Evaluation of EGM 2008 and EIGEN-6C3stat by means of data from GNSS/leveling

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Abstract

The global combined high-resolution gravity field models EGM 2008 and EIGEN-6C3stat are compared by means of gravity anomalies and the radial component of the Marussi tensor. The role of the GOCE gradiometry data is detected. GNSS/leveling provides independent data source to evaluate any gravity field model. We apply such data to test EGM 2008 (without GOCE measurements) and EIGEN-6C3stat (already with them). The GNSS/leveling data set is dense (1024 points) and precise (ellipsoidal height error below 2 cm) but is available only over the territory of the Czech Republic with this density; this test has in turn a limited validity. The RMS of height differences between GNSS/leveling and EGM 2008 or GNSS/leveling and EIGEN-6C3stat is 3.3 cm or 4.1cm, respectively.

Keywords

Gravity field evaluation – EGM 2008 – EIGEN-6C3stat – gravity anomalies – second derivatives of the disturbing potential – GNSS/leveling

1 Models tested and differences between them

The topic and the method are not new. We continue in work of many other authors, including our own work, see, e.g., Newton's Bull. 2009 (external quality evaluation reports of EGM 2008). Here we report about our recent tests with EGM 2008 (Pavlis et al 2008, 2012) and EIGEN-6C3stat (Förste et al. 2013).

Both are global combined gravity field models with high resolution due to extensive and (still) top quality and resolution terrestrial data. EGM 2008 is expanded completely up to 2159 in degree and order of spherical harmonics, EIGEN 6C3 to 1949 (in the following, the model name 'EIGEN-6C3stat' is shortened to 'EIGEN 6C3'). EGM 2008 has been prepared by the National Geospatial-Intelligence Agency, USA. EIGEN 6C3 has been elaborated jointly by GFZ (GeoForschungsZentrum), Potsdam, and GRGS (Groupe de Recherche de Geodesie Spatiale), Toulouse. This model contains GOCE satellite gradiometry data (SGG, e.g., Reigber et al. 2002, Floberghagen et al. 2011) but yet not all to the end of this mission (ESA 2014). The GOCE-SGG data were processed by the direct approach (Pail et al. 2011, Bruinsma et al. 2013) to degree 235. The DTU12 ocean geoid data (Anderson et al. 2009) and EGM2008 geoid height grid for the continents were used (for the harmonics of degrees above 235).

The models can be compared by means of gravity anomalies, Marussi tensor, invariants of the gravity field, their specific combinations and by virtual deformations computed from their harmonic geopotential coefficients (for theory and examples of various applications see Kalvoda et al. 2013; Klokočník et al. 2013). Here we make use of only the gravity anomalies and the radial component of the Marussi tensor of the second derivatives of the disturbing potential. The other quantities listed above can be used later.

Our next Figures 1, 2 b-e and 3 b, c will show the differences in the height anomalies , gravity anomalies and the radial component of the Marussi tensor between the two models and for selected regions. We are well aware that the difference only cannot say anything about the accuracy. For the accuracy assessment we have GPS/leveling data (see below). The differences exhibit short- and long-periodic features due to different data used in the tested models (more details follow).

Figure 1 shows the differences in height anomalies between EGM 2008 and EIGEN 6C3, both cut at degree and order 1949. We expect an important role of GOCE data in EIGEN 6C3 for improvement of height anomalies in remote/mountain areas.

