

Assessment of GOCE Geopotential Models

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Foreword

The Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite by European Space Agency (ESA) was launched on March 17th, 2009, and re-entered the Earth's atmosphere falling into the ocean on November 11th, 2013. Its objectives were to measure the Earth's gravity field with an accuracy of 1 mGal (one millionth of the Earth's gravity) and the geoid with an accuracy of 1-2 cm at a spatial resolution of 100 km. Up to the early 2015, five releases of GOCE-only and joint GRACE and GOCE models had been made available since the first release in 2010.

The Joint Working Group 2.3 (JWG 2.3) between the International Gravity Field Service (IGFS) and the Commission 2 of the International Association of Geodesy (IAG) for 2011-2015, “**Assessment of GOCE Geopotential Models**”, has performed assessments of the GOCE-, GRACE&GOCE-based satellite-only and combined models for the past four years. This special issue of *Newton's Bulletin* consists of 12 peer-reviewed assessment papers on these GOCE-based models using independent data: GPS-levelling, terrestrial gravity, astronomic deflections of the vertical, digital elevation models and satellite laser ranging observations. It is complementary to recent IAG symposium and the GOCE user workshop proceedings, providing valuable assessments for both users and developers of the GOCE models.

We want to thank all people who made the publication of this special issue possible. First of all, we would like to thank all authors for their contribution. Secondly, we highly appreciate careful and constructive reviews by Jan Martin Brockmann, Sean Bruinsma, Sten Claessens, Artu Ellmann, Yoichi Fukuda, Christian Gerlach, Christian Gruber, Thomas Gruber, Christian Hirt, Urs Hugentobler, Juraj Janak, Urs Marti, Pavel Novak, Laura Sanchez, Michal Sprlak, Gabriel Strykowski, Claudia Tocho, George Vergos, Marc Veronneau, Pieter Visser, Christian Voigt and one anonymous reviewer. Last but not least, Presidents of the IGFS and the Commission 2 of the IAG, Riccardo Barzaghi and Urs Marti are acknowledged for their international leadership, guidance and coordination. Special thanks are given to the International Service for the Geoid (ISG) and the Bureau Gravimétrique International (BGI) for the publication of this special issue of *Newton's Bulletin*.

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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.

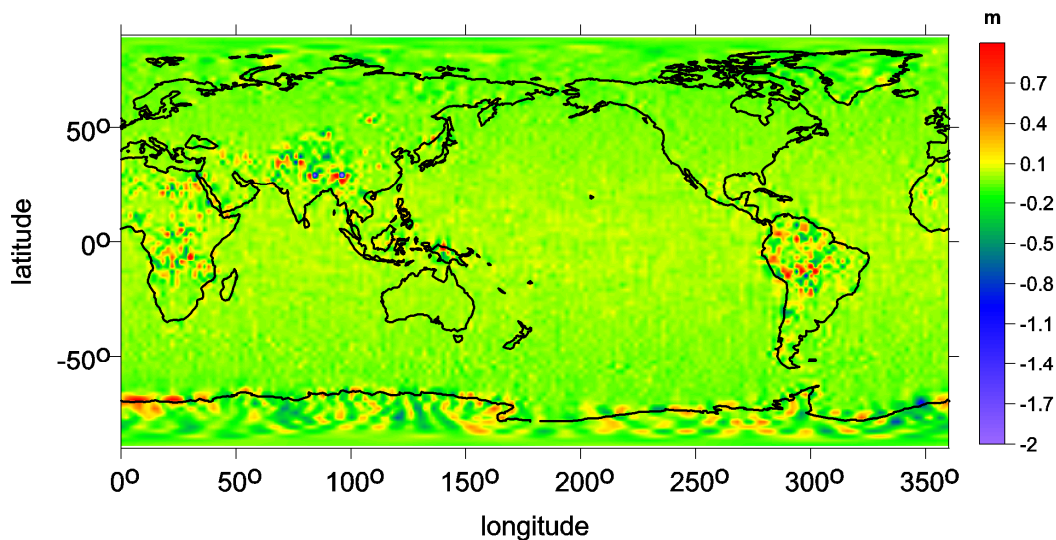


Figure 1: Differences in global height anomalies between EGM 2008 and EIGEN 6C3, both cut at degree and order 1949.

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.

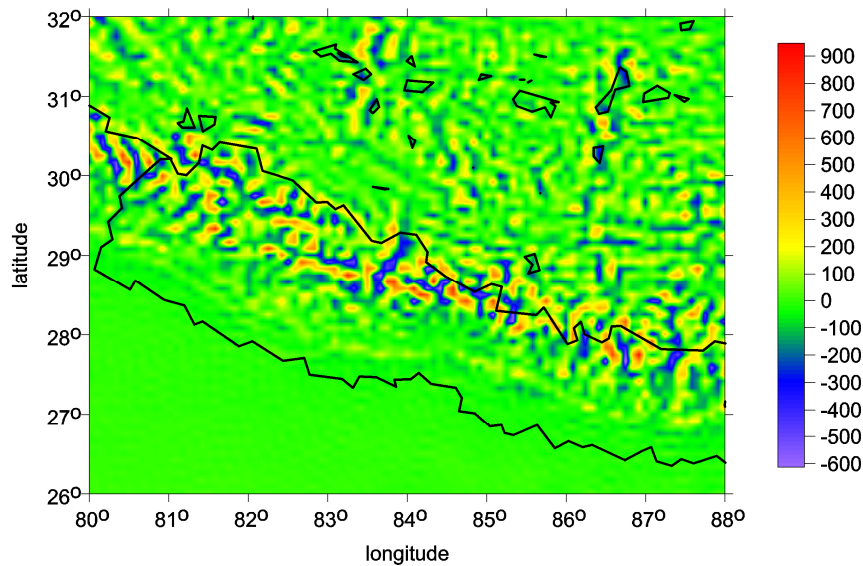
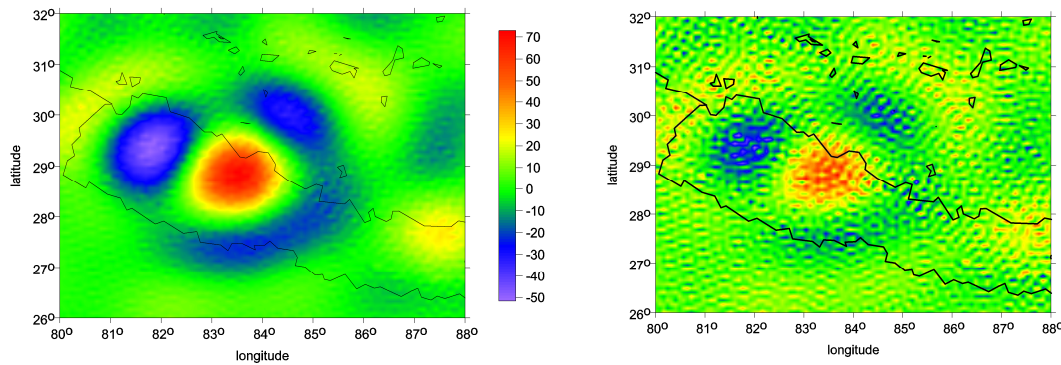


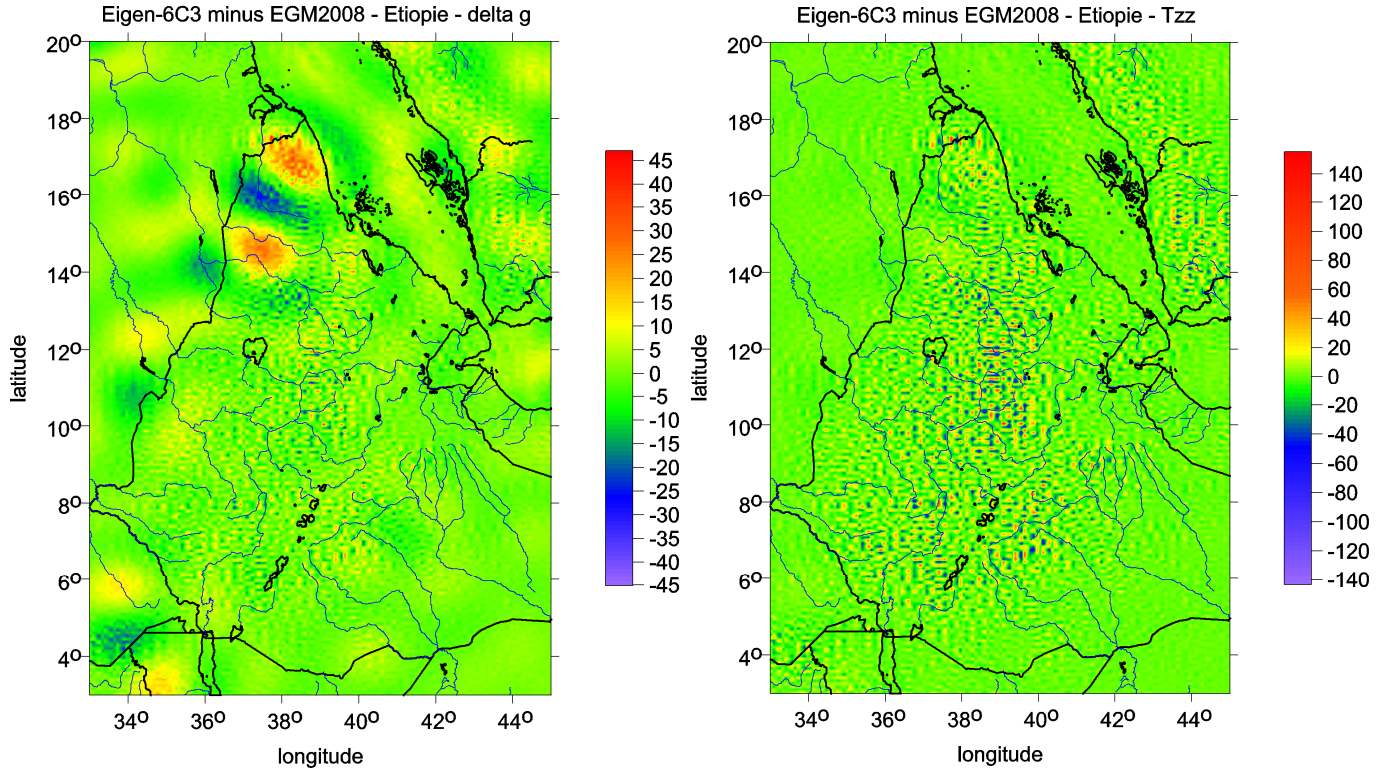
Figure 2a: The second radial derivative T_{zz} for Himalaya with EGM 2008, scale in Eötvös.



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 extent 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).

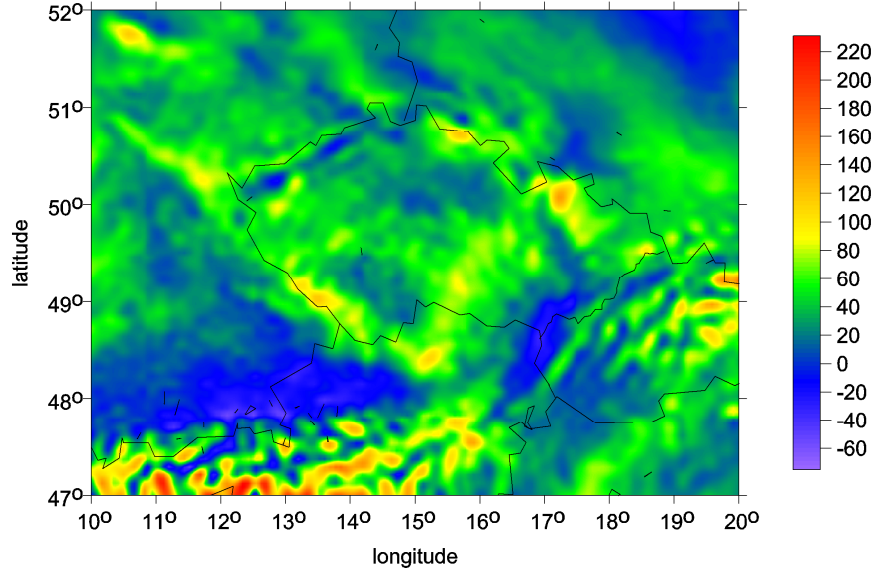
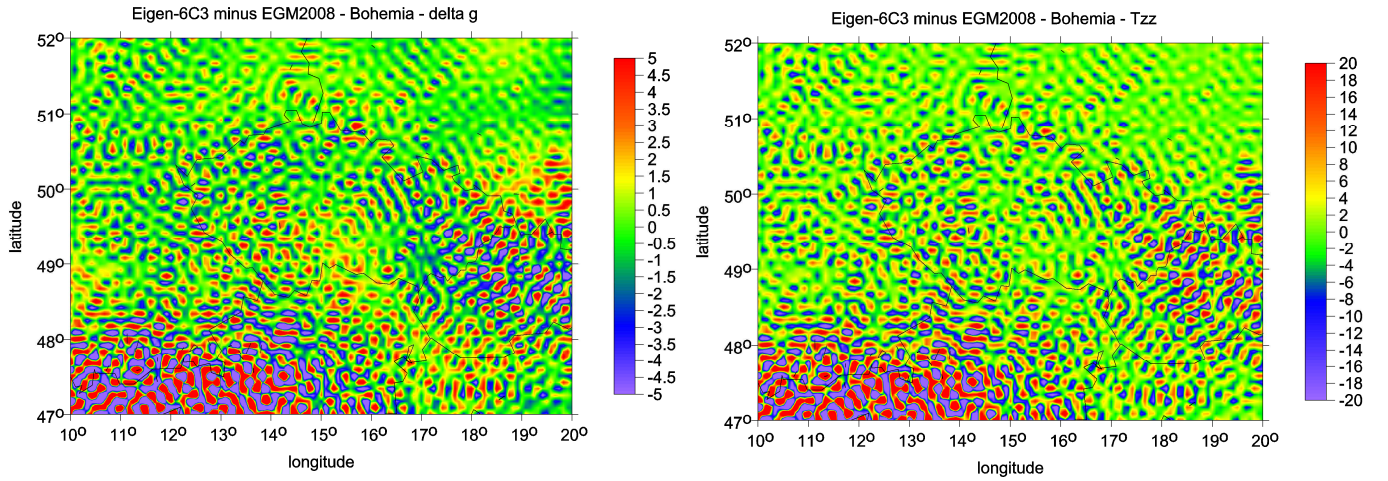


Figure 3 a: Gravity anomalies (in miligals) according to EIGEN 6C3 for the Czech Republic.



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 ζ according to a simple formula

$$\zeta = h_{GNSS} - h_{leveling} + \{2\}, \quad (1)$$

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 Kostecký 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., Kostecký 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 Figures 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.).

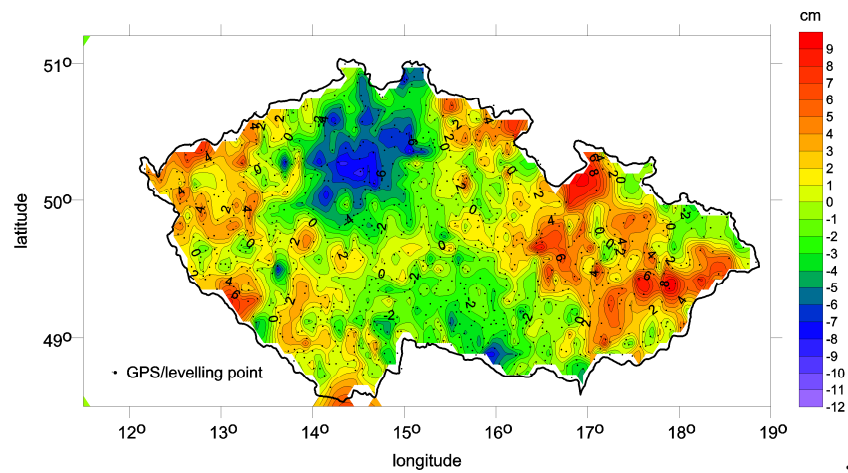


Figure 4a: Test of EGM 2008 by means of GNSS/leveling on the territory of the Czech Republic.

The values of $\zeta_{GNSS/lev} - \zeta_{EGM}$ 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.

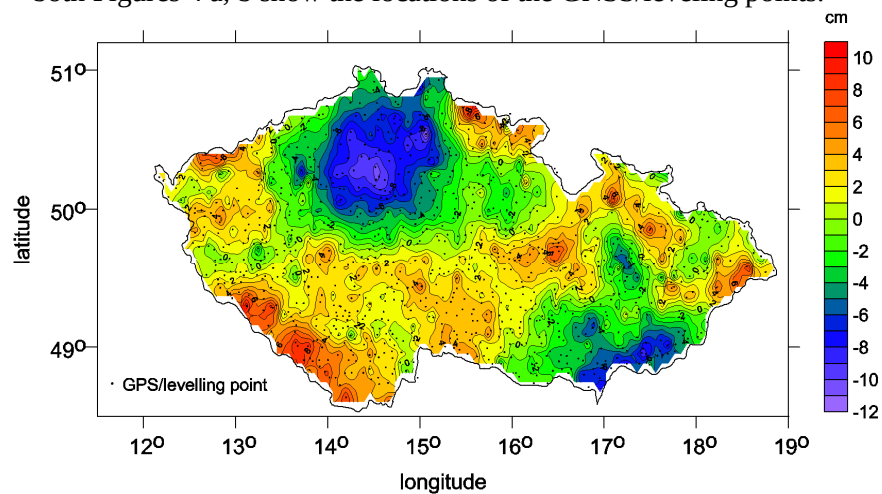


Figure 4b: Test of EIGEN 6C3 by means of GNSS/leveling on the territory of the Czech Republic – $\zeta_{GNSS/lev} - \zeta_{EIGEN}$ after removing the offset of 46 cm (caused mainly by using different ellipsoid and height system). RMS of the differences is 4.1 cm.

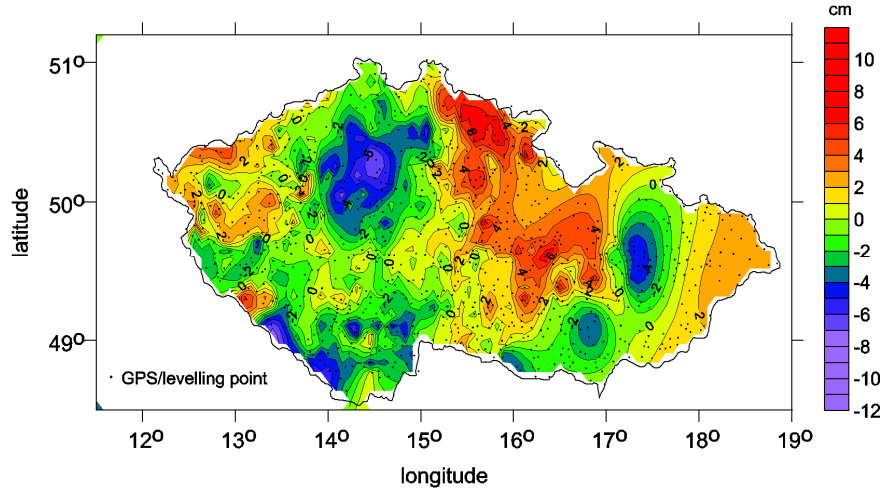
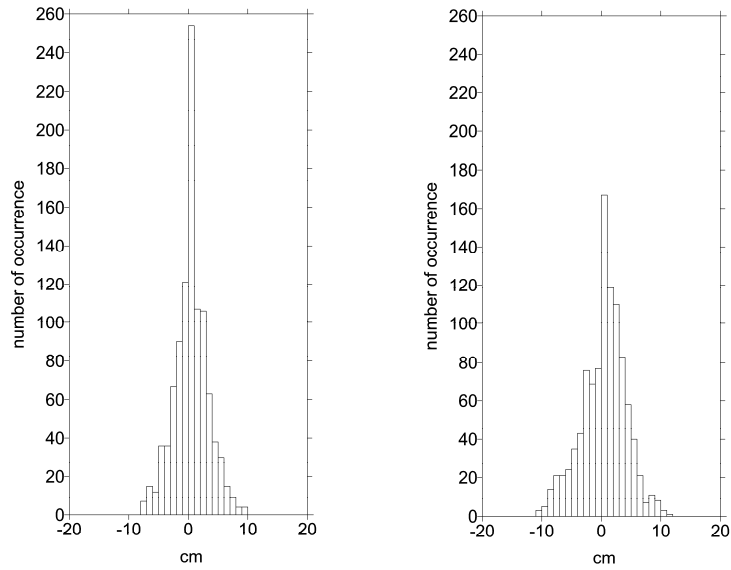


Figure 4c: Differences between quasigeoid heights determined from GNSS/leveling and model of quasigeoid EGG97 transformed to territory of the Czech Republic, see Zeman et al. (2007).



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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References

Andersen OB, Knudsen P, Berry P (2009) DNSC08 mean sea surface and mean dynamic topography models, *J Geophys Res* 114, 12 pp., 2009, doi:10.1029/2008JC005179.

Bruinsma S, Förste C, Abrikosov O, Marty J-C, Rio M-H, Mulet S, Bonvalot S (2013) The new ESA satellite-only gravity field model via the direct approach, *Geophys Res Letters* 40, 3607–3612, doi:10.1002/grl.50716.

Denker H, Barriot J-P, Barzaghi R, Fairhead D, Forsberg R, Ihde J, Kenyeres A, Marti U, Sarrailh M, Tziavos I.N: (2008) The Development of the European Gravimetric Geoid Model EGG07. Institut für Erdmessung, Leibniz Universität Hannover, Schneiderberg 50, D-30167 Hannover, Germany.

ESA (2014) GOCE End-of Mission Operations Report, GOCE Flight Control Team, document GO-RP-ESC-FS-6268, Issue 1.

Floberghagen R, Fehringer M, Lamarre D, Muzi D, Frommknecht B, Steiger C, Pineiro J, da Costa A (2011) Mission design, operation and exploitation of the gravity field and steady-state ocean circulation explorer mission, *J Geod* 85: 749–758, doi: 10.1007/s00190-011-0498-3SATELLTE.

Förste C, Bruinsma S, Abrikosov O, Flechtner F, et al (2013) EIGEN-6C3stat – The newest high resolution global combined gravity field model based on the 4th release of the GOCE Direct Approach, presented at IAG Scientific Assembly, 1-6 September, Postdam, Germany.

Kalvoda J, Klokočník J, Kostecký J, Bezděk A (2013) Mass distribution of Earth landforms determined by aspects of the geopotential as computed from the global gravity field model EGM 2008. *Acta Univ. Carolinae-Geogr.*, 48, 17-25. ISSN 0300-5402.

Klokočník J, Kalvoda J, Kostecký J, Bezděk A (2013) Gravity Disturbances, Marussi Tensor, Invariants and Other Functions of the Geopotential Represented by EGM 2008, Presented at *ESA Living Planet Symp.* 9-13 Sept. 2013, Edinburgh, Scotland. Publ. in: August 2014: *J Earth Sci. Res* 2, 88–101.

Kostecký J, Cimbálník M, Čeppek A, Douša J, Filler V, Kostecký J. jr., Nágl J, Pešek I, Šimek J (2012) Realization of S-JTSK/05. *Geodetický a kartografický obzor* 58/100, 7, 145–154 (in Czech).

Newton's Bull. (2009) External quality evaluation reports of EGM 2008. Issue 4, April 2009, Bureau Gravim. Interntl. IGS Joint Bull., ISSN 1810-8555, 331 pages.

Pail R, Bruinsma S, Migliaccio F, Foerste C, Goiginger H, Schuh W-D, Hoeck E, et al (2011) First GOCE gravity field models derived by three different approaches. *J Geod* 85, 819–843.

Pavlis NK, Holmes SA, Kenyon SC, Factor JK (2008) EGM2008: An overview of its development and evaluation, National Geospatial-Intelligence Agency, USA, presented at conference: Gravity, Geoid and Earth Observation 2008, Chania, Crete, Greece, 23–27 June.

Pavlis NK, Holmes SA, Kenyon SC, Factor JK (2012) The development and evaluation of the Earth Gravitational Model 2008 (EGM 2008), *J Geophys Res* 117: B04406, doi:10.1029/2011JB008916.

Reigber C, Luehr H, Schwintzer P (2002) Gocce gravitational gradiometry. *J Geod* 85:777–790. doi:10.1007/s00190-011-0500-0

Zeman A., Kostecký J., Kostecký J. jr., Ryšavý V. (2007) Vertical component of the Earth's surface movement in the region of Central Europe (Czech Republic) from the results of satellite geodesy methods and their comparison with the results of repeated terrestrial geodetic methods. Poster presentation at the AGU 2007 Fall meeting.

Validation of GOCE global gravitational field models in Norway

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Abstract

Numerous global gravitational field models have been derived from the GOCE satellite gravitational gradiometry mission. They differ by the harmonic analysis approach and the time span covered by the measurements. The quality of individual solutions is assessed by validating the global gravitational field models with respect to independent datasets.

Global gravitational field models based on the time-wise and the direct approach are validated in this contribution. All five releases are compared to height anomalies, free-air gravity anomalies, and deflections of the vertical over the continental part of Norway. The spectral enhancement method is applied to overcome the spectral inconsistency between the gravitational models and the terrestrial data. The three terrestrial datasets indicate comparable performance of the latest GOCE models with respect to EGM2008 up to degree and order 220 in the studied local area.

1. Introduction

The satellite gradiometry mission GOCE (ESA, 1999) was mapping the static part of the Earth's gravitational field in a homogeneous and nearly global way for more than four years. The mission main goals were very challenging. It was expected that GOCE would deliver a geoid model with an accuracy of 1-2 cm and free-air gravity anomalies with an accuracy of 1 mGal, both at the spatial resolution of 100 km.

Global gravitational field models (GGFMs) are the main results of the GOCE mission. Such models are used in realizing vertical reference frames in geodesy, exploring the interior of the Earth in geophysics and geology, studying the behavior of currents in oceanography, and detecting sea level rise and ice-melting in climatology.

Numerous GGFMs have already been derived from GOCE observations. Different strategies have been employed. They differ by a-priori information, stochastic modeling of the gravitational gradients, numerical technique for evaluation of the spherical harmonic coefficients, and combining various observation types with different time span (Pail et al., 2011, Brockmann et al., 2014, Bruinsma et al., 2014). Assessing quality of the individual solutions is therefore of crucial importance for both modelers and users.

In this study, validation of GGFMs based on the time-wise and the direct approaches is performed. We note that numerous validation studies of GOCE GGFMs have already been performed, e.g., Gruber et al. (2011), Hirt et al. (2011), Janák and Pitoňák (2011), Šprlák et

al. (2012). They reveal a consistent representation of the Earth's gravitational field by the different analysis approaches. Successive improvements of the GOCE models for higher degree and order (d/o) spherical harmonic coefficients have been reported for models implementing more data. Moreover, it has been documented that GOCE models perform better with respect to EGM2008 in areas lacking previous gravity field observations such as Africa, Himalayas and South America. In this article, we extend the studies of Šprlák et al. (2012, 2015) and Gerlach et al. (2013) where various GOCE models up to the third release were validated with various datasets over the continental part of Norway.

For the validation purpose we exploit independent datasets of height anomalies derived from Global Navigation Satellite Systems (GNSS) and leveling data, free-air gravity anomalies, and deflections of the vertical over the continental part of Norway. The terrestrial datasets are described in Section 2. The spectral enhancement method (SEM) is applied to overcome the spectral inconsistency between the models and the terrestrial data. The accuracy of SEM and the results of the validation are presented in Section 3. The outcomes of this study are given in the conclusions.

In this paper we make use of the following nomenclature: low frequencies of the gravitational field quantities correspond to spherical harmonic d/o 2-100, middle frequencies are those between d/o 101-250, high frequencies between d/o 251-2190, and very-high frequencies are above d/o 2190.

2. Description of the terrestrial datasets

2.1 GNSS/leveling points

Traditional leveling is used to determine the vertical distance of objects relative to the geoid or quasigeoid as reference surface. It is employed for geodetic tasks where physical heights are required. Time efficiency and cost has favored the use of GNSS for precise determination of geodetic positions. The height component measured by GNSS is purely geometrical and related to a reference ellipsoid. The differences between GNSS and leveling observations allow geoid/quasigeoid heights to be derived. These quantities may be used to test GGFMs.

We have employed recent GNSS/leveling data compiled by the Norwegian Mapping Authority. The leveled heights are listed in the vertical system NN2000 (Lysaker and Vestøl, 2012), which is a zero-tidal vertical reference system tied to Normaal Amsterdams Peil at epoch 2000.0. In the NN2000 system, normal heights have been adopted. Thus the GNSS/leveling dataset provides observed height anomalies which we will refer to in the following.

The GNSS observations are referred to the epoch 1995.665. Conventionally, the ellipsoidal heights are provided in the tide-free system. Due to the different reference time epochs and tide systems adopted, the postglacial uplift as well as the tidal correction have to be applied, see section 3.1 for details.

There are 1340 GNSS/leveling stations in Norway. The stations are distributed along leveling lines, see Fig 1a. The observed height anomalies vary from 18.58 m in the eastern part to 47.60 m in the western part. The accuracy of the observed height anomalies is 2-3 cm (Omang, 2014, private communication).

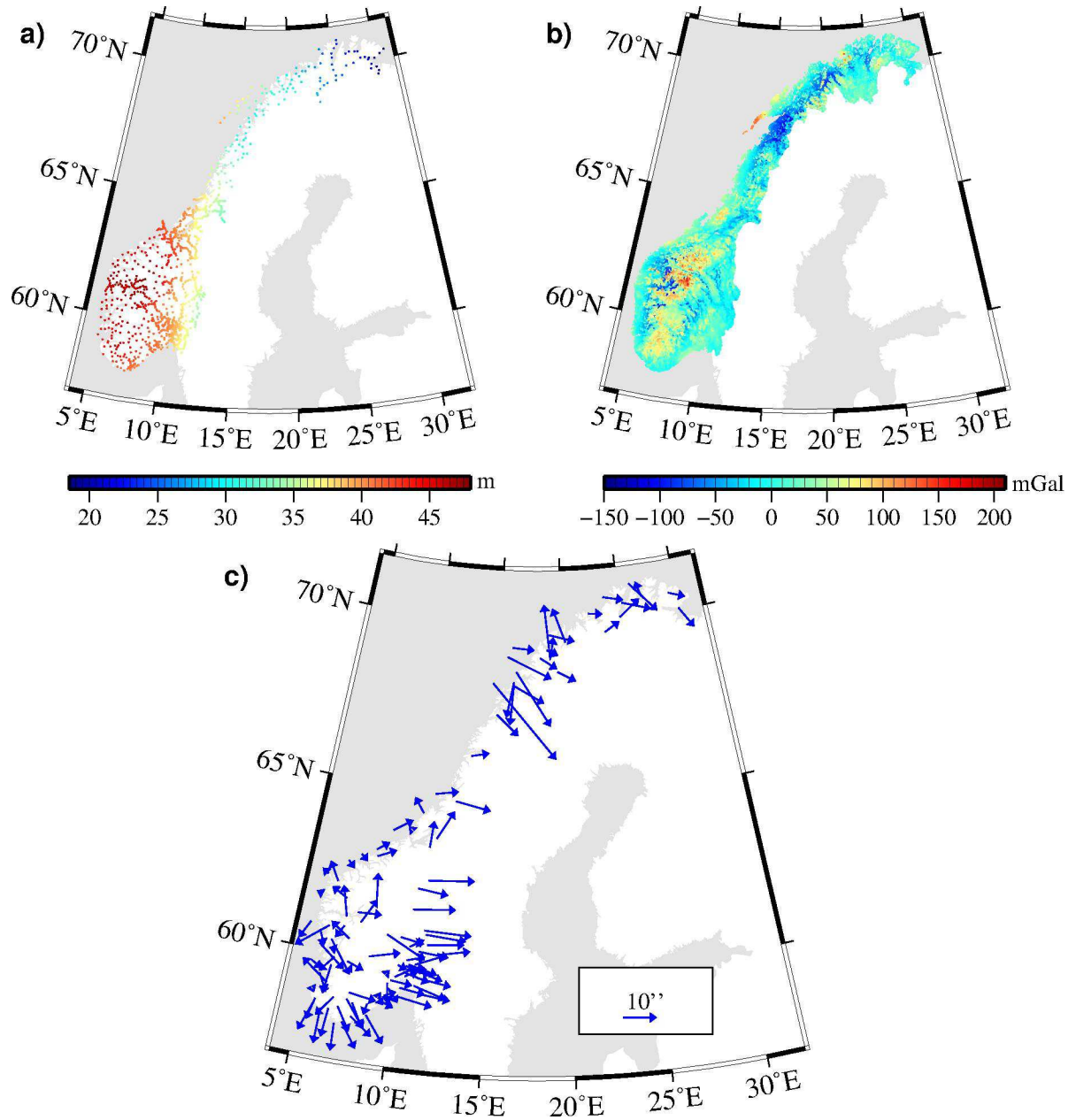


Fig. 1: Spatial distribution and magnitudes of the terrestrial datasets: a) Height anomalies, b) Free-air gravity anomalies, c) Deflections of the vertical (the arrows indicate the total deflection of the vertical).

2.2 Terrestrial free-air gravity anomalies

Terrestrial gravity data, observed by relative and absolute instruments, form the base for geoid/quasigeoid determination. The gravity reference frame in Norway (Hansson, 1978) consists of 286 primary stations, connected by relative gravimeters in early 1970s. Four stations (Hammerfest, Bodø, Trondheim, and Oslo) were observed with FG5-226 between 2005 and 2011. Absolute gravity values were derived from these time series and referred to September 2011. At this time an observing campaign at 21 primary stations were also made with A10-020 absolute gravimeter.

Attached to the primary stations are loops of 7791 secondary gravity stations, measured in the 1970s and early 1980s. The entire dataset was readjusted with respect to the absolute gravity values obtained with the FG5 and A10 instruments. In this way, the absolute level of all observations is provided by the new FG5 and A10 observations. The epoch of the newly adjusted network is 2011. Thus, comparison with GOCE observations does not require reductions for post-glacial uplift. The gravity values and also the observed free-air gravity anomalies are available in the zero tide system.

