



Publication Year	2023
Acceptance in OA	2025-03-04T14:53:32Z
Title	Regional variations of Mercury's crustal density and porosity from MESSENGER gravity data
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Publisher's version (DOI)	10.1016/j.icarus.2022.115332
Handle	http://hdl.handle.net/20.500.12386/36414
Journal	ICARUS
Volume	391

global impact fluxes and mean velocity of the impacting projectiles on Mercury (Le Feuvre and Wieczorek 2008) could potentially contribute to higher crustal porosities on Mercury than the Moon.

High crustal porosities are observed across heavily cratered regions. Impact events fracture the crust, yielding the generation of additional pore space (Reynolds 1885). A longer history of bombardment generally results in higher porosity. Low porosities are detected across the NVP, where impact bombardments after their formation ~ 4 Gy ago strongly affected their bulk density (Frank et al. 2017; Whitten et al. 2014). A region located within $210 - 240^\circ E$ longitudes and $60 - 80^\circ N$ latitudes that is characterized by high crater densities (*i.e.*, $N(20) > 150$ per million km^2) shows 10% porosities. Preexisting high porosity in the crust across this heavily cratered province may have led to the compaction of the pore space for some impacts, which may lead to equilibrium porosity after sufficient bombardment (Milbury et al. 2015).

5. Conclusions

The enhanced spatial resolution of Mercury's gravity field *HgM009* allowed us to study the properties of the crust and lithosphere by using localized spectral admittance analyses. Compared to the accuracy of other celestial bodies' gravity field, as, for example, the Moon and Mars, our knowledge of the short wavelength anomalies is still limited to a few regions of the northern hemisphere. The resolution of the gravity field is between spherical harmonic degrees 80 and 160 across the mid-northern latitudes. The gravity signal associated with those harmonics is caused by different sources, including the crustal density and thickness variations, and the flexure of the lithosphere.

To estimate the crust and lithospheric properties, we used a method that uses the combination of localized admittance spectra and predictions based on a lithospheric flexural model (Turcotte et al.

1981). The crustal density and thickness, and the elastic thickness are adjusted as free parameters to obtain a good fit between the measured and predicted spectra. Crustal thickness variations that are not associated with flexure are not included in our modeling, limiting our interpretation regarding local variations of the crustal thickness. The parameter that is best constrained in our analysis is the bulk density, and a map of its lateral variations (Figure 13) provides key information on the crustal porosity (Figure 14).

An accurate fit between measured and predicted admittance spectra is obtained across a few regions of Mercury's northern hemisphere, including the high-Mg province, the NVP, and the IcP. This may result from the resolution of the gravity field that is still limited at lower latitudes. Furthermore, the theoretical model adopted in our study accounts for top-loading only. Surface and subsurface load modeling (e.g., Grott and Wieczorek 2012; Broquet and Wieczorek 2019) may help to enhance the admittance fit between measurements and predictions. This transfer function, however, is often based on the assumption that the ratio of surface to subsurface loads is constant for all degrees (e.g., Broquet and Wieczorek 2019), which would not be well-suited for the entire northern hemisphere.

The map of the bulk density is combined with the map of the grain density (Namur and Charlier 2017; Beuthe et al. 2020) to yield the lateral variations of the upper crust porosity. Higher crustal porosities are observed across the high-Mg region.

To investigate the crust and lithosphere in the southern hemisphere, accurate measurements of gravity and topography will be acquired by the ESA mission BepiColombo that will be orbiting Mercury from December 2025 (Genova et al. 2021). Mercury's gravity field will be estimated globally to spherical harmonics degree and order 50-60. The method proposed in this study will

then be used to analyze gravity/topography admittance spectra, enabling geophysical constraints on the properties of the crust in the southern hemisphere.

Acknowledgements

The gravity field *HgM009* and the ancillary information, including the covariance matrix, presented in this study are archived at <https://sites.google.com/uniroma1.it/spring>. Our software that enables localized spectral analyses of gravity/topography correlation and admittance is based on the free software package *shtools* (Wieczorek and Meschede 2018). We are grateful to Walter S. Kiefer and an anonymous reviewer for helpful and constructive comments on previous versions of this paper. AG acknowledges funding from the *Rita Levi Montalcini Programme* of the Italian Ministry of University and Research (MUR).

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Tables

Table 1 Lower and upper limits, and step size of the parameters of interest that are used in the global theoretical admittance function (Eqs. 3 and 4).

Parameter	Lower Bound	Upper Bound	Step Size
Crustal density ρ_c (kg m ⁻³)	2200	3200	5
Crustal thickness T_c (km)	0	200	5
Elastic thickness T_e (km)	0	200	5