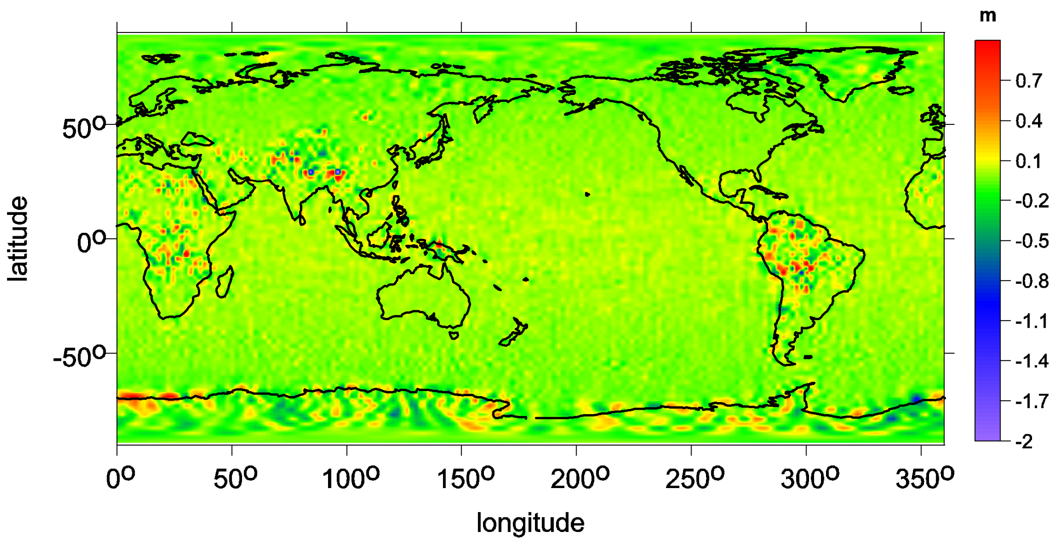


Figure 1: Differences in global height anomalies between EGM 2008 and EIGEN 6C3, both cut at degree and order 1949.

Regional differences are shown in the case of Himalaya, Ethiopia, and the Czech Republic. Much more examples are available but cannot be presented due to space reasons. We selected the following three examples: first for the area with a low quality of terrestrial data in both models (fill-in data) in a remote area with mountains, one in the area with much better data, however outside Europe (not of the best quality of terrestrial data available in EGM 2008), and one in the Czech Republic with high quality terrestrial data.

Figure 2a shows the second radial derivative of the disturbing potential T_{zz} for Himalaya with the full EGM 2008, then Figures 2b and 2c depict differences in gravity anomalies Δg and in T_{zz} between EGM 2008 and EIGEN 6C3 (cut at 1949). Figures 2d, e show the same quantities for Ethiopia. We can observe the long wavelength differences between the two models, where the influence of the GOCE data is visible.

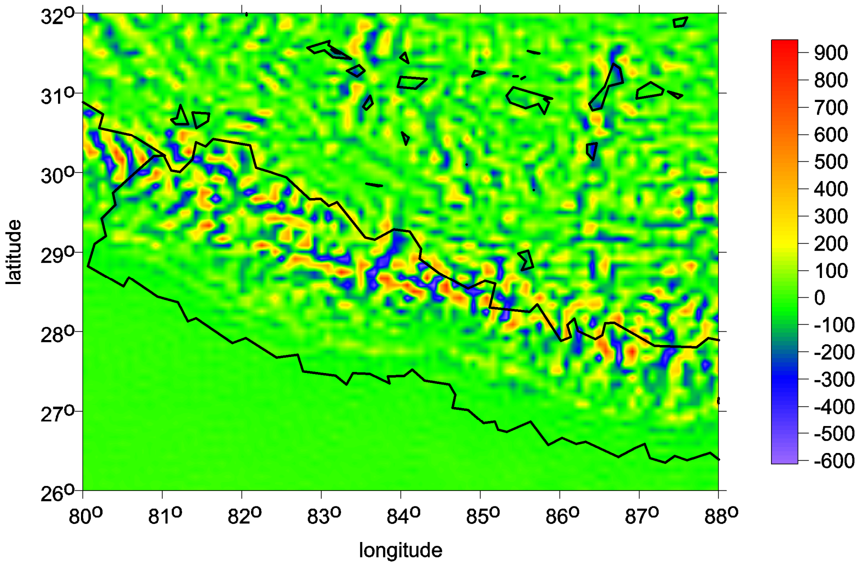
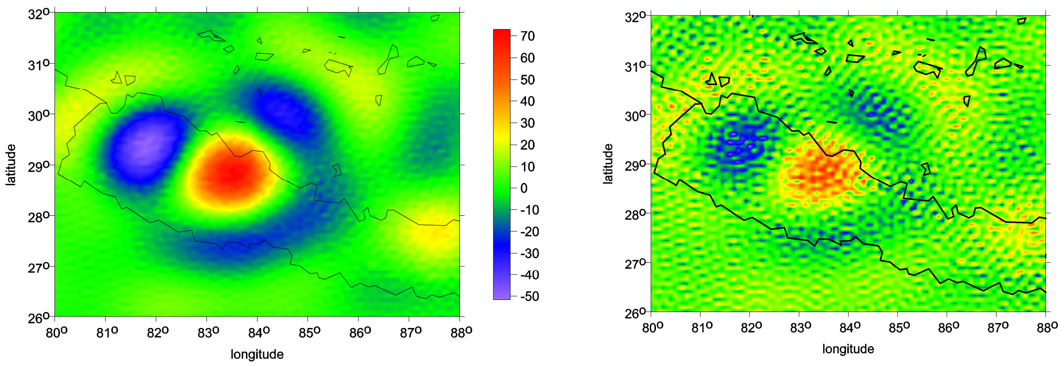


