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**VISCOELASTIC MODELING OF TIDAL STRESSES ON SATELLITES WITH AN ENHANCED SATSTRESSGUI.** D. A. Patthoff<sup>1</sup>, R. T. Pappalardo<sup>1</sup>, J. B. Li<sup>1,2</sup>, B. J. Ayton<sup>1,3</sup>, D. Dubois<sup>1,4</sup>, J. P. Kay<sup>5</sup>, S. A. Kattenhorn<sup>6</sup>. <sup>1</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA (Patthoff@jpl.nasa.gov), <sup>2</sup>Departments of Applied + Computational Mathematics and Computer Science, California Institute of Technology, Pasadena, CA, <sup>3</sup>Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Cambridge, MA, <sup>4</sup>LATMOS, University of Versailles St. Quentin, Guyancourt, France, <sup>5</sup>Department of Earth and Environmental Science, University of Illinois at Chicago, Chicago, IL, <sup>6</sup>ConocoPhillips Company, Houston, TX.

**Introduction:** Icy and rocky satellites of our solar system display a diverse range of geological deformation on their surfaces. Some moons appear old and heavily cratered showing little evidence for recent tectonism while other moons are sparsely cratered and young, some showing ongoing geologic activity. The deformation can take the form of small cracks in the surface, large double ridges that can extend for thousands of kilometers, and mountain ranges that can reach heights of several kilometers. A key source of stress that can deform satellite surfaces is the diurnal tidal deformation of the moons as they orbit their parent planets. Other secular sources of global-scale stress include: volume change induced by the melting or freezing of a subsurface liquid layer, change in the orbital parameters of the moon, a tilt in the axis of rotation (obliquity), or rotation of the outer shell of the satellite relative to the rest of the body (nonsynchronous rotation or true polar wander).

We turn to computer modeling to correlate observed structural features to the possible stresses that created them. A variety of modeling programs exist and generally assume a thin ice shell and/or a multi-layered viscoelastic satellite. The program SatStress, which was developed by Zane Crawford and documented in Wahr et al. [1], computes diurnal and nonsynchronous rotation stresses on a satellite. It was later modified into a more user-friendly version with a graphic user interface (SatStressGUI) by Kay and Kattenhorn [2]. This implementation assumes a 4-layer viscoelastic body and is able to calculate stresses resulting from diurnal tides, nonsynchronous rotation (NSR), and ice shell thickening. Here we demonstrate our recent augmentations to SatStressGUI, including the ability to generate cycloid-style lineaments, calculate stresses resulting from obliquity, and more efficiently batch process data.

**Model Setup:** SatStressGUI uses a 4-layer viscoelastic satellite model (Fig. 1) where the outer 2 layers are divided into an upper more-viscous layer and an inner less viscous layer. The third layer must be a liquid and the fourth is the core (or combined core and mantle). The user inputs the mass of the parent planet, eccentricity of the satellite, and the semi-major axis of the orbit. An NSR period can be applied if that stress is

to be calculated. The user then defines the name of each of the four layers and each layer's density, Young's Modulus (in Pa), Poisson's Ratio, thickness (in m), and viscosity (in Pa s). A tensile strength can also be applied for later plotting of predicted tensile lineaments.

Next, the user selects which stress or combination of stresses to compute (Fig. 2). We have expanded on SatStress's original abilities of calculating diurnal and NSR stresses and SatStressGUI's inclusion of ice shell thickening, adding an obliquity stress calculation. For the obliquity calculation, the user inputs the argument of periapsis and the amount of obliquity. The Love number calculation has been updated following [3,4] and now includes the ability for users to input their own Love numbers.

**Stress Calculations:** The current version of SatStressGUI allows for a user to calculate stresses at individual points or globally. For the point calculator, the user specifies a location on the surface (latitude and longitude) and a point in the orbit (degrees past periapsis). Alternatively, a plot of the stresses (Figs. 3 and 4) can be made on a global or regional scale. If the plot option is desired, the user defines the plot extents to be used, the grid spacing, the interval for which stresses will be calculated throughout an orbit, how many orbits to model, or the amount rotation the ice shell has experienced.

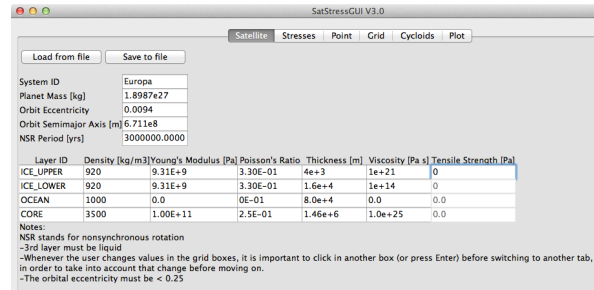
SatStressGUI now has the ability to generate cycloidal lineaments, following the assumption that one arc is created each orbit [5] (Fig. 3). The user specifies initial yield strength and propagation strength for surface fractures, and their speed, starting location, and propagation direction (east or west).

**Visualizing Stresses:** Plots of stresses can be displayed for a variety of projections including: Cylindrical, Mercator, Miller Cylindrical, Orthographic, or Polar. Either an east or west positive labeling convention can be used. The final plots display the cumulative stress resulting from each of the pre-specified sources of stress. The user can step through an orbit to see how the stresses change in magnitude and orientation.

