Fully-3D Models for Lithospheric Deformation: A Comparison With the Thinsheet and Flexure Approximations.
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Introduction: Maps of surface features are one of the easiest and most commonly collected planetary spatial datasets. Theoretical models of deformation, when tied to tectonic observations, can be interpreted in terms of major tectonic events and allow insights into the planet's history and evolution.

Present-day stress models on Mars make either a flexure [1] or a thin-sheet [2] approximation, i.e., they assume zero vertical gradients in either horizontal or vertical displacements/velocities. We present a new fully 3D method for calculating lithospheric stress and strain, which relies on neither of these assumptions, and compare it with the thinsheet and flexure methods.

Methods: Our approach is a modification on the standard Euler-Lagrange variation approach for constructing the weak form of the force balance equations.

The first key innovation is that the calculations are performed by separating all spatial dependencies into terms that can be related to coordinates on a reference surface and variations perpendicular to that surface. The problem is thus reduced to finite element calculations only in terms of the coordinates on the reference surface leading to significant computational efficiency.

The second key part is that following the methods in [3, 4] computations are performed using only the physical field quantity components that are continuous across discontinuities in the medium i.e. tractions and velocities/displacements. The resultant model gives stable results with different orders of polynomial approximations for quantities within each layer. In addition, there is good agreement between 2D great circle models and corresponding results from the 3D model.

Results: We present results for our full 3D model for Mars, as well as the thinsheet and flexure models. In all these models, we use the topography of [5] and crustal thickness model of [6], with density of the crust and the mantle of 2900 kg.m^{-3} and 3500 kg.m^{-3}, and shear modulus of 4.55*10^{10} Pa.

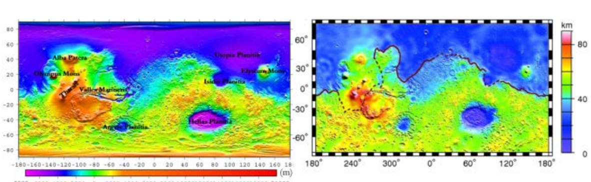

Figure 1. Topography (left) and crustal thickness (right).

Figure 2 shows the longitudinal (up), latitudinal (ut) and radial (ur) component of displacement for our 3D model. The units of displacement are Martian radii (3396 km).

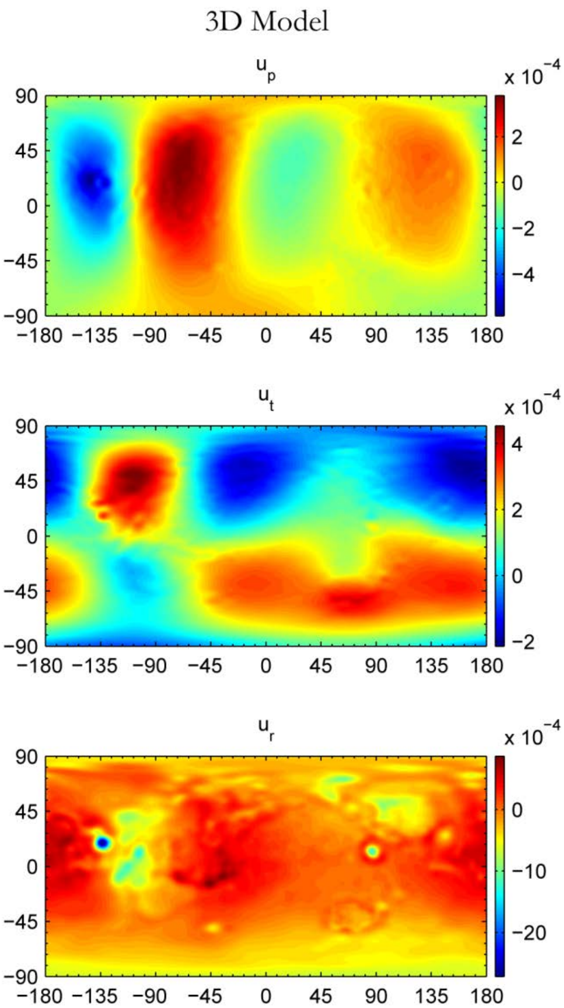

Figure 2. Longitudinal (u_p, top), latitudinal (u_t, middle) and radial (u_r, bottom) component of displacement for the 3D model.

Figures 3 and 4 show the same components of displacement but for the thinsheet and flexure models. The flexure model horizontal displacements are comparable in size to the fully 3D ones, while the thinsheet model displacements are a factor of 3-5 smaller. The horizontal displacements of both the thinsheet and the flexure approximations do not match the corresponding displacements in the 3D model at all wavelengths. The thinsheet model, in its simplest form presented here, makes no contribution to the radial displacement and matches the style of the longer wavelength features but considerably underestimates the magnitude. On the other hand the flexure model dominates the radial displacement contribution and the short wavelength features, but completely misses the style of the horizontal displacements.

A feature of the further results we will show is that high-order thinsheet approximations are much better than the flexure and simple thinsheet approximations at matching full model results, including the radial displacements. But this is achieved at much greater computational expense than full models, which are not hugely more computationally expensive than the basic approximations.