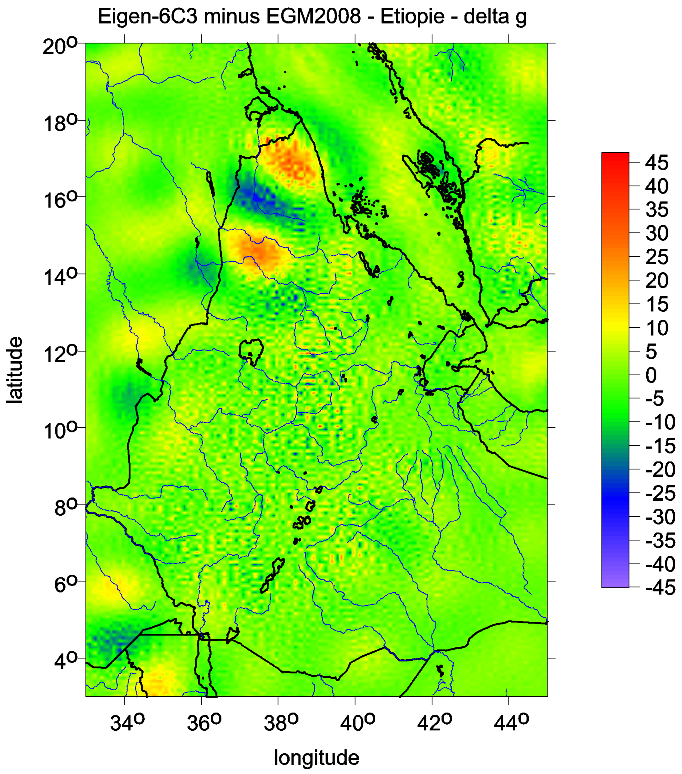
Figure 2a: The second radial derivative T_{zz} for Himalaya with EGM 2008, scale in Eötvös.