In addition to the geodetic gravity reference frame there exist a large number of relative gravimetric observations obtained for other purposes than geodesy. These terrestrial free-air gravity anomalies have been collected into a national gravity database, administered by the Geological Survey of Norway (Gellein et al., 1993). The database contains 69773 gravity stations.

Except for occasional data gaps in the central and the northern parts of Norway and very dense data along the coast in the south and south-east, the gravity stations are distributed regularly over the continental part of Norway, see Fig. 1b. The average distribution of gravity stations is 1 point per 5 km².

The observations were made over a time span of several decades using a variety of instruments. The estimated accuracy of the observed gravity is at the level of 0.2 mGal (Gellein et al., 1993). The free-air gravity anomalies range from -141.3 mGal to 205.5 mGal, with a standard deviation of 37.4 mGal and a mean value of 9.6 mGal, see Fig. 1b.

2.3 Deflections of the vertical

We have also compared GOCE models to deflections of the vertical at more than 100 observing stations in Norway. The astronomical coordinates of these stations were determined over a time span of several decades with various astronomical instruments and with inhomogeneous accuracy. Astronomical positioning was obtained in ten Laplace stations with a Prin transit instrument between 1923 and 1928 (Jelstrup, 1929) by the Geographical Survey of Norway to orient the geodetic first order network. Further extensions were made with an Askania transit instrument between 1930 and 1950. A Wild T4 was used to establish 27 Laplace stations between 1958 and 1969, and further observations were made in the 1970s with Wild T2 and Zeiss Ni 20 instruments (Blankenburgh, 1987). A total of 96 stations resulted from five decades of efforts. Some were reobserved as new instruments were introduced. Vertical deflections were determined for 22 additional stations in 1981 and 1985 with a zenith camera (Danielsen and Sundsby, 1995) leading to a database of 118 stations in total. Table 1 shows the mean standard deviations obtained with each instrument type.

	Transit instrument	T4	T2	Zenith camera
Std.dev. (ξ)	0.18	0.23	0.44	0.15
Std.dev. (η)	0.24	0.08	0.44	0.18

Tab. 1: Mean standard deviations for different types of astronomical instruments for the north-south (ξ) and east-west (η) components of the deflection of the vertical (Danielsen and Sundsby, 1995). All values are given in arc seconds.

The astronomical observations are unevenly distributed over Norway, see Fig. 1c. The majority of points are located along the coast of southern Norway. After identifying and removing eight outliers from the database (by performing the Grubb's test from the differences between the modeled and the observed deflections of the vertical), the remaining 110 stations were used in the following analysis. The NS component varies from -22.88" to +16.46". The EW component varies from -10.36" to +18.89". The total deflection of the vertical at the 110 stations is depicted in Fig. 1c.

3. Numerical experiment

3.1 Modeling of height anomalies, free-air gravity anomalies and deflections of the vertical using SEM

A consistent comparison between terrestrial (containing all spectral constituents) and satellite (containing low and middle frequency constituents) observations has to be followed in validation studies. Below we combine a high-resolution GGFM and a digital elevation model (DEM) for gravity field modeling purposes. Such combination is known as the SEM, see (Hirt et al., 2010). We firstly test the performance of SEM by direct comparison of the observed and modeled height anomalies, free-air gravity anomalies, and deflections of the vertical.

Spherical harmonic coefficients of EGM2008 (Pavlis et al., 2012) up to d/o 2190 have been exploited for evaluation of the low, middle, and high frequencies of the modeled quantities. Note that the primary and secondary stations of the Norwegian gravity network were also included in the development of EGM2008 (Omang, 2014, private communication). The synthesis was performed by the GRAFIM software (Janák and Šprlák, 2006), which avoids the numerical problems of Legendre's functions by implementing Horner's scheme (Holmes and Featherstone, 2002). For the free-air gravity anomalies and the NS component of the vertical deflection, harmonic expansions based on the ellipsoidal approximation have been applied (Wenzel, 2005). The deviation between the spherical radius and the ellipsoidal normal is accounted for by the ellipsoidal approximation. It does not affect the height anomalies and the EW component of the vertical deflection. Therefore, these two functionals have been synthesized by the standard spherical harmonic expansions.

The very-high frequencies of the modeled quantities have been calculated from a residual terrain model (RTM, Forsberg, 1984). The RTM has been constructed by subtracting the high resolution DEMs ACE2 (Berry et al., 2010) or ASTER (Tachikawa et al., 2011) with a smooth elevation model DTM2006.0 (Pavlis et al., 2007). The elevations from the DTM2006.0 have been synthesized by the GRAFIM software up to d/o 2160. Zero elevations have been considered over oceans and seas.

Numerical integration over the RTM has been performed point-wise, i.e., at each station of the height anomalies, free-air gravity anomalies and deflections of the vertical, to calculate the very-high frequencies. For simplicity, only planar approximation of the corresponding integral kernels has been considered. We have assumed a constant rock density value of 2670 kg m^{-3} of the masses within the RTM. The numerical integration has been divided into the inner and outer zone. In the inner zone we make use of the ASTER DEM with sampling of $1'' \times 1''$ of the mass elements and apply this discretization within the integration radius $\psi_0 = 0.1^\circ$.

Beyond that, the outer integration zone exploits coarser ACE2 DEM with regular sampling of $30'' \times 30''$. We have considered the size of the integration radius in the outer integration zone $\psi_0 = 0.5^\circ$ for free-air gravity anomalies and deflections of the vertical. In case of height anomalies the integration radius in the outer zone was $\psi_0 = 3.0^\circ$. Numerical experiments showed that the contributions beyond the selected integration radii are negligible. Note that the harmonic correction has to be considered for points located inside the RTM. This issue has been solved implicitly by the approach proposed in (Kadlec, 2011).

Several corrections have been calculated to avoid inconsistencies between the observed and modeled quantities. To get consistent height anomalies we have corrected the GNSS observations by a 5-year correction due to the postglacial rebound based on the model NKG2005LU (Ågren and Svensson, 2007). Due to different tide systems in GNSS and levelling data, a tidal correction (from zero-tide to tide-free system; Mäkinen and Ihde, 2008) has been considered for the leveled heights. Atmospheric correction (Wenzel, 1985) and a tidal correction (from zero-tide to tide-free system) have been applied to the observed free-air gravity anomalies. The NS component of the vertical deflection has been corrected by the topographic reduction (the synthesis is performed on the telluroid rather than on the Earth surface) and for the curvature of the normal plumb line (which links the direction of the normal gravity vector to the direction of the ellipsoidal normal). Only the first correction has also been applied for the WE component. Correction due to postglacial rebound has not been applied to the deflections of the vertical due to missing information of the exact year of observation for several of the stations. We estimate that the neglected postglacial rebound may reach up to $0.2''$, see (Gerlach et al., 2013). Note that the tidal effect may reach $0.01''$ for the deflections of the vertical and has been neglected in our numerical investigations.

Quantity	RTM	min.	max.	mean	std. dev.
ζ	no	0.102	0.477	0.351	0.051
	yes	0.202	0.608	0.470	0.067
Δg	no	-197.1	100.1	-5.7	20.7
	yes	-51.4	65.5	-0.3	4.3
ξ	no	-5.60	9.27	-0.37	2.06
	yes	-3.44	4.40	-0.38	1.20
η	no	-5.96	8.00	-0.72	2.24
	yes	-4.03	3.56	-0.59	1.47

Tab. 2: Statistics of the differences between the observed and the modeled (using EGM2008 and RTM) quantities with and without the RTM (in meters for height anomalies, in mGal for gravity anomalies, and in arc seconds for the deflections of the vertical).

We summarize the statistics of the differences between the observed and the modeled quantities in Tab. 2. In the case of height anomalies, the standard deviation of the differences increases from 0.051 m (without RTM) to 0.067 m (with RTM). Such a result is in contradiction with Hirt et al. (2010) who reported significant improvements in height anomaly modeling in Switzerland due to the RTM contribution. On the other hand, Kadlec

(2011) showed that the effect of the RTM does not contribute to better performance of SEM in modeling height anomalies in the Czech Republic. For free-air gravity anomalies, we note a decrease of standard deviation from 20.7 mGal (without RTM) to 4.3 mGal (with RTM). Thus the effect of the RTM improves the modeling by 79%. Improvements of SEM due to the RTM effect may also be seen for the deflections of the vertical. For the NS component, the standard deviation decreases from 2.06'' (without RTM) to 1.20'' (with RTM). For the EW component the standard deviation decreases from 2.24'' (without RTM) to 1.47'' (with RTM). Both components are thus improved by approximately 40 % when the RTM effect is included.

The results prove the sensitivity of free-air gravity anomalies and deflections of the vertical to very-high frequencies of the Earth's gravity field. On the other hand, RTM leads to worse performance for the height anomalies. In this case, the unmodified EGM2008 fits better to the observed height anomalies. Such result will be analyzed in more detail in our future research.

3.2 Validation of GOCE-derived GGFM

We opted for testing seven GGFM. We consider all five releases based on the time-wise approach (Pail et al., 2010, 2011, Brockmann et al., 2014) and the two most recent models based on the direct approach (Bruinsma et al., 2013, 2014), see Tab. 3.

GGFM	$N_{\max}$	Reference
TIM R1	224	(Pail et al., 2010)
TIM R2	250	(Pail et al., 2011)
TIM R3	250	
TIM R4	250	
TIM R5	280	(Brockmann et al., 2014)
DIR R4	260	(Bruinsma et al., 2013)
DIR R5	300	(Bruinsma et al., 2014)

Tab. 3: Characteristics of the validated GGFM

We have performed the validation of the GOCE-derived models as follows. The modeled quantities were determined by SEM as described in Section 3.1. Thereby we synthesized the lowest part of the spectrum from each of the GOCE models up to a variable d/o of the spherical harmonic coefficients. The variable d/o ranges from 2 up to the maximum available. Above this spectral range, we have considered the contribution of EGM2008 up to d/o 2190. Then the RTM effect has been calculated above d/o 2190. Note that we have considered the RTM effect also for the height anomalies despite its lacking improvement by SEM. This does not affect any of the conclusions. Finally, the observed and the modeled quantities have been compared and the corresponding statistics have been evaluated.

The standard deviations of differences between the observed and the modeled height anomalies are depicted in Fig. 2. The differences between all models are within 1 cm up to

d/o 160. In particular, the differences are negligible for the time-wise and the direct approach for the fourth and fifth release up to d/o 160. Theoretically, we may expect better performance of the models based on the direct approach in the low frequencies. This is due to GRACE measurements involved in the direct approach. We suppose that EGM2008 errors dominate the total error budget and overwhelm the better performance of the direct approach. Above d/o 160 we observe an exponential increase of the standard deviations. It starts at higher d/o for later releases of the GOCE models. We note a 10% increase of the standard deviation for GOCE models with respect to EGM2008 (indicated by the dashed line) at d/o 165 for TIM R1, d/o 185 for TIM R2, d/o 195 for TIM R3, d/o 200 for TIM R4, and d/o 220 for TIM R5. In other words, more gradiometric data leads to better performance of the models, as is expected. The performance of DIR R4 with respect to TIM R4 is slightly worse between degrees 175-220. However, the standard deviation for DIR R4 is lower by more than 1 cm above d/o 220. Only negligible differences are seen between DIR R5 and TIM R5 up to d/o 265. Above d/o 265 the model based on the direct approach performs better. Šprlák et al. (2015) demonstrated an improvement of third release GOCE models with respect to EGM2008 of up to 1.5 cm between d/o 100-200. However, this improvement is not as pronounced in Fig. 2. This discrepancy is due to different datasets of height anomalies. In this study we exploit height anomalies over the whole continental Norway, whereas Šprlák et al. (2015) used height anomalies over southern Norway. We also suspect that the possible improvements relative to EGM2008 are more pronounced in southern Norway. The gain of GOCE models with respect to EGM2008 over Norway will be investigated in a future study.

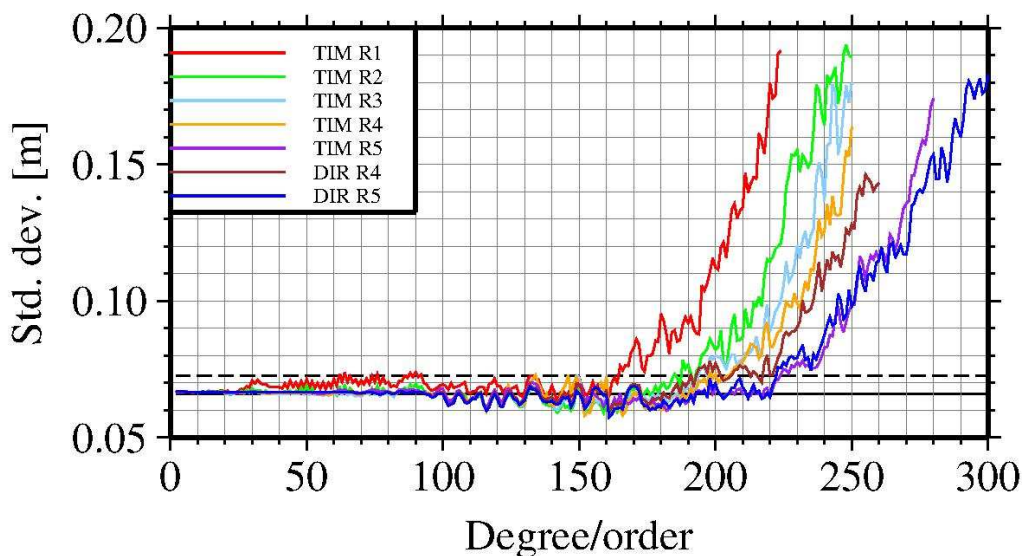


Fig. 2: Standard deviation of differences between the observed and the modeled (using the validated GOCE-derived GGFMs, EGM2008 and RTM) height anomalies as a function of d/o of the GOCE-derived GGFMs (RTM included). The solid black line represents the standard deviation of differences between the observed and the modeled (using EGM2008 and RTM) height anomalies. The dashed black line represents the standard deviation of differences between the observed and the modeled (using EGM2008 and RTM) height anomalies increased by 10%.

Validation by the free-air gravity anomalies offers a possibility to confirm the above results. The standard deviations of differences are shown in Fig. 3. As for height anomalies, we observe the similar performance of all models up to d/o 150 and then the exponential increase depending on the time span of gradiometric data. The difference of several tenths of mGal

above d/o 210 and reaching 1 mGal at d/o 250 shows better performance of DIR R4 relative to TIM R4. The latest release gives identical results for both approaches up to d/o 250. Above this d/o the direct approach performs better. However, in contrast to height anomalies, the 10% increase of the standard deviation for GOCE models with respect to EGM2008 is reached for higher d/o, see Fig. 2. Also we do not observe any deviations with respect to EGM2008 below d/o 150. Both of these observations originate from the sensitivity of free-air gravity anomalies to higher frequencies. The accuracy of SEM in the case of free-air gravity anomalies (on the level of 4.3 mGal, Tab. 2) overwhelms the magnitudes of the differences between EGM2008 and GOCE models (reaching only a few mGal).

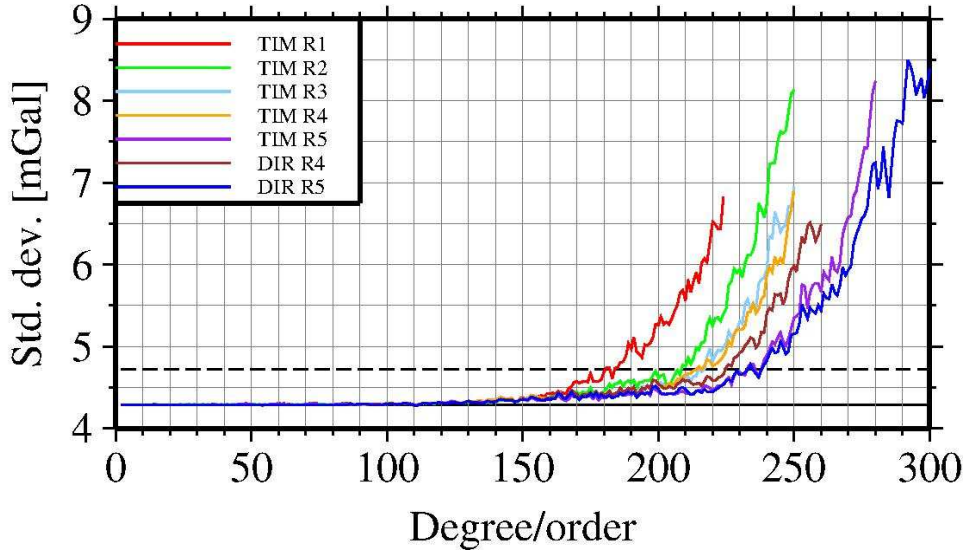


Fig. 3: Standard deviation of differences between the observed and the modeled (using validated GOCE-derived GGFM, EGM2008 and RTM) free-air gravity anomalies as a function of d/o of the GOCE GGFM (RTM included). The solid black line represents the standard deviation of differences between the observed and the modeled (using EGM2008 and RTM) free-air gravity anomalies. The dashed black line represents the standard deviation of differences between the observed and the modeled (using EGM2008 and RTM) free-air gravity anomalies increased by 10%.

The deflections of the vertical may also confirm the above results. The standard deviations of differences are shown in Fig. 4. We observe similar performance of the models up to d/o 160. Above this d/o the models differ based on the release. Good agreement between the last two releases of the time-wise and direct approach is confirmed. However, in contrast to height and free-air gravity anomalies, the standard deviations exceed the 10 % threshold even at higher d/o. This may be explained by the different spectral sensitivity of the vertical deflections. Small deviations are visible when comparing the corresponding curves for the NS and EW components. We identify possible improvements, which are less significant compared to height anomalies, relative to EGM2008 for the NS component between d/o 100-200. However, this is not demonstrated by the EW component. Also the improvements with more gradiometric data are not so significant for the EW component. In other words, the spectral range of the crossing for the curves corresponding to the first and the last release with the line indicating the 10 % threshold is wider for the NS component as compared to the EW component. We suppose that this may be related to the different spatial resolution of GOCE observations in both principal directions. At high latitudes, such as it is the case for Norway, the spatial resolution is higher in EW direction than in NS direction for the same d/o

numbers. Consequently, the point of divergence (where the curves in Figure 4 start to deviate from the EGM2008 baseline) is shifted towards higher spherical harmonic degrees in case of the EW-component as compared to the NS-component.

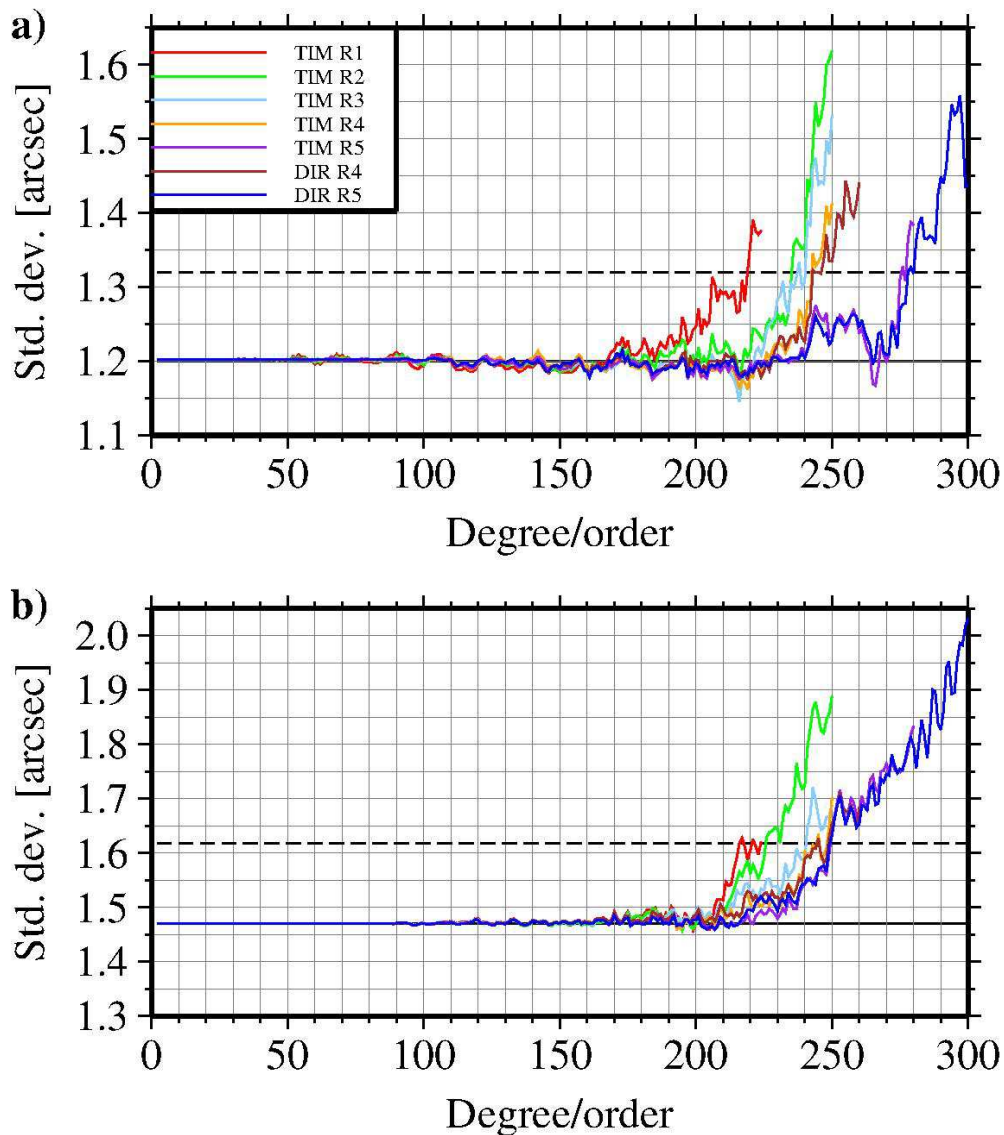


Fig. 4: Standard deviation of differences between the observed and the modeled (using validated GOCE-derived GGFM, EGM2008 and RTM) deflection of the vertical as a function of d/o of the GOCE GGFM (RTM included): a) NS component, b) EW component. The solid black line represents the standard deviation of differences between the observed and the modeled (using EGM2008 and RTM) deflections of the vertical. The dashed black line represents the standard deviation of differences between the observed and the modeled (using EGM2008 and RTM) deflections of the vertical increased by 10%.

Conclusions

Homogeneous sets of height anomalies, free-air gravity anomalies, and deflections of the vertical have been produced from new terrestrial measurements in Norway. These were exploited for validation of seven GOCE-based models.

Numerical experiments have proven that the gravitational attraction of local masses, computed from DEMs, is important to free-air gravity anomalies and deflections of the

vertical. However, height anomalies fit better to the pure EGM2008 model when not taking RTM effects into account.

We found the performance of all models to be very similar up to d/o 160 in the studied local area. We suppose that EGM2008 errors dominate the total error budget and do not allow for seeing better performance of the direct approach in the low frequencies. With more GOCE observations available, higher d/o are determined more accurately. Such finding definitely confirms results of existing studies. Models of the latest (fifth) release compare well to EGM2008 up to d/o ~220. Validation by height anomalies may suggest possible improvements by the GOCE models with respect to EGM2008 in the middle frequencies. This improvement was not proven by free-air gravity anomalies and deflections of the vertical due to their sensitivity to higher frequencies.

Future experiments will be performed to investigate the better fit of pure EGM2008 model to the observed height anomalies. Also possible systematic effects, either due to EGM2008 or the terrestrial datasets, will be investigated. Future models based on GOCE observations will be validated. These tasks are important for improvements of the gravity field over Norway.

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References

- Berry PAM, Smith RG, Benveniste J (2010) ACE2: The New Global Digital Elevation Model. In: Mertikas SP (Ed.) Gravity, Geoid and Earth Observation, IAG Symposia, Vol. 135, 23-27 June 2008, Chania, Greece, pp 231-238
- Blankenburgh JC (1987) Geodesi med stjerner og satelliter i Norge. Bilag til Kart og Plan nr. 1 – 1987: 91-95 (in Norwegian)
- Brockmann JM, Zehentner N, Höck E, Pail R, Loth I, Mayer-Gürr T, Schuh W-D (2014) EGM_TIM_RL05: An independent geoid with centimeter accuracy purely based on the GOCE mission. *Geophysical Research Letters*, 41: 8089-8099
- Bruinsma SL, Förste C, Abrikosov O, Lemoine J-M, Marty J-C, Mulet S, Rio M-H, Bonvalot S (2014) ESA's satellite-only gravity field model via the direct approach based on all GOCE data. *Geophysical Research Letters*, 41: 7508-7514
- Bruinsma SL, Förste C, Abrikosov O, Marty J-C, Rio M-H, Mulet S, Bonvalot S (2013) The new ESA satellite-only gravity field model via direct approach. *Geophysical Research Letters*, 40: 3607-3612
- Danielsen J, Sundsbj J (1995) Målinger med senitkamera for loddavvik. Faglig melding, Geodesidivisjonen, Statens kartverk (in Norwegian)
- ESA (1999) Gravity field and steady-state ocean circulation mission. Reports for Mission Selection, the Four Candidate Earth Explorer Core Missions, ESA SP-1233(1)
- Forsberg R (1984) A study of terrain reductions, density anomalies and geophysical inversion methods in gravity field modeling. Report No. 355, Department of Geodetic Science and Surveying, Ohio State University, Columbus, USA
- Gellein J, Olesen O, Reitan M, Sæther PO (1993) Brukerbeskrivelse – database of prosessering av gravimetriske data. Intern NGU Rapport Nr. 93.019, Norges Geologiske Undersøkelse, Trondheim, Norge (in Norwegian)
- Gerlach C, Šprlák M, Bentel K, Pettersen BR (2013) Observation, validation, modeling – historical lines and recent results in Norwegian gravity field research. *Kart og Plan* 73: 128-151
- Gruber T, Visser PNAM, Ackermann C, Hosse M (2011) Validation of GOCE gravity field models by means of orbit residuals and geoid comparison. *Journal of Geodesy*, 85: 845-860
- Harsson BG (1978) Beregning av det norske gravimeterbasisnettet. In Proceedings, NKG General Assembly, Oslo (in Norwegian)

- Hirt C, Featherstone WE, Marti U (2010) Combining EGM2008 and SRTM/DTM2006.0 residual terrain model data to improve quasigeoid computations in mountainous areas devoid of gravity data. *Journal of Geodesy*, 84: 557-567
- Hirt C, Gruber T, Featherstone WE (2011) Evaluation of the first GOCE static gravity field models using terrestrial gravity, vertical deflections and EGM2008 quasigeoid heights. *Journal of Geodesy*, 85: 723-740
- Holmes SA, Featherstone WE (2002) A unified approach to the Clenshaw summation and the recursive computation of very high degree and order normalized associated Legendre functions. *Journal of Geodesy*, 76: 279-299
- Janák J, Pitoňák M (2011) Comparison and testing of GOCE global gravity models in central Europe. *Journal of Geodetic Science*, 1: 333-347
- Janák J, Šprlák M (2006) A new software for gravity field modelling. *Geodetic and Cartographic Horizon*, 52: 1-8 (in Slovak)
- Jelstrup HJ (1929) Determinations of astronomical longitudes, latitudes and azimuths. *Geodetiske arbeider*, hefte II (1929) og III (1931), Norges geografiske opmåling (in Norwegian)
- Kadlec M (2011) Refining gravity field parameters by residual terrain modeling. Doctoral Thesis, Department of Mathematics, Faculty of Applied Sciences, University of West Bohemia, Pilsen, Czech Republic, 150 p.
- Lysaker DI, Vestøl O (2012) Norwegian vertical reference system NN2000. Norwegian Mapping Authority, Hønefoss, Norway (in preparation)
- Mäkinen J, Ihde J (2008) The permanent tides in height systems. In: Sideris MG (Ed.) *Observing our Changing Earth*, IAG Symposia, Vol. 133, 2-13 July, 2007, Perugia, Italy, pp 81-87
- Pail R, Bruinsma S, Migliaccio F, Förste C, Goiginger H, Schuh WD, Höck E, Reguzzoni M, Brockmann JM, Abrikosov O, Veicherts M, Fecher T, Mayrhofer R, Krasbutter I, Sansó F, Tscherning CC (2011) First GOCE gravity field models derived by three different approaches. *Journal of Geodesy*, 85: 819-843
- Pail R, Goiginger H, Mayrhofer R, Schuh WD, Brockmann JM, Krasbutter I, Höck E, Fecher T (2010) GOCE gravity field model derived from orbit and gradiometry data applying the time-wise method. In: *Proceedings of the ESA Living Planet Symposium*, 28 June - 2 July 2010, Bergen, Norway
- Pavlis NK, Factor JK, Holmes SA (2007) Terrain-related gravimetric quantities computed for the next EGM. In: *Gravity Field of the Earth*, *Proceedings of the 1st International Symposium of the International Gravity Field Service*, Harita Dergisi, Special Issue 18, Istanbul, Turkey, pp 318-323
- Pavlis NK, Holmes SA, Kenyon SC, Factor JK (2012) The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). *Journal of Geophysical Research*, Vol. 117, B04406, 38 pp, doi:10.1029/2011JB008916
- Šprlák M, Gerlach C, Pettersen BR (2012) Validation of GOCE global gravity field models using terrestrial gravity data in Norway. *Journal of Geodetic Science*, 2: 134-143
- Šprlák M, Pettersen BR, Omang OCD, Lysaker DI, Sekowski M, Dykowski P (2015) Comparison of GOCE global gravity field models to test fields in southern Norway. In: Marti U (Ed.) *Gravity, Geoid and Height Systems*, IAG Symposia, Vol. 141, 9-12 October, 2012, Venice, Italy, pp. 59-65
- Tachikawa T, Hato M, Kaku M, Iwasaki A (2011) The characteristic of ASTER GDEM version 2. In: *IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, July 24-29, Vancouver, Canada, pp 3657-3660
- Wenzel HG (1985) *Hochauflösende Kugelfunktionsmodelle für das Gravitationspotential der Erde*, Wissenschaftliche Arbeiten der Fachrichtung Vermessungswesen der Universität Hannover, Nr. 137, Geodätisches Institut der Universität Hannover (in German)
- Wenzel HG (2005) Global models of the gravity field of high and ultra-high resolution. In: *International School for the Determination and Use of the Geoid*, 31 January - 5 February 2005, Budapest, Hungary, International Geoid Service, 36 p.
- Ågren J, Svensson R (2007) Postglacial land uplift model and system definition for the new Swedish height system RH 2000. *Reports in Geodesy and Geographical Information Systems*, LMV-Rapport 2007:4, National Land Survey of Sweden, Gävle, Sweden, 124 p.

Evaluation of GOCE-based Global Geoid Models in Finnish Territory

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Abstract

The gravity satellite mission GOCE made its final observations in the fall of 2013. By then it had exceeded its expected lifespan of 20 months with 35 additional months and observed the Earth's gravitational field from a lower orbit as originally planned during the last 6 months of its mission lifetime. Thus, the mission collected more data from the Earth's gravitational field than expected, and more comprehensive global geoid models have been derived ever since. The GOCE High-level Processing Facility (HPF) by ESA has published GOCE global gravity field models annually. We compared all of the 13 HPF-models as well as 3 additional GOCE, 12 GRACE and 6 combined GOCE+GRACE models with GPS-levelling data and gravity observations in Finland. The most accurate models were also compared against high resolution global geoid models EGM96 and EGM2008.

The models were evaluated up to four different degrees and order: 150 (the common maximum for the GRACE models), 200, 240 (the common maximum for the GOCE models) and maximum. When coefficients up to degree and order 150 are used, the results from the GOCE models are better than EGM96 (with height anomalies) and are comparable with the latest GRACE models and EGM2008. Similar results are achieved with the coefficients up to 200, as the GOCE models perform clearly better than EGM96 when comparing with the GPS-levelling datasets. When coefficients up to 240 or maximum are used the results of the GOCE-based models are comparable with the high resolution models. The best performance of the satellite-only models is not usually achieved with the maximum coefficients, since the highest coefficients (above 240) are less accurately determined.

Keywords: GOCE, GRACE, Geoid model, GPS-levelling, Gravity, EGM2008, EGM96

1 Introduction

The start of the millennium has been an era of the global gravity satellite missions. It started with Challenging Minisatellite Payload (CHAMP), followed by Gravity Recovery And Climate Experiment (GRACE) and most recently the Gravity field and steady-state Ocean Circulation Explorer (GOCE). GOCE made its final observations in the fall of 2013, by then it had exceeded its expected lifespan of 20 months with 35 additional months due to milder solar winds. The last six months of its mission GOCE flew in much lower orbits than originally planned. Thus, the mission was a huge success, since GOCE not only collected more data but also denser data from the Earth's gravitational field than ever imagined, and more comprehensive global geoid models have been derived ever since.

In this study the global geoid models produced by the GOCE and GRACE satellite missions are studied. Altogether 16 GOCE models, 12 GRACE models and 6 combined GOCE+GRACE models are evaluated using Finnish terrestrial data to see how well the models perform relative to each other, but also to see their absolute agreement with terrestrial data. The latest models are also compared against pre-GOCE high resolution global geoid models EGM96 and EGM2008 to see the effect of the GOCE mission on the longer wavelengths in the lower degrees and orders.

2 Description of satellite gravity field models

In the following we shortly describe the global satellite gravity field models that were evaluated over Finland. The section is divided into three subsections: 2.1 GOCE models, 2.2 GRACE models and 2.3 combined GOCE+GRACE models.

2.1 GOCE models

We analyzed all of the GOCE global gravity field models that were calculated by the GOCE High-level Processing Facility (HPF) of ESA (Rummel et al., 2004). The HPF uses three different gravity field modelling methods resulting in three different models: direct (DIR), time-wise (TIM) and space-wise (SPW). A description of the three methods is given in (Pail et al., 2011). The first two DIR models are calculated starting with an a-priori model (EIGEN-5C for DIR1 and ITG-Grace2010s for DIR2), whereas all the follow-on DIR models use the previous model as an a-priori and complementary (GRACE and Laser Geodynamics Satellites (LAGEOS)) data to improve the lower degrees and orders. The TIM and SPW models are based on GOCE data only, although SPW uses a priori high resolution combined models for variance and covariance modelling. DIR and TIM models have been released for 5 data levels and SPW models for 3 data levels.