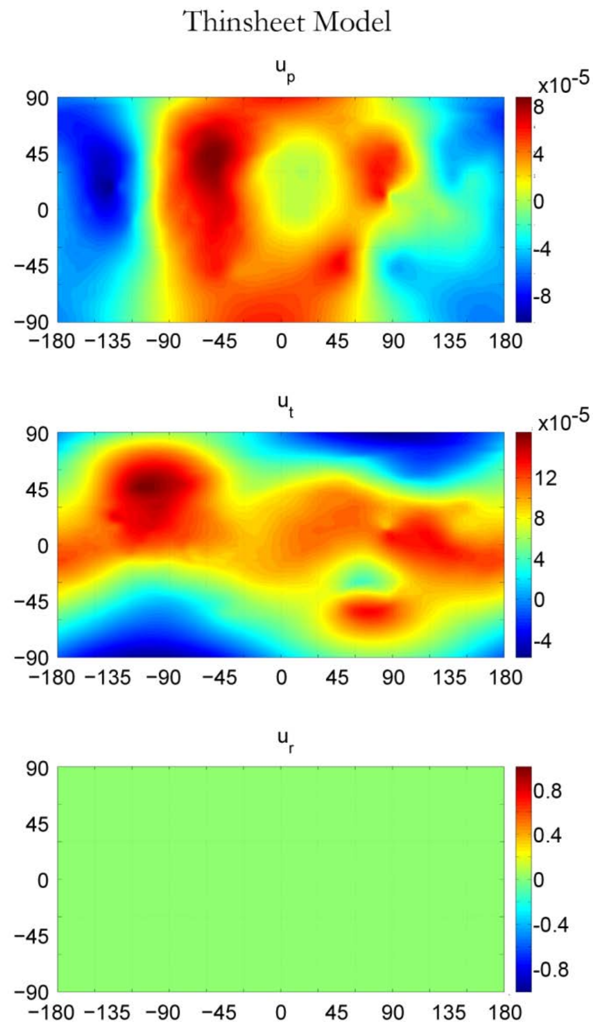

Figure 3. Components of displacement for the thinsheet model.

Though the approximations, apart from high-order thinsheet ones, perform badly in matching full models, there is marked improvement when the full problem is split into two complementary parts that added together equate to the full problem. The split is made by considering the presumptions involved in the approximations and partitioning the body force and boundary conditions accordingly. Thinsheet implicitly assumes isostatic balance, whereas flexure is premised on departures from isostatic balance being the critical driving mechanism, and effectively discards the body force along with any horizontal tractions. When the appropriate subdivision of these terms is made, all approximations bar simplest thinsheet perform satisfactorily. The basic thinsheet approximation still underestimates the horizontal displacements, by ~30%, but gets their directions close to being correct.

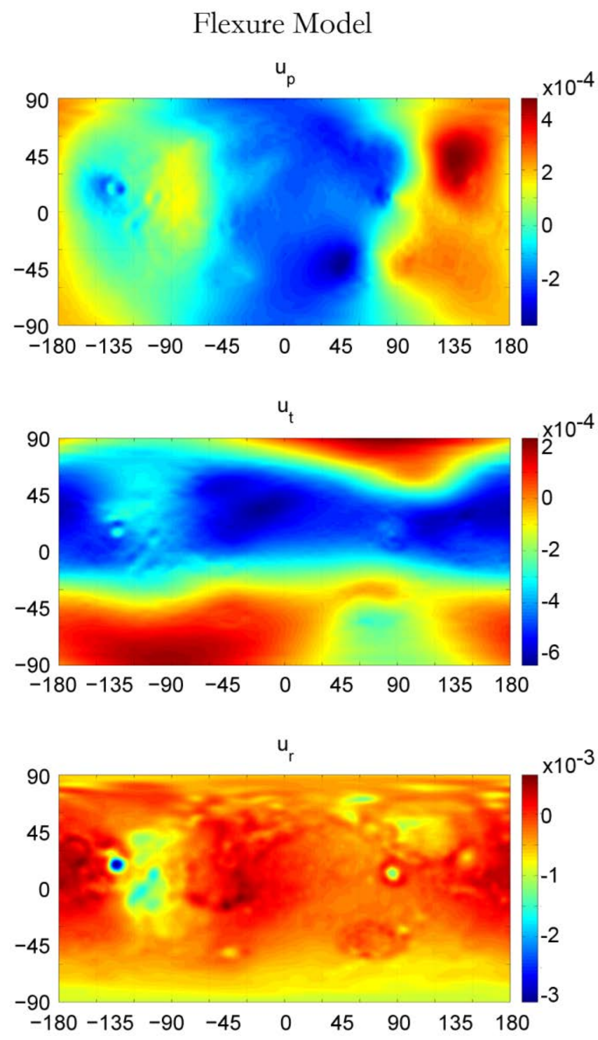

Figure 4. Components of displacement for the flexure model.

References: [1] Banerdt W. and Golombek M. (2000) LPS XXXI,, Abstract #2038. [2] Dimitrova L.L. (2009). ProQuest/UMI. [3] Haines A.J. and de Hoop M.V. J (1996). Math. Phys., 37, 3854-3881. [4] Haines A.J. et al (2004), GJI,159, 643-657. [5] Zuber M.T. et al (2000) Science, 287, 1788-1793. [6] Neumann G. et al (2004) JGR, 108, E08002.