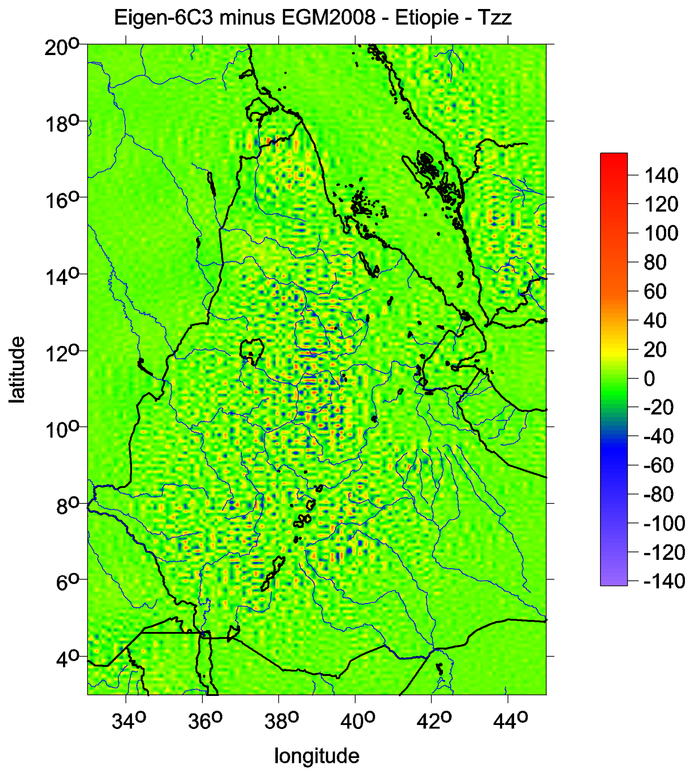


Figures 2b and **2c:** Differences in gravity anomalies Δg and in T_{zz} between EGM 2008 and EIGEN 6C3 (both cut at degree and order 1949) for Himalaya (in miligals and Eötvös, respectively). Note a long-wavelength character of the difference and its size.

Finally, Figures 3a–c show the detailed gravity anomalies from EIGEN 6C3 and differences in gravity anomalies Δg and in T_{zz} between EGM 2008 and EIGEN 6C3 for the Czech Republic. The differences are small, on a level of precision of both models, thus they look randomly (mostly artifacts), excluding a real trend to increase the difference in directions to the mountains outside the territory of the Czech Republic (Alps and Carpathian belt).

In general the differences are of short as well as of long (or medium) wavelength. The short-periodic or small scale differences shown in Figures 3 b,c, and to certain extend also in Figures 2 c-e arise due to the fact that the EIGEN 6C3 model is limited by degree and order 1949 (see Förste et al. 2013). They are more pronounced in the more sensitive T_{zz} component than in Δg. We guess that the longer wavelengths differences reflect a positive role of GOCE data in EIGEN 6C3, mainly in remote (mountain) areas, but we cannot decide which model is better. For this purpose, we seek for an independent, sufficiently precise and as global as possible data set. We have the GPS/leveling data, independent of the models, very precise but not global.





Figures 2d and **2e:** Differences in gravity anomalies Δg and in T_{zz} between EGM 2008 and EIGEN 6C3 for Ethiopia (in miligals and Eötvös, respectively).

