination), $a^*$ (semi-major axis), $\omega^*$ (argument of pericenter), and $\epsilon$ (eccentricity). Other variables are: $\Theta^*$ is the sidereal time of the reference meridian, $m^*$ is the mass of the planet, $G$ is Newton's gravitational constant, the $P_{lm}(\cos\theta)$ are associated Legendre functions, and the $F_{lmp}(i^*)$ and $G_{lpq}(\epsilon)$ are polynomials given in Tables 2 and 3 of Kaula (1964). For most satellites of interest $r/a^*\ll 1$. For Europa, for example, $r/a\leqslant 0.0023$. Thus, as is usual, we keep only $l=2$ terms in (A.1). We set $i^*=0$ (since we are assuming the satellite's obliquity vanishes), which causes the only non-zero $F_{2mp}(i^*)$ to be $F_{220}=3$, and $F_{201}=-1/2$. We assume the eccentricity is small ($\epsilon\sim 0.0094$ for Europa), and expand $G_{lpq}(\epsilon)$ in powers of $\epsilon$ keeping terms only up to first order. We set $M^*=nt$ (which is exact for Keplerian orbits), and assume $\Theta^*=(n+b)t$ ($\Theta^*$ represents the angular displacement between the vector to the planet and the $x$-axis in our satellite-fixed coordinate system). By choosing $M^*=nt$, we are defining $t=0$ as the time of periapse. Because the inclination vanishes, there is no distinction between $\Omega^*$ and $\omega^*$, and only the sum $(\Omega^*+\omega^*)$ appears in the final solution. We set this sum to zero, which, together with our assumption that $\Theta^*=0$ at $t=0$, implies that not only is the satellite at periapse at time $t=0$, but its $x$-axis is pointing toward the planet at that time. The longitude, $\phi$, of a point in the satellite is defined as the angle eastward (i.e. counterclockwise as seen from above the rotation axis) from this $x$-axis. Using expressions for the $P_{lm}(\cos\theta)$ gives:

$$\begin{aligned} V_T(r,\theta,\phi,t) = {} & Z\left(\frac{r}{R_s}\right)^2\left[\frac{1}{6}\left(1-3\cos^2\theta\right)+\frac{1}{2}\sin^2\theta\cos(2\phi+2bt)\right. \\ & + \frac{\epsilon}{2}\left(1-3\cos^2\theta\right)\cos(nt) \\ & + \frac{\epsilon}{4}\sin^2\theta\left[7\cos\left(2\phi-(n-2b)t\right)\right. \\ & \left.\left. - \cos\left(2\phi+(n+2b)t\right)\right]\right], \end{aligned} \tag{A.2}$$

where

$$Z=\frac{3Gm^*R_s^2}{2a^{*3}}, \tag{A.3}$$

and $R_s$ is the radius of the satellite.

The last two terms on the right-hand side of Eq. (A.2) have angular frequencies of $(n-2b)$ and $(n+2b)$, respectively. Because $b$ (the rate of NSR) is much smaller than $n$ (the mean motion; which, for a satellite in near-synchronous rotation, is about equal to the diurnal rotation rate), we can ignore $b$ in both those frequencies. In that case, $V_T$ reduces to Eq. (1) in the main text, reproduced here:

$$V_T(r,\theta,\phi,t)=Z\left(\frac{r}{R_s}\right)^2[T_*+T_0+T_1+T_2], \tag{A.4}$$

given that

$$T_*=\frac{1}{6}\left(1-3\cos^2\theta\right), \tag{A.5}$$

$$T_0=\frac{1}{2}\sin^2\theta\cos(2\phi+2bt), \tag{A.6}$$

$$T_1=\frac{\epsilon}{2}\left(1-3\cos^2\theta\right)\cos(nt), \tag{A.7}$$

$$T_2=\frac{\epsilon}{2}\sin^2\theta\left[3\cos(2\phi)\cos(nt)+4\sin(2\phi)\sin(nt)\right]. \tag{A.8}$$

## Appendix B. Surface stresses for elastic satellites

The stress tensor associated with the tidal displacement vector, is given by Eq. (8) in the main text:

$$\tau=\lambda(\nabla\cdot\vec{s})+\mu\left[\nabla\vec{s}+(\nabla\vec{s})^T\right]. \tag{B.1}$$

We use this relation, together with the surface displacement components first defined in Eqs. (9)–(11):

$$s_r(r=R_s,\theta,\phi,t)=\left(\frac{h}{g}\right)V_T\bigg|_{r=R_s}, \tag{B.2}$$

$$s_\theta(r=R_s,\theta,\phi,t)=\left(\frac{\ell}{g}\right)\frac{\partial V_T}{\partial\theta}\bigg|_{r=R_s}, \tag{B.3}$$

$$s_\phi(r=R_s,\theta,\phi,t)=\left(\frac{\ell}{g\sin\theta}\right)\frac{\partial V_T}{\partial\phi}\bigg|_{r=R_s} \tag{B.4}$$