Figures

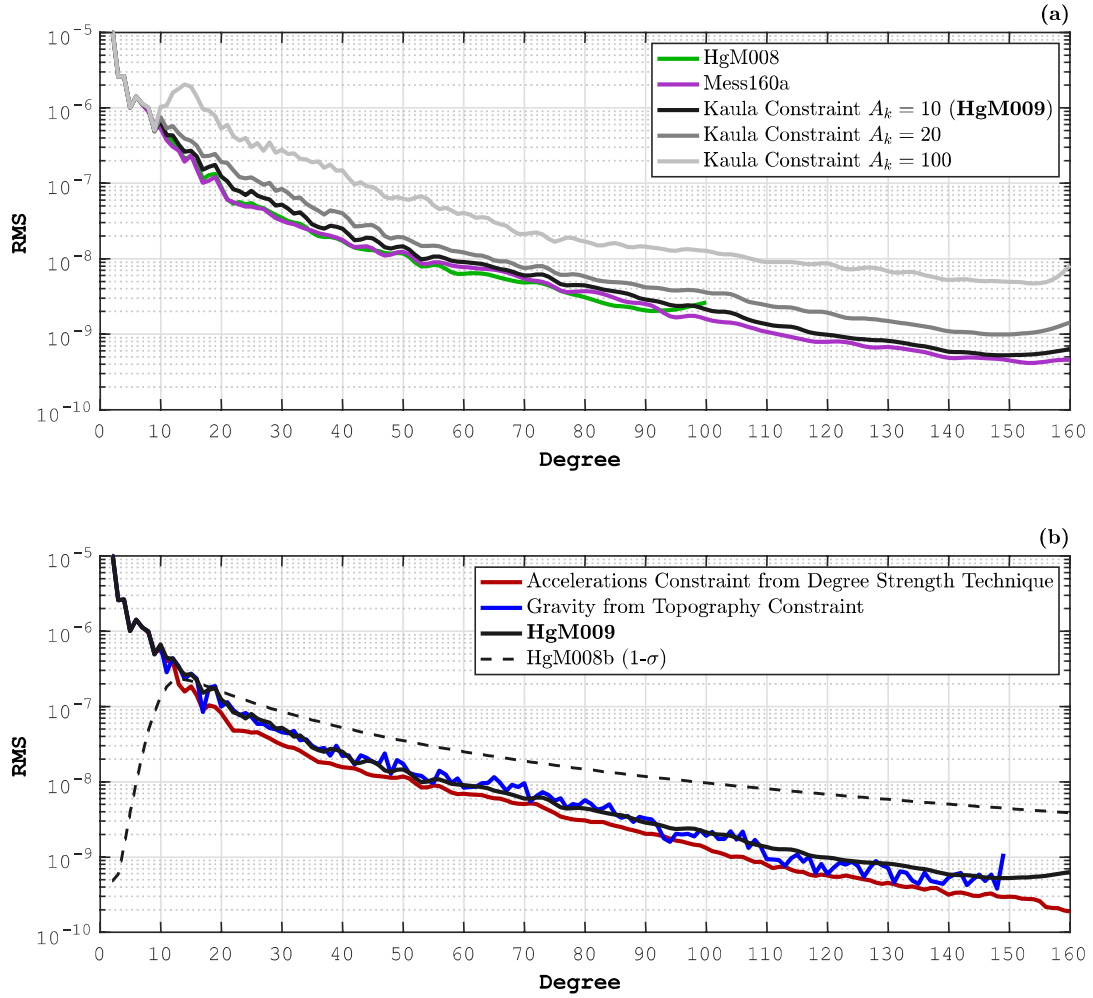


Figure 1 Power spectra of the gravity solutions obtained by using an *a priori* constraint based on (a) the Kaula rule with different A_k parameters and (b) the degree strength map (red) and the gravity from topography (blue). The gravity solution, HgM009, is expanded to degree and order 160 and is retrieved with a looser Kaula constraint ($A_k=10$) compared to the latest solutions HgM008 (green) and Mess160a (purple).

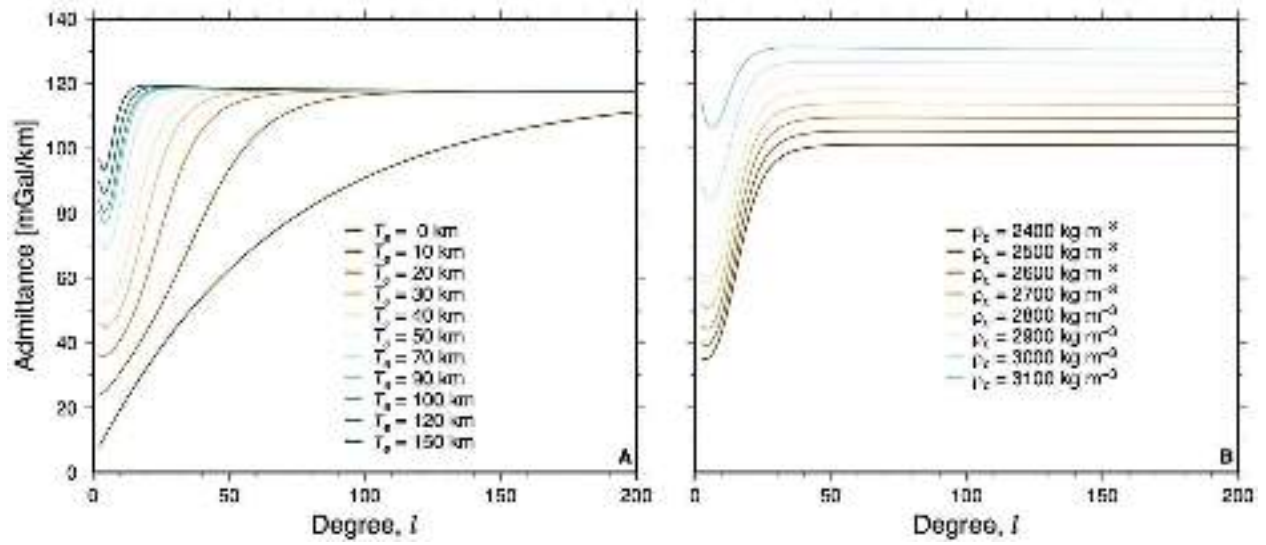


Figure 2 (A) Global gravity/topography admittances for crustal thickness and density of 35 km and 2800 kg m⁻³, respectively. (B) Global gravity/topography admittances for crustal and elastic thickness of 35 km and 50 km, respectively.

