Mercury's crustal thickness estimation with BepiColombo MORE investigation

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Introduction:

The crustal thickness of a planet is an essential clue to its geophysical and geological history. For Mercury, discerning this layer's depth offers insights into the planet's formative stages, its differentiation, and its evolutionary path. Earlier estimates, derived from Earth-based radar and data from Mariner 10, suggested a crustal thickness ranging between 100 and 300 km, assuming that Mercury's topography at degree 2 is balanced by Airy isostasy [1]. Successive investigations suggested a maximal thickness < 200 km, considering the planet's thermal history and a model for the viscous relaxation of topography and its compensation at the crust-mantle interface [2]. This upper bound was then corrected to 140 km to comply with observed faulting depths [3]. The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission has enriched our understanding of Mercury geophysical properties providing radio tracking and topographic data, used to map crustal thickness across the planet's northern hemisphere. Although informative, the initial maps relied on assumed mean crustal thickness values used just for visualization purposes, which causes the main uncertainty of the model [4]–[6]. A significant advancement was the explicit estimation of Mercury's mean crustal thickness using geoid-to-topography ratios (GTRs). This method analyzes the state of crustal compensation, its thickness, and density using admittance analysis, a technique applied successfully to lunar and other planetary studies [7]–[9]. For Mercury, this approach indicated an average GTR of approximately 9 m/km, suggesting an average crustal thickness of 35 ± 18 km, limiting the investigation to those regions of the planet's northern hemisphere where the assumption of local compensation by Airy isostasy is plausible [10]. This analysis utilized the classical formulation of Airy isostasy, where columns of material in the crust possess equal masses. Alternative approaches, employing equal pressures [11], have been used to model GTRs [12], comparing these models to the 9 m/km value measured in [10] using MESSENGER gravity and topography data. This updated assumption provided a lower average crustal thickness of 26 ± 11 km. Recent reanalysis of the entire MESSENGER radio tracking data with a refined dynamical model of the spacecraft provided a new estimate of Mercury's gravity field up to degree and order 160 (named HgM009) enabling a deeper investigation of Mercury's crustal and lithospheric properties [13]. This investigation was limited to selected regions in the northern hemisphere, due to MESSENGER's highly eccentric orbit. These studies have revealed the lateral variations in the bulk density of the upper crust and have also provided estimates of elastic and crustal thickness over a few regions. With the imminent ESA/JAXA BepiColombo mission to Mercury, there is an expectation of a greater accuracy and a more uniform resolution in the measurement of the Hermean gravitational field. This study evaluates how BepiColombo's refined gravity data can enhance the accuracy of measurements regarding Mercury's crustal thickness.

Method: The gravity field measured using radio tracking data can be compared with the one due to topographic reliefs measured by a laser altimeter to provide the Bouguer anomalies. The comparison between maps of Bouguer anomalies and topography underlines the correlation between gravity and topography. If topography is isostatically compensated, this can be detected by the map of the Bouguer anomalies. By downward continuning Bouguer anomalies to a hypothetical density interface below the planetary surface it is possible to obtain spherical harmonic coefficients h_{lm} describing relief along that interface to degree l and order m:

$$h_{lm} = w_l \left[\frac{C_{lm}^{BA} M(2l+1)}{4\pi\Delta\rho D^2} \left(\frac{R}{D}\right)^l - D \sum_{n=2}^{l+3} \frac{(h^n)_{lm}}{D^n n!} \prod_{j=1}^{n} \frac{(l+4-j)}{l+3} \right]$$

where w_l is a stabilizing filter for downward continuing the Bouguer anomaly, M is the planet's mass, R is the planetary radius, $R - D$ is the average crustal thickness, $\Delta\rho$ is the crust-mantle density contrast, and C_{lm}^{BA} represents the Bouguer anomaly spherical harmonic coefficients.

In [14], the authors developed this method to produce maps of the crustal thickness of the Moon. The uncertainty connected to the measured Moho interface depends on uncertainty on a number of model parameters: the crust-mantle density contrast, the average crustal thickness and the Bouguer anomaly computed using the measured gravity and topography spherical harmonic coefficients. In this work, we combine simulated BepiColombo gravity field and topographical data, to infer the attainable uncertainty in determining Mercury's crust thickness.

Numerical simulations:

In this work we performed a Monte Carlo analysis considering realistic ranges for all the model parameters of interest to study how the estimated crustal thickness is influenced by each one. We used a set of perturbed versions of the new MESSENGER gravity field HgM009 [13] based on the covariance matrix obtained by recently updated simulations of BepiColombo MORE. Regarding the topographic data, we used the MESSENGER gtmes_150v05 dataset. Together with the gravity field, we also analyzed the effect of imprecise knowledge of the crust-mantle density contrast and the average value of Mercury's crustal thickness, leveraging on the methods reported in [10], [12].

For each set of model parameters, we obtain the corresponding Moho interface. Finally, we analyze the obtained distribution of crustal thickness maps to infer the corresponding estimation uncertainty. We compare the result obtained through the expected performance of the BepiColombo gravity experiment with the ones provided by MESSENGER data, using the same assumptions.

Our findings demonstrate how the combination of BepiColombo high precision gravity measurements and topographic data will provide significantly improved indications on Mercury's crustal thickness and its associated uncertainty.

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