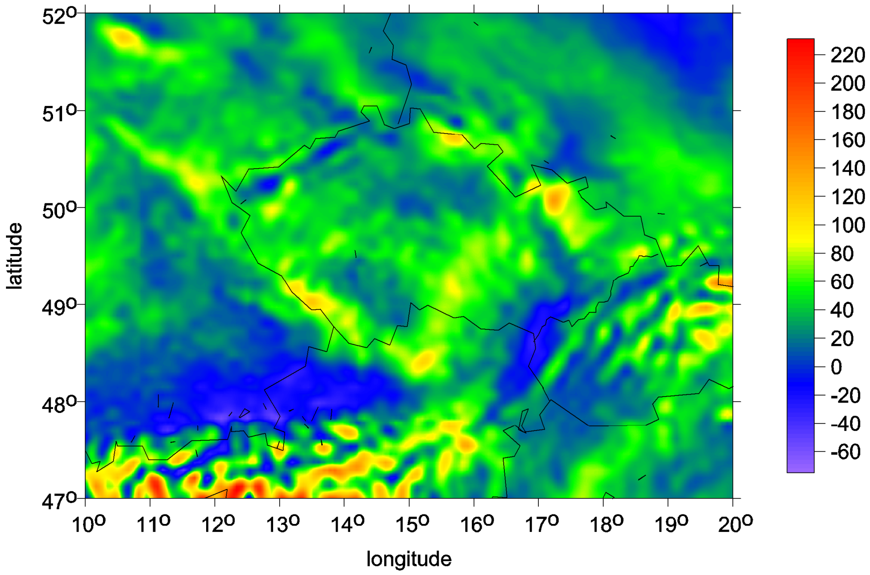
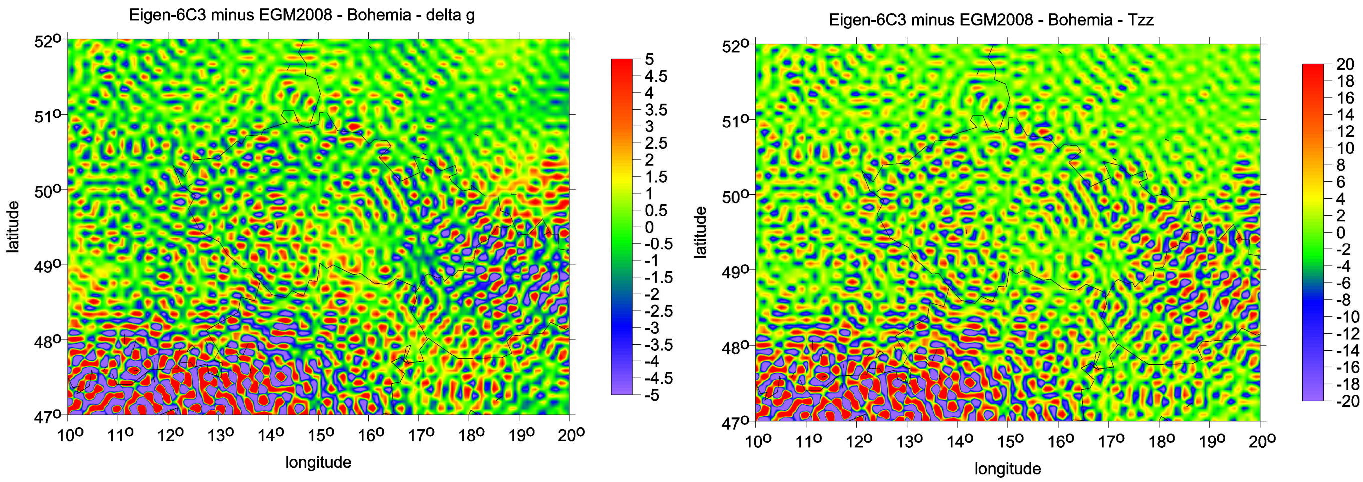


Figure 3 a: Gravity anomalies (in miligals) according to EIGEN 6C3 for the Czech Republic.



Figures 3 b, c: Differences in gravity anomalies Δg and in T_{zz} between EGM 2008 and EIGEN 6C3 for the Czech Republic (in miligals and Eötvös, respectively).

2 GNSS/leveling

2.1 Evaluation – method and data

A network of geodetic points has been established on the territory of the Czech Republic during 1996–2006. It enables a direct computation of the height anomaly ξ according to a simple formula

$$\xi = h_{GNSS} - h_{leveling} + \{2\}, \qquad (1)$$

where h_{GNSS} is the ellipsoidal height with respect to a reference ellipsoid (here GRS80) derived from measurements by the GNSS technology, $h_{leveling}$ is the physical (sea-level) height derived from the leveling, here the normal height according to Molodensky in the Baltic vertical datum and {*2*} are small terms of second order, accounting for the curvature of the plumb line.