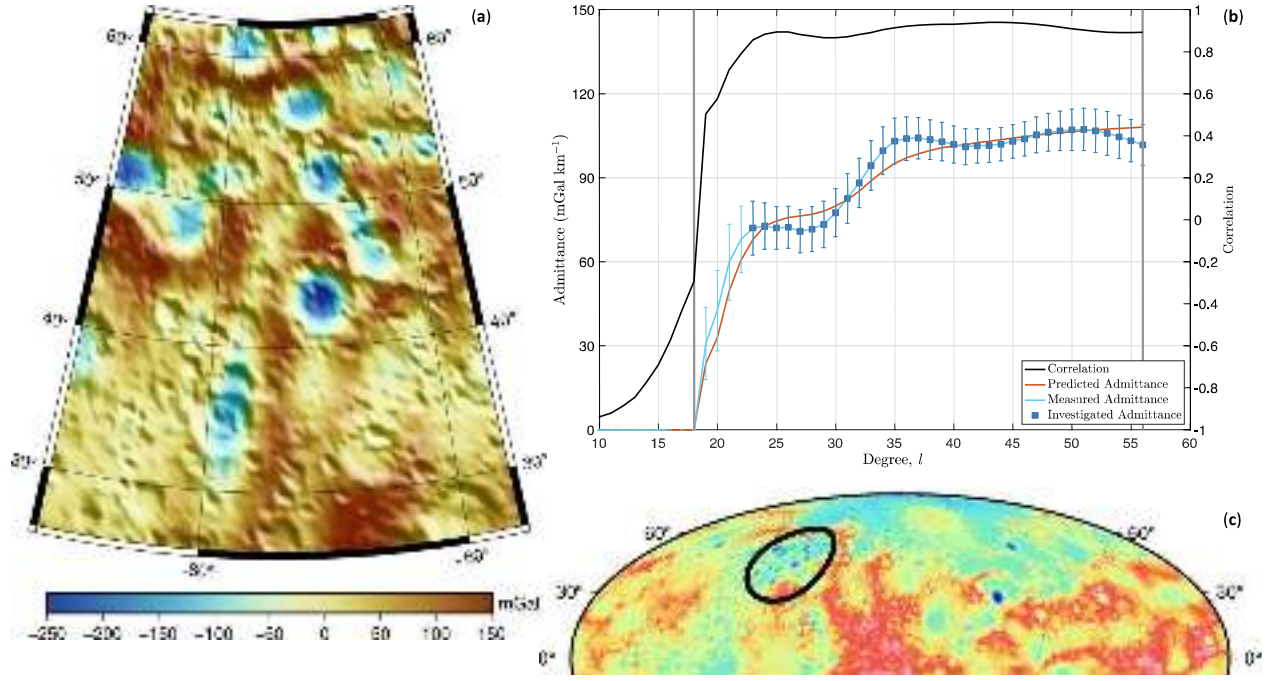


Figure 3 (a) Local map of free-air gravity anomaly (mGal) shown over shaded topographic relief in a Lambert Conformal Conic projection, and (b) correlation and admittance between gravity and topography localized on (c) a spherical cap centered at 286°E longitude and 44°N latitude. The localization windowing is carried out with a 18° radius, a concentration factor of 0.999 ($L_{win} = 18$), and a spherical harmonic expansion to degree $l_{max} = 74$. The measured admittance is compared to the predicted admittance spectra based on the surface loading model presented in Sec. 2.3. The investigated admittance spectrum includes spherical harmonic degrees that provides a signal to noise ratio larger than (correlation $\gamma(l) > 0.816$). The vertical gray lines show the range of spherical harmonic degrees between L_{win} and $l_{max} - L_{win} = l_{DS}$ where l_{DS} is the degree resolution resulting from the degree strength map (Figure S1).

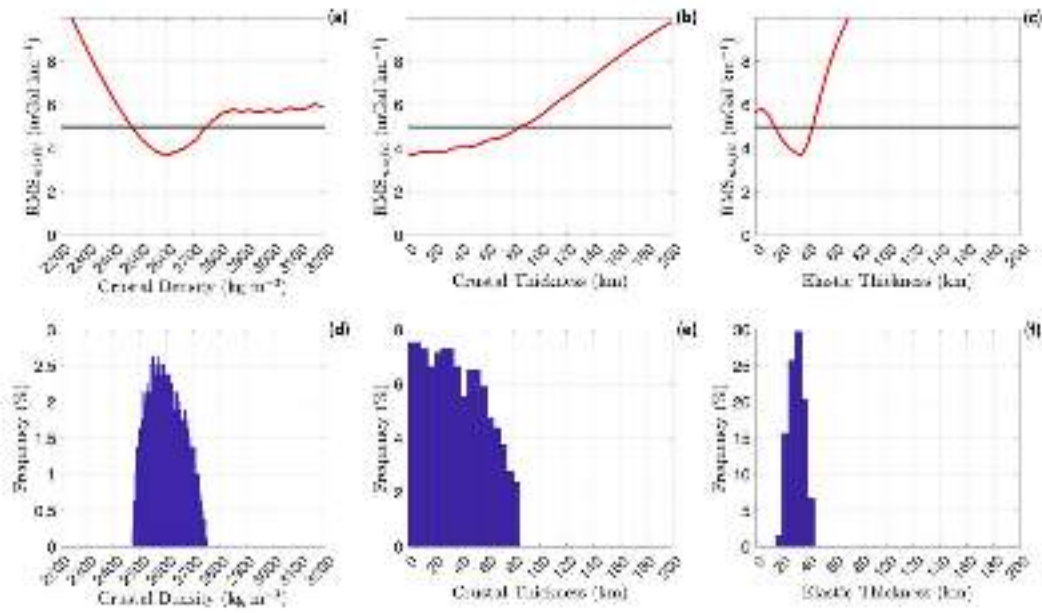


Figure 4 (a-b-c) Misfit plots and **(d-e-f)** histograms for the crustal density and thickness, and elastic thickness resulting from the comparison between measured and predicted localized admittance shown in Figure 3-b. The black horizontal line shows the RMS of the formal uncertainties of the local admittance, $\bar{\sigma}$, and the red curve the RMS_{misfit} as function of the estimated parameter.