In addition to the models by HPF, we analyzed three alternative global gravity field models from GOCE: the ITG model by Schall et al. (2014) and the JYY models by Yi et al. (2013). Table 1 gives an overview of the GOCE models analyzed in this study. More information on the models can be found at the website of the International Center for Global Gravity Field Models (ICGEM, 2015).

Table 1: GOCE global gravity field models.

Model (maximum d/o)	Reference	Model (maximum d/o)	Reference
GO_CONS_GCF_2_DIR_R1 (240)	Bruinsma et al., 2010	GO_CONS_GCF_2_TIM_R4 (250)	Pail et al., 2011
GO_CONS_GCF_2_DIR_R2 (240)	Bruinsma et al., 2010	GO_CONS_GCF_2_TIM_R5 (280)	Pail et al., 2011
GO_CONS_GCF_2_DIR_R3 (240)	Bruinsma et al., 2010	GO_CONS_GCF_2_SPW_R1 (210)	Migliaccio et al., 2010
GO_CONS_GCF_2_DIR_R4 (260)	Bruinsma et al., 2013	GO_CONS_GCF_2_SPW_R2 (240)	Migliaccio et al., 2011
GO_CONS_GCF_2_DIR_R5 (300)	Bruinsma et al., 2013	GO_CONS_GCF_2_SPW_R4 (280)	Gatti et al., 2014
GO_CONS_GCF_2_TIM_R1 (224)	Pail et al., 2010a	ITG-Goce02 (240)	Schall et al., 2014
GO_CONS_GCF_2_TIM_R2 (250)	Pail et al., 2011	JYY_GOCE02S (230)	Yi et al., 2013
GO_CONS_GCF_2_TIM_R3 (250)	Pail et al., 2011	JYY_GOCE04S (230)	Yi et al., 2013

2.2 GRACE models

For the comparison to the lower degrees and orders of the GOCE models, we analyzed 12 GRACE models with 6 alternative solutions: AIUB, EIGEN, GGM, ITG, ITSG and Tongji. An overview of the GRACE models is given in Table 2.

Table 2: GRACE global gravity field models.

Model (maximum d/o)	Reference	Model (maximum d/o)	Reference
AIUB-GRACE02S (150)	Jäggi et al., 2009	GGM05S (180)	Tapley et al., 2013
AIUB-GRACE03S (160)	Jäggi et al., 2011	ITG-Grace02s (170)	Mayer-Gürr et al., 2006
EIGEN-GRACE02S (150)	Reigber et al., 2005	ITG-Grace03 (180)	Mayer-Gürr et al., 2007
EIGEN-5S (150)	Förste et al., 2008	ITG-Grace2010s (180)	Mayer-Gürr et al., 2010
GGM02S (160)	Tapley et al., 2005	ITSG-Grace2014k (200)	Mayer-Gürr et al., 2014
GGM03S (180)	Tapley et al., 2007	Tongji-GRACE01 (160)	Chen et al., 2013

2.3 Combined GOCE+GRACE models

In addition to the GOCE and GRACE models, we analyzed 6 combined GOCE+GRACE models with 3 alternative solutions: EIGEN, GOCO, and GOGRA. An overview of the combined GOCE+GRACE models is given in Table 3.

Table 3: Combined GOCE+GRACE global gravity field models.

Model (maximum d/o)	Reference	Model (maximum d/o)	Reference
EIGEN-6S2 (260)	Rudenko et al., 2014	GOCO03S (250)	Mayer-Gürr et al., 2012
GOCO01S (224)	Pail et al., 2010b	GOGRA02S (230)	Yi et al., 2013
GOCO02S (250)	Goiginger et al., 2011	GOGRA04S (230)	Yi et al., 2013

3 Datasets of the ground truth in Finland

The GOCE- and GRACE-based global gravity field models, described in section 2, were evaluated over Finland. In the evaluation, GPS-levelling data and gravity data of Finland were used for the comparison of height anomalies and gravity anomalies, respectively. Below, in sections 3.1 and 3.2 the data are described.

3.1 GPS-levelling data

For the comparison of the height anomalies, two GPS-levelling datasets were used: The European Vertical Reference Network - Densification Action (EUVN-DA) dataset and a dataset of the National Land Survey (NLS) of Finland.

The EUVN-DA dataset consists of the 50 Finnish EUVN-DA GPS-levelling points (Ollikainen, 2006). The points have EUREF-FIN GPS coordinates as well as N2000 heights (Bilker-Koivula, 2010). The dataset of the NLS of Finland consists of 526 GPS-levelling points taken from the register of the NLS. The accuracy (classes 1 to 3) and distribution of the points is not homogenous and the dataset partly overlaps with the EUVN-DA dataset. The coverage of the datasets in the Finnish territory is presented in Figure 1 (left and middle).

Both GPS-levelling datasets were corrected for the land uplift taking place between the epoch of the N2000 levelling data (2000.0) and the epoch of the EUREF-FIN GPS data (1997.0). The GPS data was transformed to epoch 2000.0 using vertical velocities taken from the NKG2005LU land uplift model (Vestøl, 2005; Ågren and Svensson, 2007). For a more detailed description of the GPS-levelling datasets see Bilker-Koivula (2015).

3.2 Gravity data

For the comparison of the free-air gravity anomalies the gravity database of the Finnish Geospatial Research Institute (FGI, former Finnish Geodetic Institute) was used (see Figure 1, right). The database contains gravity observations from early 20th century to present. Observations include terrestrial gravity measurements as well as measurements at sea, mainly on ice.

All of the gravity data in the gravity database of the FGI were transformed from epoch 1963.0 to 2000.0, which is the epoch of the current national height system of Finland N2000. In addition, the tide system was changed from mean tide to the zero tide. Gravity data from before 1938, mainly pendulum data, was removed from the used dataset. The coverage of the gravity dataset (altogether 39 318 points) is presented with the GPS-levelling datasets in Figure 1.

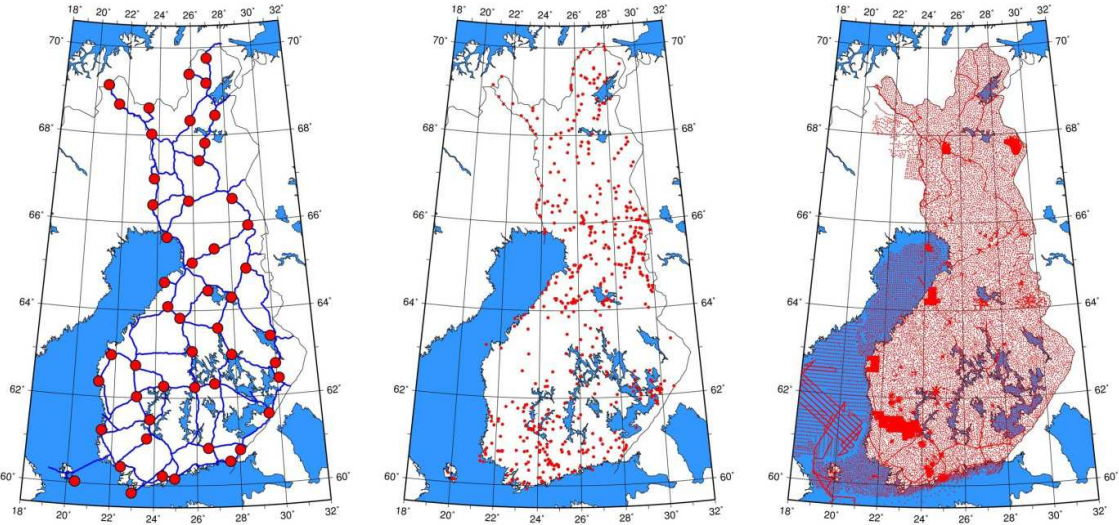


Figure 1: The coverage of the GPS-levelling and gravity datasets over Finland: EUVN-DA with 1st order precise levelling network (left), NLS (middle) and gravity database of the FGI (right).

4 Evaluation of the height and gravity anomalies

The global satellite gravity field models, described in section 2, were compared with the ground data described in section 3. For the comparison, height anomalies and free-air gravity anomalies were calculated from the global models by using the pyGravsoft-software (Forsberg and Tscherning, 2008).

To take care of the omission error, global models are commonly complemented with coefficients of the high resolution model EGM2008 (Pavlis et al., 2012). However, Bilker-Koivula (2015) has shown that there are problems with the EGM2008 model in the Eastern part of Finland. East of the 29 degree longitude line larger discrepancies are found in comparisons with GPS/levelling and gravity data than in the rest of the country. This is most probably due to the lower resolution gravity data used in EGM2008 over Northern Russia. This data was used east of the 29 degree longitude line, which lies for most part within Finnish borders. Using EGM2008 to take care of the omission error would introduce the problems of the EGM2008 into our results. We therefore decided not to complement the models with coefficients of the EGM2008 model. As a result, the omission error is still present in our results. However, when all models are evaluated to a common maximum degree, the omission error will be common for all the models and differences in results can be interpreted as coming from differences in the models.

To remove a possible offset and tilt, a first order polynomial is fitted through the comparison differences and then removed from the differences. Then the standard deviation is calculated from the remaining differences. Results are presented and discussed in the sections below.

4.1 GOCE models versus GPS-levelling and gravity data

At first, all of the GOCE models by HPF were calculated up to degree and order 200 as well as 240 (where models that have maximum degree and order lower than 240 were excluded) and compared against GPS-levelling and gravity data. The results of the comparisons can be seen in Figure 2 (d/o 200) and Figure 3 (d/o 240), where the standard deviations of the height anomalies compared to EUVN-DA and NLS data are presented with columns (primary axis) and the gravity anomalies compared to terrestrial gravity data with dotted line (secondary axis).

The performances of the HPF models are quite similar when developed up to degree and order 200. There are no significant improvements to be seen between the later models comparing to earlier

models. However, when the models are developed up to degree and order 240 it is clearly seen how the later models perform better, with the exception of DIR1 where higher resolution combined model EIGEN-5C was included as an a-priori. This improvement of later models was expected, as they include more GOCE data leading to a better determination of the higher degrees and orders above 200.

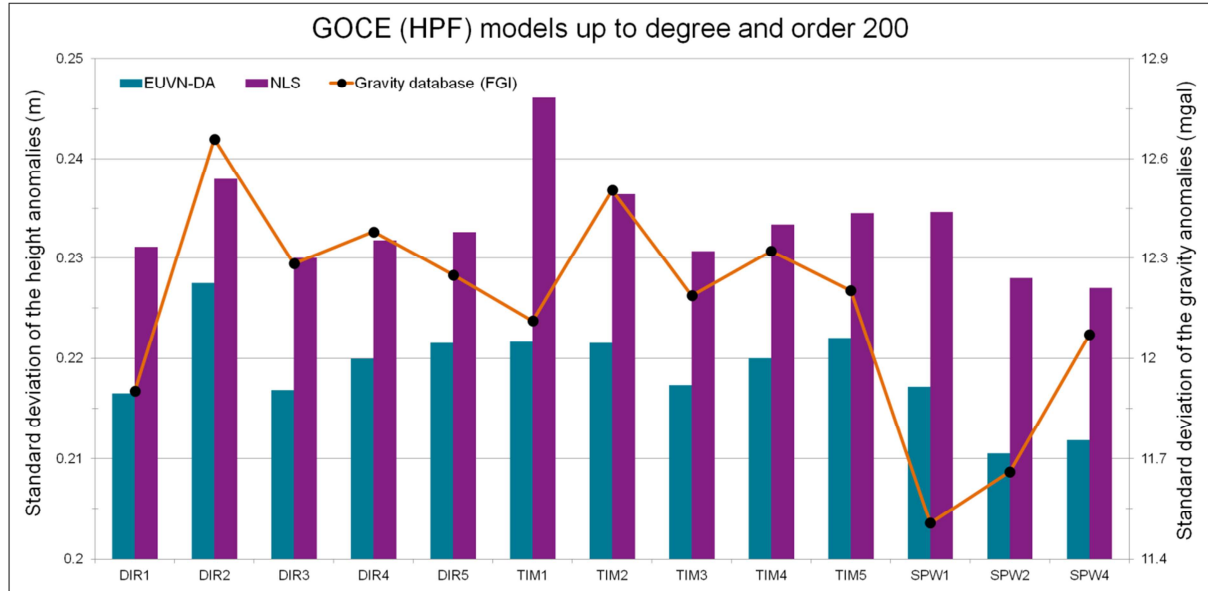


Figure 2: Comparison of the height and gravity anomalies from the GOCE (HPF) models using coefficients up to 200 against GPS-levelling and gravity data: standard deviations of the differences (m) and (mgal).

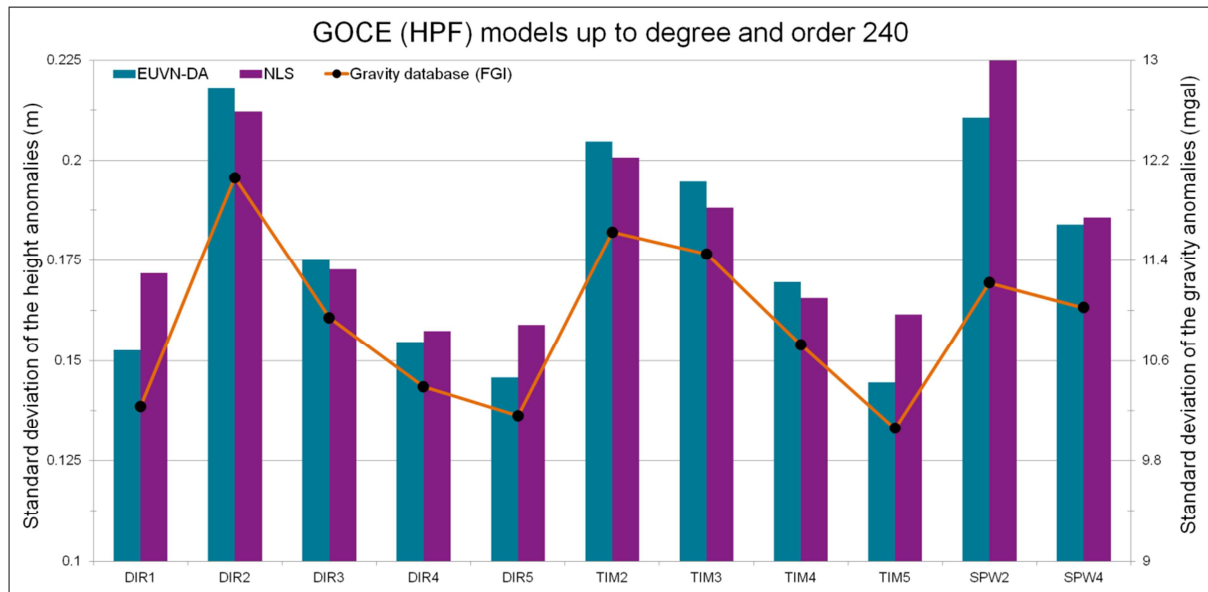


Figure 3: Comparison of the height and gravity anomalies from the GOCE (HPF) models using coefficients up to 240 against GPS-levelling and gravity data: standard deviations of the differences (m) and (mgal).

Generally, the DIR models agree better with the GPS-levelling and gravity data, most probably due to the use of complementary data from the observations of GRACE and LAGEOS. However, an interesting behavior of SPW models is seen from the Figure 2 and 3, as SPW models seem to be superior at degree 200, but deteriorates significantly when comparing with the other HPF models at degree 240.

Next, we calculated the height and gravity anomalies from all of the GOCE models, described in Table 1, using all available coefficients and compared them with the GPS-levelling and gravity data.

The results are presented in Figure 4. The best results with maximum coefficients are achieved with the latest DIR and TIM models, where the standard deviations of the height anomalies are for the DIR5 model 0.163 m (EUVN-DA) and 0.165 m (NLS), and for the TIM5 model 0.163 m (EUVN-DA) and 0.179 m (NLS). Standard deviations of the gravity anomalies behave in a similar fashion: 9.91 mgal (DIR5) and 10.14 mgal (TIM5). However, the best results are obtained with the latest models developed to degree and order 240 (Figure 3). One should keep this in mind when using GOCE-only models e.g. in geoid calculation or in the unification of height systems.

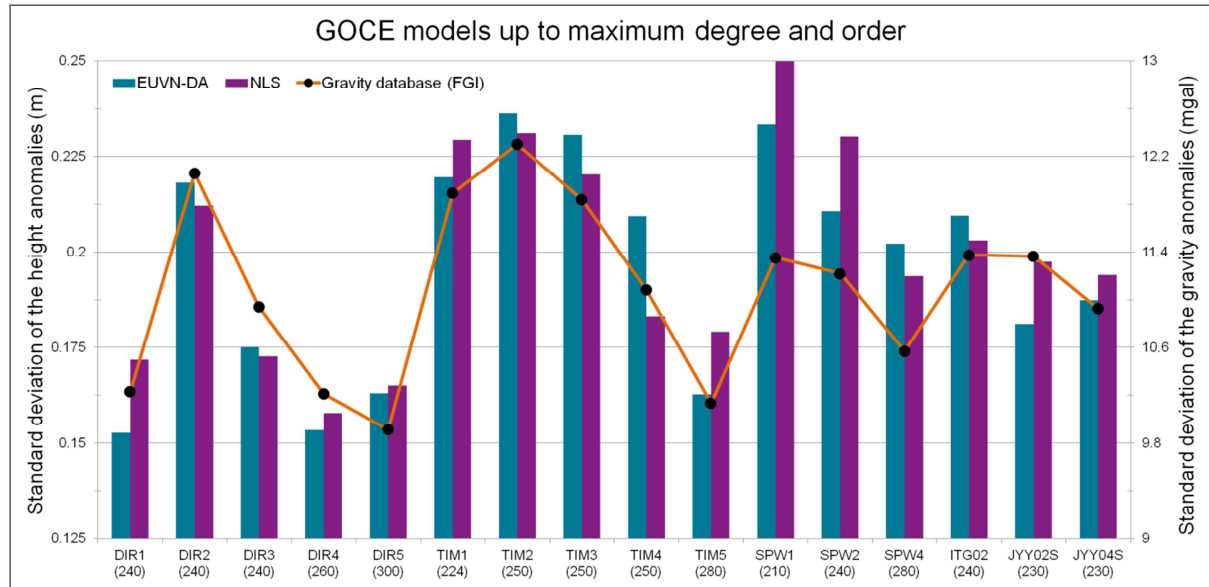


Figure 4: Comparison of the height and gravity anomalies from the GOCE models using all available coefficients against GPS-levelling and gravity data: standard deviations of the differences (m) and (mgal).

4.2 GOCE models compared with GRACE models

In the next comparison we include the GOCE HPF models, the GRACE models (described in Table 2) and the pre-GOCE high resolution geoid models EGM96 (Lemoine et al., 1998) and EGM2008 (Pavlis et al., 2012). The high resolution models are included to show the impact of the GOCE mission for the lower degrees and orders.

The models were developed up to degree and order 150 and the calculated height and gravity anomalies were compared with those of the GPS-levelling (only EUVN-DA results are shown here) and gravity datasets. The results are presented in Figure 5, where the color of the column represents different type of models: teal for GOCE, purple for GRACE and lime for high resolution. The results of the GRACE models vary, especially with the earlier models where the standard deviations of the height anomalies were near half a meter. However, the latest GRACE models perform well, particularly for gravity anomalies, and quite consistently.

All of the GOCE models give more or less similar results when only the coefficients up to degree and order 150 are used. When comparing with the GPS-levelling (EUVN-DA) data, the results from the GOCE models are better than EGM96 and are comparable with the latest GRACE models and EGM2008. The result for the EGM2008 could be expected as the model already includes GRACE data for these wavelengths.

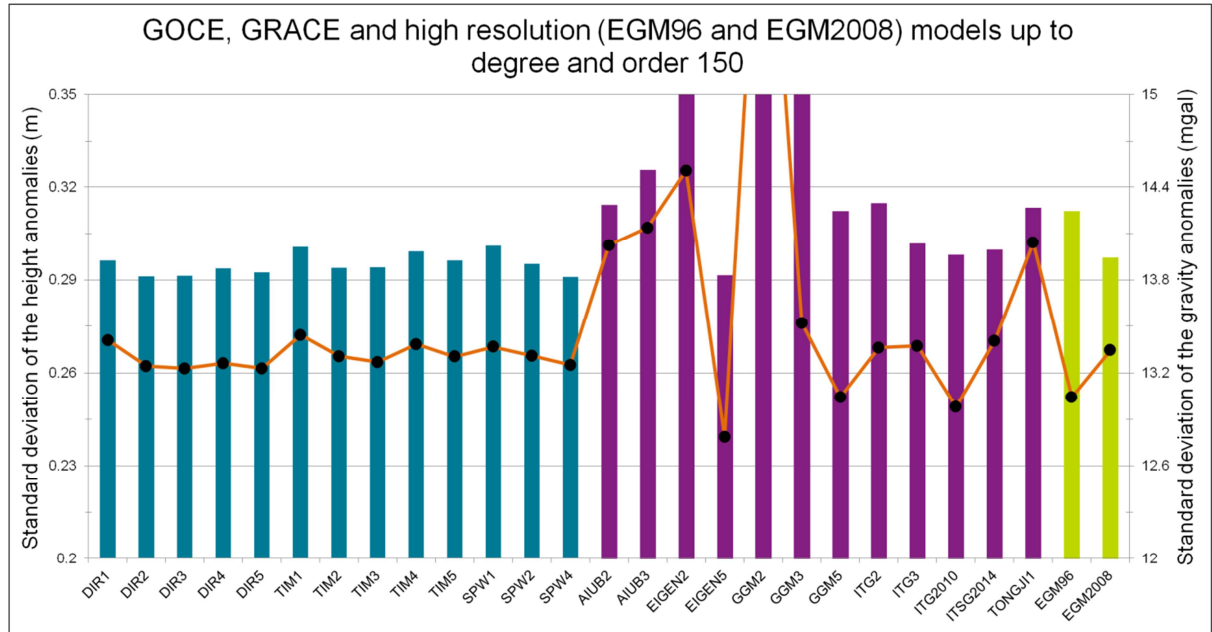


Figure 5: Comparison of the height and gravity anomalies from the GOCE (teal), GRACE (purple) and high resolution (lime) models using coefficients up to 150 against GPS-levelling (only EUVN-DA) and gravity data: standard deviations of the differences (m) and (mgal).

4.3 Latest GOCE and combined GOCE+GRACE models versus GPS-levelling and gravity data

The comparisons in the final section include the latest GOCE (DIR5, TIM5, SPW4 and JYY04S) and combined GOCE+GRACE (EIGEN-6S2, GOCO03S and GOGRA04S) models as well as high resolution geoid models EGM96 and EGM2008. First, the satellite-only models were developed together with the high resolution models up to degree 200 (Figure 6) and 240 (Figure 7) and compared against the GPS-levelling and gravity datasets. Lastly, the satellite-only models were developed up to degree 240 and maximum (Figure 8), to compare the differences at the higher degrees and orders of the models.

The results in Figure 6 indicate that the GOCE-based models perform better than EGM96 and quite equally with EGM2008 when developed up to degree and order 200. This proves that GOCE has improved the knowledge of the long wavelengths of the Earth's gravitational field. When developed up to degree and order 240 the best satellite-only (DIR5, TIM5 and EIGEN-6S2) models are at the same level as the high resolutions models in Finland: at 15 cm for the height anomalies and at 10 mgal for the free-air gravity anomalies.

The comparisons of Figures 6 and 7 show that the high resolution EGM96 and EGM2008 models perform surprisingly well over Finland even when looking at the lower degrees and orders of the models, which are the weak points of the high resolution models. The excellent performance is due to the good high resolution terrestrial data that was already available in the area of Finland for the EGM96 and EGM2008 (the same gravity data was used for both models), the latter including also the GRACE data. Globally, however, these models do not perform equally well everywhere due to the inhomogeneous distribution of the terrestrial gravity data, whereas the satellite-only models will perform homogeneously everywhere on the globe. Also a small tilt may be present in the EGM96 over Finland due to long wavelength errors in the model, but this is removed in our results by fitting a 1st order polynomial tilt. The satellite-only models do not show significant tilts over Finland.

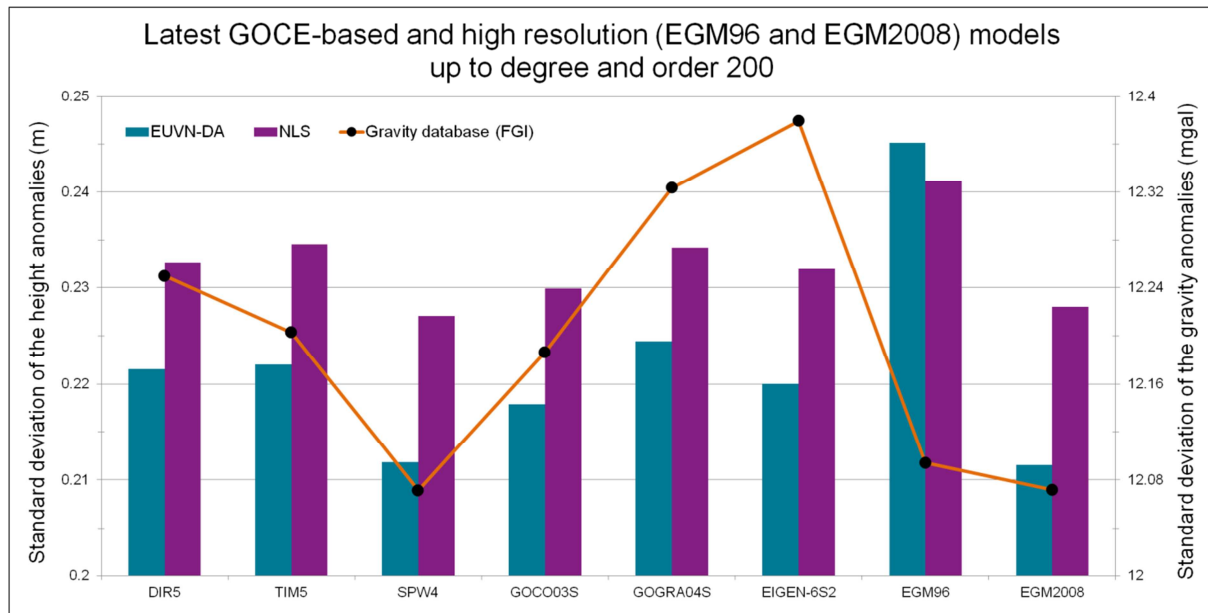


Figure 6: Comparison of the height and gravity anomalies from the latest GOCE-based satellite-only models (GOCE and GOCE-GRACE) and high resolution (EGM96 and EGM2008) models using coefficients up to 200 against GPS-levelling and gravity data: standard deviations of the differences (m) and (mgal).

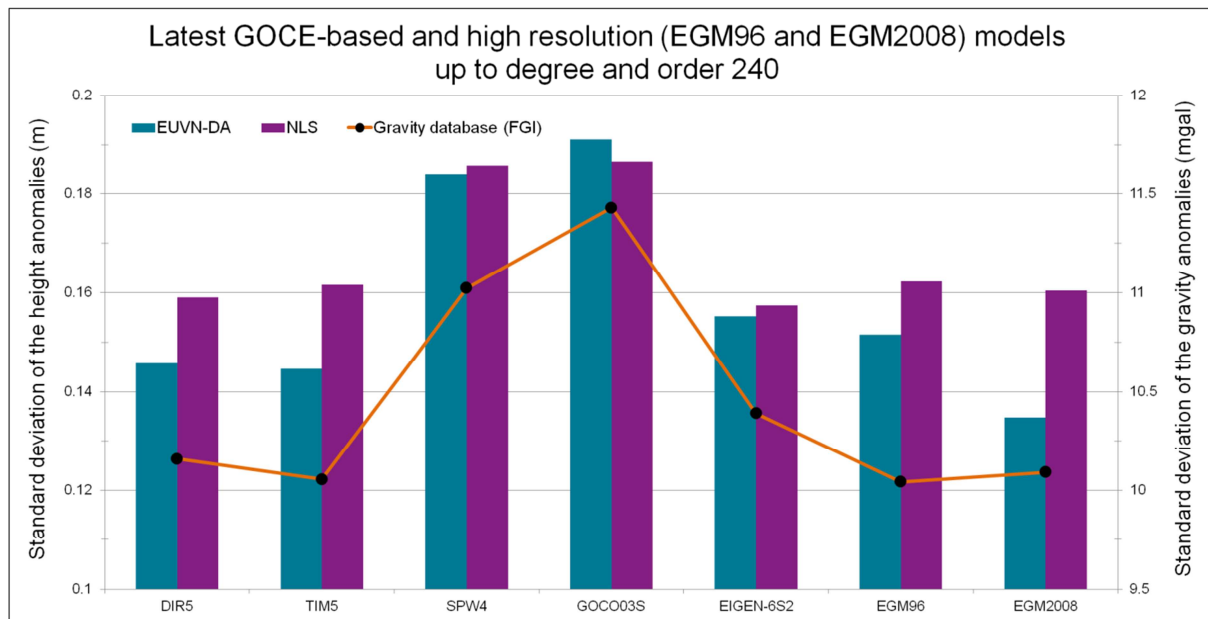


Figure 7: Comparison of the height and gravity anomalies from the latest GOCE-based satellite-only models (GOCE and GOCE-GRACE) and high resolution (EGM96 and EGM2008) models using coefficients up to 240 against GPS-levelling and gravity data: standard deviations of the differences (m) and (mgal).

At the final comparison the models were evaluated by using coefficients up to 240 as well as maximum and the calculated height and gravity anomalies were compared once again with the datasets. The results of the final comparison are presented in the Figure 8. All of the models give standard deviations of the height anomaly differences of less than 20 cm and of gravity anomaly differences of around 10 mgal over Finland. In addition, Figure 8 expresses that the best performance of the satellite-only models is not usually achieved with the maximum coefficients, since the highest coefficients (above 240) are less accurately determined.

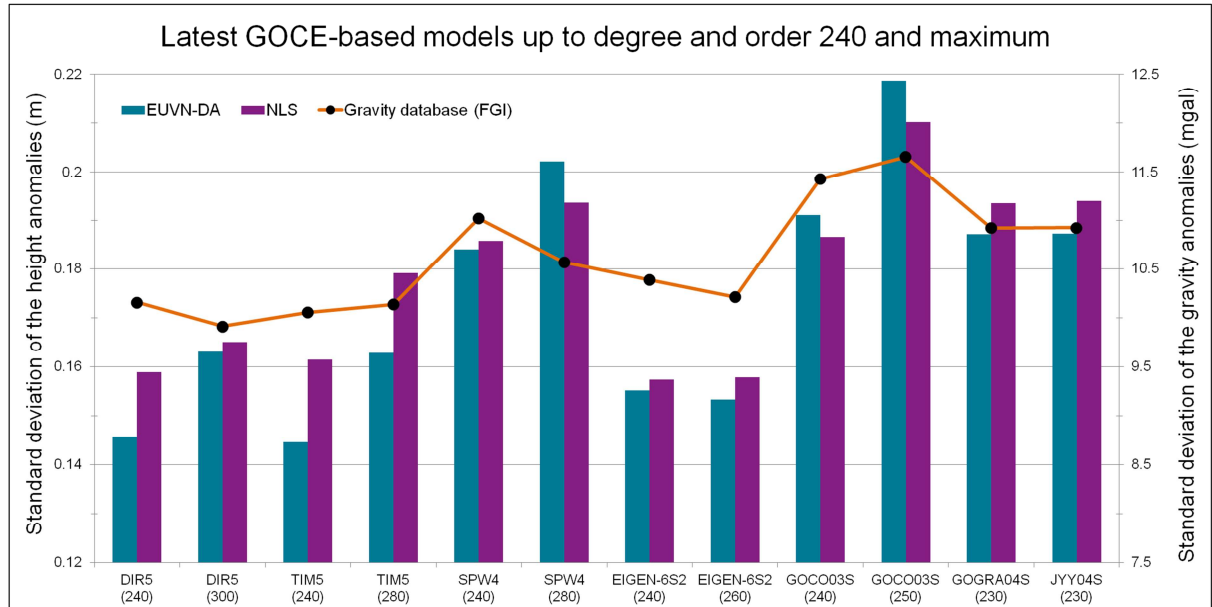


Figure 8: Comparison of the height and gravity anomalies from the latest GOCE-based satellite-only models (GOCE and GOCE+GRACE) using coefficients up to 240/maximum against GPS-levelling and gravity data: standard deviations of the differences (m) and (mgal).

Differences in the free-air gravity anomalies between the latest GOCE models (DIR5, GOCO03S and EIGEN-6S2) and gravity data over Finland are presented in Figure 9, where the comparison has been made with the coefficients up to degree and order 240. Minor differences can be seen between the models. Overall, DIR5 seems to be performing quite smoothly over Finland, especially in the Southern Finland. As for the Northern Finland, EIGEN-6S2 is the most steady satellite-only gravity field model.