The method and results are described in Kostelecký et al (2012). The network containing 1024 points regularly covering the territory of the Czech Republic has been surveyed by Land Survey Office with the aim to rectify the gravimetric quasigeoid. The GNSS coordinates were measured on selected trigonometric points of the Czech Geodetic Control. The height of these points was already known from trigonometry with precision of decimeters; thus, the most precise heights of these points were determined by the method known as “precise geometric leveling” using the nearest points of the Czech State Leveling Network. The accuracy of the physical heights is better than 0.5 cm with respect to the nearest points of the State Leveling Network. For all 1024 points we can then compute the height anomalies by Eq. (1). The accuracy of the GNSS ellipsoidal heights is 1.5–2.0 cm. The total error of the height anomaly ξ varies between 1.6 and 2.1 cm, see e.g., Kostelecký et al. (2012).

2.2 Evaluation of results

The results from the GNSS/leveling (with precision about 2 cm) have been used to validate EGM 2008 and EIGEN 6C3 on the territory of the Czech Republic. Height anomaly from the gravity model has been computed in all GPS/leveling points. Figure 4a shows the test of EGM 2008, i.e. GNSS/leveling minus EGM 2008 height anomalies. RMS of the differences is 3.3 cm. Figure 4b shows the result for EIGEN 6C3; RMS of the differences here is 4.1 cm, slightly worse than for EGM 2008. In this case we used the full models, it means the resolution of EIGEN 6C3 is a bit lower and may result in a smoothing.

The maximum/minimum values of the differences in Figures 4a,b are -8 cm/+10 cm for the EGM 2008 and -12 cm/+12 cm for the EIGEN 6C3, respectively. The semi-major axis of an ellipsoid used to compute the height anomaly from the model is 6378136.3 m for both models. The quasigeoid heights from the GNSS/leveling are computed with respect to the GRS80 ellipsoid with semimajor axis 6378137.0 m; according to Eq. (1) the GNSS/leveling quasigeoid height is computed as a difference between the ellipsoidal and leveling heights. The difference between these two reference ellipsoids is thus 70 cm. A constant shift between both of the surfaces is 43 or 46 cm, respectively (see Figures 4a,b), and a residual constant shift therefore 27 and 24 cm, respectively. This can be due to *i)* by using the Baltic high system and by *ii)* comparison of the height anomaly (models) and quasigeoid (which yields 1–3 cm for the Czech Republic – see Denker et al., 2008); the height anomaly has been computed from EGM 2008 and EIGEN 6C3, the GNSS/leveling provides the quasigeoid.

The differences shown in Figures 4a, b were analysed and discussed. Both cases in Figues 4a, b show a hollow in the northern part of the Czech Republic. We computed the histograms of occurrence of the differences, see Figure 5a for EGM 2008, Figure 5b for EIGEN 6C3. For the EGM 2008, we have much more small values around zero than for the EIGEN 6C3. In both cases, however, the histograms reveal existence of a systematic effect, but it is not too serious.

The reason for the depression in the northern Czech Republic is not fully understood, but we are sure that it is not an artifact of the method or computations. To support this statement we added Figure 4c with differences between GNSS/leveling and Quasigeoid model EGG97 (Denker et al., 2008). This figure shows a systematic trend, but the differences between GNSS/leveling and quasigeoid of EGG97 (the only model that does not incorporate GRACE or GOCE data) are little bit lower than those shown in Figures 4a, b. If the same feature shows up (like the depression in the northern Czech Republic) it is very likely, that it is not connected to the satellite data. The depression depicted in Figures 4a-c in the northern part of Czech Republic can be caused by *i)* inaccuracy of terrain gravity measurements and/or *ii)* by local recent movements (GNSS observations are from the epoch 2003 and the leveling heights are from 1986 and older). Note also that the authors of both the models estimate precision of heigh anomalies computed from them in Europe to 10 – 15 cm RMSE (Foerste et al. 2013) and the total error of the GNSS/leveling quasigeoid is about 2 cm (see above, Sect 2.1.).