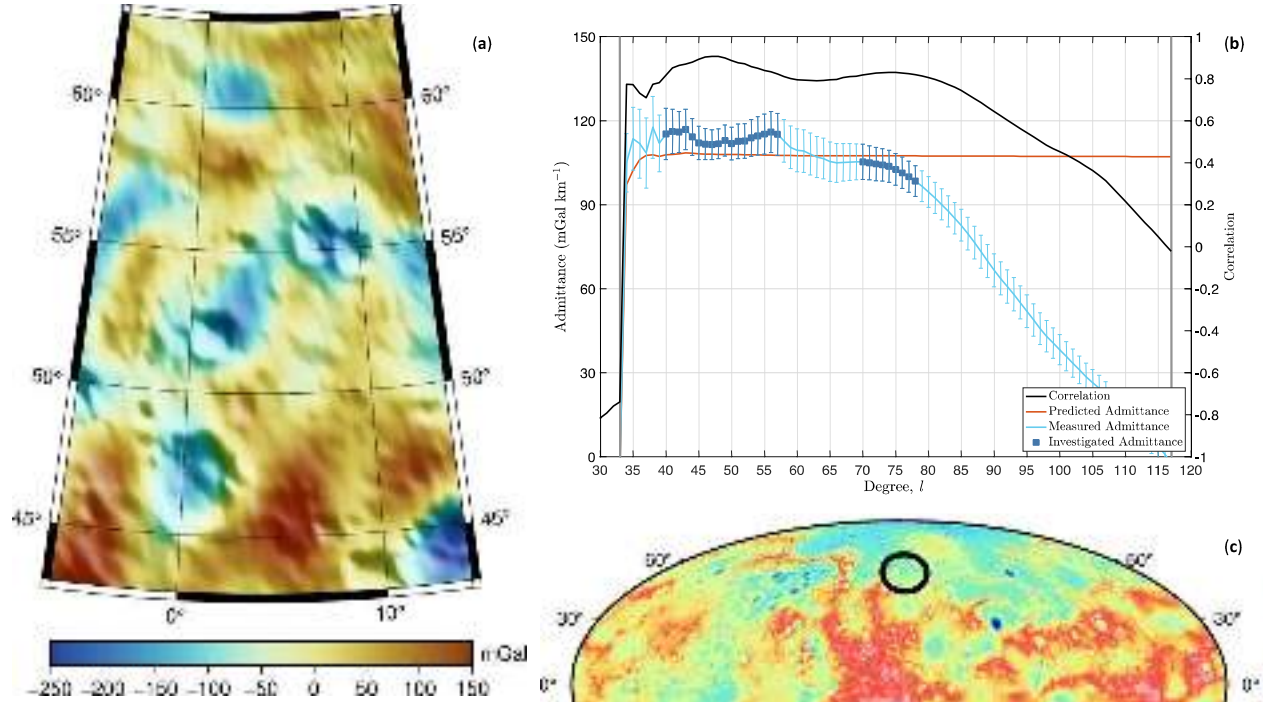


Figure 5 (a) Local map of free-air gravity anomaly (mGal) shown over shaded topographic relief in a Lambert Conformal Conic projection, and (b) correlation and admittance between gravity and topography localized on (c) a spherical cap centered at 4°E longitude and 53°N latitude. The localization windowing is carried out with a 10° radius, a concentration factor of 0.999 ($L_{win} = 33$), and a spherical harmonic expansion to degree $l_{max} = 148$ (see caption of Figure 3 for more details).

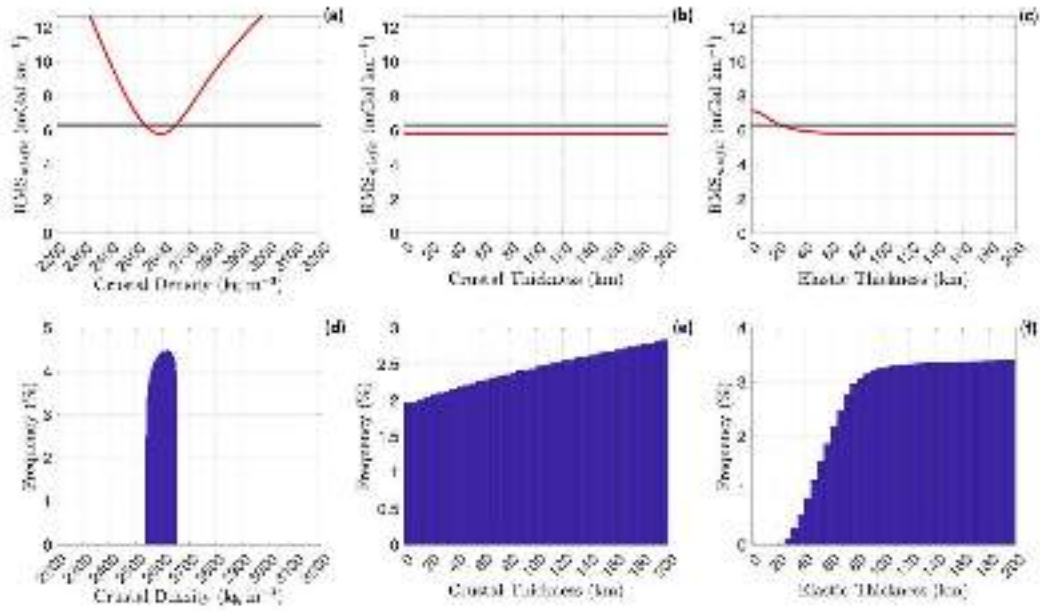


Figure 6 (a-b-c) Misfit plots and **(d-e-f)** histograms for the crustal density and thickness, and elastic thickness resulting from the comparison between measured and predicted localized admittance shown in Figure 5-b. The black horizontal line shows the RMS of the formal uncertainties of the local admittance, $\bar{\sigma}$, and the red curve the RMS_{misfit} as function of the estimated parameter.