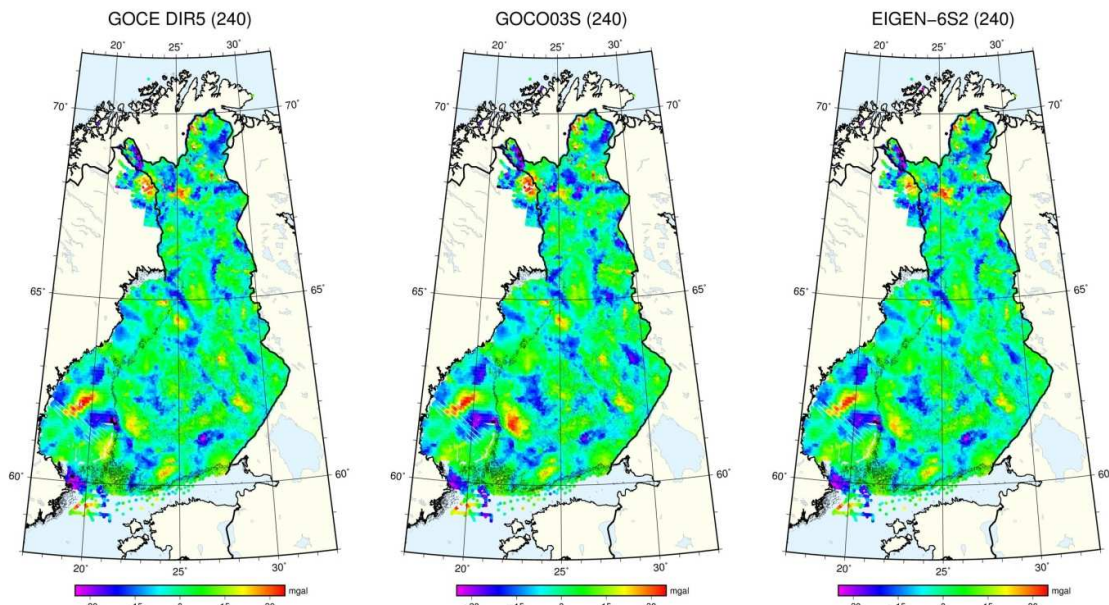


Figure 9: Differences in the free-air gravity anomalies between the latest GOCE models (DIR5, GOCO03S and EIGEN-6S2) and gravity data over Finland. The comparison has been made with the coefficients up to degree and order 240.

5 Conclusions

In this study we compared altogether 16 GOCE models, 12 GRACE models and 6 combined GOCE+GRACE models with GPS-levelling data and gravity observations in Finland. The latest satellite-only models were compared against high resolution global geoid models EGM96 and EGM2008.

The models were evaluated up to four different degrees and order: 150 (the common maximum for the GRACE models), 200, 240 (the common maximum for the GOCE models) and maximum. When coefficients up to degree and order 150 are used, the results from the GOCE models are better than EGM96 (with height anomalies) and are comparable with the latest GRACE models and EGM2008. Similar results are achieved with the coefficients up to 200, as the GOCE models perform clearly better than EGM96 when comparing with the GPS-levelling datasets.

The performances of the GOCE models are quite similar when developed up to degree and order 200. There are no significant improvements to be seen between the later models comparing to earlier models. However, when the models are developed up to degree and order 240 it is clearly seen how the later models perform better. This improvement of later models was expected, as they include more GOCE data leading to a better determination of the higher degrees and orders above 200.

Generally, all of the latest GOCE and GOCE+GRACE models give standard deviations of the height anomaly differences of around 15 cm and of gravity anomaly differences of around 10 mgal over Finland, when coefficients up to 240 or maximum are used. The results are comparable with the results of the high resolution models. The best performance of the satellite-only models is not usually achieved with the maximum coefficients, since the highest coefficients (above 240) are less accurately determined.

Even at the lower degrees and orders, the high resolution EGM96 and EGM2008 models performed very well over Finland when compared to the satellite-only models. The excellent performance is due to the good high resolution terrestrial data that was already available in the area of Finland for the EGM96 and EGM2008. Globally, however, these models do not perform equally well everywhere due to the inhomogeneous distribution of the terrestrial gravity data, whereas the satellite-only models will perform homogeneously everywhere on the globe.

We will continue the study by using the GOCE-only models in combination with the terrestrial gravity data in the calculation of a geoid model for Finland. Then the true value of the GOCE mission for regional geoid modelling can be analyzed. Additionally, we will investigate filtering of the terrestrial data to the same resolution as the GOCE models in order to remove the problem of the omission error in the comparisons.

References

- Ågren, J. & Svensson, R. (2007): Postglacial Land Uplift Model and System Definition for the New Swedish Height System RH 2000. LMV-Rapport 2007:4. Reports in Geodesy and Geographical Information Systems. Gävle, Sweden. 124 p. ISSN 280-5731.
- Bilker-Koivula, M. (2010): Development of the Finnish height conversion surface FIN2005N00. Nordic Journal of Surveying and Real Estate Research. Vol. 7:1. pp. 76-88. ISSN 1459-5877.
- Bilker-Koivula, M. (2015): Assessment of high resolution global gravity field models for geoid modelling in Finland. In: Marti, U. (ed.): Proceedings of the International Symposium on Gravity, Geoid and Height Systems (GGHS2012). IAG Symposium. Vol. 141. In print.
- Bruinsma, S. L., Marty, J. C., Balmino, G., Biancale, R., Foerste, C., Abrikosov, O. & Neumayer, H. (2010): GOCE Gravity Field Recovery by Means of the Direct Numerical Method. ESA Living Planet Symposium 2010. Bergen, Norway. 27.6–2.7.2010.
- Bruinsma, S. L., Foerste, C., Abrikosov, O., Marty, J. C., Rio, M. H., Mulet, S. & Bonvalot, S. (2013): The new ESA satellite-only gravity field model via the direct approach. Geophysical Research Letters. Vol. 40:14. pp. 3607–3612. DOI: 10.1002/grl.50716.

- Chen, Q., Shen, Y., Hsu, H., Zhang, X., Chen, W. & Lou, L. (2013): Tongji-GRACE01-A GRACE-only Static Gravity Field Model Recovered From GRACE Level-1B Observations using Modified Short Arc Approach. Paper will be submitted recently.
- Forsberg, R. & Tscherning, C. C. (2008): An overview manual for the GRAVSOFT Geodetic Gravity Field Modelling Programs. 2. edition, August 2008. Available online: http://www.researchgate.net/publication/258889946_An_overview_manual_for_the_GRAVSOFT_Geodetic_Gravity_Field_Modelling_Programs. Accessed 23.2.2015.
- Förste, C., Flechtner, F., Schmidt, R., Stubenvoll, R., Rothacher, M., Kusche, J., Neumayer, K.H., Biancale, R., Lemoine, J. M., Barthelmes, F., Bruinsma, S. L., König, R. & Meyer, U. (2008): EIGEN-GL05C - A new global combined high-resolution GRACE-based gravity field model of the GFZ-GRGS cooperation. Geophysical Research Abstracts. Vol. 10. EGU2008-A-03426. SRef-ID: 1607-7962/gra/EGU2008-A-03426.
- Gatti, A., Reguzzoni, M., Migliaccio, F. & Sansò, F. (2014): Space-wise grids of gravity gradients from GOCE data at nominal satellite altitude. 5th International GOCE User Workshop. Paris (UNESCO), France. 25–28.11.2014.
- Goiginger, H., Höck, E., Rieser, D., Mayer-Gürr, T., Maier, A., Krauss, S., Pail, R., Fecher, T., Gruber, T., Brockmann, J. M., Krasbutter, I., Schuh, W. D., Jäggi, A., Prange, L., Hausleitner, W., Baur, O. & Kusche, J. (2011): The combined satellite-only global gravity field model GOCO02S. Presented at the 2011 General Assembly of the European Geosciences Union. Vienna, Austria. 4–8.4.2011.
- International Center for Global Gravity Field Models (ICGEM). (2015): Global Gravity Field Models. Available online: <http://icgem.gfz-potsdam.de/ICGEM/modelstab.html>. Accessed 23.2.2015.
- Jäggi, A., Meyer, U., Beutler, G., Prange, L., Dach, R. & Mervart, L. (2011): AIUB-GRACE03S: A static gravity field model computed with simultaneously solved-for time variations from 6 years of GRACE data using the Celestial Mechanics Approach. Paper in preparation.
- Jäggi, A., Beutler, G., Meyer, U., Prange, L., Dach, R. & Mervart, L. (2012): AIUB-GRACE02S: Status of GRACE Gravity Field Recovery using the Celestial Mechanics Approach. In: Kenyon, S. et al. (eds.). Geodesy for Planet Earth. IAG Symposium. Vol. 136. pp. 161–169. Berlin Heidelberg, Germany: Springer-Verlag. DOI: 10.1007/978-3-642-20338-1_20.
- Lemoine, F. G., Kenyon, S. C., Factor, J. K., Trimmer, R. G., Pavlis, N. K., Chinn, D. S., Cox, C. M., Klosko, S. M., Luthcke, S. B., Torrence, M. H., Wang, Y. M., Williamson, R. G., Pavlis, E. C., Rapp, R. H. & Olson, T. R. (1998): The Development of the Joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96. NASA Technical Paper, NASA/TP1998206861. Goddard Space Flight Center. Greenbelt. USA.
- Mayer-Gürr, T., Eicker, A. & Ilk, K. H. (2006): ITG-GRACE02s: a GRACE gravity field derived from short arcs of the satellite's orbit. Proceedings of the First Symposium of International Gravity Field Service. Istanbul, Turkey. 28.8–1.9.2006.
- Mayer-Gürr, T., Eicker, A. & Ilk, K. H. (2007): ITG-Grace03 Gravity Field Model. Available online: <http://www.igg.uni-bonn.de/apmg/index.php?id=itg-grace03>. Accessed 23.2.2015.
- Mayer-Gürr, T., Kurtenschach, E. & Eicker, A. (2010): ITG-Grace2010 Gravity Field Model. Available online: <http://www.igg.uni-bonn.de/apmg/index.php?id=itg-grace2010>. Accessed 23.2.2015.
- Mayer-Gürr, T., Rieser, D., Höck, E., Brockmann, J. M., Schuh, W. D., Krasbutter, I., Kusche, J., Maier, A., Krauss, S., Hausleitner, W., Baur, O., Jäggi, A., Meyer, U., Prange, L., Pail, R., Fecher, T. & Gruber, T. (2012): The new combined satellite only model GOCO03s. Abstract submitted to GGHS2012. Venice (Poster).
- Mayer-Gürr, T., Zehentner, N., Klinger, B. & Kvas, A. (2014): ITSG-Grace2014: a new GRACE gravity field release computed in Graz. GRACE Science Team Meeting (GSTM). Potsdam, Germany. 29.9–1.10.2014.
- Migliaccio, F., Reguzzoni, M., Sansò, F., Tscherning, C. C. & Veicherts, M. (2010): GOCE data analysis: the space-wise approach and the first space-wise gravity field model. ESA Living Planet Symposium 2010. Bergen, Norway. 27.6–2.7.2010.
- Migliaccio, F., Reguzzoni, M., Gatti, A., Sansò, F. & Hecceg, M. (2011): A GOCE-only global gravity field model by the space-wise approach. Proceedings of the 4th International GOCE User Workshop. Munich, Germany. 31.3–1.4.2011.
- Ollikainen, M. (2006): The EUVN_DA campaign in Finland. Publications of the Finnish Geodetic Institute 135. 39 p.
- Pail, R., Goiginger, H., Mayrhofer, R., Schuh, W., Brockmann, J. M., Krasbutter, I., Höck, E. & Fecher, T. (2010a): GOCE gravity field model derived from orbit and gradiometry data applying the time-wise method. ESA Living Planet Symposium 2010. Bergen, Norway. 27.6–2.7.2010.

- Pail, R., Goiginger, H., Schuh, W. D., Hoeck, E., Brockmann, J. M., Fecher, T., Gruber, T., Mayer-Gürr, T., Kusche, J., Jäggi, A. & Rieser, D. (2010b): Combined satellite gravity field model GOCO01S derived from GOCE and GRACE. *Geophysical Research Letters*. Vol. 37:20. DOI: 10.1029/2010GL044906.
- Pail, R., Bruinsma, S., Migliaccio, F., Christoph, F., Goiginger, H., Schuh, W. D., Hoeck, E., Reguzzoni, M., Brockmann, J. M., Abrikosov, O., Veicherts, M., Fecher, T., Mayrhofer, R., Krasbutter, I., Sansò, F. & Tscherning, C. C. (2011): First GOCE gravity field models derived by three different approaches. *Journal of Geodesy*. Vol. 85:11. pp. 819-843. DOI: 10.1007/s00190-011-0467-x.
- Pavlis, N. K., Holmes, S. A., Kenyon, S. C. & Factor, J. K. (2012): The development and evaluation of the Earth Gravitational Model (EGM2008). *Journal of Geophysical Research*. Vol. 117:B4. 38 p. DOI: 10.1029/2011JB008916.
- Reigber, C., Schmidt, R., Flechtner, F., König, R., Meyer, U., Neumayer, K. H., Schwintzer, P. & Zhu, S. Y. (2005): An Earth gravity field model complete to degree and order 150 from GRACE: EIGEN-GRACE02S. *Journal of Geodynamics*. Vol. 39:1. pp. 1–10. ISSN 0264-3707.
- Rudenko, S., Dettmering, D., Esselborn, S., Schoene, T., Förste, C., Lemoine, J. M., Ablain, M., Alexandre, D. & Neumayer, K. H. (2014): Influence of time variable geopotential models on precise orbits of altimetry satellites, global and regional mean sea level trends. *Advances in Space Research*. Vol. 54:1. pp. 92–118. DOI 10.1016/j.asr.2014.03.010.
- Rummel, R., Gruber, T. & Koop, R. (2004): High level processing facility for GOCE: products and processing strategy. In: Lacoste, H. (ed): *Proceedings of the 2nd international GOCE user workshop “GOCE, The Geoid and Oceanography”*. ESA SP-569, ESA. ISBN 92-9092-880-8; ISSN:1609-042X.
- Schall, J., Eicker, A. & Kusche, J. (2014): The ITG-Goce02 gravity field model from GOCE orbit and gradiometer data based on the short arc approach. *Journal of Geodesy*. Vol. 88:4. pp. 403-409. DOI 10.1007/s00190-014-0691-2.
- Tapley, B. D., Ries, J., Bettadpur, S., Chambers, D., Cheng, M., Condi, F., Gunter, B., Kang, Z., Nagel, P., Pastor, R., Pekker, T., Poole, S. & Wang, F. (2005): GGM02 - An improved Earth gravity field model from GRACE. *Journal of Geodesy*. Vol. 79:8. pp. 467–478. DOI: 10.1007/s00190-005-0480-z.
- Tapley, B. D., Ries, J., Bettadpur, S., Chambers, D., Cheng, M., Condi, F. & Poole, S. (2007): The GGM03 Mean Earth Gravity Model from GRACE. *Eos Trans., AGU* 88:52. Fall Meet., Suppl., Abstract G42A-03.
- Tapley, B. D., Flechtner, F., Bettadpur, S. & Watkins, M. M. (2013): The status and future prospect for GRACE after the first decade. *Eos Trans., Fall Meet., Suppl.*, Abstract G22A-01.
- Vestøl, O. (2005): Determination of Postglacial Land Uplift in Fennoscandia from Leveling, Tide-gauges and Continuous GPS Stations using Least Squares Collocation. *Journal of Geodesy*. Vol. 80:5. pp. 248–258. DOI:10.1007/s00190-006-0063-7.
- Yi, W., Rummel, R. & Gruber, T. (2013): Gravity field contribution analysis of GOCE gravitational gradient components. *Studia Geophysica et Geodaetica*. Vol. 57:2. pp. 174-202. ISSN (Online) 1573-1626. DOI 10.1007/s11200-011-1178-8.

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Validation of GOCE Gravity Field Models in Germany

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Abstract

The fifth release of global gravity field models (GGMs) from the GOCE mission published in mid-2014 are based on observation data from the whole mission lifetime. High precision gravity field data sets in Germany are utilized to validate the GOCE GGMs of the fourth and fifth release processed by the time-wise (TIM) and the direct approach (DIR) as well as their internal uncertainty estimates. The comparisons are performed between EGM2008 and the GOCE GGMs up to spherical harmonic degree and order (d/o) 200 in terms of quasigeoid heights, gravity anomalies and vertical deflections. For the comparisons of GPS/levelling data and astrogeodetic vertical deflections with the GOCE GGMs, the different spectral characteristics of the data sets are considered by modelling the high frequency signals above d/o 200 by EGM2008 and detailed topographic information within the residual terrain model (RTM) approach. The RMS differences of all comparisons are introduced as observations within a least squares adjustment in order to estimate the commission errors of the GOCE GGMs as well as the uncertainties from all other terms involved in the comparisons, i.e. EGM2008, RTM effects and GPS/levelling. The commission errors of the fifth release GOCE GGMs up to d/o 200 are estimated to 2.5 cm and 2.4 cm for TIM5 and DIR5, respectively, as well as 0.66 mGal and 0.10" for both models in terms of quasigeoid heights, gravity anomalies and vertical deflections, respectively. This is in good agreement with the formal error degree variances of TIM5, while for DIR5 a factor of 3 is proposed. Moreover, both fifth release GOCE GGMs show significant improvements of approx. 30% compared to their predecessors.

1 Introduction

The GOCE mission aims at providing the geoid and gravity anomalies with an uncertainty of 1-2 cm and 1 mGal, respectively, both at a resolution of 100 km, corresponding to spherical harmonic degree and order (d/o) 200 (e.g. Pail et al. 2011); this is equivalent to 0.15" for single vertical deflection components (Voigt and Denker 2014). The GOCE High-level Processing Facility (HPF) generated five releases of global gravity field models (GGMs), which are based on 2, 6, 12 and 27 months as well as 4 years of GOCE observations. The processing follows three different approaches, i.e. the direct (DIR), the time-wise (TIM) and the space-wise (SPW) approach. However, the releases of the space-wise (SPW) approach GGMs stopped after release two. The approaches are outlined in Pail et al. (2011). While the TIM GGMs are based on GOCE observations only, the DIR GGMs build combination solutions of GOCE data combined with multi-year GRACE and SLR (see also Table 1). Detailed information on the fifth release GOCE GGMs TIM5 and DIR5 can be found in Brockmann et al. (2014) and Bruinsma et al. (2014), respectively.

In order to ensure high quality GOCE products, various internal and external calibration and validation techniques are of vital importance. Focusing on the external validation of GOCE GGMs by external gravity field data sets, numerous studies have been carried out using vari-

ous validation methods and global as well as regional data sets since the first release GOCE GGMs were published in 2010. The first release GOCE GGMs were evaluated e.g. by Gruber et al. (2011) and Hirt et al. (2011). Studies on the first to the third release GOCE GGMs can be found e.g. in Voigt and Denker (2014a), while the fourth release GOCE GGMs are analyzed e.g. by Yi and Rummel (2014), Godah et al. (2014) and Rexer et al. (2013). The performance analyses of GOCE GGMs up to the fifth release by HPF were recently presented by Gruber and Rummel (2014).

The objective of this study is to validate the GOCE GGMs of the fifth release by gravity field data sets in Germany. This includes analyses of the improvement relative to the fourth release GOCE GGMs and of the absolute performance as well as of the uncertainty estimates. In this context, the ultra-high degree spherical harmonic model EGM2008 (Pavlis et al. 2012) is employed as well as the current GPS/levelling data set and astrogeodetic vertical deflections in Germany. All GGM and terrestrial quantities were referred to GRS80 and the zero-tide system. Section 2 describes the internal uncertainty estimates of the GOCE GGMs under evaluation. In section 3, the gravity field data sets in Germany used for the evaluation of the GOCE GGMs are introduced and compared in terms of quasigeoid heights. Section 4 explains the applied validation methods and gives the results of the comparisons with the GOCE GGMs, which are used in section 5 within a common least squares adjustment in order to estimate the uncertainty contributions of all terms involved in the comparisons.

2 Internal Uncertainty Estimates of the Global Gravity Field Models

Error degree variances are commonly used for internal uncertainty estimates of GGMs. Figure 1 shows the positive square roots of the sum of the error degree variances in terms of geoid heights, gravity anomalies and single vertical deflection components for the GOCE GGMs under evaluation as well as for EGM2008 up to degree 250, hereinafter referred to as cumulative errors and used as commission errors. For the computation of the error degree variances for single vertical deflection components see Voigt and Denker (2014). Regarding the aspired GOCE spatial resolution of 100 km, corresponding to d/o 200, the cumulative errors are 2.2 cm, 0.59 mGal and 0.09" for TIM5, while DIR5 provides 0.8 cm, 0.21 mGal and 0.03" in terms of geoid heights, gravity anomalies and vertical deflections, respectively. These numbers represent an improvement of approx. 40% to the predecessor models. However, the formal estimates of TIM5 and DIR5 differ by a factor of 3 and one of the key questions is how realistic these formal estimates really are and whether they should be calibrated, e.g. with regard to proper weighting procedures in the context of high resolution geoid determination based on GGMs. In Bruinsma et al. (2014), a calibration factor of 2 is stated for DIR5 based on the comparisons with GPS/levelling data in Germany (see also sections 3 and 5).

Some remarks on the error degree variance approach are appropriate. First, the error degree variances do not take into account correlations among the coefficients. Second, the handling

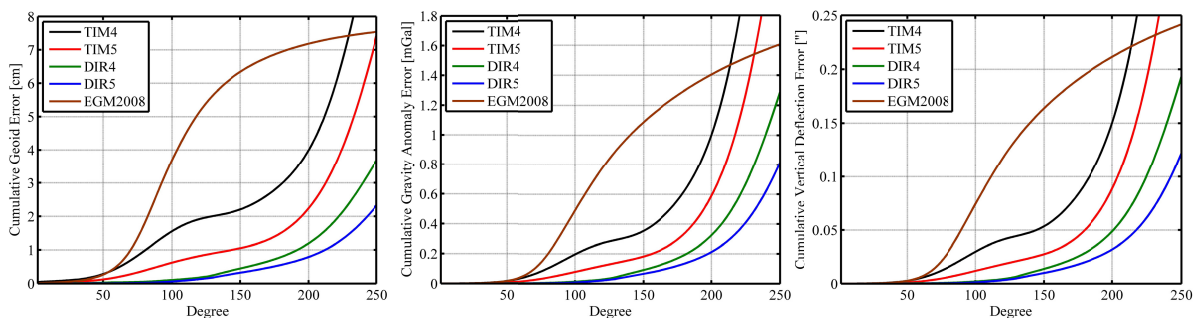


Figure 1 Cumulative errors of current global gravity field models in terms of geoid (left), gravity anomalies (middle) and vertical deflections (right)

Table 1 Cumulative errors for various GGMs up to d/o 200 and 2159, respectively, in terms of geoid (ζ), gravity anomalies (Δg), and vertical deflections (ξ, η)

GGM	Data	d/o	ζ [cm]	Δg [mGal]	ξ, η ["]
TIM4	GOCE (27 months)	2-200	4.0	1.00	0.15
TIM5	GOCE (4 years)	2-200	2.2	0.59	0.09
DIR4	GOCE (27 months), GRACE, SLR	2-200	1.2	0.32	0.05
DIR5	GOCE (4 years), GRACE, SLR	2-200	0.8	0.21	0.03
EGM2008	GRACE, terrestrial and altimetric data	2-200	7.2	1.40	0.21
EGM2008	GRACE, terrestrial and altimetric data	2-2159	8.2	4.22	0.63

of the polar gap problem in the GOCE processing, affecting the zonal and near-zonal coefficients, has also an impact on the supplied spherical harmonic coefficient standard deviations, particularly on the GOCE only TIM models. And third, the uncertainties of the GOCE GGMs depend on the geographical latitude. Hence, latitude-dependent standard deviations from the propagation of the full variance covariance matrix of the spherical harmonic coefficients should be preferred. Brockmann et al. (2014) specify a global mean geoid accuracy of 2.4 cm for TIM5 up to d/o 200. For latitudes between 47° and 55° covering Germany, the corresponding values are 1.5 cm and 1.3 cm, respectively, from the variance covariance propagation. This is a decrease by a factor of 1.6 compared to the cumulative geoid error of 2.2 cm in Table 1.

3 Comparisons of the External Data Sets in Germany

For the evaluation of the GOCE GGMs, high precision gravity field data sets in Germany are used. Besides the ultra-high degree spherical harmonic model EGM2008 complete to d/o 2159 and additional coefficients up to degree 2190 (Pavlis et al. 2012) based on ITG-Grace03s as well as high precision terrestrial and altimetric data ($\sigma=0.1$ -1.0 mGal in Germany), a data set of 954 GPS/levelling points ($\sigma=1$ -2 cm) exist; further details on the terrestrial data sets can be found e.g. in Ihde et al. (2010). In addition, a unique data set of 370 astrogeodetic vertical deflections ($\sigma=0.08''$) along two 600 km long profiles are available, traversing through a subset of 46 GPS/levelling points in total. These are 29 additional vertical deflection stations in comparison to previous studies, e.g. Voigt and Denker (2014a) resulting from the connection to the future GPS/levelling data set from the renewal of the German height reference network (2006-2012). The method of astronomical topographic levelling (astro levelling) is used to compute quasigeoid heights with regard to a vertical datum fixed in the starting points of the profiles. For details on this data set and comprehensive studies on astrogeodetic gravity field modelling see Voigt (2013) with the first results published in Voigt et al. (2009).

One of the main advantages of the three data sets, i.e. EGM2008, GPS/levelling and the astrogeodetic vertical deflections, is that they are fully independent and thus provide valuable uncertainty estimates by applying a cross-validation in terms of quasigeoid heights. However, the different spectral characteristics of the terrestrial data and EGM2008, which is limited to the maximum degree and order, should be considered. The high frequency signal beyond degree 2190 and order 2159 are modelled by detailed topographic information from SRTM3 v4.1 (Jarvis et al. 2008) and the residual terrain model (RTM) approach with regard to Earth2012 (Hirt et al. 2012), a spherical harmonic model of the Earth's topography (with water) used as reference topography (see also Gruber et al. 2011).

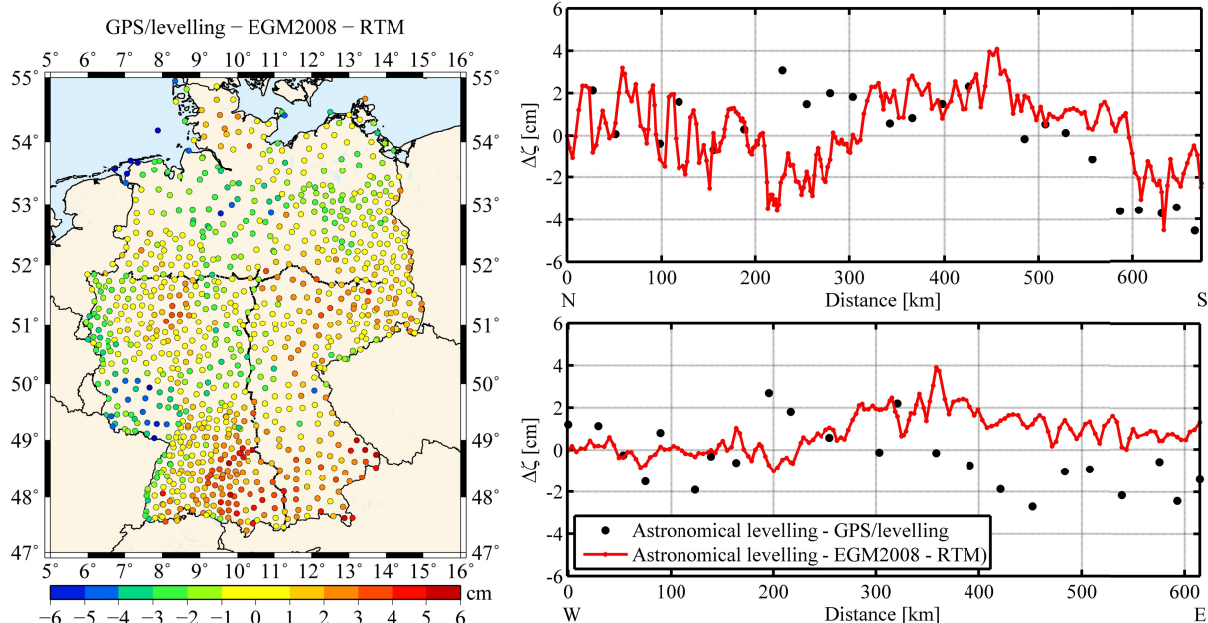


Figure 2 Differences between GPS/levelling data and quasigeoid heights from EGM2008+RTM (left) with the astrogeodetic vertical deflection stations (black dots); quasigeoid differences between astro levelling and GPS/levelling as well as EGM2008+RTM along the North-South (top right) and the West-East profile (bottom right)

Figure 2 shows the quasigeoid differences between the three data sets in Germany without applying any fitting or correction surface. The comparison between GPS/levelling and EGM2008 augmented by RTM effects on 954 stations in Germany yield an RMS difference of 2.1 cm with a range from -7.3 cm to 5.8 cm. This number represents an improvement of approx. 25% to the RMS difference of 2.8 cm specified in previous studies, where the reference topography was built by a moving average filter in conjunction with a spatial low pass filter, e.g. Voigt and Denker (2014a).

In addition, the astrogeodetic profile lines are shown in Figure 2 (left) with RMS differences of 2.2 cm and 1.6 cm between GPS/levelling and EGM2008+RTM along the North-South profile (from North N to South S) and the West-East profile (from West W to East E). This is in good agreement with the slightly larger value of 2.1 cm on the GPS/levelling stations, implying that the subset of 46 points along the profiles is quite representative for the whole data set of 954 points in Germany. The differences of the quasigeoid heights between astro levelling and GPS/levelling as well as EGM2008+RTM (Figure 2, right) are in the range of ± 4 cm with RMS differences of 2.2 cm and 1.7 cm along the North-South profile as well as 1.5 cm and 1.3 cm, respectively, along the West-East profile. The consistently larger differences along the North-South profile can be attributed to the rugged terrain.

The uncertainties of the three data sets along the profiles can be determined from the RMS differences between them. In Table 2, the merged RMS differences between two data sets in each case along both profiles are shown as off-diagonal elements. On the main diagonal, the uncertainties of the individual data sets resulting from the RMS differences are displayed with 1.0, 1.6 and 1.1 cm for the quasigeoid heights from astro levelling, GPS/levelling and EGM2008+RTM, respectively. For example, the merged RMS difference of 1.9 cm between GPS/levelling and EGM2008+RTM along both profiles can be explained by the uncertainties of the data sets with $\sqrt{1.6^2 + 1.1^2}$. Hence, the three data sets are well suited for the validation of the GOCE GGMs with aspired (and stated) commission errors of 1-2 cm at a resolution of 100 km. Gruber and Rummel (2014) provide an RMS difference of 2.0 cm between the GPS/levelling data and EGM2008+RTM in Germany after applying a planar fit, while esti-

Table 2 RMS differences (off-diagonal) between the data sets and uncertainties (main diagonal) of the data sets in terms of quasigeoid heights along the profiles in Germany [cm]

Data Set	Astro levelling	GPS/levelling	EGM2008+RTM
Astro levelling	1.0	1.8	1.4
GPS/levelling		1.6	1.9
EGM2008+RTM			1.1

imating the uncertainty of the (planarly fitted) GPS/levelling data to 2.1 cm, which seems rather pessimistic as also EGM2008+RTM uncertainties contribute to the differences.

4 Comparisons between the External Data Sets and the GOCE Gravity Field Models in Germany

The three data sets introduced in the last section are used for the evaluation of the GOCE GGMs. In order to consider the spectral characteristics of the GGM and the terrestrial data, three different methods are applied for the comparisons of EGM2008, GPS/levelling data and the astrogeodetic vertical deflections with the GOCE GGMs. It should be noted that the GPS/levelling data and the astrogeodetic vertical deflections are fully independent of all GOCE GGMs, while EGM2008 is also independent of the TIM models. However, the long-wavelength signals of EGM2008 and the DIR models are correlated by the GRACE data included in both solutions.

The first method is the direct comparison of quasigeoid heights, gravity anomalies and vertical deflections from EGM2008 up to a certain maximum degree and order with corresponding functionals of the GOCE GGMs. This method has the advantage that signals of the same spectral band can be compared directly. The spherical harmonic syntheses are carried out on a $1' \times 1'$ grid over Germany containing 316,800 grid points in total. Figure 3 shows the differences between the quasigeoid heights from EGM2008 and the GOCE GGMs up to d/o 200. The RMS differences, also displayed in Table 3, decrease from 3.4 to 2.7 cm (TIM4 vs. TIM5) and from 3.8 to 2.7 cm (DIR4 vs. DIR5) with the fifth release GGMs performing quite similar but DIR5 being slightly superior to TIM5, probably because of the GRACE data included. The typical difference patterns significantly decrease from release 4 to 5, indicating the increasing accuracy of the GOCE GGMs in areas with high quality terrestrial gravity data included in EGM2008. Corresponding differences are computed as well in terms of gravity anomalies and vertical deflection components with RMS values of 0.72 mGal and 0.11", respectively, for both TIM5 and DIR5 showing again an improvement of approx. 30% against their predecessors. These results already demonstrate the high accuracy level of the fifth release GOCE GGMs with the aim of providing gravity anomalies with an uncertainty of 1 mGal up to d/o 200 well achieved.

