An approach to Moho discontinuity recovery from on-orbit GOCE data with application over Indo-Pak region

Mehdi Eshagh[a] and Matloob Hussain[a,b,*]

[a]Department of Engineering Science, University West, Trollhättan Sweden
[b]Department of Earth Sciences, Quad-i-Azam University, Islamabad, Pakistan
mehdi.eshagh@hv.se, mutloob.hussain@hv.se

Abstract

Here, a modified form of Vening Meinesz-Moritz (VMM) theory of isostasy for the second-order radial derivative of gravitational potential, measured from the Gravity field and steady-state Ocean Circulation Explorer (GOCE), is developed for local Moho depth recovery. An integral equation is organised for inverting the GOCE data to compute a Moho model in combination with topographic/bathymetric heights of SRTM30, sediment and consolidated crystalline basement and the laterally-varying density contrast model of CRUST1.0. We also computed Moho models from EGM2008, CRUST1.0, Meier and Stolk over Indo-Pak plate and compare results with our GOCE based Moho Model. The model is closest to the regional one with a standard deviation of 5.5 km and a root mean squares error of 7.8 km, which is 2.3 km smaller than the corresponding one based on EGM2008.

Introduction

We introduce an alternative approach for local Moho depth recovery from on-orbit GOCE data and apply it over Indo-Pak continental plate and its surroundings. We adopted the updated method of VMM for the Moho recovery from gravity disturbances (Sjöberg et al. 2015) and combine it with the scheme proposed by Eshagh (2014 a,b). Here, we develop an integral equation for the conversion of second-order radial derivative of the gravitational potential of GOCE (ESA 2012) to a specific quantity. This quantity will be used with topographic/bathymetric (TB) information from the shuttle radar topographic mission (SRTM30) (Farr et al. 2007), density contrast, sediment and crystalline data of CRUST1.0 (Laske et al. 2013) for local Moho recovery. The recovered Moho model will be compared with seismic Moho models of the CRUST1.0 and those presented by Meier et al. (2007) and Stolk et al. (2013). We name them here Meier and M13_Eurasia models here.

Gravimetric approach to Moho modelling by GOCE data

Generally, a Moho can be computed based on the VMM theory of isostasy. We modified the mathematical relationship given by Sjöberg et al. (2015) for Moho recovery in its spherical harmonics:

$$T_n = \frac{1}{4\pi G\Delta\rho}\left(-A_{C0}\delta_{n0} + \frac{2n+1}{n-1}\left(\delta g_n^{\mathrm{TB}} + \delta g_n^{\mathrm{sed}} + \delta g_n^{\mathrm{cry}} - \delta g_n\right)\right) \text{ and } A_{C0} = \frac{4\pi G\Delta\rho R}{3}\left[\left(1-\frac{T_0}{R}\right)^3 - 1\right]$$

where δg_n^{TB} is Topography/bathymetry effect, $\delta g_n^{\mathrm{sed}}$ Sediment effect and $\delta g_n^{\mathrm{cry}}$ crystalline basement effect on gravity disturbance δg_n. A_{C0} is the attraction of compensation and mathermically defined as shown. T_0 is a priori mean Moho depth and in this case it is 35 km

In this study, we consider the second-order radial derivative of the Earth's disturbing potential, which is derived by subtracting the second-order radial derivative of normal gravitational potential of GRS80 from the real gradients of GOCE. It contains stronger signals than the rest of the derivatives and mathematically simple as well. The above equation is a function of gravity disturbance and we try to connect this quantity to the Laplace harmonic of the second-order derivative of disturbing potential $V_{rr,n}$. We can write (cf. Eshagh 2014a):

$$\delta g_n = \frac{r^2}{R}\frac{1}{n+2}\frac{1}{s^{n+1}}V_{rr,n} \text{ where } s = \left(\frac{R}{r}\right)^{n+1} \text{ and finally, we can find the spectral relation between } T_n \text{ and } V_{rr,n}$$