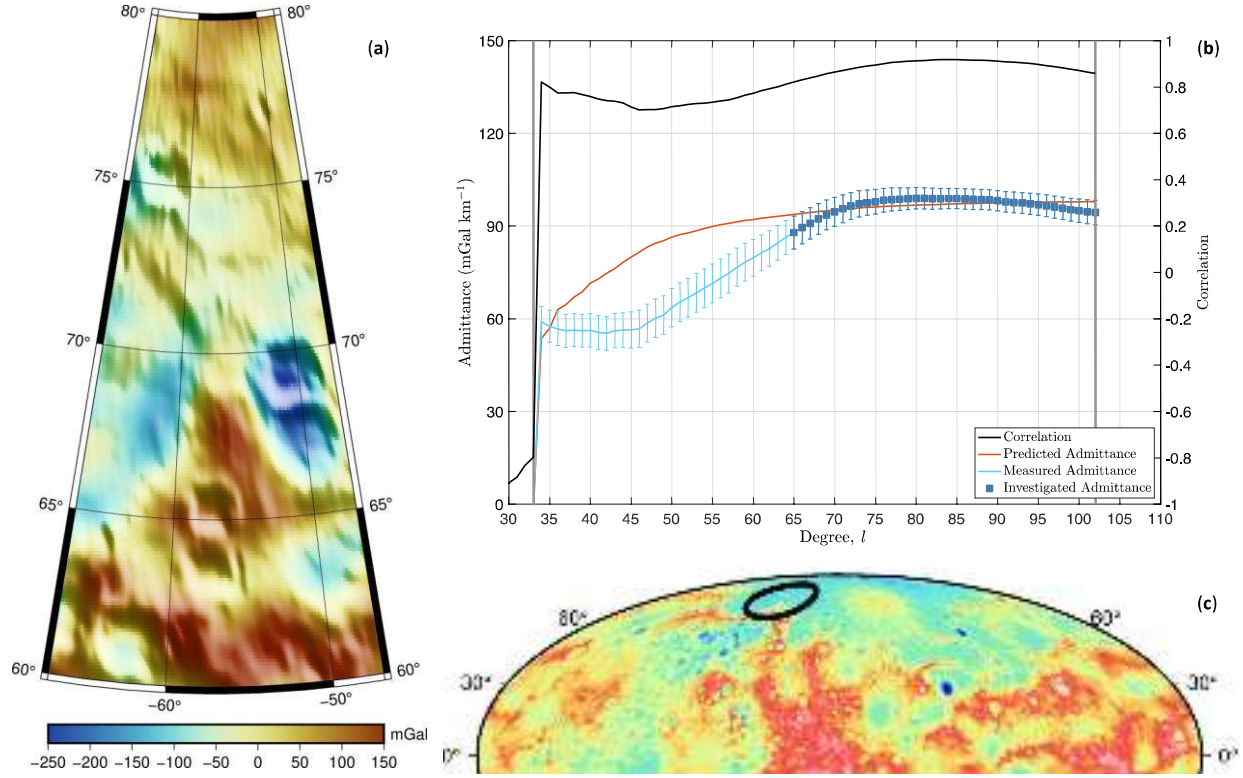


Figure 7 (a) Local map of free-air gravity anomaly (mGal) shown over shaded topographic relief in a Lambert Conformal Conic projection, and (b) correlation and admittance between gravity and topography localized on (c) a spherical cap centered at 303°E longitude and 70°N latitude. The localization windowing is carried out with a 10° radius, a concentration factor of 0.999 ($L_{win} = 33$), and a spherical harmonic expansion to degree $l_{max} = 135$ (see caption of Figure 3 for more details).

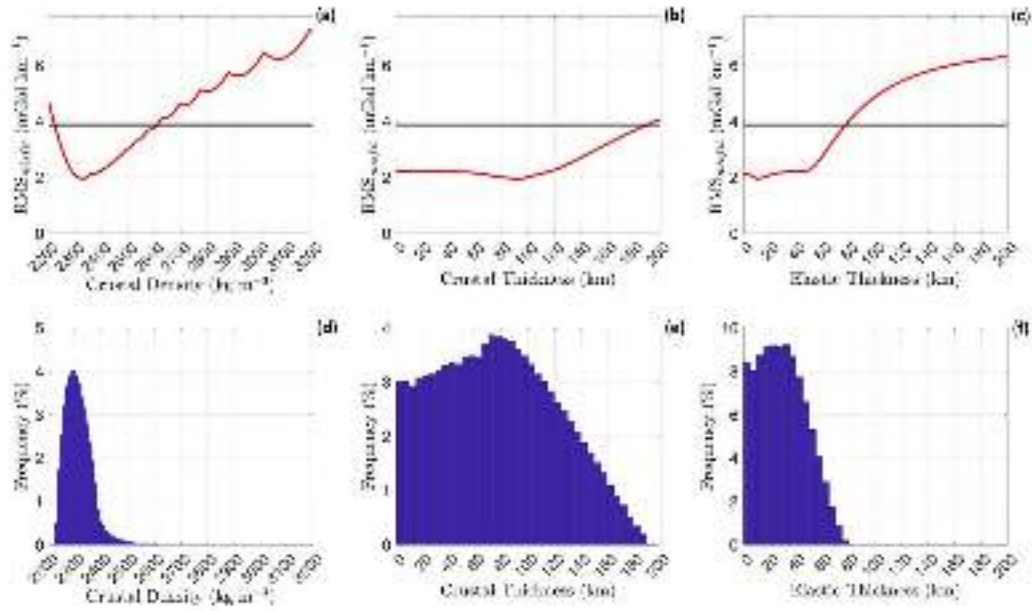


Figure 8 (a-b-c) Misfit plots and **(d-e-f)** histograms for the crustal density and thickness, and elastic thickness resulting from the comparison between measured and predicted localized admittance shown in Figure 7-b. The black horizontal line shows the RMS of the formal uncertainties of the local admittance, $\bar{\sigma}$, and the red curve the RMS_{misfit} as function of the estimated parameter.