The second method applies the GPS/levelling data in Germany. For a thorough validation of the GOCE GGMs, the different spectral characteristics of both data sets are considered, i.e., the high-frequency signals beyond the maximum d/o 200, which are not included in the GOCE GGMs but represent a significant portion of the entire spectrum, are taken into account. For this purpose, the high frequency signals above d/o 200 are modelled by EGM2008 up to degree 2190 and order 2159, while beyond this degree RTM effects are utilized (see section 3). The differences between the GPS/levelling data and quasigeoid heights from GOCE GGMs augmented by EGM2008 signals and RTM effects are depicted in Figure 4. Again, the RMS differences (also shown in Table 3) decrease significantly from 3.8 to 3.1 cm (TIM4 vs. TIM5) and from 4.1 to 3.0 cm (DIR4 vs. DIR5). These differences are strongly correlated with the differences shown in Figure 3 to approx. 85% for the release 4 and 75% for the re-

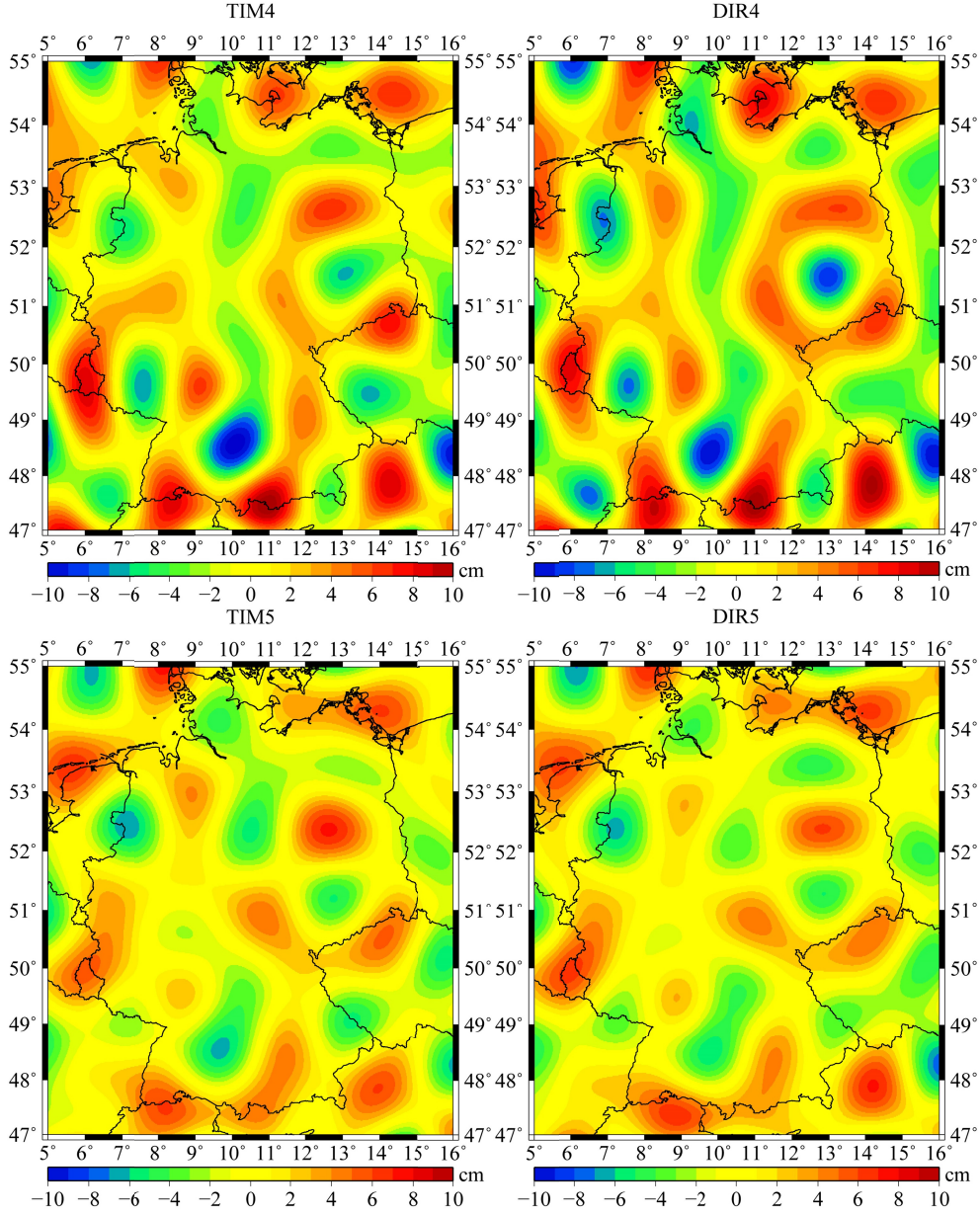


Figure 3 Differences between quasigeoid heights from EGM2008 and GOCE GGMs up to d/o 200

least 5 GGMs. This implies two aspects. First, the uncertainties of the GOCE GGMs contribute most to the differences and, second, both validation methods are consistent. However, the RMS quasigeoid differences between GPS/levelling and the GOCE GGMs are slightly larger than the corresponding values between EGM2008 and the GOCE GGMs. This shows that EGM2008 up to d/o 200 is somewhat superior to the sum of uncertainties from GPS/levelling, EGM2008 between d/o 201 and 2159 and RTM effects. In addition, uncertainties arising from the spectral break between the GOCE GGMs and EGM2008 at d/o 200 could have an effect on this comparison. This can be reduced by applying a proper weighting function, e.g. by using the error degree variances of the GOCE GGMs and EGM2008 within a certain spectral band around the maximum degree of the GOCE GGMs. However, this is not done here in order to use identical GOCE signals in the comparisons.

Within the third method, the astrogeodetic vertical deflections along the profiles are compared with corresponding values from the GOCE GGMs. On the one hand, vertical deflections are quite suitable for the validation of the higher degree signals, where quasigeoid heights are not that sensitive. But on the other hand, the comparison on the basis of vertical deflections lacks

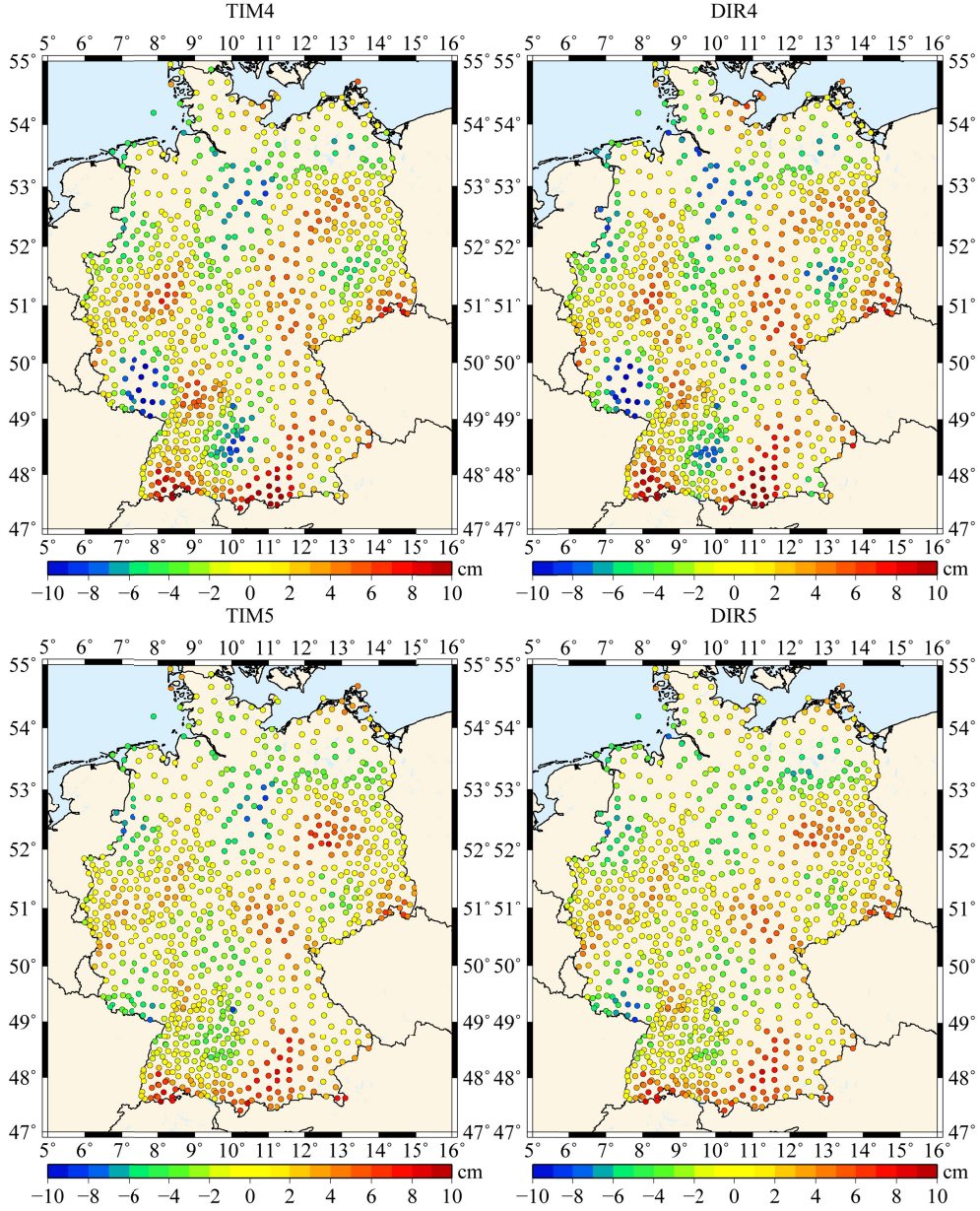


Figure 4 Differences between GPS/levelling data and quasigeoid heights from GOCE GGMs up to d/o 200 augmented by EGM2008 signals up to d/o 2159 and RTM effects

Table 3 RMS differences between external data sets and GOCE GGMs in terms of quasigeoid heights (ζ), gravity anomalies (Δg), and vertical deflections (ξ, η)

GGM	EGM2008			GPS/levelling		Astrogeodetic vertical deflections	
	ζ [cm]	Δg [mGal]	ξ, η ["]	ζ [cm]		ξ, η ["]	
TIM4	3.4	0.94	0.15	3.8		0.30	
TIM5	2.7	0.72	0.11	3.1		0.29	
DIR4	3.8	1.06	0.16	4.1		0.31	
DIR5	2.7	0.72	0.11	3.0		0.28	
EGM2008+RTM	-	-	-	2.1		0.27	

of the strong influence of high frequency effects around the observation points, e.g. the vertical deflection signal beyond d/o 2159 is 1.65" while it is just 2.3 cm for quasigeoid heights (see Voigt and Denker 2014). In principle, the validation is based on the same strategy as the

second method but with an additional spatial Gaussian filtering of 9 km width (corresponding to d/o 2159) in order to further reduce unmodelled high-frequency effects; see also Voigt and Denker (2014). The RMS differences of these comparisons are shown in Table 3, where the statistics of the individual components along the two profiles are already merged, only slightly decreasing from 0.30 to 0.29" (TIM4 vs. TIM5) and from 0.31 to 0.28" (DIR4 vs. DIR5). This result clearly indicates the impact of unmodelled high frequency effects coming mostly from density variations not captured by the RTM effects.

5 External Uncertainty Estimates of the Global Gravity Field Models

The uncertainties of the GOCE GGMs are estimated externally on the basis of the comparisons carried out in the last section. For this purpose, the RMS differences of Table 3 are introduced as observations within a common least squares adjustment. The general relation between the observation vector $\mathbf{l}$ and the vector $\mathbf{x}$ of the unknown parameters is given by $\mathbf{l} + \mathbf{v} = \mathbf{A}\mathbf{x}$ with the residuals $\mathbf{v}$ and the design matrix $\mathbf{A}$ aiming at the minimization of $\mathbf{v}^T \mathbf{P} \mathbf{v}$, where $\mathbf{P}$ is the weighting matrix. The unknown parameters are the scaling factors of the cumulative error degree variances of the GOCE GGMs TIM4 and TIM5 as well as DIR4 and DIR5 up to d/o 200. In addition, a scaling factor of the cumulative error degree variances of EGM2008 and another for an a priori uncertainty of the RTM effects are estimated as well as the uncertainty of the GPS/levelling data, as the RMS differences result from the contributions of all data sets involved in the comparisons. A redundancy of 15 results follows from the 22 RMS differences and the 7 unknown parameters. The uncertainty of the astrogeodetic vertical deflections is known to be $\sigma_{\text{Astro}} = 0.08''$ from the comparisons with gravimetric vertical deflections in flat areas (Voigt 2013) as well as from repeated observations (Hirt and Seeber 2008) and set as a constant.

The relations between the observations and the unknown parameters are shown in order to set up the design matrix $\mathbf{A}$. The first method of section 4 gives RMS differences between EGM2008 and the GOCE GGMs in terms of quasigeoid heights, gravity anomalies and vertical deflections up to d/o 200, which can be explained by

$$\text{RMS}(\text{EGM2008-GOCE}) = (m_{\text{GOCE}} \cdot \sigma_{\text{GOCE}}^2 + m_{\text{EGM2008}} \cdot \sigma_{\text{EGM2008}}^2)^{1/2} \quad (1)$$

with the unknown scaling factors m_{GOCE} and m_{EGM2008} of the cumulative error degree variances σ_{GOCE}^2 and $\sigma_{\text{EGM2008}}^2$ for the GOCE GGMs and EGM2008 up to d/o 200, respectively. The positive square roots of the cumulative error degree variances, referred to as cumulative errors, are shown in Table 1. From the second method, the RMS differences between GPS/levelling (GPS/lev) and the GOCE GGM quasigeoid heights follow from

$$\text{RMS}(\text{GPS/lev-GOCE}) = (m_{\text{GOCE}} \cdot \sigma_{\text{GOCE}}^2 + m_{\text{EGM2008}} \cdot \sigma_{\text{EGM2008}}^2 + m_{\text{RTM}} \cdot \sigma_{\text{RTM}}^2 + \sigma_{\text{GPS/lev}}^2)^{1/2}, \quad (2)$$

where $\sigma_{\text{EGM2008}}^2$ herein is the cumulative error degree variance between of EGM2008 between d/o 201 and 2159. Two additional unknown scaling factor are introduced, i.e. the scaling factor m_{RTM} for the RTM effects in terms of quasigeoid heights with respect to an a priori uncertainty σ_{RTM} (see below) and the uncertainty of the GPS/levelling data $\sigma_{\text{GPS/lev}}$. The RMS differences between the astrogeodetic vertical deflections (Astro) and corresponding values from the GOCE GGMs within the third method results from

$$\text{RMS}(\text{Astro-GOCE}) = (m_{\text{GOCE}} \cdot \sigma_{\text{GOCE}}^2 + m_{\text{EGM2008}} \cdot \sigma_{\text{EGM2008}}^2 + m_{\text{RTM}} \cdot \sigma_{\text{RTM}}^2 + \sigma_{\text{Astro}}^2)^{1/2} \quad (3)$$

Table 4 Structure of the design matrix **A** with the non-zero elements symbolized by *

Method	Functional	m_{GOCE}	$m_{EGM2008}$	m_{RTM}	$\sigma_{GPS/lev}$
EGM2008-GOCE	ζ	*	*	0	0
EGM2008-GOCE	Δg	*	*	0	0
EGM2008-GOCE	ξ, η	*	*	0	0
GPS/lev-GOCE-EGM2008-RTM	ζ	*	*	*	*
Astro-GOCE-EGM2008-RTM	ξ, η	*	*	*	0
GPS/lev-EGM2008-RTM	ζ	0	*	*	*
Astro-EGM2008-RTM	ξ, η	0	*	*	0

with the unknown scaling factors of the cumulative error degree variances and the RTM effects of (2), but now in terms of vertical deflections. A constant a priori value of $\sigma_{RTM}=0.20''$ is chosen for the uncertainty of the RTM effects in terms of vertical deflections with regard to the RMS differences in Table 3. This corresponds to $\sigma_{RTM}=0.07$ cm for the RTM effects in terms of quasigeoid heights according to the degree variance model of Tscherning and Rapp (1974). In Table 4, the principal structure of the design matrix **A** is given showing the individual contributions of the comparisons with regard to the estimated parameters. It should be noted that this matrix is of full rank. For the set-up of the stochastic model, uncorrelated observations are assumed with empirically determined a priori standard deviations for the RMS differences of $\sigma_{RMS(\zeta)}=0.05$ cm, $\sigma_{RMS(\Delta g)}=0.1$ mGal and $\sigma_{RMS(\xi, \eta)}=0.01''$ in terms of quasigeoid heights, gravity anomalies and vertical deflections, respectively. However, the ratios of the a priori standard deviations mostly affect the estimated standard deviations of the parameters, but not the parameters themselves. The relations between the observations and the unknown parameters (1) to (3) are non-linear. Hence, they have to be linearized at approximate values for each iteration step.

The parameters estimated within the least squares estimation are shown in Table 5 together with their standard deviations. Applying the square roots of the estimated scaling factors to the cumulative errors of the GGMs in Table 1 and to the a priori standard deviations of the RTM effects leads to the estimated uncertainties shown in Table 6. The commission error of EGM2008 is 1.0 cm, 0.20 mGal and 0.03'' up to d/o 200 in terms of quasigeoid heights, gravity anomalies and vertical deflections, respectively. The uncertainty of 0.1 cm for the RTM effects in terms of quasigeoid heights is quite negligible, while it amounts to 0.24'' in terms of vertical deflections. In total, this method proposes a cumulative error of 1.2 cm for EGM2008+RTM and the full spectral band in terms of quasigeoid heights, while the uncertainty of the GPS/levelling data is 1.7 cm. This is fully compatible with the numbers of 1.1 cm and 1.6 cm, respectively, determined along the profiles (section 3). The commission errors of the release 5 GOCE GGMs up to d/o 200 are estimated to 2.5 cm for TIM5 and 2.4 cm for DIR5 as well as 0.66 mGal and 0.10'' for both GGMs. The slightly lower value of DIR5 in terms of quasigeoid heights is probably related to the GRACE data included. The estimated

Table 5 Estimated parameters and standard deviations from the least squares adjustment

Parameters	
m_{TIM4}	0.69 ± 0.02
m_{TIM5}	1.26 ± 0.04
m_{DIR4}	9.41 ± 0.19
m_{DIR5}	9.64 ± 0.32
$m_{EGM2008}$	0.02 ± 0.00
m_{RTM}	1.46 ± 0.06
$\sigma_{GPS/lev}$ [cm]	1.7 ± 0.04

Table 6 Estimated uncertainties of all terms involved in the comparisons and standard deviations in terms of quasigeoid heights (ζ), gravity anomalies (Δg), and vertical deflections (ξ, η) from the least squares adjustment

Data Set	d/o	ζ [cm]	Δg [mGal]	ξ, η ["]
TIM4	2-200	3.3 ± 0.04	0.83 ± 0.009	0.13 ± 0.001
TIM5	2-200	2.5 ± 0.04	0.66 ± 0.011	0.10 ± 0.002
DIR4	2-200	3.7 ± 0.04	0.99 ± 0.010	0.15 ± 0.001
DIR5	2-200	2.4 ± 0.04	0.66 ± 0.011	0.10 ± 0.002
EGM2008	2-200	1.0 ± 0.07	0.20 ± 0.013	0.03 ± 0.002
EGM2008	2-2159	1.2 ± 0.08	-	0.09 ± 0.006
RTM	>2159	0.1 ± 0.00	-	0.24 ± 0.005
GPS/levelling	2- ∞	1.7 ± 0.04	-	-
Astrogeodetic vertical deflections	2- ∞	-	-	0.08 (const)

standard deviations of the commission errors are on the level of <0.1 cm, 0.01 mGal and $<0.01''$, respectively, for quasigeoid heights, gravity anomalies and vertical deflections confirming a high consistency of the applied data sets and the validation methods.

The estimated parameters shown in Table 5 suggest that the cumulative errors of the DIR models from Table 1 should be factorized by 3.1 for the latitudes of Germany, while the corresponding values for the TIM models seem to be quite reasonable with factors of 0.8 and 1.1 (TIM4 and TIM5, respectively). However, a higher factor of 1.8 for the commission error results from the propagation of the TIM5 full variance covariance matrix of 1.4 cm up to d/o 200. The estimates are somewhat pessimistic for the GOCE GGMs with regard to a calibration factor of 2 for DIR5 (Bruinsma et al. 2014) and an overall performance of 1.8 cm or better for both release 5 GGMs up to d/o 200 (Gruber and Rummel 2014).

This method can be used in all countries with GPS/levelling data sets, e.g. the countries of the EUVN-DA (European Vertical Reference Network - Densification Action), provided that no systematic errors are present in the terrestrial data sets. For the case that only GPS/levelling data and no astrogeodetic vertical deflections exist or should be used, it has to be noted that the uncertainties of GPS/levelling and the RTM effects should be estimated together. While the uncertainties of EGM2008 and GPS/levelling can strongly vary between countries, the accuracy of the GOCE GGMs shall only show a latitude dependency. However, it should be further noted that such comparisons represent just a small spot check with regard to the aspired GOCE resolution of 100 km and that the quality of the results depends on the size of the test area.

6 Summary and Conclusions

For the validation of the fourth and fifth release GOCE GGM and their internal uncertainty estimates, comparisons have been carried out with external data sets in Germany, i.e. EGM2008, GPS/levelling data and astrogeodetic vertical deflections. While the gravity field functionals from EGM2008 and the GOCE GGMs are compared directly up to d/o 200, the comparisons between the GOCE GGMs and the GPS/levelling data as well as the astrogeodetic vertical deflections presuppose the consideration of the different spectral characteristics. This is done by modelling the high frequency signals above d/o 200 by EGM2008 as well as detailed topographic information and the RTM approach.

The RMS differences of the three comparisons reveal a high consistency, and are introduced as observations within a least squares adjustment for the estimation of the uncertainties of all terms involved in the comparisons. While the uncertainties of EGM2008 quasigeoid heights

and GPS/levelling in Germany are estimated to 1.2 and 1.7 cm, respectively, the commission errors of the GOCE GGMs up to d/o 200 are 2.4 and 2.5 cm for TIM5 and DIR5, respectively, as well as 0.66 mGal and 0.10" for both release 5 models in terms of quasigeoid heights, gravity anomalies and vertical deflections. These figures are fully compatible with the formal error degree variances of TIM5, while a factor of 3 should be applied to the formal cumulative errors of DIR5.

The validation results can be used for the calibration of the formal error degree variances of the GGMs and be used for setting up a realistic weighting procedure in the context of high resolution quasigeoid modelling. The release 5 GOCE GGMs based on observation data from the whole mission lifetime do not fully reach the level of EGM2008 up to d/o 200 in Germany with high quality terrestrial gravity data included in the solution. But nevertheless, GOCE could come into play in countries with high quality terrestrial data, as the major uncertainty contributions of high resolution quasigeoid solutions come from the spectral band between d/o 50 and 360 (Denker 2013).

References

- Brockmann JM, Zehentner N, Höck E, Pail R, Loth I, Mayer-Gürr T, Schuh WD (2014) EGM_TIM_RL05: An Independent Geoid with Centimeter Accuracy Purely Based on the GOCE Mission. *Geophys. Res. Lett.* 41, doi:10.1002/2014GL061904
- Bruinsma SL, Förste C, Abrikosov O, Lemoine JM, Marty JC, Mulet S, Rio MH, Bonvalot S (2014) ESA's satellite-only gravity field model via the direct approach based on all GOCE data. *Geophys. Res. Lett.* 41, pp. 7508-7514, doi:10.1002/2014GL062045
- Denker H (2013) Regional Gravity Field Modelling: Theory and Practical Results. In G. Xu (Ed.), *Sciences of Geodesy II*, pp. 185-291, Springer Berlin Heidelberg, doi:10.1007/978-3-642-28000-9_5
- Godah W, Szelachowska M, Krynski J (2014) Accuracy assessment of GOCE-based geopotential models and their use for modelling the gravimetric quasigeoid – A case study for Poland. *Geodesy and Cartography* 63, pp. 3-24, doi:10.2478/geocart-2014-0001
- Gruber T, Rummel R (2014) GOCE Gravity Field Models – Overview and Performance Analysis. 5th International GOCE User Workshop, Paris, 25 November, 2014
- Gruber T, Visser P, Ackermann C, Hosse M (2011) Validation of GOCE gravity field models by means of orbit residuals and geoid comparisons. *J Geod* 85, pp. 845-860, doi: 10.1007/s00190-011-0486-7
- Hirt C, Seeber G (2008) Accuracy analysis of vertical deflection data observed with the Hannover Digital Zenith Camera System TZK2-D. *J Geod* 82, pp. 347-356, doi:10.1007/s00190-007-0184-7
- Hirt C, Gruber T, Featherstone WE (2011) Evaluation of the first GOCE static gravity field models using terrestrial gravity, vertical deflections and EGM2008 quasigeoid heights. *J Geod* 85, pp. 723-740, doi: 10.1007/s00190-011-0482-y
- Hirt C, Kuhn M, Featherstone WE, Goettl F (2012) Topographic/isostatic evaluation of new-generation GOCE gravity field models. *J. Geophys. Res.* 117, B05407, doi:10.1029/2011JB008878
- Ilde J, Wilmes H, Müller J, Denker H, Voigt C, Hosse M (2010) Validation of Satellite Gravity Field Models by Regional Terrestrial Data Sets. In: *System Earth via Geodetic-Geophysical Space Techniques (Advanced Technologies in Earth Sciences)*, pp. 277-296, doi: 10.1007/978-3-642-10228-8_22
- Jarvis A, Reuter HI, Nelson A, Guevara E (2008) Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database (<http://srtm.csi.cgiar.org>)
- Pail R, Bruinsma S, Migliaccio F, Förste C, Goiginger H, Schuh WD, Höck E, Reguzzoni M, Brockmann JM, Abrikosov O, Veicherts M, Fecher T, Mayrhofer R, Krasbutter I, Sansò F, Tscherning CC (2011) First GOCE gravity field models derived by three different approaches. *J Geod* 85, pp. 845-860, doi: 10.1007/s00190-011-0467-x
- Pavlis NK, Holmes SA, Kenyon SC, Factor JK (2012) The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). *J. Geophys. Res.* 117, B04406, doi:10.1029/2011JB008916
- Rexer M, Hirt C, Pail R, Claessens S (2013) Evaluation of the third- and fourth-generation GOCE Earth gravity field models with Australian terrestrial gravity data in spherical harmonics. *J Geod* 88, pp. 319-333, doi: 10.1007/s00190-013-0680-x
- Tscherning CC, Rapp RH (1974) Closed Covariance Expressions for Gravity Anomalies, Geoid Undulations, and Deflections of the Vertical Implied by Anomaly Degree Variance Models. Reports of the Department of Geodetic Science 208, The Ohio State University, Columbus, Ohio

- Voigt C (2013) Astrogeodätische Lotabweichungen zur Validierung von Schwerefeldmodellen, Wissenschaftliche Arbeiten der Fachrichtung Geodäsie und Geoinformatik der Leibniz Universität Hannover, Nr. 305, <http://dgk.badw.de/fileadmin/docs/c-702.pdf> (in German)
- Voigt C, Denker H (2014) Validation of Second-Generation GOCE Gravity Field Models by Astrogeodetic Vertical Deflections in Germany. IAG Symp. 139, pp. 291-296, doi:10.1007/978-3-642-37222-3_38
- Voigt C, Denker H (2014a) Regional Validation and Combination of GOCE Gravity Field Models and Terrestrial Data. In: Observation of the System Earth from Space - CHAMP, GRACE, GOCE and Future Missions, GEOTECHNOLOGIEN Science Report No. 20, Springer, pp. 139-145, doi:10.1007/978-3-642-32135-1_18
- Voigt C, Denker H, Hirt C (2009) Regional astrogeodetic validation of GPS and levelling data and quasigeoid models, IAG Symp. 133, pp. 413-420, doi: 10.1007/978-3-540-85426-5_49
- Yi W, Rummel R (2014) A comparison of GOCE gravitational models with EGM2008. Journal of Geodynamics 73, pp. 14-22, doi:10.1016/j.jog.2013.10.004

On the accuracy assessment of the consecutive releases of GOCE-based GGMs over the area of Poland

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Abstract

Since ESA released to the public domain the first Global Geopotential Model (GGM) based on GOCE satellite mission data, an extensive validation/evaluation of those models has been conducted worldwide to assess their accuracy. The paper provides an accuracy assessment of 1st – 5th release GOCE-based GGMs developed with the use of the direct solution and the time-wise solution strategies over the area of Poland.

Free-air gravity anomalies and height anomalies computed from those GGMs have been compared with the corresponding ones obtained from EGM08. Moreover, height anomalies determined from GOCE-based GGMs were compared with the corresponding ones obtained from three different GNSS/levelling data sets with the use of the spectral enhancement method. The results obtained reveal clear improvement for the consecutive releases of GOCE-based GGMs investigated. The 5th release GOCE-based GGM developed with the use of time-wise strategy shows the best performance. Its fit over the area of Poland to the terrestrial data in terms of the standard deviation is 0.84 mGal for gravity anomalies and in the range of 2.8 – 3.4 cm for height anomalies.

Keywords. Free-air gravity anomaly, global geopotential model, GNSS/levelling, GOCE, height anomaly.

1 Introduction

Since the launch of the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) satellite mission dedicated Earth gravity field modelling several Global Geopotential Models (GGMs) based on GOCE data were developed. So far, five consecutive releases of GOCE-based GGMs have been made available for scientific use by the European Space Agency (ESA). They are provided in the form of a set of dimensionless coefficients of a spherical harmonic series up to a specified degree and order (d/o). These coefficients are the result of the gravity field modelling process using level 0 and level 1b products of ~2 months (1st release), ~8 months (2nd release), ~12 months (3rd release), ~27 months (4th release), and ~42 months (5th release) GOCE satellite mission observation data (see Pail et al., 2011; Bruinsma et al., 2013; Brockmann et al., 2014). Three different strategies were applied for modelling the Earth gravity field within the ESA GOCE high-level processing facility (Rummel et al., 2004). They are denoted as the direct solution, the time-wise solution and the space-wise solution. The last one was implemented only in 1st and 2nd release GOCE-based GGMs. The main characteristics of those solutions have been briefly described in Rummel et al. (2004) as well as in Pail et al. (2011). Moreover, different GGMs based on

GOCE satellite mission observation data have been developed by other research institutions, e.g. Delft University, German Research Centre for Geosciences (GFZ), and Graz University.

In order to ensure the quality of GOCE-based GGMs for local gravity field modelling it is important to validate them using an optimum evaluation method employing independent, possibly high quality gravity field functionals. Thus, since the ESA released the first GOCE-based GGM to the public domain, several studies have instantly been undertaken by numerous research groups to validate those models. They were performed in different parts of the world using different validation procedure and different data sets, e.g. the validation conducted by Ihde et al. (2010) in Germany, Janak and Pitonak (2011) in Central Europe, Hirt et al. (2011) and Yi and Rummel (2014) worldwide, Šprlák et al. (2012) in Norway, Guimarães et al. (2012) and Ferreira et al. (2013) in Brazil, Ince et al. (2012) in Canada, Amjadiparvar et al. (2013) in North America, Vergos et al. (2014) in Greece, Alothman et al. (2014) in Saudi Arabia, Godah and Krynski (2015) in Sudan, Tocho et al. (2014) in Argentina, and Rexer et al. (2014) in Australia. For the area of Poland, 1st – 4th release GOCE-based GGMs have been evaluated using EGM08 and GNSS/levelling data (Godah and Krynski, 2012, 2013; Godah et al., 2014; Godah, 2014). The aim of this paper is to assess the accuracy of GOCE-based GGMs over the area of Poland, including those developed with the use of whole set of GOCE mission data. The 1st – 5th release of GOCE-based GGMs developed with the use of the direct solution and the time-wise solution strategies have been evaluated using EGM08 and GNSS/levelling data.

The description of the GGM and external data used is given in the section 2. In sections 3 and 4, the evaluation methodologies are specified and their results are analysed. In section 5, the conclusions and recommendations concerning the accuracy of the sequential GOCE-based GGMs over the area of Poland are drawn.

2 Data used

The data sets used throughout this investigation consist of (1) 1st – 5th release GOCE-based GGMs as well as EGM08 (Pavlis et al., 2012), and (2) GNSS/levelling data. The GOCE-based GGMs are analyzed in section 2.1 and the external data in section 2.2 below.

2.1 Global Geopotential Models

The 1st – 5th release GOCE-based GGMs developed with the use of the time-wise (TIM) solution and the direct (DIR) solution strategies have been validated over the area of Poland. These models were developed and released for the public use by ESA. They are also available in the International Centre for Global Earth Models (ICGEMs) <http://icgem.gfz Potsdam.de /ICGEM/>. The basic and most important information on these GGMs can be found in the ESA's web page <https://earth.esa.int/> and on the header information of the GGMs files and the associated files from the ICGEM. The characteristics of those models are summarized in Tables 1a and 1b.

Moreover, beside GOCE-based GGMs, EGM08 has also been used as a reference model for the validation of the former as well as for estimating higher frequency components of the gravity signal, i.e. gravity signal beyond the applied maximum d/o of GOCE-based GGMs. EGM08 was earlier extensively

evaluated over the area of Poland using over 1000 high quality height anomalies obtained from GNSS/levelling data as well as regional precise quasigeoid models. Since the high quality mean $5' \times 5'$ terrestrial free-air gravity anomalies from Poland were provided for developing EGM08, the model shows an excellent performance over the area of Poland. It provides height anomalies with accuracy at the level of 2 cm (Krynski and Kloch, 2009; Lyszkowicz, 2009) which corresponds to the accuracy of the existing gravimetric quasigeoid in Poland. It should be noted that free-air gravity anomalies calculated from EGM08 can be considered equivalent to the terrestrial ones when validating GOCE-based GGMs in Poland. Moreover, EGM08 can be considered as a useful tool to detect outliers among GNSS/levelling data available in Poland (c.f. Krynski and Kloch, 2009). In the validation of GOCE-based GGMs using EGM08 spectral consistency can easily be ensured (see sections 3.1 and 4.1).

Table 1a: The main characteristics of GOCE-based GGMs developed with the use of time-wise solution strategy.

GGM	TIM-R1	TIM-R2	TIM-R3	TIM-R4	TIM-R5
Name in ICGEM	GO_CONS_GCF_2_TIM_R1	GO_CONS_GCF_2_TIM_R2	GO_CONS_GCF_2_TIM_R3	GO_CONS_GCF_2_TIM_R4	GO_CONS_GCF_2_TIM_R5
Maximum d/o	224	250	250	250	280
Semi-major axis a [m]	6378136.30	6378136.30	6378136.30	6378136.30	6378136.46
GOCE data	~2 months	~8 months	~12 months	~26.5 months	~42 months
Kaula's regularization d/o	170 onward	180 onward	180 onward	180 onward	200 onward
Time of releasing	2010	2011	Nov. 2011	Mar. 2013	Jul. 2014
Reference	Pail et al. (2010)	Pail et al. (2011)	Pail et al. (2011)	Pail et al. (2011)	Brockmann et al. (2014)

Table 1b: The main characteristics of GOCE-based GGMs developed with the use of direct solution strategy.

