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Can Tidal Tomography be Used to Unravel the Long-wavelength Structure of the Lunar Interior?

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The Moon displays a number of hemispherically asymmetric features that may be related to long- wavelength structure and dynamics in the lunar mantle. Here we propose to use observations of the non-degree-2 gravitational response of the Moon to degree-2 tidal forcing to constrain the long-wavelength lunar mantle structure. For a planetary body with laterally varying structure, degree-2 tidal forces excite gravitational response at non-degree-2 harmonics due to mode coupling effects. Theory has been long established for computing the elastic response of a spherically symmetric terrestrial planetary body to both body tide and surface loading forces. However, for a planet with laterally heterogeneous mantle structure, the response is usually computed using a fully numerical approach. In this paper, we develop a semi-analytic method based on perturbation theory to solve for the elastic response of a planetary body with lateral heterogeneities in its mantle. We present a derivation of the governing equations for our second-order perturbation method and use them to study the high-order tidal effects caused by mode coupling between degree-2 body tide forcing and the laterally heterogeneous elastic structure of the mantle. We test our method by applying it to the Moon in which small long-wavelength lateral heterogeneities are assumed to exist in the elastic moduli of the lunar mantle. The tidal response of the Moon is determined mode by mode, for lateral heterogeneities with different depth ranges within the mantle and different horizontal scales. Our perturbation method solutions are compared with numerical results, showing remarkable agreement between the two methods. We conclude that our perturbation method provides accurate results and can be adapted to address a variety of forward and inverse response problems. We show that if there is $\sim$5% lateral variations in lunar mantle shear wave speed at degree-1, the degree-3 response due to the mode-couple could reach to $\sim$2% of the degree-2 primary response. We suggest that if observations from recent lunar missions such as SELENA and GRAIL could be used to determine the non-degree-2 tidal response, it might be possible to place constraints on the lunar mantle structure.