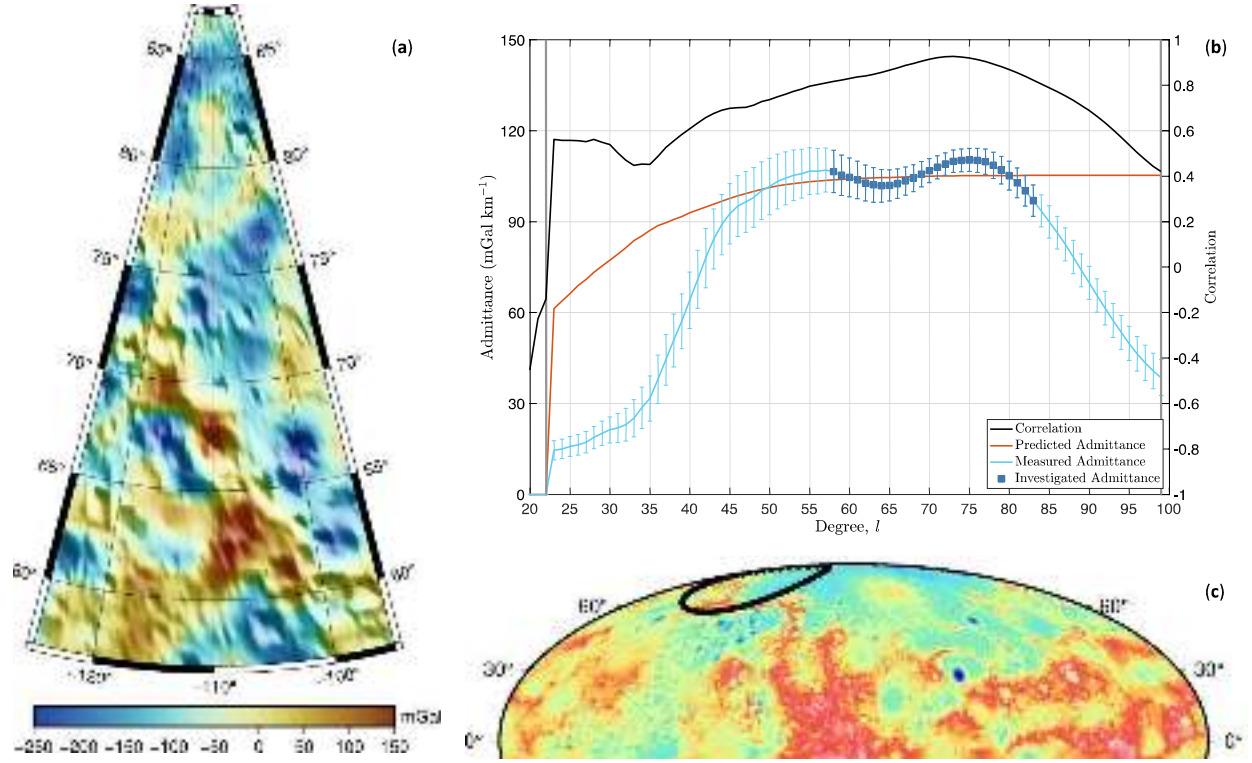


Figure 9 (a) Local map of free-air gravity anomaly (mGal) shown over shaded topographic relief in a Lambert Conformal Conic projection, and (b) correlation and admittance between gravity and topography localized on (c) a spherical cap centered at 250°E longitude and 72°N latitude. The localization windowing is carried out with a 15° radius, a concentration factor of 0.999 ($L_{win} = 22$), and a spherical harmonic expansion to degree $l_{max} = 121$ (see caption of Figure 3 for more details).

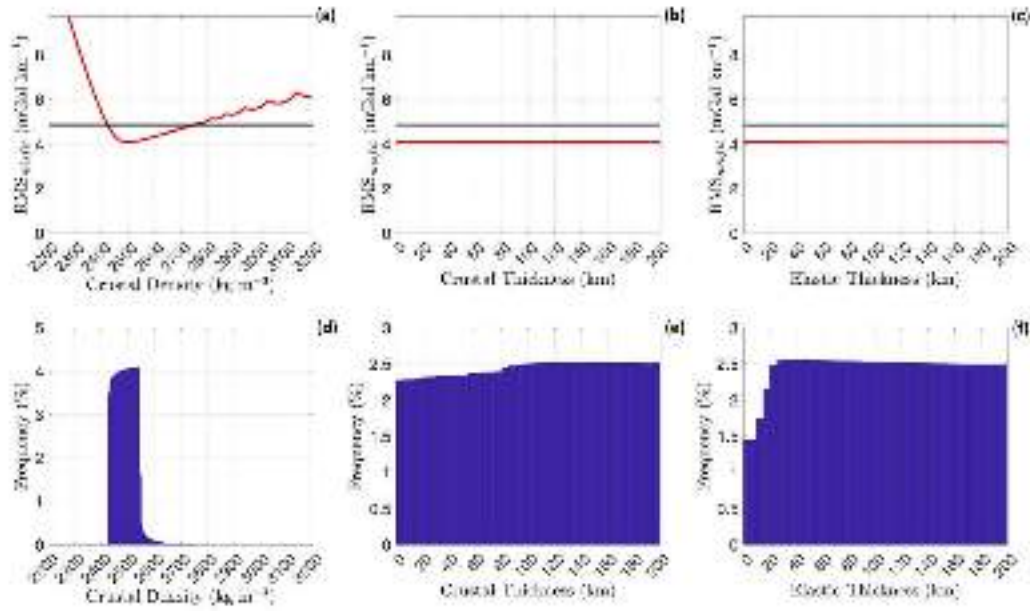


Figure 10 (a-b-c) Misfit plots and **(d-e-f)** histograms for the crustal density and thickness, and elastic thickness resulting from the comparison between measured and predicted localized admittance shown in Figure 9-b. The black horizontal line shows the RMS of the formal uncertainties of the local admittance, $\bar{\sigma}$, and the red curve the RMS_{misfit} as function of the estimated parameter.