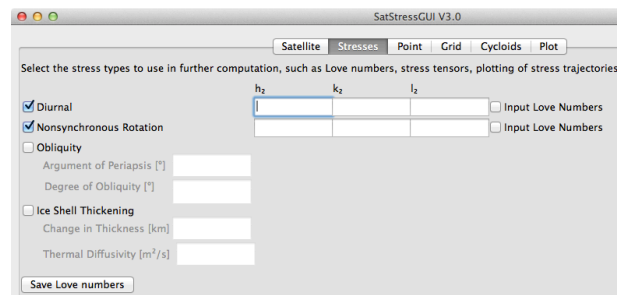
**References:** [1] Wahr et al. (2009) *Icarus* 200, 188-206. [2] Kay & Kattenhorn (2009) *41<sup>st</sup> LPSC Abstract #2046*. [3] Dahlen & Tromp (1998) *Princeton*

University Press. [4] Zábranová, et al. (2009) *Science Prague*, 243-260. [5] Hoppa et al. (1999) *Science* 285, 1899-1902.

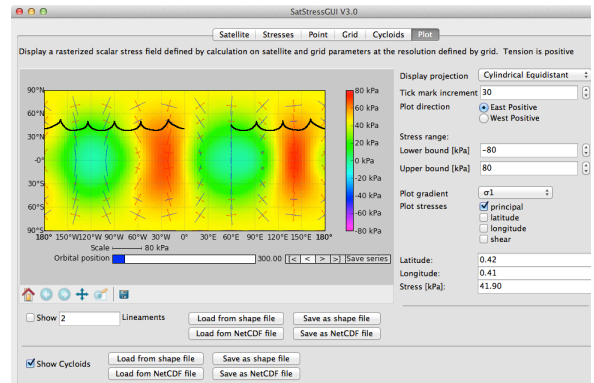
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**Fig. 1:** Screen capture of SatStressGUI showing a generalized Europa model with a 3 Myr NSR period. All parameters can be modified as appropriate to other satellites and to the constitutive properties (density, Young's Modulus, Poisson's Ratio, thickness, and viscosity) of the ice or rock layers.

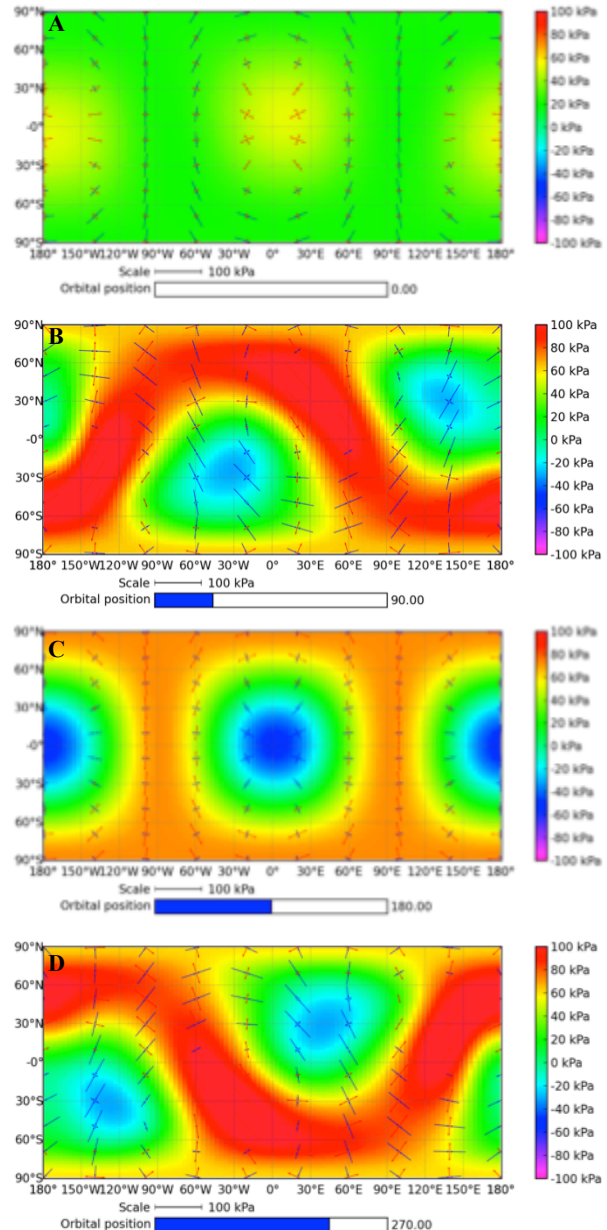


**Fig. 2:** Screen capture of the stresses input tab. The user can have SatStressGUI calculate Love numbers (default) or users can input their own. The user also selects the desired stress or combination of stresses to be calculated. The selection here indicates that combined NSR and diurnal stresses are to be calculated.



**Fig. 3:** Screen capture of the plotting functions for

SatStressGUI with simulated cycloidal fractures. The user can specify the stress range and which stresses to plot ( $\sigma_1$ ,  $\sigma_3$ , average stress, or differential stress). Tick marks show the directions of the chosen stresses. Here we show the results from the sample Europa shown in (Fig. 1). Tension is defined as positive and the yield strength was set to 50 kPa and a fracture propagation speed is 2 m/s.



**Fig. 4:** Plots of stress resulting from diurnal stress combined with 1° of obliquity and the argument of periapsis set to 0° for (a) periapsis, (b) 90° past periapsis, (c) apoapsis, and (d) 90° past apoapsis. Tension is defined as positive.