from the following relation:

$$T_n = \frac{1}{4\pi G\Delta\rho}\left(-A_{C0} + \frac{2n+1}{n-1}\left(\delta g_n^{\mathrm{TB}} + \delta g_n^{\mathrm{sed}} + \delta g_n^{\mathrm{cry}}\right) - W_n\right), \text{ where } W_n = \frac{2n+1}{(n-1)(n+2)}\frac{r^2}{R}\frac{1}{s^{n+1}}V_{rr,n}$$

where, W_n can be written as an integral form from Heiskanen and Moritz 1967, p. 30. After solving the integral equation for W_n we can obtain W from $r^2V_{rr,n}$ and taking the summation, we obtain the Moho depth:

$$T = \frac{1}{4\pi G\Delta\rho}\left(-A_{C0} + \sum_{\substack{n=0\\n\neq 1}}^{\infty}\frac{2n+1}{n-1}\left(\delta g_n^{\mathrm{TB}} + \delta g_n^{\mathrm{sed}} + \delta g_n^{\mathrm{cry}}\right) - W\right)$$

where W is the contribution of gravimetric data and the rest of the components can be derived from seismic data.

Solution of Integral Equation

The following integral equation:

$$\frac{R}{4\pi}\iint_{\sigma} K(s,\psi)W d\sigma = r^2 V_{rr}$$

firstly, it is descritised according to the resolution of the desired Moho depths. This process leads to the following system of equations of Gauss-Markov type:

$$\mathbf{Ax} = \mathbf{L} - \boldsymbol{\varepsilon} \text{ where } \mathrm{E}\{\boldsymbol{\varepsilon}\boldsymbol{\varepsilon}^{\mathrm{T}}\} = \sigma_0^2\mathbf{Q};\ \mathrm{E}\{\boldsymbol{\varepsilon}\} = 0$$

where $\mathbf{A}$ is the coefficient, $\mathbf{x}$ is the vector of W for above integral equation and $\mathbf{L}$ is the vector of $r^2V_{rr,n}$. E{.} stands for the statistical expectation operator; $\mathbf{Q}$ is the cofactor matrix and is the a priori variance factor. In addition, we assume that $\mathbf{Q} = \mathbf{I}$ and $\sigma_0^2 = 1$ in this study. This system of equations is solved by the Tikhonov regularisation,

Numerical Investigation

The study area for this research is bounded by 10°N to 50°N latitude and 50°E to 90°E longitude mainly comprising the Indo-Pak subcontinent and adjoining areas. The Indo-Pak plate has active tectonics on its margins e.g. in the north and northwest it has Himalayan orogenic belt towards south mid-Indian ridge and towards southwest it has Makran subduction zone.