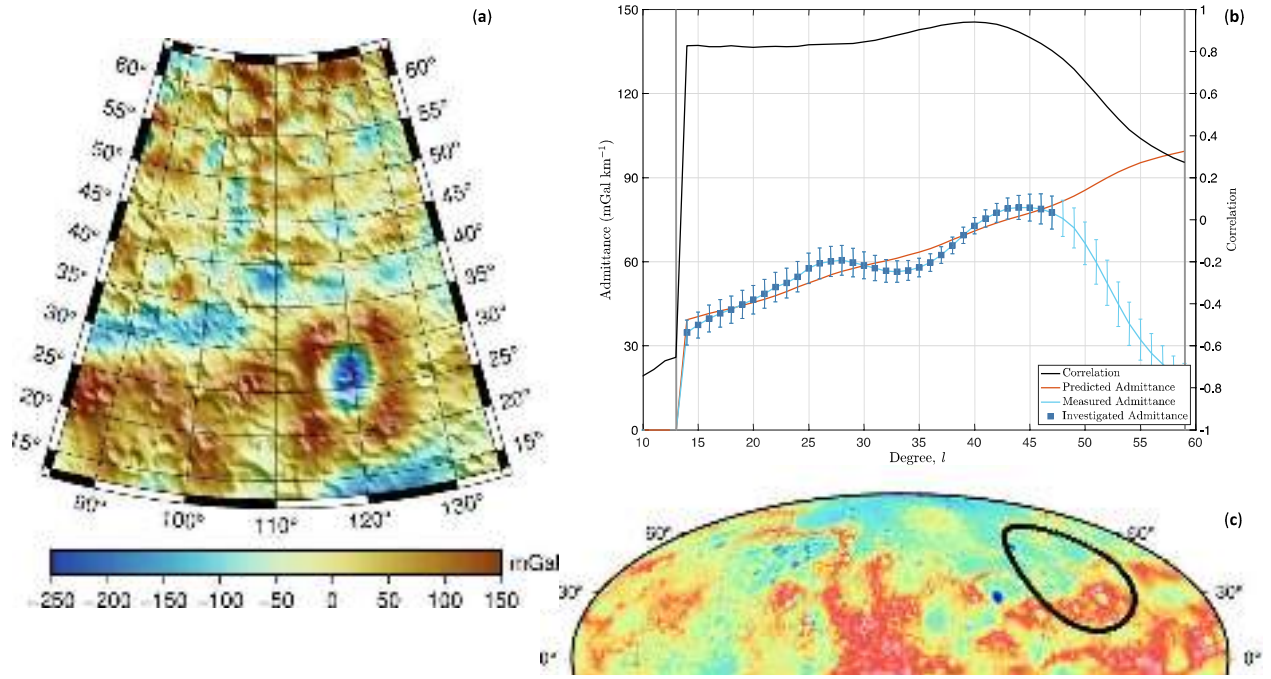


Figure 11 (a) Local map of free-air gravity anomaly (mGal) shown over shaded topographic relief in a Lambert Conformal Conic projection, and (b) correlation and admittance between gravity and topography localized on (c) a spherical cap centered at 110°E longitude and 38°N latitude. The localization windowing is carried out with a 25° radius, a concentration factor of 0.999 ($L_{win} = 13$), and a spherical harmonic expansion to degree $l_{max} = 72$ (see caption of Figure 3 for more details).

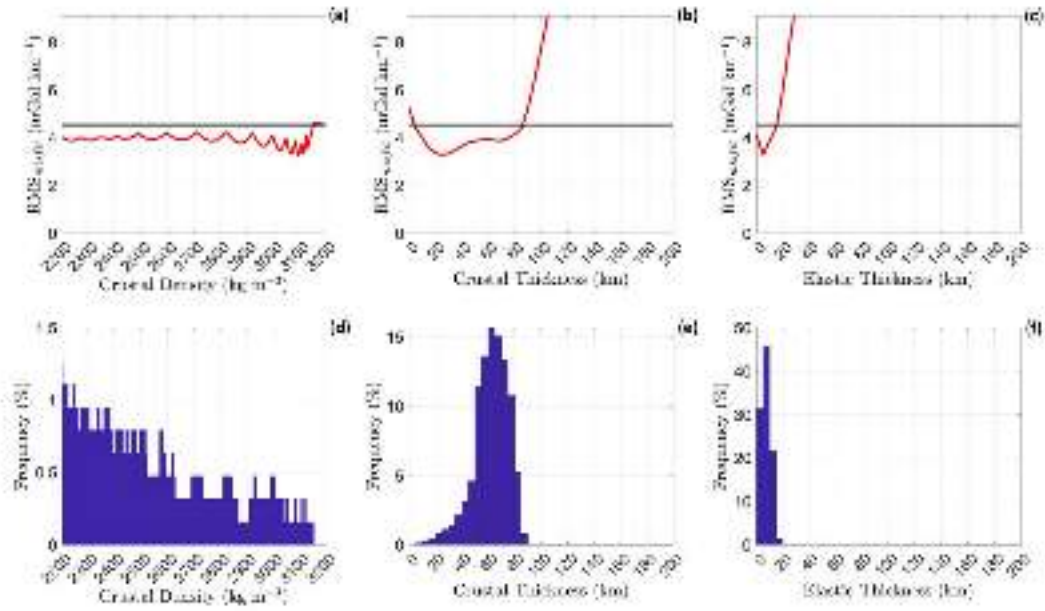


Figure 12 (a-b-c) Misfit plots and **(d-e-f)** histograms for the crustal density and thickness, and elastic thickness resulting from the comparison between measured and predicted localized admittance shown in Figure 11-b. The black horizontal line shows the RMS of the formal uncertainties of the local admittance, $\bar{\sigma}$, and the red curve the RMS_{misfit} as function of the estimated parameter.