GGM	DIR-R1	DIR-R2	DIR-R3	DIR-R4	DIR-R5
Name in ICGEM	GO_CONS_GCF_2_DIR_R1	GO_CONS_GCF_2_DIR_R2	GO_CONS_GCF_2_DIR_R3	GO_CONS_GCF_2_DIR_R4	GO_CONS_GCF_2_DIR_R5
Maximum d/o	240	240	240	260	300
Semi-major axis a [m]	6378136.46	6378136.46	6378136.46	6378136.46	6378136.46
GOCE data	~2 months	~8 months	~12 months	~28 months	~42 months
GRACE data	7.5 years	7.5 years	7 years	~7 years	10 years
LAGEOS-1/2 SLR data	7 years	7 years	7 years	~25 years	25 years
Kaula's regularization d/o	-	150 onward	200 onward	200 onward	-

Time of releasing	2010	2011	Nov. 2011	Mar. 2013	Jul. 2014
Reference	Bruinsma et al. (2010)	Bruinsma et al. (2010)	Bruinsma et al. (2010)	Bruinsma et al. (2013)	Bruinsma et al. (2013)

2.2 GNSS/levelling data

The height anomalies obtained from GNSS/levelling data (Fig. 1) at 184 GNSS/levelling control traverse sites, 315 POLREF (GNSS/levelling network used as extension of ETRF, established in 1994-1996) sites, and 58 EUVN (densification of the European Vertical Reference Network, established in 1999) sites were used for the validation of GOCE-based GGMs. The 868 km long GNSS/levelling control traverse was established in 2003–2004 for the verification and the accuracy estimation of gravimetric quasigeoid models in Poland as well as for the evaluation of interpolation algorithms used for the application of GNSS/levelling quasigeoid models. The accuracy of height anomalies for GNSS/levelling control traverse sites is estimated to be 1–2 cm (Krynski and Lyszkowicz, 2006; Krynski, 2007) while the accuracy of height anomalies for the sites of POLREF and EUVN networks is estimated to be 3 – 4 cm, and 2 cm, respectively (e.g. Krynski, 2007).

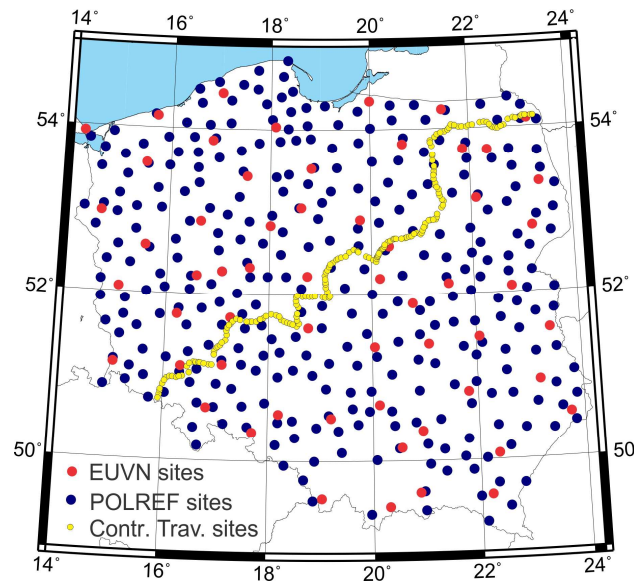


Figure 1: The location of the POLREF, EUVN and the GNSS/levelling control traverse sites.

3 Methodology

During the last years, numerous procedures were developed and implemented to evaluate gravity functionals determined from GOCE-based GGMs, for example, the spectral enhancement method (SEM) (Gruber, 2009; Hirt et al., 2011), Gauss' based low-pass filter (Voigt et al., 2010), low-pass filtering based on Fast Fourier Transform (Šprlák et al., 2011), inverse distance weight low-pass filter (Godah and Krynski, 2015), and a method by means of orbit residuals and geoid comparisons (Gruber et al., 2011). In this work, two gravity functionals, i.e. height anomalies and free-air gravity anomalies, obtained from

GOCE-based GGMs have been evaluated using EGM08 as well as GNSS/levelling data. The height anomalies ζ and gravity anomalies Δg at point $P(\varphi, \lambda, r)$ are obtained from GGMs as follows

$$\zeta_{(\varphi, \lambda, r)} = \frac{GM}{r\gamma} \sum_{n=2}^{\infty} \left(\frac{a}{r}\right)^n \sum_{m=0}^n \bar{R}_{nm} \bar{Y}_{nm}(\varphi, \lambda) \quad (1)$$

$$\Delta g_{(\varphi, \lambda, r)} = \frac{GM}{r^2} \sum_{n=2}^{\infty} (n-1) \left(\frac{a}{r}\right)^n \sum_{m=0}^n \bar{R}_{nm} \bar{Y}_{nm}(\varphi, \lambda) \quad (2)$$

with

$$\bar{R}_{nm} = \begin{cases} \Delta \bar{C}_{nm} & m \geq 0 \\ \Delta \bar{S}_{n|m|} & m < 0 \end{cases} \quad (3)$$

and

$$\bar{Y}_{nm} = \begin{cases} \bar{P}_{nm}(\cos \varphi) \cos m\lambda & m \geq 0 \\ \bar{P}_{nm}(\cos \varphi) \sin |m| \lambda & m < 0 \end{cases} \quad (4)$$

where r is the distance to the geocentre, φ and λ are the spherical latitude and longitude of the computation point P , respectively, GM is the product of the Newtonian gravitational constant G and the Earth's mass M , a is the semi-major axis of the reference ellipsoid, $\bar{P}_{nm}$ is the fully normalised associated Legendre function of degree n and order m , $\Delta \bar{C}$ and $\Delta \bar{S}_{n|m|}$ are fully normalised spherical harmonic coefficients of the disturbing gravity potential, being defined as differences between the actual and the normal gravity potential (Torge and Müller, 2012), and γ is the normal gravity referred to the point P at the physical surface of the Earth.

3.1 The use of EGM08 for validation of GOCE-based GGMs

With the use of Eqs. (1) and (2), free-air gravity anomalies $\Delta g_{(\text{GOCE})}$ and $\Delta g_{(\text{EGM08})}$, and height anomalies $\zeta_{(\text{GOCE})}$ and $\zeta_{(\text{EGM08})}$ were calculated over the area of Poland from GOCE-based GGMs (Table 1) and from EGM08, respectively. The contribution of GOCE SGG (satellite gravity gradiometer) data to the development of GGMs is expected significant in the spectral band from d/o 100 to $N_{\max}$ of the model. The extremely high performance of gradiometer is confined to the so-called measurement bandwidth (MBW), while noise is increasing outside the measurement bandwidth (c.f. Rummel, 2010). The gravity functionals have been calculated from GOCE-based GGMs and from EGM08 truncated to the same d/o (i.e. d/o from 100 to $N_{\max}$ of the model with d/o 10 step). They were determined on grids from $1.8^\circ \times 1.8^\circ$ to $(180/N_{\max})^\circ \times (180/N_{\max})^\circ$, respectively, corresponding to the spatial resolution of truncated model. The differences

$$\delta \zeta_{(\text{GGM})} = \zeta_{(\text{EGM08})} - \zeta_{(\text{GOCE})} \quad (5)$$

$$\delta\Delta g_{(\text{GGM})} = \Delta g_{(\text{EGM08})} - \Delta g_{(\text{GOCE})} \quad (6)$$

were analysed.

3.2 The use of GNSS/levelling data for validation of GOCE-based GGMs

Theoretically, ground truth data, e.g. free-air gravity anomalies and height anomalies, obtained from terrestrial measurements contain the full spectral information on the Earth's gravity field. On the other hand, the GGMs are presented by finite series of spherical harmonic expansion truncated at a specific spectral band. Thus, in order to compare gravity functionals obtained from GGMs with the corresponding ones obtained from terrestrial data, the spectral inconsistency between the data being used in the validation must be considered.

Herein, the SEM was applied to validate height anomalies obtained from GOCE-based GGMs. In this method, height anomalies $\zeta_{(\text{GOCE})}$ were determined from GOCE-based GGMs, up to a certain applied maximum d/o (N_{max}), while the medium/short wavelength components of height anomalies $\zeta_{(\text{EGM08})}$ was compensated using EGM08 coefficients from d/o $N_{\text{max}+1}$ to d/o 2190. According to the SEM method, differences between height anomalies obtained from GOCE-based GGMs and the corresponding ones obtained from GNSS/levelling data were computed as follows

$$\delta\zeta = \zeta_{(\text{GNSS/levelling})} - \left\{ \zeta_0 + \zeta_{(\text{GOCE})} \Big|_2^{N_{\text{max}}} + \zeta_{(\text{EGM08})} \Big|_{N_{\text{max}+1}}^{2190} \right\} \quad (7)$$

where the term $\zeta_{(\text{GNSS/levelling})}$ presents height anomalies obtained from GNSS/levelling data. The additive term ζ_0 in Eq. (7) presents the so called zero-degree term of the geoid height, which is equal to zero if the reference ellipsoid has the same mass as the Earth and the same potential as the geoid (Heiskanen and Moritz, 1967). Otherwise ζ_0 is determined as follows (ibid):

$$\zeta_0 = \frac{GM - GM_0}{R\bar{\gamma}} - \frac{W_0 - U_0}{\bar{\gamma}} \quad (8)$$

where M_0 is the mass of the reference ellipsoid, U_0 is the gravity potential of the ellipsoid, R is the mean radius of the reference ellipsoid, and $\bar{\gamma}$ presents the mean normal gravity at the surface of the reference ellipsoid. The values of these parameters are related to the Geodetic Reference System 1980 (Moritz, 2000). On the other hand, W_0 is the gravity potential of the Earth which together with M are among numerical standards of the International Earth Rotation and Reference Systems Service Conventions (McCarthy and Petit, 2004). The term ζ_0 plays an essential role for best fitting ellipsoid (Heiskanen and Moritz, 1967) and thereby the realization of local datum.

4 Results and analysis

4.1 Validation of GOCE-based GGMs using EGM08

Based on the methodology specified in section 3.1, GOCE-based GGMs (Table 1) have been validated using EGM08. Figure 2 shows standard deviations of the differences between EGM08- and GOCE-determined height anomalies and free-air gravity anomalies for the same harmonic degrees of expansion. Moreover, the statistics of those differences at d/o 200, which corresponds to the objective of the GOCE mission in terms of spatial resolution, are given in Table 2. As an example, Figures 3 and 4 depict the distribution of differences between free-air gravity anomalies and height anomalies determined using EGM08 and the corresponding ones obtained from GOCE-based GGMs developed with the use of time-wise strategy at d/o 200.

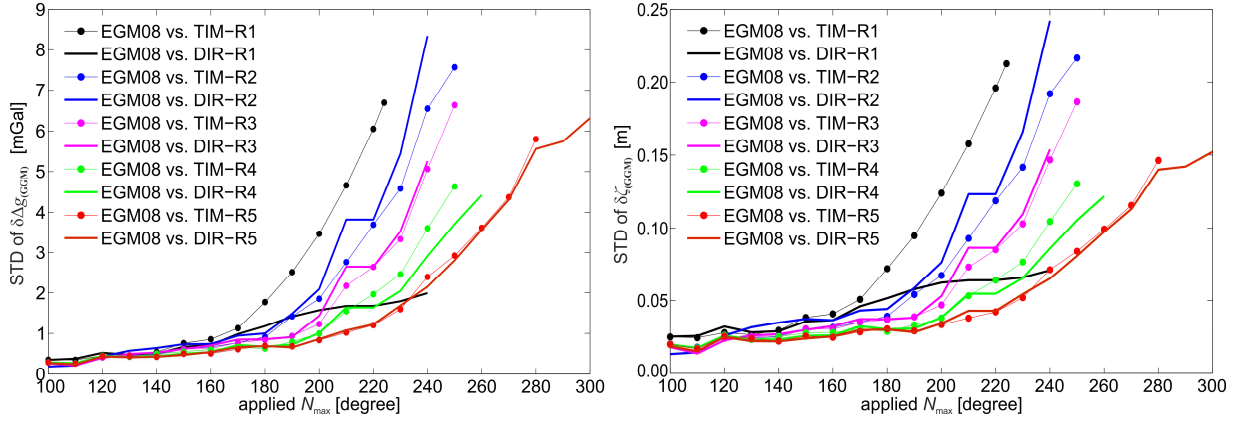


Figure 2: Standard deviations of differences between free-air gravity anomalies (left) and height anomalies (right) obtained from EGM08 and GOCE-based GGMs (the applied $N_{\max} = 100, 110, 120, \dots, 280/300$).

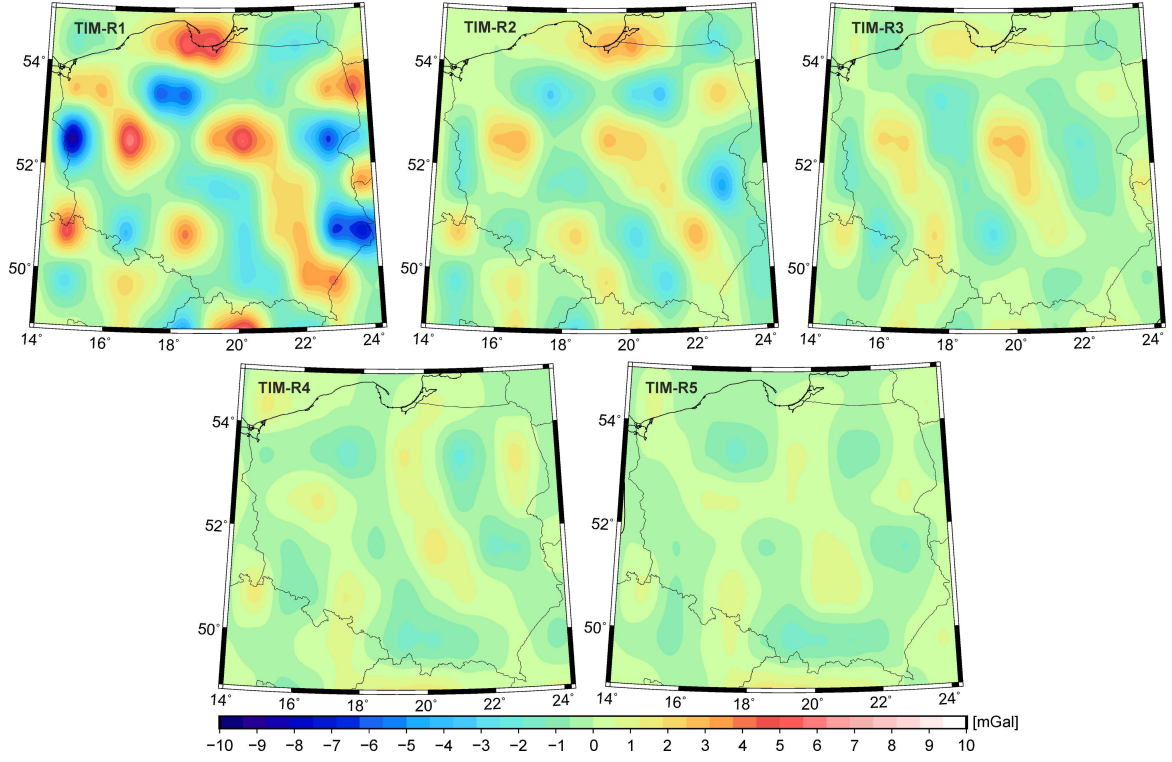


Figure 3: Differences between free-air gravity anomalies $\delta\Delta g_{(GGM)}$ obtained from EGM08 and TIM GOCE-based GGMs (the applied $N_{\max} = 200$).

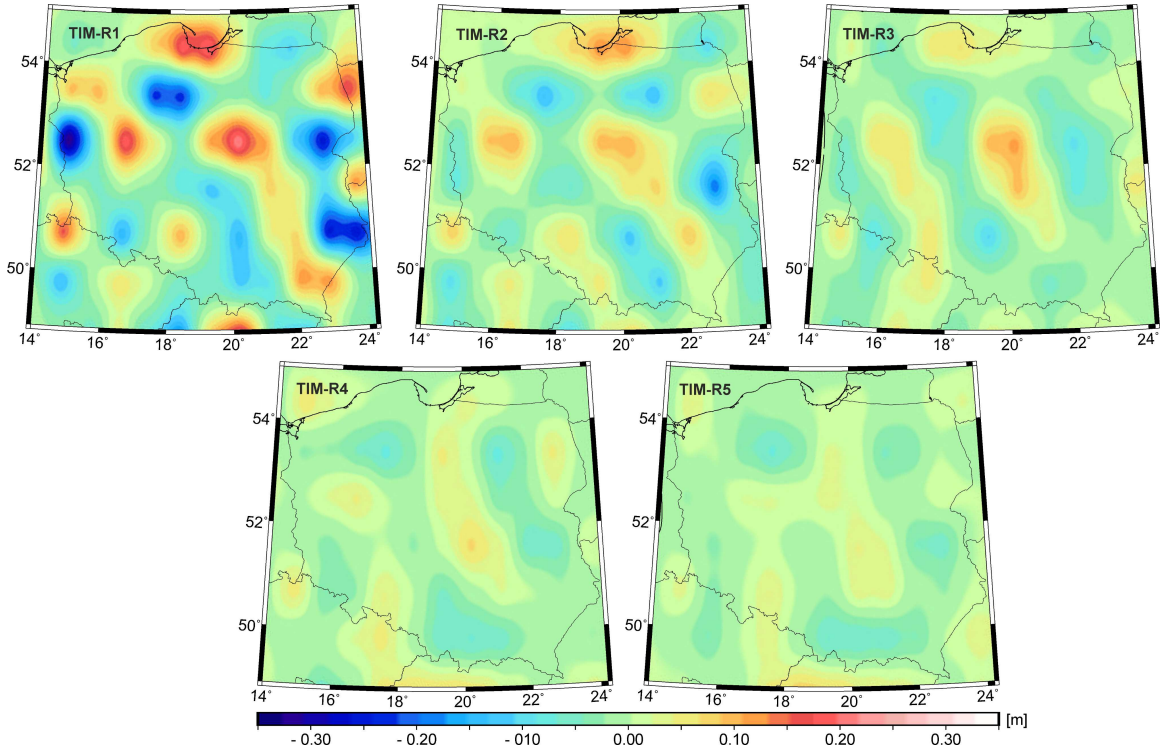


Figure 4: Differences between height anomalies $\delta\zeta_{(\text{GGM})}$ obtained from EGM08 and TIM GOCE-based GGMs (the applied $N_{\text{max}} = 200$).

Table 2: Statistics of the differences between EGM08- and GOCE-derived height anomalies and free-air gravity anomalies (the applied $N_{\text{max}} = 200$).

GGM	$\delta\Delta g_{(\text{GGM})}$ [mGal]				$\delta\zeta_{(\text{GGM})}$ [m]			
	Min	Max	Mean	STD	Min	Max	Mean	STD
TIM-R1	−9.07	9.64	0.07	3.47	−0.328	0.348	−0.010	0.124
DIR-R1	−3.78	4.21	0.06	1.57	−0.153	0.168	0.004	0.062
TIM-R2	−4.78	5.71	0.02	1.85	−0.189	0.205	−0.004	0.067
DIR-R2	−5.41	5.43	−0.03	2.09	−0.194	0.192	0.000	0.076
TIM-R3	−3.36	3.02	−0.02	1.23	−0.123	0.114	−0.005	0.047
DIR-R3	−4.20	4.17	−0.01	1.43	−0.154	0.146	0.000	0.053
TIM-R4	−2.32	1.91	−0.05	1.00	−0.084	0.079	−0.003	0.038
DIR-R4	−2.76	2.29	−0.06	1.01	−0.096	0.092	−0.001	0.038
TIM-R5	−2.27	2.08	−0.03	0.84	−0.083	0.088	−0.001	0.033
DIR-R5	−2.46	1.76	−0.04	0.86	−0.090	0.078	0.000	0.034

The results presented in Figures 2 – 4 together with those in Table 2 exhibit clear improvement in terms of both height anomalies and free-air gravity anomalies as the volume of GOCE data incorporated in the various releases of GGMs is increasing. The only exception is DIR-R1 that strongly relies on EGM08, since EIGEN5C has been used as a-priori information in its development. At d/o 200, this improvement in terms of the standard deviation of differences from 1st to 5th release is about 2.6 mGal and 9 cm in free-air gravity anomalies and height anomalies, respectively. Besides the contribution of added GOCE data, this improvement might also be caused by the effect of the improved L1b-processing in the gradiometry (Stummer et al., 2012) as well as the use of the energy-integral method (Badura, 2006) when developing the TIM-R4 and TIM-R5 instead of using the short-arc method (Mayer-Gurr et al., 2006) for processing the GOCE SST observations.

The results presented in Figure 2 and Table 2 indicate that GGMs based on the whole data set from the GOCE satellite mission, i.e. the 5th release solutions, are consistent up to d/o 200. This may indicate that GOCE data only, as in TIM solutions, are suitable for modelling the spectral bands from d/o 100 onward. Their fit to EGM08 in terms of the standard deviations of differences of free-air gravity anomalies and height anomalies do not exceeds 1 mGal and 4 cm, respectively. At their maximum degree of expansion the fit of GGMs investigated to EGM08 in terms of the standard deviation of differences of height anomalies and free-air gravity anomalies reaches 12 cm and 6 mGal, respectively. Figure 2 also illustrates that for the higher coefficients, i.e. from d/o 200 onward, the standard deviations of the differences are increasing significantly. It may indicate reasonably the large commission error of those coefficients because the signal noise is expected to become higher at spectral bands beyond d/o 200 (Rummel, 2010)

as well as because they were estimated with the use of Kaula regularization (see Table 1). However, adding more data from the GOCE satellite mission has also essentially reduced the noise and therefore, the commission error of the higher coefficients. This indicates that GOCE provides valuable information about the Earth gravity field beyond d/o 200. It may reveal the ability of the GOCE-type satellite gradiometry mission to increase the spatial resolution of the Earth gravity field models, which can be very useful for planning or designing the future missions.

4.2 Validation of GOCE-based GGMs using GNSS/levelling data

The accuracy of height anomalies determined from the preceding investigation of GOCE-based GGMs has also been assessed using height anomalies obtained from POLREF, EUVN as well as from GNSS/levelling control traverse sites. Figure 5 illustrates standard deviations of $\delta\zeta$ differences determined with the use of Eq. (7). As already mentioned, GOCE-based GGMs have been truncated at the spectral bands from d/o 100 to d/o 300 and extended to d/o 2190 using EGM08. The statistics of these differences for GOCE-based GGMs truncated to d/o 200 and extended with EGM08 from d/o 201 to d/o 2190 are presented in Table 3. It should be mentioned that the influence of the local topography effect has been neglected. This is because the estimated contribution of high frequency gravity signal, i.e. from d/o 2191 onward, to the determination of height anomalies for the GNSS/levelling data used does not exceed 3 mm in terms of standard deviation of differences (Godah et al., 2014). Thus, height anomalies obtained from GGMs (GOCE-based extended with EGM08) could be representative at the GNSS/levelling points.

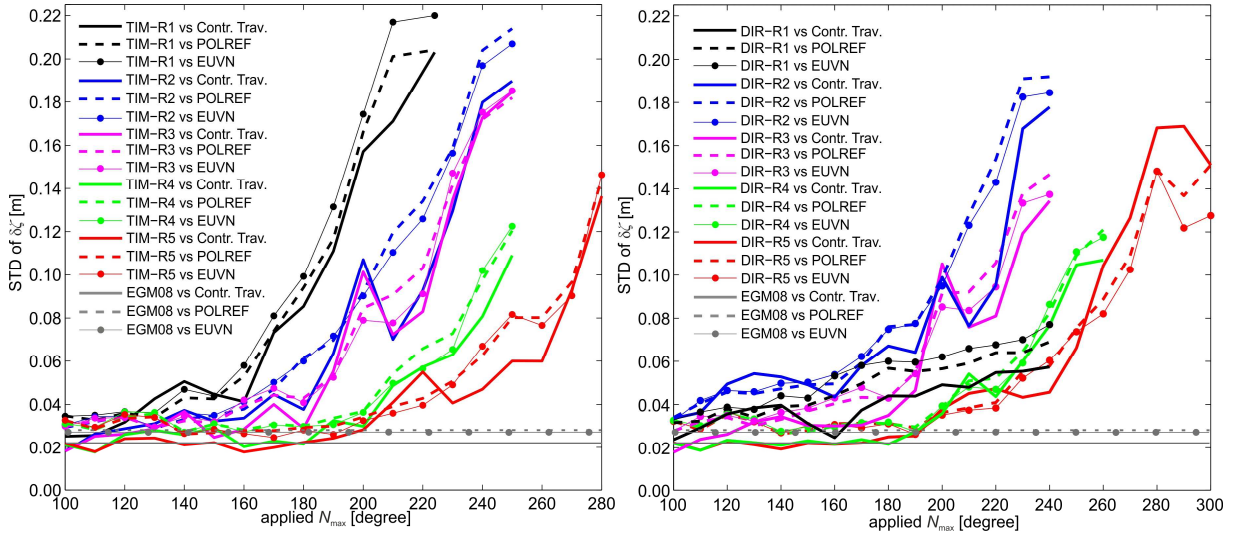


Figure 5: Standard deviations of differences between height anomalies obtained from GNSS/levelling data and from TIM (left) and DIR (right) GOCE-based GGMs (the applied $N_{\max} = 100, 110, 120, \dots, 280/300$).

Table 3: Statistics of differences between height anomalies obtained from GNSS/levelling data and the corresponding ones obtained from GOCE-based GGMs extended with EGM08 (the applied $N_{\max}$ of GOCE-based GGMs is d/o 200); unit [m].

GGM	POLREF				EUVN				GNSS/level. control traverse			
	Min	Max	Mean	STD	Min	Max	Mean	STD	Min	Max	Mean	STD
TIM-R1	-0.322	0.560	0.085	0.166	-0.254	0.415	0.081	0.174	-0.175	0.393	0.049	0.157
DIR-R1	-0.048	0.301	0.100	0.057	-0.013	0.270	0.095	0.062	-0.018	0.194	0.080	0.049
TIM-R2	-0.128	0.356	0.090	0.092	-0.122	0.246	0.089	0.090	-0.190	0.261	0.029	0.107
DIR-R2	-0.145	0.398	0.101	0.098	-0.135	0.290	0.101	0.095	-0.148	0.247	0.074	0.099
TIM-R3	-0.160	0.352	0.089	0.084	-0.071	0.256	0.089	0.079	-0.172	0.284	0.090	0.101
DIR-R3	-0.177	0.329	0.090	0.091	-0.126	0.278	0.095	0.085	-0.212	0.282	0.088	0.105
TIM-R4	-0.036	0.207	0.093	0.037	-0.007	0.168	0.088	0.036	-0.025	0.122	0.055	0.030
DIR-R4	-0.035	0.209	0.095	0.039	0.025	0.191	0.090	0.039	-0.023	0.136	0.057	0.036
TIM-R5	-0.021	0.210	0.094	0.034	-0.006	0.156	0.086	0.032	0.005	0.118	0.066	0.028
DIR-R5	-0.013	0.213	0.095	0.036	0.008	0.164	0.087	0.035	-0.007	0.137	0.068	0.038

As in the case of the comparison of gravity functionals obtained from GOCE-based GGMs investigated with the corresponding ones from EGM08, the results presented in Figure 5 and Table 3 exhibit clear improvement in terms of standard deviations of differences of height anomalies when adding more GOCE data. The only exception is DIR-R1. The improvement observed is about 14 cm from 1st to 5th release. The results show that the fit of the 5th release GOCE-based GGMs to GNSS/levelling data in terms of standard deviations of the height anomaly differences does not exceed 4 cm up to d/o 200 and 15 cm at maximum d/o of the models. Further analysis regarding the results presented in Table 3 reveals that GGMs developed with the use of the whole set of GOCE data (5th release solutions) fit to GNSS/levelling data within the range from 2.8 cm to 3.8 cm at d/o 200 in terms of standard deviations of differences, which corresponds to the accuracy of GNSS/levelling data (cf. section 2.2).

Taking into consideration the error resulting from the combination of the ellipsoidal heights obtained from GNSS observations with normal heights obtained from spirit levelling as well as the correlation between the coefficients of EGM08 and the GOCE-based GGMs merged in the SEM procedure applied, the accuracy of 5th release GOCE-based GGMs could merely be estimated to 1-2 cm.

The GOCE-based GGMs are completely independent of the local terrestrial data and expected to provide homogeneous and uniform information of the Earth's gravity field. Thus, the 5th release of GOCE-based GGMs could be expected to provide height anomalies with an accuracy of 1-2 cm at any place on the Earth, except the poles and their adjacent areas that were not flown over by the GOCE satellite. Likewise, when validating GOCE-based GGMs using EGM08 (Fig. 5) the standard deviation of differences between height anomalies obtained from GNSS/levelling data and from GOCE-based GGMs starts significantly increasing beyond d/o 200. The results obtained also show clear improvement for the coefficients beyond d/o 200 for the consecutive releases of GOCE-based GGMs. This may verify that adding more data from the GOCE satellite mission is remarkable enhancing the fit of GOCE-based GGMs to GNSS/levelling data.

5 Conclusions and recommendations

In this paper, the accuracy of the consecutive GOCE-based GGMs (1st – 5th releases of TIM and DIR solutions) has been estimated over the area of Poland. Gravity functionals determined from those GOCE-based GGMs have been compared with the corresponding ones obtained from EGM08 as well as from three different GNSS/levelling data sets.

Within the same release, the results of the comparison exhibit consistency for models developed with the use of both TIM and DIR strategies. The results obtained reveal a remarkable improvement for the consecutive releases of GOCE-based GGMs, i.e. from those developed from only ~2 months GOCE data (1st release) to the latest ones developed with the use of the whole set of GOCE mission data (5th release). At d/o 200, the observed improvements of the models in terms of the standard deviation of differences in free-air gravity anomalies and height anomalies are about 2.6 mGal and 9 to 14 cm, respectively. The results also reveal an essential improvement for modelling the Earth's gravity field beyond d/o 200, which could be very useful for designing future dedicated gravity satellite missions. Regarding the result obtained, the TIM-R5 shows the best performance over the area of Poland. It provides the standard deviation of differences of 2.8 – 3.4 cm in height anomalies and 0.84 mGal in gravity anomalies.

Taking into the consideration the accuracy of EGM08 and GNSS/levelling data used, the evaluation of gravity functionals determined from GOCE-based GGMs at d/o 200 indicates that the models developed with the use of the whole set of GOCE mission data, i.e. the 5th release, could provide free-air gravity anomalies and height anomalies with an accuracy of 1 mGal and 1 – 2 cm, respectively. It can lead to the conclusion that the goal of GOCE mission has been achieved. Over all, the TIM-R5 could be recommended for recovering the long wavelength components (approx. up to d/o 200) of the geoid over the area of Poland.

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References

- Allothman A., Bouman J., Gruber T., Lieb V., Alsubaei M., Alomar A., Fuchs M., Schmidt M., (2014): *Validation of Regional Geoid Models for Saudi Arabia using GPS/Levelling Data and GOCE Models*, In: U. Marti (ed) Gravity, Geoid and Height Systems, IAG Symposia 141: 193–199.
- Amjadiparvar B., Rangelova E.V., Sideris M.G., Véronneau M., (2013): *North American height datums and their offsets: The effect of GOCE omission errors and systematic levelling effects*, Journal of Applied Geodesy 7(1): 39–50.
- Badura T., (2006): *Gravity field analysis from satellite orbit information applying the energy integral approach*, PhD thesis, Graz University of Technology, Graz, Austria.
- Brockmann J.M., Zehentner N., Höck E., Pail R., Loth I., Mayer-Gürr T., Schuh W.-D., (2014): *EGM_TIM_RL05: An independent geoid with centimeter accuracy purely based on the GOCE mission*, Geophys. Res. Lett., 41(22): 8089–8099.

- Bruinsma S.L., Förste C., Abrikosov O., Marty J.-C., Rio M.-H., Mulet S., Bonvalot S., (2013): *The new ESA satellite-only gravity field model via the direct approach*, Geophys. Res. Lett., 40(14): 3607–3612.
- Bruinsma S.L., Marty J.C., Balmino G., Biancale R., Foerste C., Abrikosov O., Neumayer H., (2010): *GOCE Gravity Field Recovery by Means of the Direct Numerical Method*, Proc. of the ESA Living Planet Symposium, 28 June – 2 July 2010, Bergen, Norway.
- Ferreira V.G., Zhang Y., de Freitas S.R.C., (2013): *Validation of GOCE gravity field models using GPS-leveling data and EGM08: a case study in Brazil*, J. Geodetic Sciences 3(3): 209–218.
- Godah W., (2014): *Contribution of the GOCE-based gravity field modelling to local geoid determination*. PhD Thesis, Faculty of Geodesy and Cartography, Warsaw University of Technology, Warsaw, Poland.
- Godah W., Krynski J., (2012): *Validation of GOCE geopotential models over Poland using the EGM2008 and GPS/levelling data*, Geoinformation Issues 3(1): 5–17.
- Godah W., Krynski J., (2013): *Evaluation of recent GOCE global geopotential models over the area of Poland*. Acta Geodynamica et Geomaterialia 10(3–171): 379–386.
- Godah W., Krynski J., (2015): *Comparison of GGMs based on one year GOCE observations with the EGM08 and terrestrial data over the area of Sudan*, Int. J. of Applied Earth Observation and Geoinformation 35: 128–135.
- Godah W., Szelachowska M., Krynski J., (2014): *Accuracy assessment of GOCE-based geopotential models and their use for modelling the gravimetric quasigeoid – A case study for Poland*, Geodesy and Cartography, Walter de Gruyter, Warsaw, 63(1): 3–24.
- Gruber T., (2009): *Evaluation of the EGM2008 gravity field by means of GPS-Leveling and sea surface topography solutions*, Special Issue: In External quality evaluation reports of EGM2008. Newton's Bulletin 4: 3–17.
- Gruber T., Visser M., Ackermann C., Hosse M., (2011): *Validation of GOCE gravity field models by means of orbit residuals and geoid comparisons*, J. Geodesy 85(11): 845–860.
- Guimarães G., Matos A., Blitzkow D., (2012): *An evaluation of recent GOCE geopotential models in Brazil*, J. Geodetic Science 2(2): 144–155.
- Heiskanen W.A., Moritz H., (1967): *Physical geodesy*, W.H. Freeman and Company, San Francisco.
- Hirt C., Gruber T., Featherstone W.E., (2011): *Evaluation of the first GOCE static gravity field models using terrestrial gravity, vertical deflections and EGM2008 quasigeoid heights*, J. Geod 85(10): 723–740.
- Ilde J., Wilmes H., Müller J., Denker H., Voigt C., Hosse M., (2010): *Validation of Satellite Gravity Field Models by Regional Terrestrial Data Sets, System Earth via Geodetic-Geophysical Space Techniques*, Advanced Technologies in Earth Sciences, 2010, Part 3: 277–296.
- Ince E.S., Sideris M.G., Huang J., Véronneau M., (2012): *Assessment of the GOCE-Based Global Gravity Models in Canada*. GEOMATICA 66(2): 125–140.
- Janak J., Pitonak M., (2011): *Comparison and testing of GOCE global gravity models in Central Europe*, J. Geodetic Science 1(4): 333–347.
- Krynski J., (2007): *Precise quasigeoid modelling in Poland—Results and accuracy estimation* (in Polish), Monographic series of the Institute of Geodesy and Cartography, Nr 13, Warsaw, Poland (266 pp).
- Krynski J., Kloch G., (2009): *Evaluation of the performance of the new EGM08 global geopotential model over Poland*, Geoinformation Issues 1(1): 7–17.
- Krynski J., Lyszkowicz A., (2006): *The overview of precise quasigeoid modelling in Poland*, 2nd Workshop on International Gravity Field Research 2006, 8–9 May 2006, Smolenice, Slovakia, Contributions to Geophysics and Geodesy, Special issue, WIGFR 2006, Geophysical Institute of Slovak Academy of Sciences: 113–149.
- Lyszkowicz A., (2009): *Assessment of accuracy of EGM08 model over the area of Poland*, UWM Olsztyn, Techn. Sc. 12: 118–134.
- Mayer-Gurr T., Eicker A., Ilk K.H., (2006): *Gravity Field Recovery from GRACE-SST Data of Short Arcs*, In: J. Flury, R. Rummel, C. Reigber, M. Rothacher, G. Boedercker, U. Schreiber (eds) Observation of the Earth System from Space, Springer Berlin / Heidelberg: 131–148.
- McCarthy D., Petit G., (eds) (2004): *IERS Conventions (2003)*. IERS Technical Note 32, BKG, Frankfurt.
- Moritz H., (2000): *Geodetic Reference System 1980*, J. Geodesy, 74(1): 128–133.