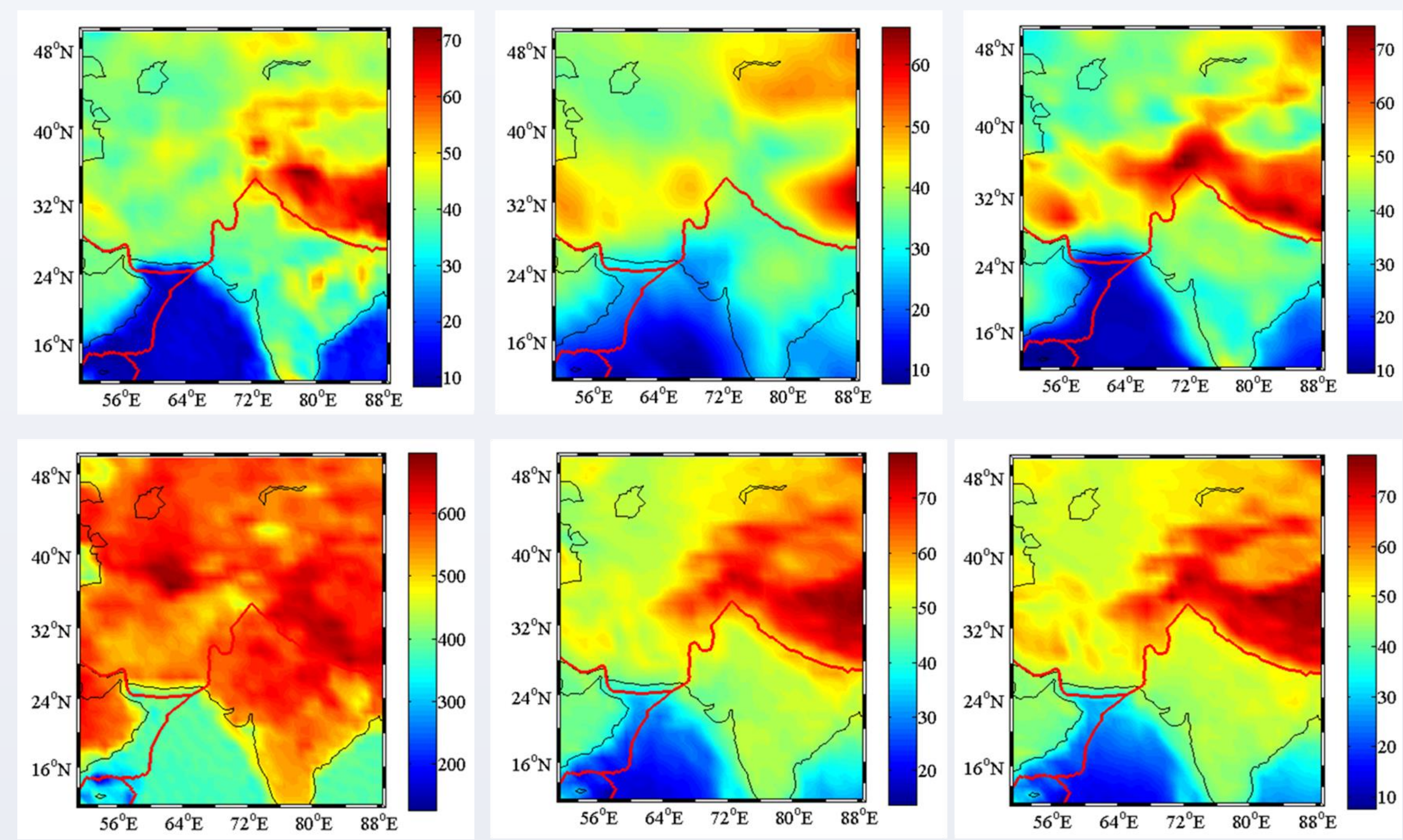

Figure 1: Indo-Pak Moho models from a) CRUST1.0 [km], b) Meier Moho model [km], c) M13_Eurasia [km] and d) density-contrast from CRUST1.0 [kgm-3] used, as well as e) EGM2008 Moho model and finally, f) GOCE-based Moho model [km]

In Figures 1a and 1c, the deepest Moho is clearly evident along Himalayas and its subordinate ranges. These two models are clearly in correlation as far as deepest Moho is concerned in contrast to Figure 1b, which is clearly missing information over Himalayas. Lack of seismic data in CRUST1.0 and Meier Moho model over western and northwestern part of Indo-Pak plate can be justified by Figure 1c. We can see more local features in the M13_Eurasia Moho model over the areas, which are clearly missing in the other two seismic models. For example, the western extension of Himalayan mountains are very-well traceable in Figure 1c. Tarim basin is clearer in Figure 1c than other two seismic models. Mt. Damavand of Zagros ranges and Mt. Everest of Karakoram range are more visible in Figure 1c. The M13_Eurasia Moho model is missing fine details over Indian platform area and no visible anomalies can be seen in Figure 2c, in contrast to CRUST1.0. From Figures 1e and 1f, it can be observed that the EGM2008 Moho model is smoother than that of gradiometric one and anomalous features of the region are less perceptible. The GOCE signals appear to be much stronger over Zagros-Alborz mountains of Iran, Makran subduction zone, Suleiman-Kirthar fold belt of Pakistan and the mountain ranges surrounding Tarim basin e.g. Pamir-Tien Shan and Altyn ranges. In spite of the dissimilarities between EGM2008 and GOCE-based Moho models, both are in fairly good agreement for mountainous region of the Indo-Pak plate. As far as, the platform area of the plate is concerned, both the models show poor consistency and the GOCE-based model is in good connection with CRUST1.0 model. From above discussion we can say that, the GOCE-based Moho model is in better agreement to CRUST1.0 and M13_Eurasia model and it designates more anomalous features and fine details over the area.