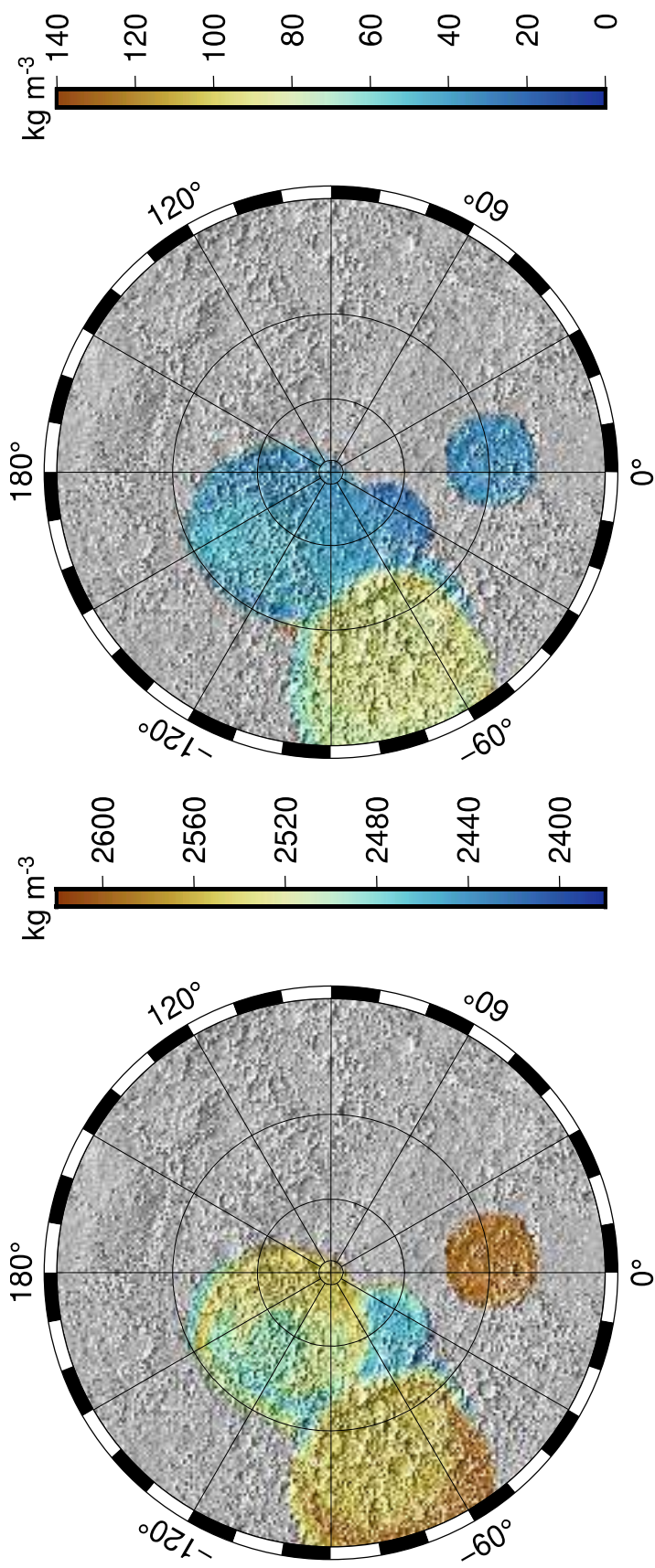


Figure 13 Maps of the lateral variations of the **(left)** crust bulk density and **(right)** its uncertainty in a polar stereographic projection from 30°N-latitude. Grey colors show regions where the localized gravity/correlation admittance spectra do not allow to constrain the crustal density.

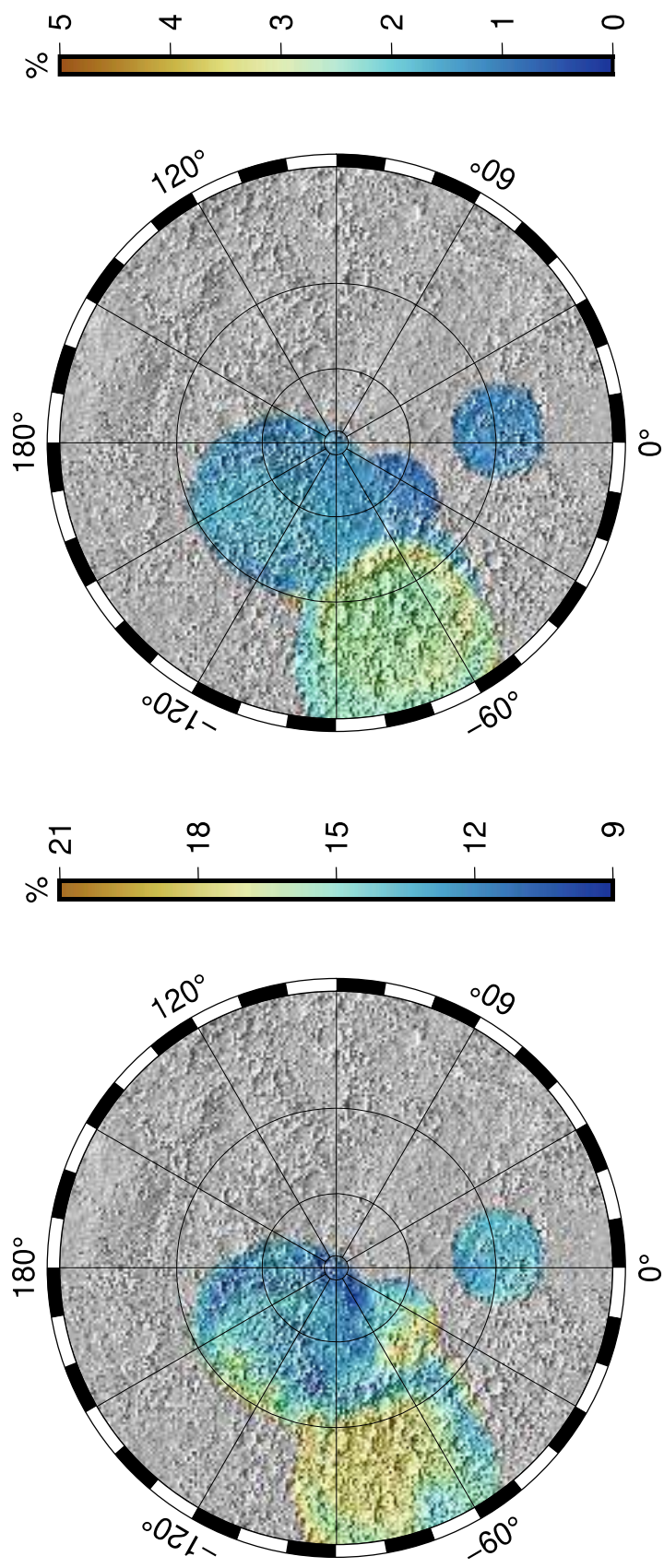


Figure 14 Maps of the lateral variations of the **(left)** surface porosity and **(right)** its uncertainty in a polar stereographic projection from 30°N-latitude. The lateral variations of the surface porosity are computed by comparing the bulk density retrieved from local admittance analyses and the grain density reported by Beuthe et al. 2020