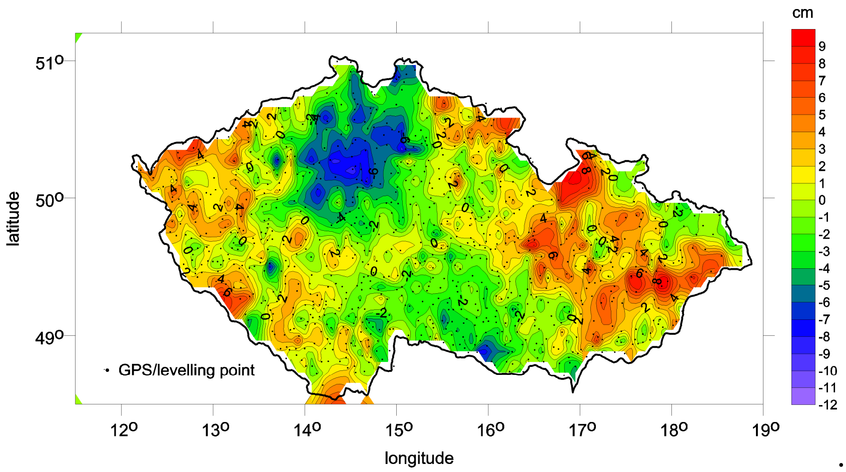


Figure 4a: Test of EGM 2008 by means of GNSS/leveling on the territory of the Czech Republic. The values of $\xi_{GNSS/lev} - \xi_{EGM}$ after removing of the offset of 43 cm (caused mainly by using different ellipsoid and height systems) are shown. RMS of the differences is 3.3 cm. The black dots in both Figures 4 a, b show the locations of the GNSS/leveling points.

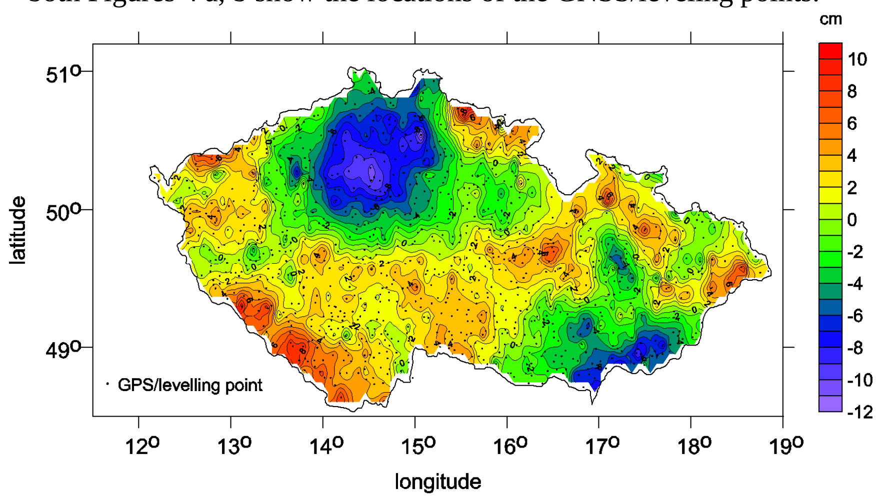


Figure 4b: Test of EIGEN 6C3 by means of GNSS/leveling on the territory of the Czech Republic – $\zeta_{GNSS/lev} - \zeta_{EIGEN}$ after removing the offset of 46 cm (caused mainly by using different ellipsoid and height system). RMS of the differences is 4.1 cm.