- Pail R., Bruinsma S., Migliaccio F., Förste C., Goiginger H., Schuh W., Höck E., Reguzzoni M., Brockmann J., Abrikosov O., Veicherts M., Fecher T., Mayrhofer R., Krasbutter I., Sansò F., Tscherning C.C., (2011): *First GOCE gravity field models derived by three different approaches*, J. Geodesy 85(11): 819–843.
- Pail R., Goiginger H., Mayrhofer R., Schuh W.-D., Brockmann J.M., Krasbutter I., Hoeck E., Fecher T., (2010): *Global gravity field model derived from orbit and gradiometry data applying the time-wise method*, Proc. of ESA Living Planet Symposium, 28 June – 2 July 2010, Bergen, Norway, ESA SP-686.
- Pavlis N.K., Holmes S.A., Kenyon S.C., Factor J.K., (2012): *The development and evaluation of the earth gravitational model 2008 (EGM2008)*, J. Geophys. Res. 117(B04406): 1–38.
- Rexer M., Hirt C., Pail R., Claessens S., (2014): *Evaluation of the third- and fourth-generation GOCE Earth gravity field models with Australian terrestrial gravity data in spherical harmonics*, J. Geodesy 88(4): 319–333.
- Rummel R., (2010): *GOCE: Gravitational gradiometry in a satellite*, In: W. Freedon, M.Z. Nashed, T. Sonar (eds), Handbook of Geomathematics 2: 93–103.
- Rummel R., Gruber T., Koop R., (2004): *High level processing facility for GOCE: products and processing strategy*, Proc of the 2nd International GOCE User Workshop “GOCE, The Geoid and Oceanography”, Frascati, Italy, 8–10 March 2004, ESA SP-569.
- Šprlák M., Gerlach C., Omang O., Pettersen B., (2011): *Comparison of GOCE Derived Satellite Global Gravity Models with EGM2008, the OCTAS Geoid and Terrestrial Gravity Data: Case Study for Norway*, Proc. 4th International GOCE User Workshop, TUM, Munich, Germany, 31 March – 1 April 2011, ESA SP-696.
- Šprlák M., Gerlach C., Pettersen B., (2012): *Validation of GOCE global gravity field models using terrestrial gravity data in Norway*, J. Geodetic Science 2(2): 134–143.
- Stummer C., Siemes C., Pail R., Frommknecht B., Floberghagen R., (2012): *Upgrade of the GOCE Level 1b gradiometer processor*, Advances in Space Research 49(4): 739–752.
- Tocho C., Vergos G.S., Pacino M.C., (2014): *Evaluation of the latest GOCE/GRACE derived Global Geopotential Models over Argentina with collocated GPS/Leveling observations*, In: U. Marti (ed) Gravity, Geoid and Height Systems, IAG Symposia 141: 75–83.
- Torge W., Müller J., (2012): *Geodesy*, 4th edition, Walter de Gruyter, Berlin-Boston.
- Vergos G.S., Grigoriadis V.N., Tziavos I.N., Kotsakis C., (2014): *Evaluation of GOCE/GRACE Global Geopotential Models over Greece with collocated GPS/Levelling observations and local gravity data*, In: U. Marti (ed) Gravity, Geoid and Height Systems, IAG Symposia 141: 85–92.
- Voigt C., Rülke A., Denker H., Ihde J., Liebsch G., (2010): *Validation of GOCE products by terrestrial data sets in Germany*. Geotechnologien Science Report 17: 106–111.
- Yi W., Rummel R., (2014): *A Comparison of GOCE Gravitational Models with EGM2008*, J. Geodyn. 73: 14–22.

Assessing the GOCE models accuracy in the Mediterranean area

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Abstract

The GOCE satellite mission has significantly improved the results obtained with the previous satellite missions CHAMP and GRACE. Using GOCE data satellite Global Geopotential Models were developed using three different approaches, namely the direct, the time-wise and the space-wise approaches. The last releases of these models are complete to degree and order 300 (direct approach) and 280 (time-wise and space-wise approaches). In this paper, the different releases of the three estimation methodologies are compared with observed gravity and GPS/levelling data in the Mediterranean area and in particular, the Italian and Greek databases are considered. Comparisons are also carried out with respect to EGM2008 in order to check for possible improvements in the medium frequencies. For the validation of GOCE and GOCE/GRACE models, the spectral enhancement approach has been used, during which the models are augmented with EGM2008, up to its full degree of expansion, and terrain effects. These enhanced GOCE/GRACE geoid heights and gravity anomalies are then compared with the local data and statistics of the residuals have been computed. These comparisons show that significant improvements are obtained when Greek data are considered while the same doesn't occur with the Italian data.

Key words: GOCE Global Geopotential Models, gravity data, GPS/levelling undulations

1 Introduction

The Gravity field and Ocean Circulation Explorer (GOCE, ESA 1999) Earth Explorer mission of the European Space Agency (ESA) started on March 17th, 2009 when the GOCE satellite was launched from the Plesetsk cosmodrome in Russia. It was launched on a quasi-circular, quasi-polar orbit (having an inclination $i = 96.7^\circ$) at an altitude of about 250 km. As it is well known, this mission was devoted to the estimation of the Earth's gravity field based on the principle of gradiometric measurements (Floberghagen et al. 2011). The GOCE spacecraft carried an array of three pairs of tri-axial electrostatic accelerometers arranged along three orthogonal axes, constituting a gradiometer allowing the estimation of the second derivatives of the gravitational potential. The mission ended on November 11th, 2013 after more than four and a half years (much more than the official schedule which was planned on a two years lifetime).

The observations collected during the GOCE mission have been treated according to different data analysis strategies. Three methods were officially devised for handling the data and estimating satellite only global geopotential models: the direct approach (DIR; Bruinsma et al., 2013), the time-wise approach (TIM; Pail et al., 2011) and the space-wise approach

(SPW; Migliaccio et al., 2004). In addition to these official approaches, others have been proposed, e.g. those by Yi (2012) and Schall et al. (2014). In recent years, several releases of these GOCE models have been computed. The first GOCE-only model was computed in July 2010 (to degree and order 224; Pail et al. 2010) while the latest models (released in July 2014) extend up to harmonic degree and order 280 (TIM and SPW) and 300 (DIR). The mission objectives of GOCE were aiming at an accuracy of 1 cm and 1 mGal for spatial wavelengths of 100 km (Floberhagen et al. 2011). The latest, release 5 models, reach a cumulative geoid error of 1 cm at d/o 207 (DIR-R5) and d/o 145 (TIM-R5). It should be noted that these numbers refer to the formal internal accuracy of the models as derived from the error degree variances of their spherical harmonic coefficients. Improvements from the first to the last releases are mainly based on the increasing number of processed data and, in the case of the last releases, also on the lower orbits of the GOCE satellite. Up to now (beginning of 2015), five releases of the time-wise and direct approaches have been computed (Brockmann et al., 2014; Bruinsma et al., 2014). The estimated space-wise releases are three and the last one is described in Gatti et al. (2014).

In this paper, these GOCE based global geopotential models are compared with observed gravity data and GPS/levelling derived undulations, using the spectral enhancement method, as previously done by, e.g. Gruber et al. (2011), Šprlák et al. (2012), Tocho et al. (2014), Vergos et al. (2014) and Yi and Rummel (2014). In these studies, it was found that the main contribution from GOCE, as far as the Release 2 and Release 3 models are concerned, is up to d/o 180-190 and 195-220, respectively. Within the present study, data in the central Mediterranean area, covering Italy and the surrounding areas, and Greece are considered in these comparisons and checked against the EGM2008 global geopotential model (Pavlis et al., 2012).

2 The Italian and the Greek databases

2.1 The Italian gravity, GPS/leveling data and the DTM used for the validation

The Italian gravity data set is based on a collection of data coming from different sources. Data have been collected on a long time span (mostly between the fifties and the seventies) and have thus different precisions and accuracies that cannot be properly assessed due to lack of metadata (in a very loose way, it can be stated that the mean precision is around 0.5 mgal). They are also referred to different horizontal, vertical and gravimetric reference systems. In the framework of the Italian geoid computation, they have been homogenized for coordinate and gravimetric reference systems and checked for possible outliers (Barzaghi et al., 2007). This gravity database covers the area $5^{\circ} \leq \lambda \leq 20^{\circ}$, $35^{\circ} \leq \varphi \leq 49^{\circ}$ and contains 450,336 values which implies a mean spatial density between gravity points of 20". The horizontal coordinates are referred to the ETRS89 reference system while orthometric heights are given in the Italian height system originating, for the peninsular part of Italy, at the Genova tide gauge (Sicily and Sardinia height networks are referred to Catania and Cagliari tide gauges, respectively). Gravity data are framed to the IGSN71/GRS80 system. The plot of the Italian gravity data is shown in Figure 1 while Mean, Standard Deviation (St. Dev.), Minimum and Maximum of the gravity anomalies are listed in Table 1. It must be also mentioned that the Italian gravity database has been included (to an unknown extent) in the database for EGM2008 computation.

GPS/levelling data have been surveyed by IGM (Istituto Geografico Militare) in the framework of the Italian GNSS reference network IGM95 (Surace, 1997). This network consists of more than 2000 points having a mean distance between points that was originally of about 20 km. In the past decade, the network has been densified to reach a mean distance

between points of about 7.5 km. The last adjustment of the network has been computed by IGM at the beginning of 2009 in the ETRF2000(2008.0) frame. The mean precision in each of the three coordinates is around 5 cm (1σ). In the peninsular part of Italy, 977 benchmarks of this network have been levelled with high precision spirit levelling thus allowing the estimation of geoid undulations. The distribution of these GPS/levelling points is plotted in Figure 2 and the statistics are shown in Table 1. These values will be considered in the comparisons. GPS/levelling points over Sicily and Sardinia will not be considered to avoid in-homogeneities among the data (as mentioned, they refer to different tide gauges).

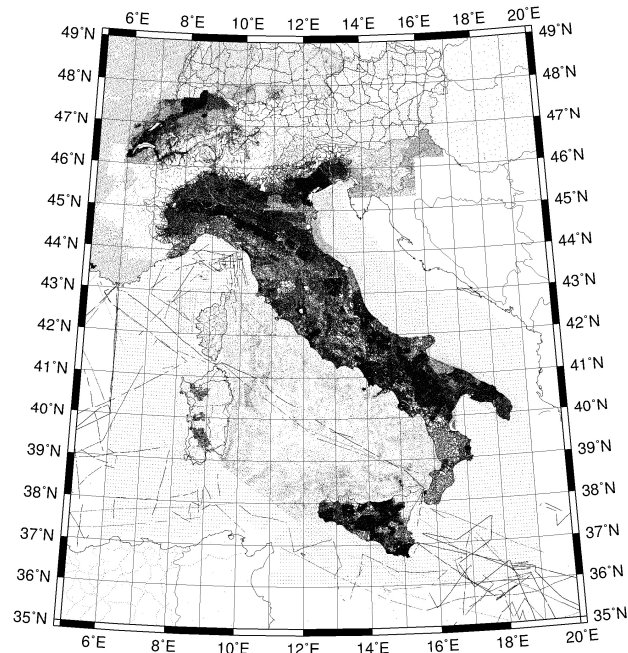


Figure 1: The Italian gravity database

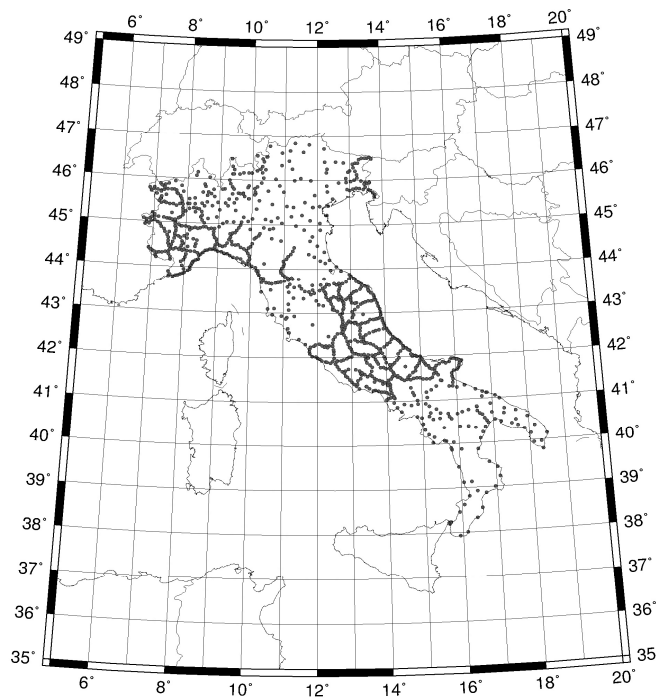


Figure 2: The GPS/leveling points over the Italian area (mainland)

Table 1: Statistics of the original free-air gravity anomalies and GPS/Levelling geoid heights in the Italian area

	Mean	St. Dev.	Min	Max
$\Delta g_{\text{obs}}(\text{mGal})$	10.660	60.601	-163.200	269.710
$N^{\text{GPS/Lev}}(\text{m})$	46.635	3.431	36.378	54.805

The DTM compiled for estimating the last Italian geoid ITALGEO05 (Barzaghi et al., 2007) has been considered for the GOCE models validation. This DTM is mainly based on the SRTM3 (Shuttle Radar Topography Mission, <http://dds.cr.usgs.gov/srtm/>) at the spatial resolution of $3'' \times 3''$. Other considered sources of information are:

- the Italian DTM (based on map digitalization) that has been used to fill the gaps in the Italian land region and for a strip of bathymetry near the coasts, where high resolution digitalised bathymetry is available;
- the $1' \times 1'$ NOAA bathymetry (<https://128.160.23.42/dbdbv/dbvquery.html>) that has been used in deep seas areas;
- the GTOPO30 DTM (<http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html>) that has been considered for the remaining areas with no data.

The area covered by this DTM/bathymetry model is $3^\circ \leq \lambda \leq 22^\circ$, $33^\circ \leq \varphi \leq 50^\circ$ and, on each side, is at least 1° larger than the area containing gravity data and GPS/levelling data. The resulting grid has a regular geographical mesh of $3'' \times 3''$ (Borghi et al., 2007).

2.2 The Greek gravity, GPS/leveling data and the DTM used for the validation

The local data used over the Greek territory, refer to gravity anomaly data and GPS/Levelling observations covering the entire part of continental Greece and the surrounding marine areas. As far as the gravity anomaly data are concerned, they come from a local gravity database that has been compiled in the frame of the determination of a new Greek geoid model (Tziavos et al., 2012; 2013). This set comprises a number of 294,777 irregular point free-air gravity anomalies (cf. Tziavos et al., 2010) covering the entire Hellenic territory (islands included) as well as parts of the neighbouring Balkan countries. Their accuracy (estimated through least-squares prediction) is at the ± 2.25 mGal level, and they are framed to IGSN71/GRS80 with a mean density of $\sim 2''$. It should be noted that this is not the formal accuracy of the data, which is largely unknown, but the standard deviation of the differences after least-squares prediction. The formal accuracy of the Greek gravity data is unknown, since they have been collected over the past decades, from the early '50s to late '80s, with different instrumentation and measurement procedures and from different research groups. Therefore, their real accuracy cannot be accessed, given that in most cases no metadata are available. On the other hand, it should be within the 0.5 mGal level, given that the relative gravity surveys carried out were performed, in most cases, by forming loops, where the first and the last points of these loops belonged to the Greek gravity network. The available gravity data over Greece are presented in Figure 3.

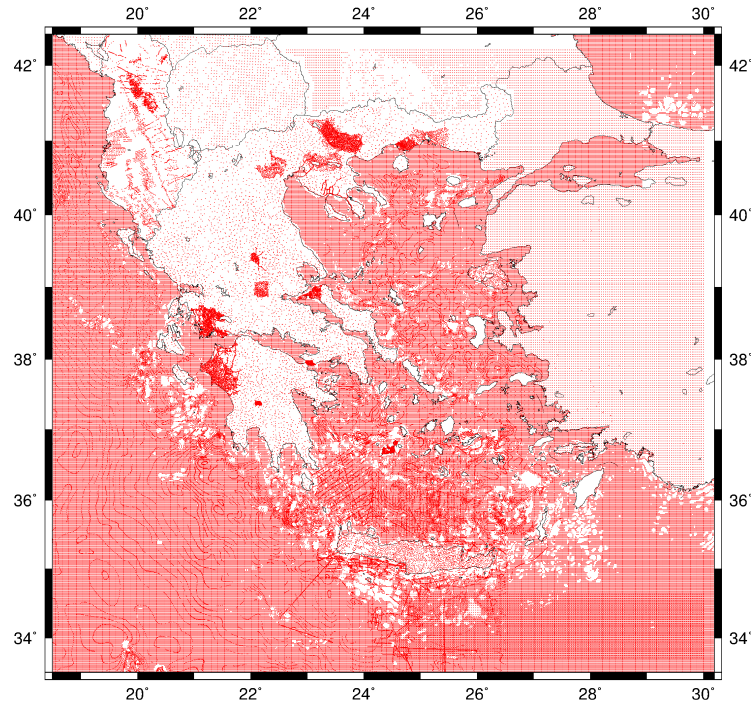


Figure 3: The Greek gravity database (294,777 irregular points)

The set of collocated GPS and Levelling data on Benchmarks (BM) (1542 BMs) is based on historical orthometric heights from the HMGS (Hellenic Military Geographic Service) measured during the establishment of the Hellenic Vertical Datum (HVD) and ellipsoidal heights collected within the HEPOS (Hellenic Positioning System) project (Gianniou, 2008). The HVD in principle models the physical heights as Helmert orthometric heights, while their tie is to the tide-gauge station situated at Piraeus harbour, so that the HVD origin is relative to a MSL determined with sea level measurements for the period 1933-1978. Today, the true accuracy of the HVD is unknown, since a) it was not uniformly adjusted, b) it is not maintained by HMGS, and c) the formal errors provided by HMGS are ambiguous and over optimistic (Kotsakis and Katsampalos, 2010; Tziavos et al., 2012; Vergos et al., 2014). The ellipsoidal heights were determined in ITRF00 (epoch $t=2007.236$) with their horizontal and vertical accuracy being estimated from the analysis of the original GPS observations to 1-4 cm (1σ) and 2-5 cm (1σ), respectively (Gianniou, 2008; Kotsakis and Katsampalos, 2010). The available GPS/Leveling BMs are evenly distributed within 22x28 km blocks over the entire country, so that in each block there are at least eight BMs (implying a mean distance of 8.8 km), where both orthometric heights are available and ellipsoidal heights have been measured. It should be noted that the orthometric heights refer to the mean-tide (MT) system, so their conversion to the TF system has been performed according to Ekman (1989). The distribution of the available GPS/Leveling data over Greece is shown in Figure 4. The statistics of these values are collected in Table 2.

Table 2: Statistics of the original free-air gravity anomalies and GPS/Leveling geoid heights over Greece.

	Mean	St. Dev.	Min	Max
$\Delta g_{\text{obs}}(\text{mGal})$	-22.731	74.118	-236.099	269.927
$N^{\text{GPS/Lev}}(\text{m})$	35.605	5.762	19.485	43.883

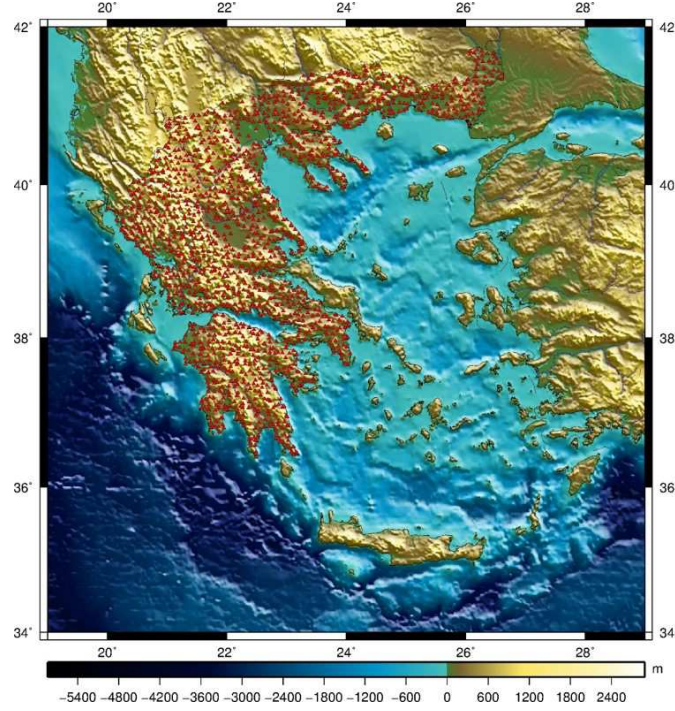


Figure 4: The GPS/leveling points in Greece (1542 BMs)

The topography and bathymetry model used for the GOCE models validation has been estimated for the entire Greek territory aiming at the determination of a new gravimetric geoid model for Greece (Tziavos et al., 2010). It has been based on the 3'' $\times$ 3'' SRTM data over continental Greece, while voids have been filled with data from available local DTMs from the HMGS. Over other countries, bicubic spline interpolation has been used due to the unavailability of local DTMs in order to fill-in voids in the original SRTM database. This resulted in the estimation of a new 3'' SRTM DTM model over all land areas in Greece (SRTMGr) within the region bounded between $30.5^\circ \leq \varphi \leq 44.5^\circ$ and $16.5^\circ \leq \lambda \leq 33.0^\circ$. In order to estimate terrain effects for marine areas as well, the SRTMGr model has been augmented with the latest bathymetry models by the Danish National Space Agency-DTU2010 (Andersen, 2010) and the Scripps Institute of Oceanography-SIOv11.1 (Smith and Sandwell 1997). Note that the DBMs (Digital Bathymetry Models) have a spatial resolution of 1' only, so they have been re-gridded to agree with the 3'' spatial resolution of the SRTMGr model on land. A careful editing has been performed across the land-sea boundary in order to avoid double entries from the DTM and DBMs and using the coastline provided by the Generic Mapping Tools (Wessel and Smith 1998).

3 Validation of GOCE models

The accuracy of the GOCE global models has been evaluated considering the statistics of the residual data. In performing these comparisons, residual data have been computed according to the following scheme

$$\Delta g_{res} = \Delta g_{obs} - \Delta g^{GOCE} \Big|_2^k - \Delta g^{EGM 2008} \Big|_{k+1}^{2159} - \Delta g_{RTE} \quad (1)$$

$$N_{res} = N_{obs} - N^{GOCE} \Big|_2^k - N^{EGM 2008} \Big|_{k+1}^{2159} - N_{RTE} \quad (2)$$

The residuals Δg_{res} and N_{res} data are computed from the observed Δg_{obs} and N_{obs} by removing the medium wavelength components using GOCE models up to different degree k and the high frequencies using the EGM2008 global geopotential model from $k+1$ to 2159 (where it is available at full degree and order). Furthermore, the very high frequency components, mainly related to the terrain effect, have been accounted for Residual Terrain Effect (RTE) computation (Forsberg, 1984). The adopted reduction scheme is set up in order to enhance the GOCE model contribution up to the selected degree k . Also, the EGM2008 reduced data

$$\Delta g_{res} = \Delta g_{obs} - \Delta g^{EGM2008} \Big|_2^{2159} - \Delta g_{RTE} \quad (3)$$

$$N_{res} = N_{obs} - N^{EGM2008} \Big|_2^{2159} - N_{RTE} \quad (4)$$

have been calculated and used as reference values. In the Italian area, the RTE effect has been computed using the DTM described in section 2.1. The reference DTM used in RTE evaluation has been obtained by filtering the detailed DTM with a moving average window having a 3' radius (this window size has been defined based on a statistical analysis on the residuals for different smoothing versions of the detailed DTM). The RTE has been computed with the TC program of the GRAVSOFT package (Tscherning et al., 1994), with an integration radius of 80 km for gravity and 120 km for undulation¹, with the standard density value of 2.67 g/cm³.

In the Greek area, the same computation for the RTE effects has been carried out. The RTE effects on geoid heights and gravity anomalies are estimated from a 3" resolution digital terrain and bathymetry model (Tziavos et al., 2010). The, smooth but varying, reference surface needed for the RTE effect is constructed by averaging the fine resolution topography grid (described in section 2.2) and then low-pass filtering the average grid generated by taking moving averages of an appropriate number of adjacent blocks (Tziavos et al., 2010). The statistics of the gravity anomaly and undulation residuals obtained using models at full resolutions are summarized in Table 3 and Table 4 for the Italian database. The statistics for the Greek database are presented in Table 5 and Table 6. The residuals have been computed for each considered model, i.e. for five DIRs, five TIMs and three SPWs releases.

¹Different integration radii have been adopted based on some tests that have been done in the context of the Italian geoid estimation. These tests prove that, by increasing the integration radius, asymptotic RTE values for gravity and undulation are reached to $r=80$ km and $r=120$ km respectively.

Table 3: The statistics of the gravity anomaly residuals: the Italian database (450336 points)

MODEL	Max. degree	Mean(mgal)	St. Dev. (mgal)	Min(mgal)	Max(mgal)
DIR_r1	240	-0.730	8.162	-94.883	68.129
DIR_r2	240	-1.042	10.044	-93.916	74.628
DIR_r3	240	-0.800	9.809	-101.644	65.813
DIR_r4	260	-0.888	9.894	-102.047	67.320
DIR_r5	300	-0.508	12.909	-105.167	80.974
TIM_r1	224	-0.952	10.692	-102.385	66.108
TIM_r2	250	-0.912	11.505	-98.406	73.525
TIM_r3	250	-0.833	10.419	-102.638	66.069
TIM_r4	250	-0.927	9.354	-99.996	66.537
TIM_r5	280	-0.295	10.362	-105.448	66.532
SPW_r1	210	-0.935	9.752	-98.841	71.103
SPW_r2	240	-0.648	13.807	-100.069	68.723
SPW_r4	280	-0.390	13.125	-103.595	70.727
EGM2008	2159	-1.107	7.717	-95.462	69.501

Table 4: The statistics of the undulation residuals: the Italian database (977 points)

MODEL	Max. degree	Mean(m)	St. Dev. (m)	Min(m)	Max(m)
DIR_r1	240	-0.776	0.178	-1.294	-0.366
DIR_r2	240	-0.784	0.208	-1.396	-0.127
DIR_r3	240	-0.760	0.222	-1.343	-0.010
DIR_r4	260	-0.774	0.221	-1.396	-0.251
DIR_r5	300	-0.750	0.306	-1.637	0.205
TIM_r1	224	-0.763	0.274	-1.764	-0.090
TIM_r2	250	-0.756	0.271	-1.474	0.060
TIM_r3	250	-0.757	0.232	-1.360	-0.053
TIM_r4	250	-0.774	0.204	-1.355	-0.252
TIM_r5	280	-0.757	0.242	-1.467	-0.067
SPW_r1	210	-0.751	0.251	-1.664	-0.148
SPW_r2	240	-0.721	0.410	-1.974	0.421
SPW_r4	280	-0.749	0.323	-1.716	0.067
EGM2008	2159	-1.577	0.264	-2.200	-1.064

Table 5: The statistics of the gravity anomaly residuals: the Greek database (294777 points)

MODEL	Max. degree	Mean(mgal)	St. Dev. (mgal)	Min(mgal)	Max(mgal)
DIR_r1	240	0.713	5.372	-83.079	100.626
DIR_r2	240	0.823	7.857	-76.673	101.588
DIR_r3	240	0.621	7.529	-84.445	101.879
DIR_r4	260	0.525	8.046	-83.217	97.533
DIR_r5	300	0.326	9.326	-84.740	108.615
TIM_r1	224	0.307	8.671	-88.912	101.309
TIM_r2	250	0.473	8.520	-85.038	102.942
TIM_r3	250	0.525	8.175	-85.082	99.831
TIM_r4	250	0.617	6.878	-85.566	100.406
TIM_r5	280	0.417	7.751	-85.608	105.093
SPW_r1	210	0.413	8.143	-79.785	103.705
SPW_r2	240	0.203	10.511	-89.751	109.243
SPW_r4	280	0.498	8.777	-86.951	106.485
EGM2008	2159	0.568	5.316	-82.685	101.410

Table 6: The statistics of the undulation residuals: the Greek database (1542 points)

MODEL	Max. degree	Mean(m)	St. Dev. (m)	Min(m)	Max(m)
DIR_r1	240	-0.384	0.165	-0.973	0.206
DIR_r2	240	-0.397	0.195	-1.005	0.259
DIR_r3	240	-0.391	0.157	-0.882	0.144
DIR_r4	260	-0.386	0.218	-1.063	0.321
DIR_r5	300	-0.394	0.259	-1.291	0.532
TIM_r1	224	-0.406	0.276	-1.148	0.372
TIM_r2	250	-0.385	0.222	-1.189	0.396
TIM_r3	250	-0.385	0.204	-1.042	0.284
TIM_r4	250	-0.381	0.180	-0.977	0.167
TIM_r5	280	-0.395	0.226	-1.115	0.338
SPW_r1	210	-0.420	0.257	-1.165	0.338
SPW_r2	240	-0.384	0.243	-1.039	0.364
SPW_r4	280	-0.402	0.215	-1.146	0.211
EGM2008	2159	-0.416	0.139	-0.894	0.060

The plots of the gravity and undulation residuals from $k=100$ to models full resolution (in $\Delta k = 5$ steps) are shown from Figure 5 to Figure 10 for the Italian databases and from Figure 11 to Figure 16 for the Greek databases.