Conclusions

We have developed the Vening Meinesz-Moritz (VMM) theory further and presented an integral approach to recover Moho depths from the on-orbit GOCE data and applied it over Indo-Pak plate. Our approach is based on considering full topographic/bathymetric (TB) effect from SRTM30, instead of the Bouguer correction. Adopting the same principle, we also recycled EGM2008 for Moho over the same area for comparison purpose. The kernel of our integral formula is well-behaving and suggests that the local recovery of W from the GOCE data is successful. This function along with TB, sediments and crystalline basement effects are used to compute the Moho depths. Our GOCE-based Moho model contains more local details and it is in a good agreement with the seismic Moho models than that of EGM2008 with smaller root mean squares error. The numerical results show that the best RMS belongs to the differences between the GOCE-based and M13_Eurasia Moho model. This value is 2.3 km smaller than that of the EGM2008 and M13_Eurasia Moho model.

References

Eshagh, M., 2014a. Determination of Moho discontinuity from satellite gradiometry data: linear approach, Geodynamics Research International Bulletin 1 (2), pp. 1–13.

Eshagh, M., 2014b. From satellite gradiometry data to subcrustal stress due to mantle convection, Pure and Applied Geophysics 171, pp. 2391-2406, doi: 10.1007/s00024-014-0847-2.

Farr, T. G., Paul, A. R., Edward, C., Robert, C., Riley, D., Scott, H., Michael, K., Mimi, P., Ernesto Rodriguez, Ladislav, R., David, S., Shaffer, S., Joanne, S., 2007. The Shuttle Radar Topography Mission, Reviews of Geophysics 45, RG2004, doi:10.1029/2005RG000183.

Heiskanen, W., Moritz, H., 1967. Physical geodesy, W.H. Freeman and company, San Francisco and London.

Laske, G., Masters, G., Ma, Z., Pasyanos, M., 2013. Update on CRUST1.0 - A 1-degree Global Model of Earth's Crust. In EGU General Assembly Conference Abstracts 15, 2658.

Meier, U., Curtis, A., Trampert, J., 2007. Global crustal thickness from neural network inversion of surface wave data, Geophysical Journal International 169, pp. 706-722, doi: 10.1111/j.1365-246X.2007.03373.x

Pavlis, N., Holmes, S.A., Kenyon, S.C., Factor, J.K., 2008. An Earth Gravitational model to degree 2160: EGM2008. Presented at the 2008 General Assembly of the European Geosciences Union, Vienna, Austria, April 13-18, 2008.

Sjöberg, L.E., Bagherbandi, M., Tenzer, R., 2015. On Gravity Inversion by No-Topography and Rigorous Isostatic Gravity Anomalies. Pure and Applied Geophysics 172 (10), pp. 2669-2680, doi: 10.1007/s00024-015-1032-y

Stolk, W., Kaban, M., Beekman, F., Tesauro, M., Mooney, W. D., Cloetingh, S., 2013: High resolution regional crustal models from irregularly distributed data: Application to Asia and adjacent areas. - Tectonophysics 602, pp. 55-68, doi:10.1016/j.tecto.2013.01.022