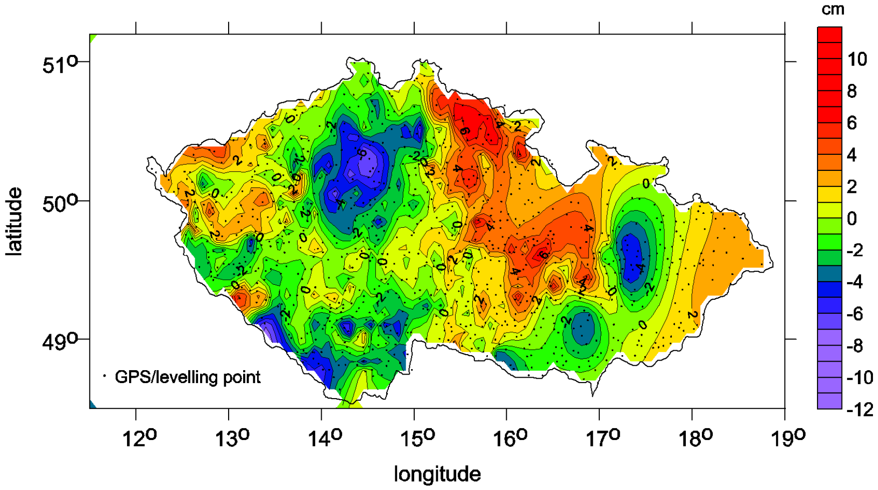
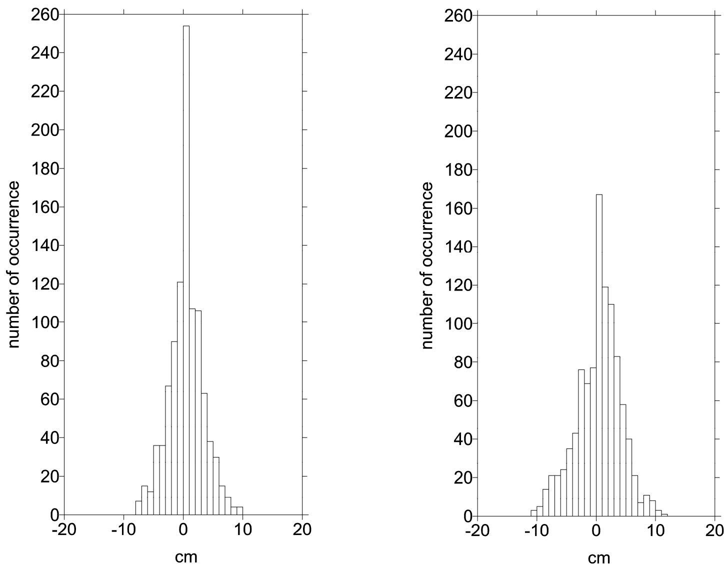


Figure 4c: Differences between quasigeoid heights determined from GNSS/leveling and model of quasigeoid EGG97 transformed to territory of the Czech Republic, see Zeman et al. (2007).



Figures 5a,b: Histograms with the numbers of occurrence of the height differences shown in Figures 4a,b. Figure 5a is for EGM 2008, Figure 5b for EIGEN 6C3. A systematic error is indicated this way.

3 Conclusions

The global combined high-resolution gravity field models EGM 2008 and EIGEN-6C3stat have been compared by means of various functions of the disturbing gravity potential. We show here examples of differences in Δg and in T_{zz} for Himalaya, Ethiopia, and the Czech

Republic. We can observe long wave differences between the two models in remote areas with worse terrestrial data, where a positive role of the GOCE data is visible.

GNSS/leveling data over the territory of the Czech Republic has been used as an independent data source to evaluate the models EGM 2008 (without GOCE gradiometry measurements) and EIGEN-6C3stat (already with them). This is an "absolute test", but feasible only for a small territory (with dense data, however). The RMS of differences between the GNSS/leveling observations and EGM 2008 or EIGEN-6C3stat over the Czech Republic are 3.3 cm or 4.1cm, respectively. Note: meantime (after submitting this manuscript to review) a new version of EIGEN models, called EIGEN 6C4, has been issued (with all GOCE data during its lifetime, and expanded up to degree and order 2160, as is the EGM 2008) and will be tested soon.

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