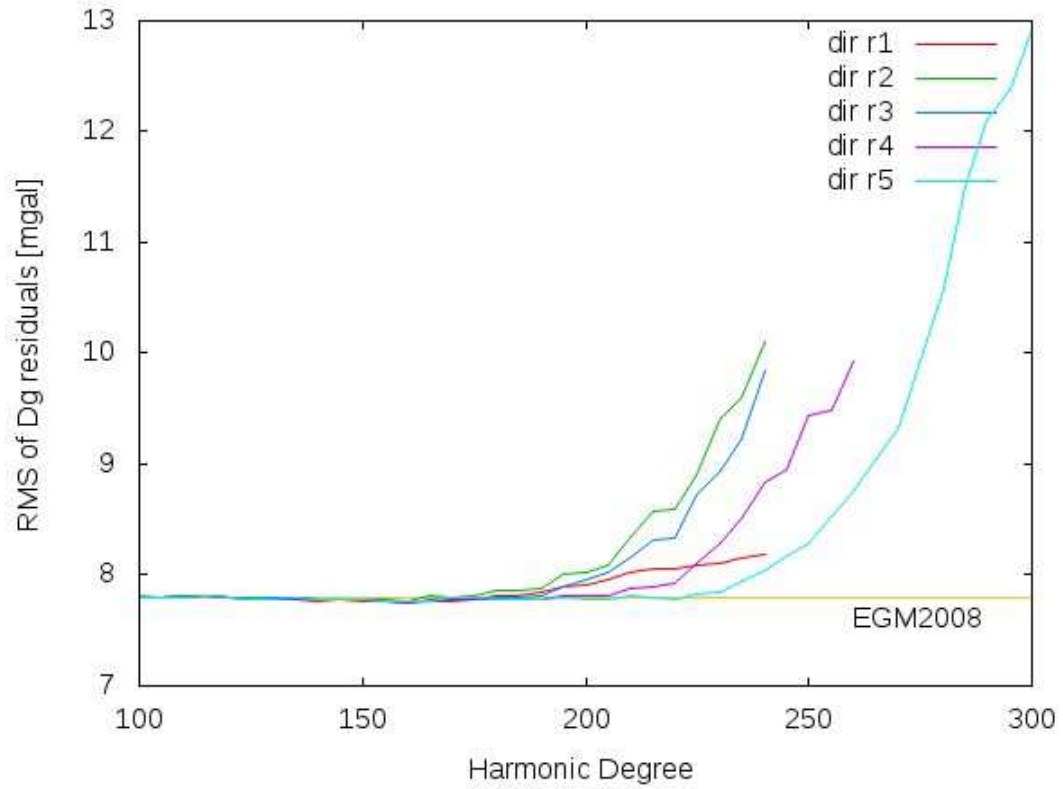


Figure 5: The r.m. s. of the residuals gravity data: the Italian database vs the DIR models

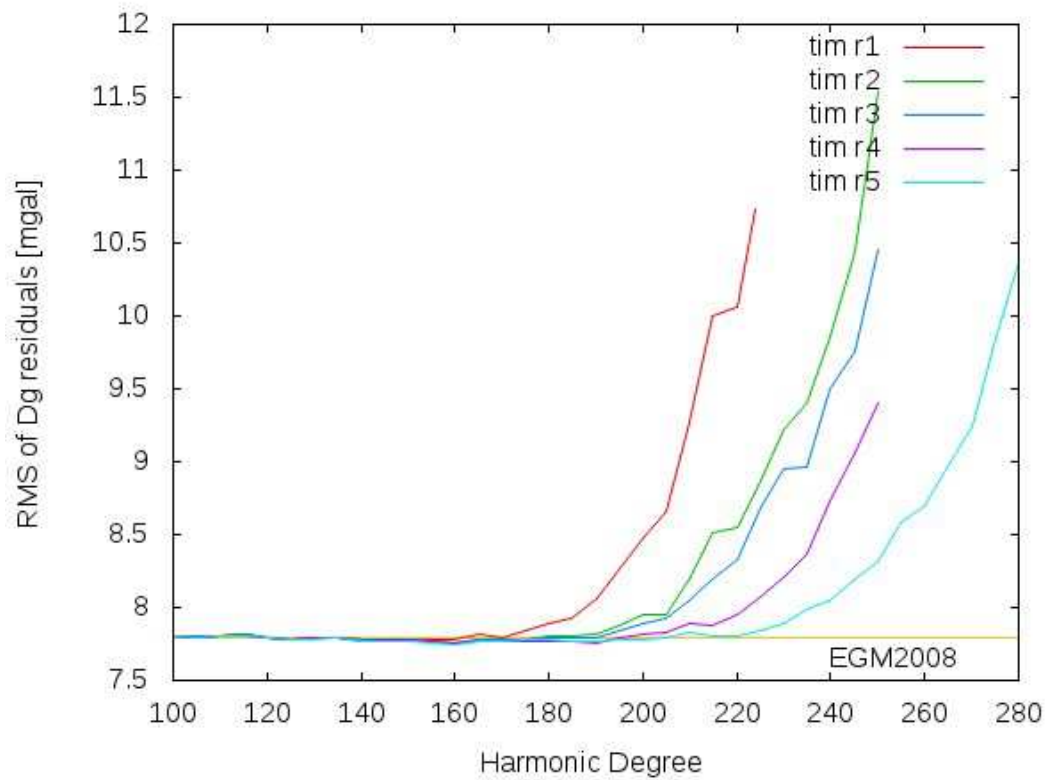


Figure 6: The r.m.s. of the residuals gravity data: the Italian database vs the TIM models

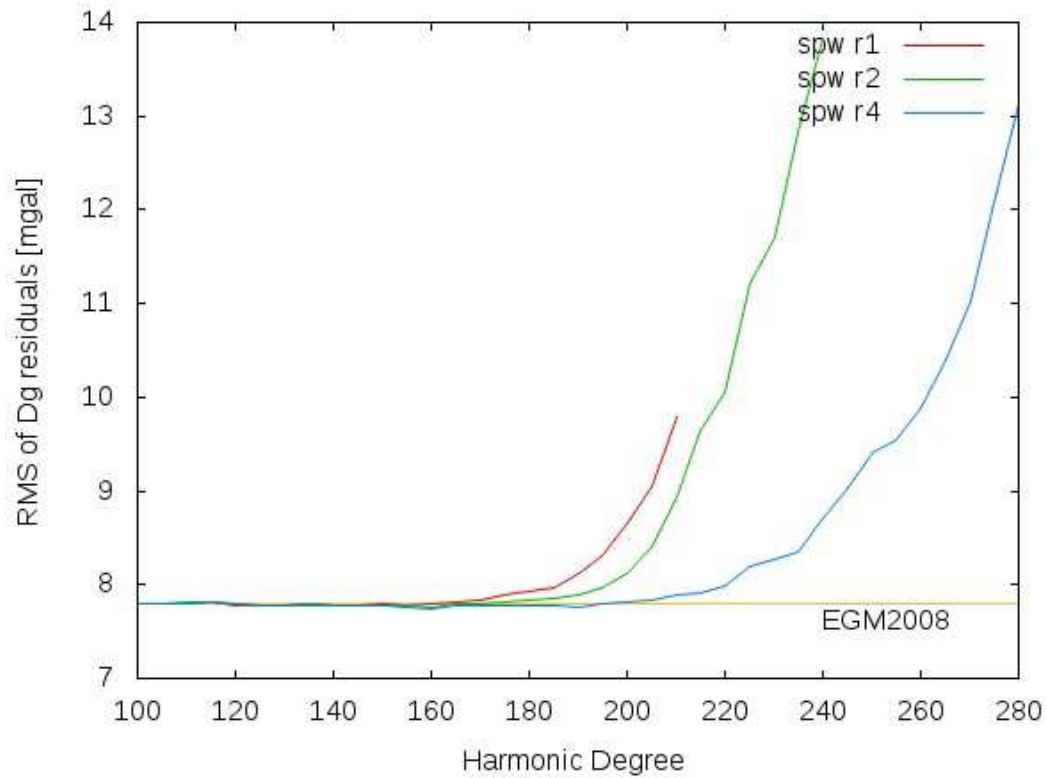


Figure 7: The r.m.s. of the residuals gravity data: the Italian database vs the SPW models

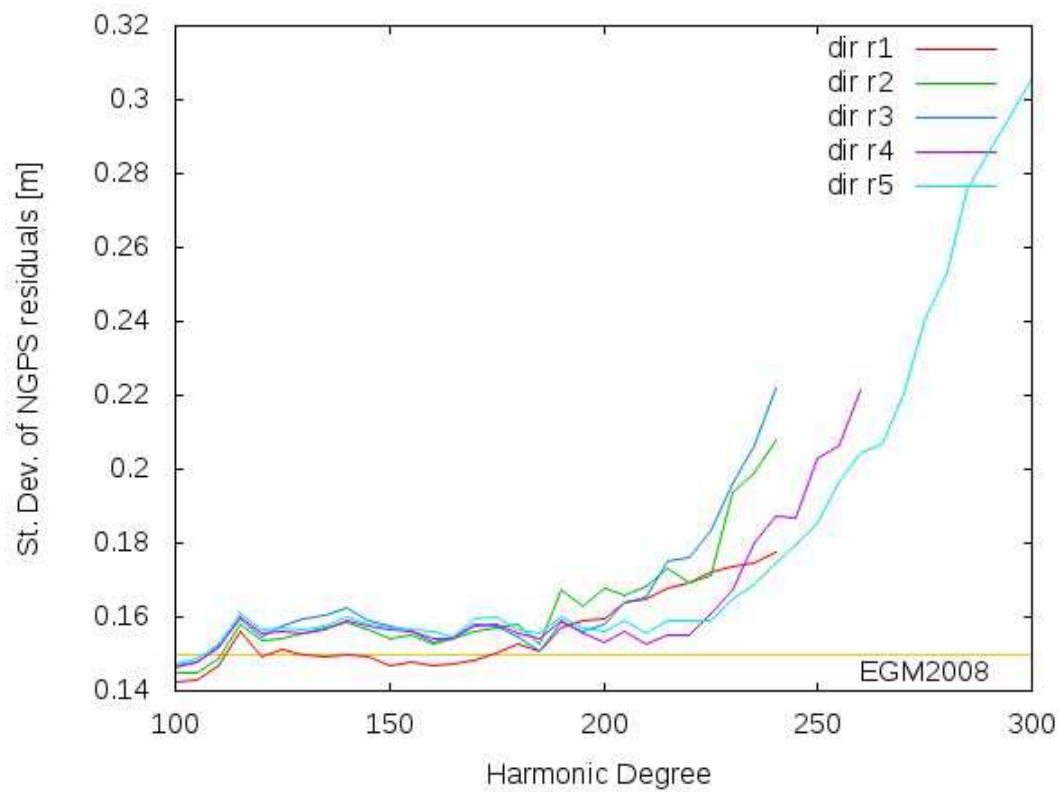


Figure 8: The St. Dev. of the residuals GPS/leveling data: the Italian database vs the DIR models

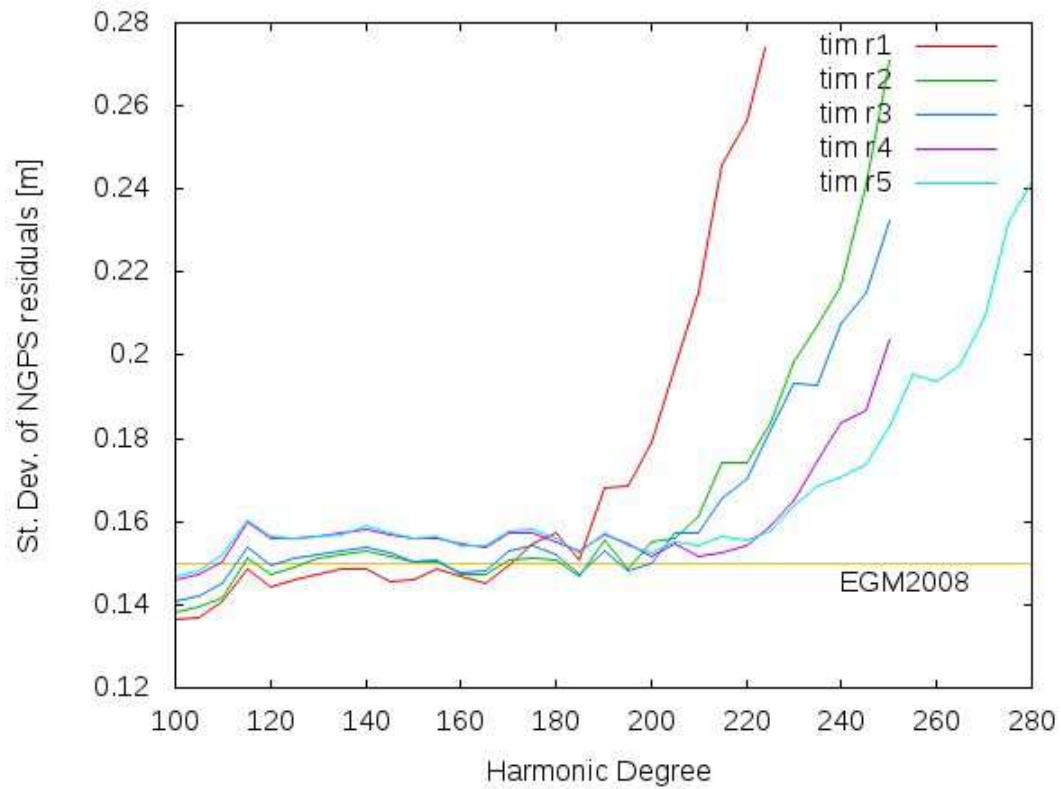


Figure 9: The St. Dev. of the residuals GPS/leveling data: the Italian database vs the TIM models

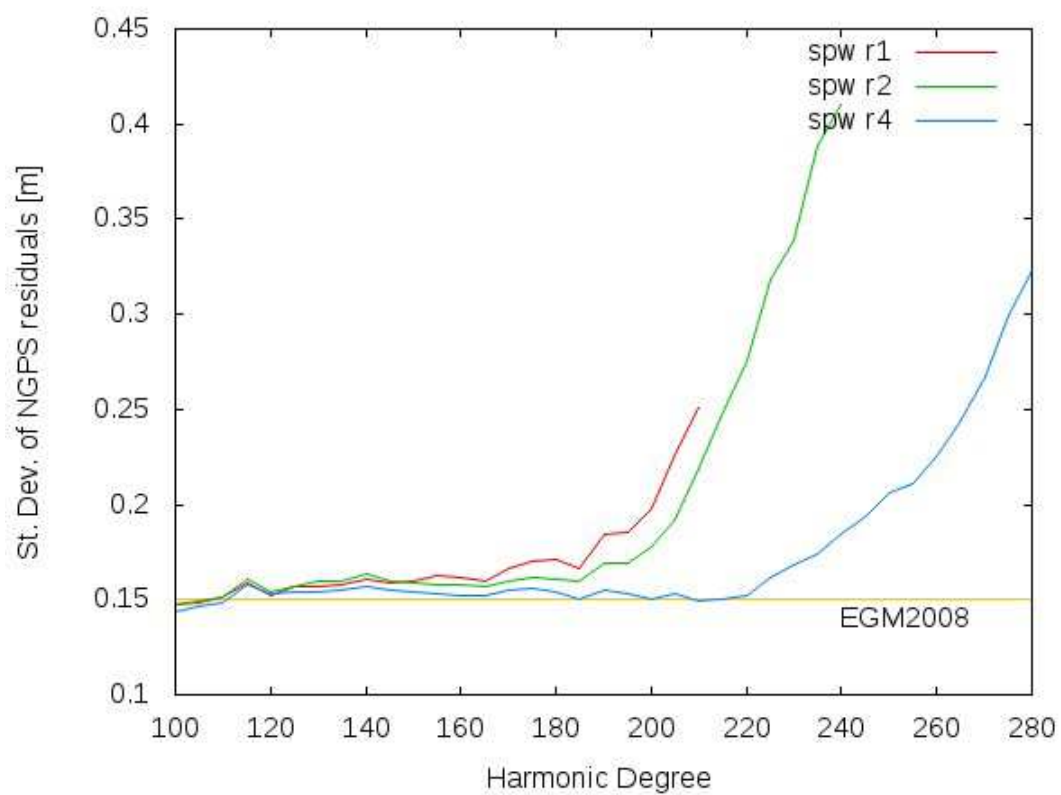


Figure 10: The St. Dev. of the residuals GPS/leveling data: the Italian database vs the SPW models

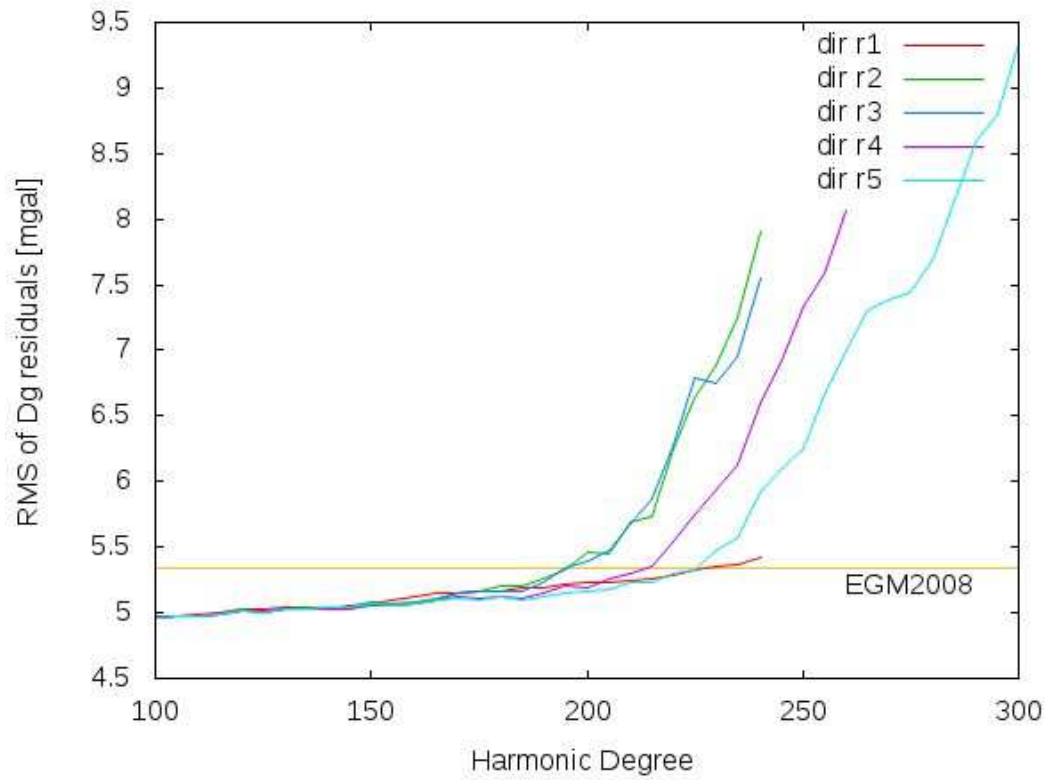


Figure 11: The r.m.s. of the residuals gravity data: the Greek database vs the DIR models

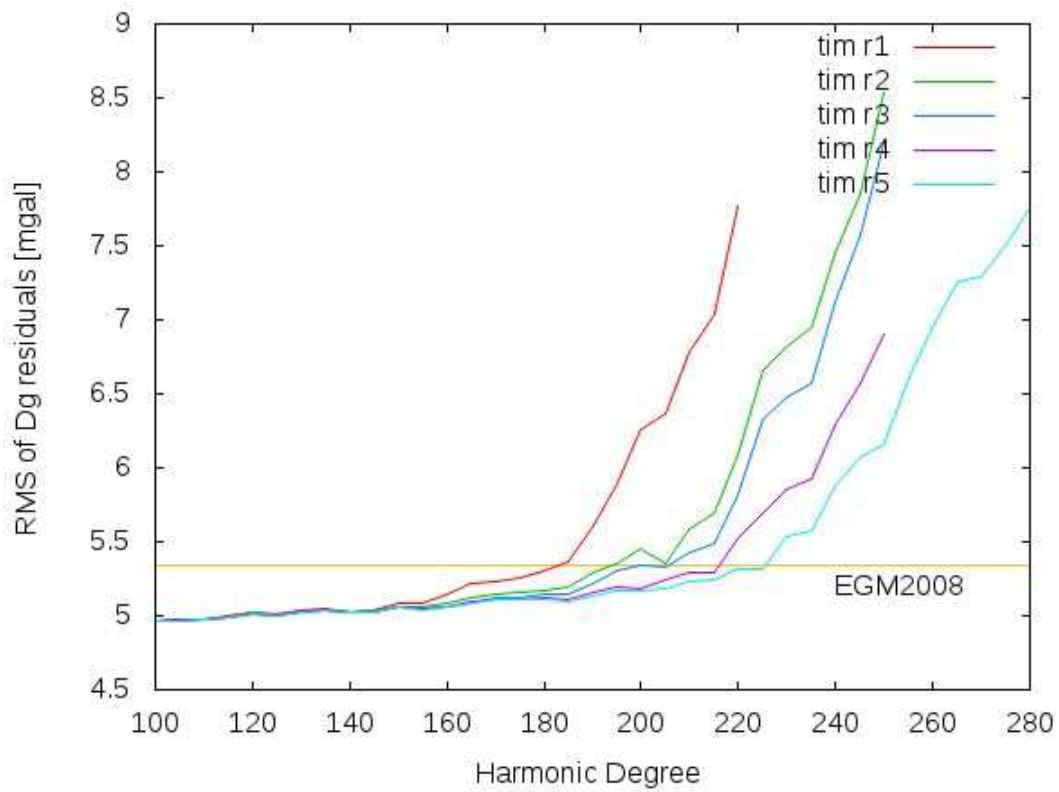


Figure 12: The r.m.s. of the residuals gravity data: the Greek database vs the TIM models

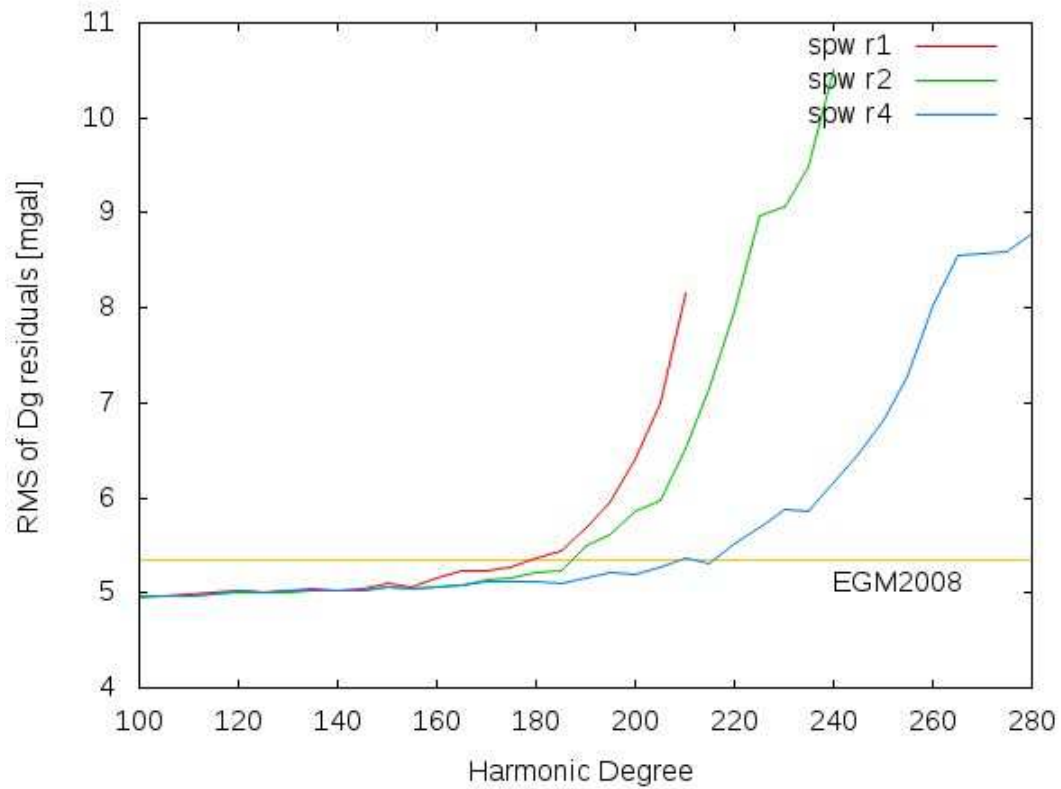


Figure 13: The r.m.s. of the residuals gravity data: the Greek database vs the SPW models

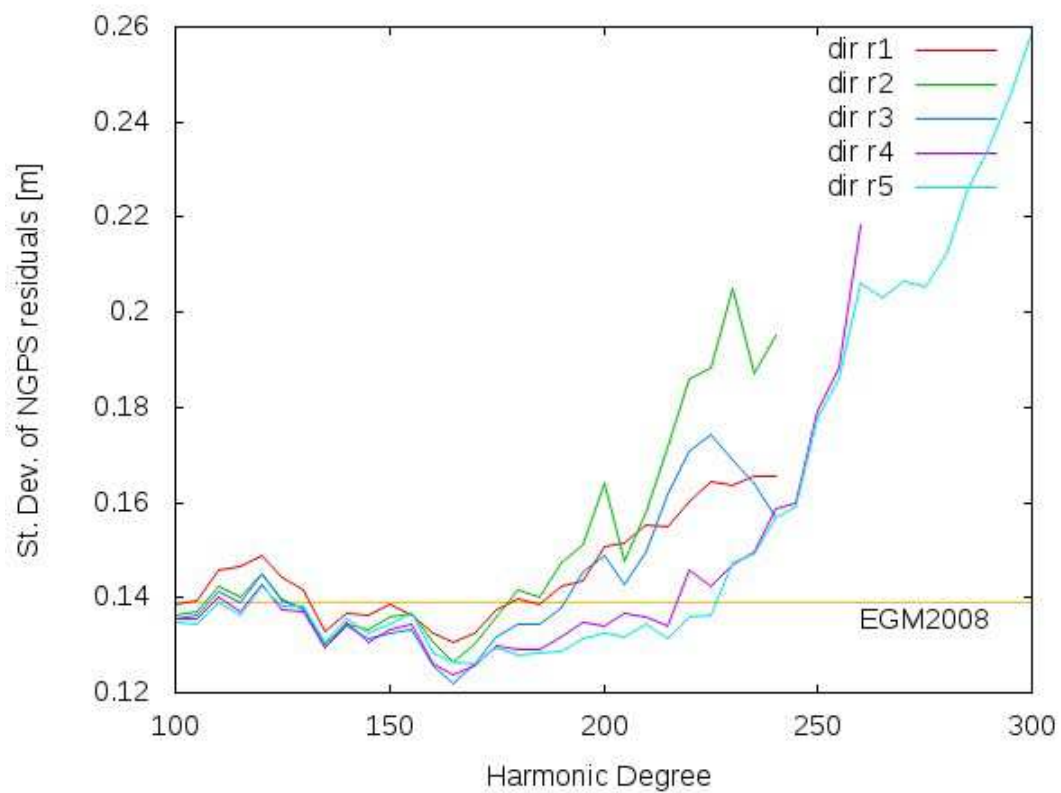


Figure 14: The St. Dev. of the residuals GPS/leveling data: the Greek database vs the DIR models

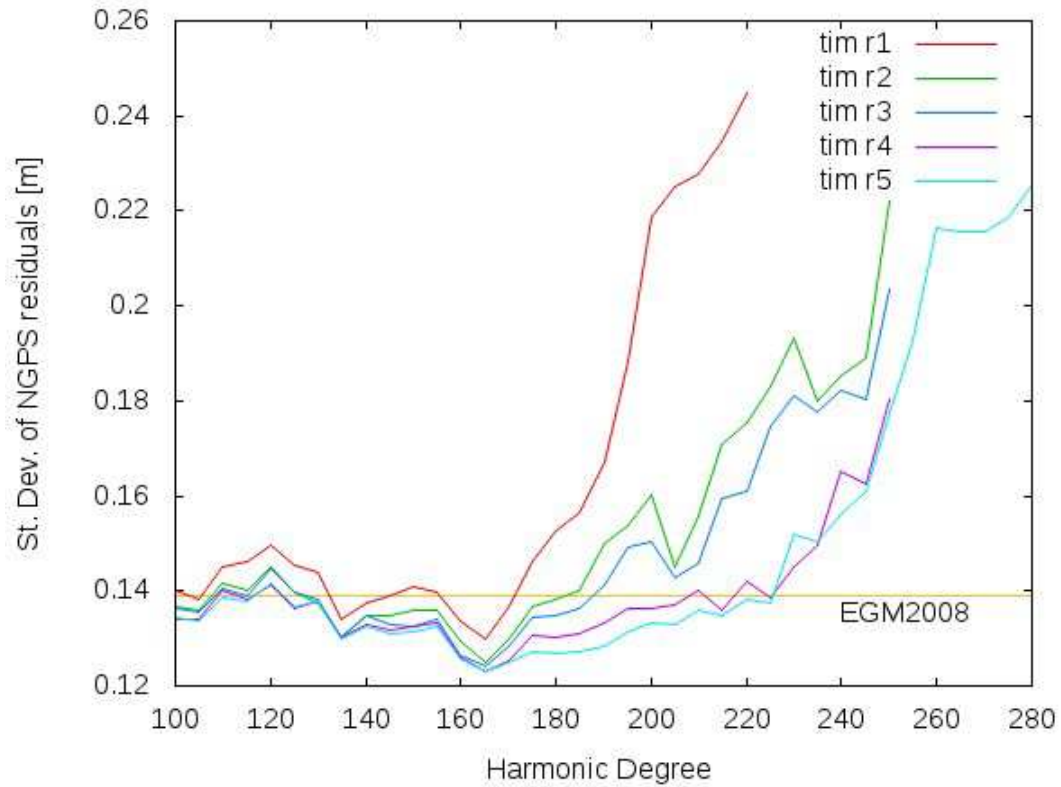


Figure 15: The St. Dev. of the residuals GPS/leveling data: the Greek database vs the TIM models

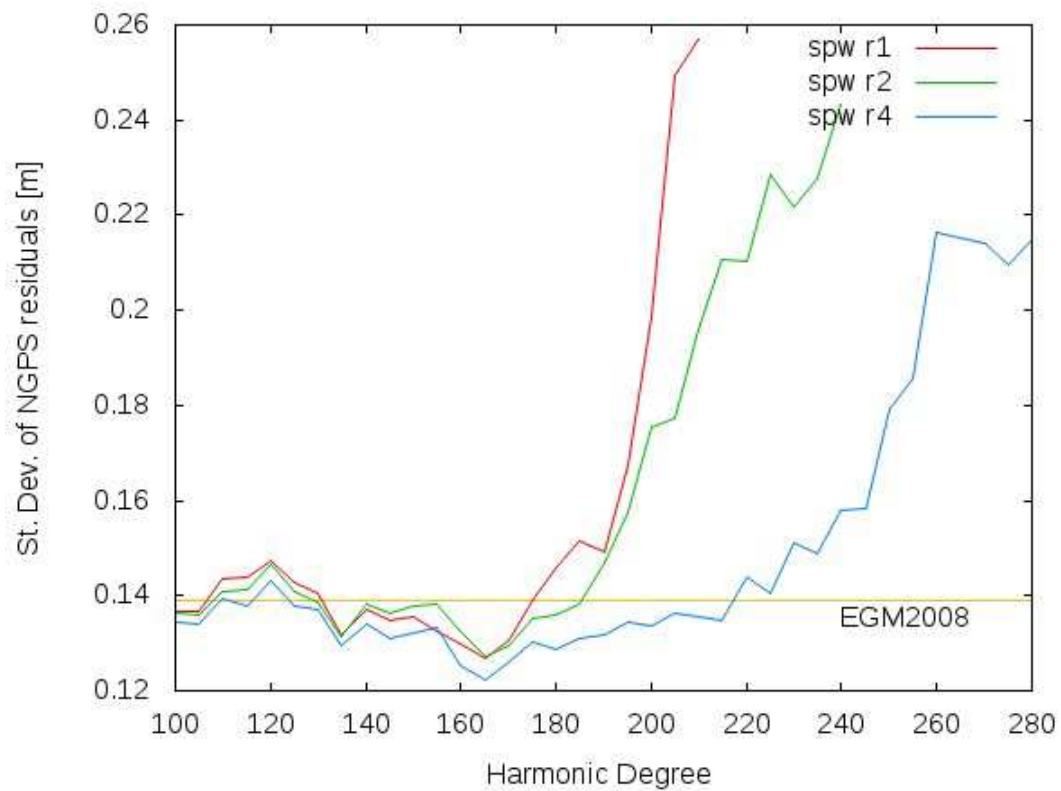


Figure 16: The St. Dev. of the residuals GPS/leveling data: the Greek database vs the SPW models

4 Comments and discussion

Over Italy, and as far as the evaluation of gravity data is concerned, no significant improvements are clearly visible in the medium frequency band, up to degree 200-220 (see Figures 5-7). As for the case of the Greek gravity database (see the discussion in the next paragraphs), there is an improvement in the GOCE models while moving from the first to the last release. This is basically due to the data included in the solutions. However, in all the tested models/releases, the r.m.s. are equivalent (or worse) to those obtained using EGM2008. Particularly, this holds also for the last releases of the models, up to degree 200 for the SPW-R4 solutions and 220 for the TIM-R5 and DIR-R5 solutions (see Figure 17-left panel). The only remarkable improvement is in the mean (see Table 3). The mean of the residuals for the last releases are remarkably smaller than the one obtained with EGM2008. Particularly, the TIM-R5 residuals have a mean value of -0,39 mGal that is nearly one fourth of the EGM2008 value. This proves that low frequency biases are accounted for in the GOCE GGMs. In comparing the different GOCE models, TIM-R5 is the one having the lower residuals St. Dev. as compared e.g. to those of the last releases DIR-R5 and SPW-R4. Also, as expected, the SPW-R4 model gives poorer results because it doesn't include the lower orbit data.

From the evaluation of the gravity anomaly data set over Greece it was concluded that the residual fields of the GOCE/GRACE models provide slightly better results than EGM2008, in terms of the St. Dev., and the improvement is at the 0.5 mGal level. It should be noted that as in the evaluation with the GPS/Levelling data, the contribution of GOCE/GRACE GGMs is filled with EGM2008 and RTE in order to reduce the omission error. TIM-R5 is better than EGM2008 up to d/o 230 (see Figure 12) while the overall best results are achieved at d/o 212, where TIM-R5 provides both the smallest St. Dev. and range compared to EGM008 by 0.5 and 5 mGal, respectively. The mean reduction is also seen and it drops from 0.57 to 0.45 mGal. This reduction might seem insignificant, but the fact that the already small mean w.r.t. EGM2008 reduces further, is a positive sign as to the reduction of long and medium wavelength errors due to GOCE. With the inclusion of more GOCE data, the useful spectral range increases from d/o 185 to 190, 195, 218 and 230 for TIM-R1, TIM-R2, TIM-R3, TIM-R4 and TIM-R5, respectively. DIR-R5 provides better results compared to EGM2008 up to d/o 232 (see Figure 11), while the overall best results in terms of both the St. Dev. and range of the differences are found at d/o 214, being the same as those of TIM-R5. Between the various versions, DIR-R1 and DIR-R2 show similar performance up to d/o ~180, while DIR-R4 brings significant improvement boosting the useful spectral range from d/o 195 to d/o 210. The inclusion of the lower orbit GOCE data boosts even further the useful envelop up to d/o 232 for DIR-R5. SPW-R4 provides worse results (see Figure 13), as expected due to the fact that it does not include the lower orbit GOCE data, and is better than EGM2008 up to d/o 218. Such a behaviour is expected since the main contribution of the lower orbit GOCE data is expected in the higher degrees of the GOCE GGMs. This becomes more evident in Figure 17, where the results for TIM-R5, DIR-R5 and SPW-R4 are depicted. It is clear that these GGMs have similar performance up to d/o 187, while above that the contribution of the lower orbit GOCE SGG data becomes evident in DIR-R5 and TIM-R5, since they remain lower than EGM2008 up to higher harmonic degrees. Nevertheless, even though SPW-R1 and SPW-R2 show a more or less similar performance, better than EGM2008 up to d/o 178 and 183, respectively, SPW-R4 improves considerably the rms of the residuals and reaches a useful spectral range up to d/o 218. The cross-comparison of the Greek gravity data with the ones over Italy seems to indicate that the precision of the latter is lower. The St. Dev. of the residuals in the Italian area are always larger (~7.8 mGal in the best case) than those obtained

with the Greek data (~ 5.1 mGal). This can explain the behaviour at medium frequencies: Italian data could be too noisy to reveal the medium frequency improvements (below degree 200-220) w.r.t. EGM2008.

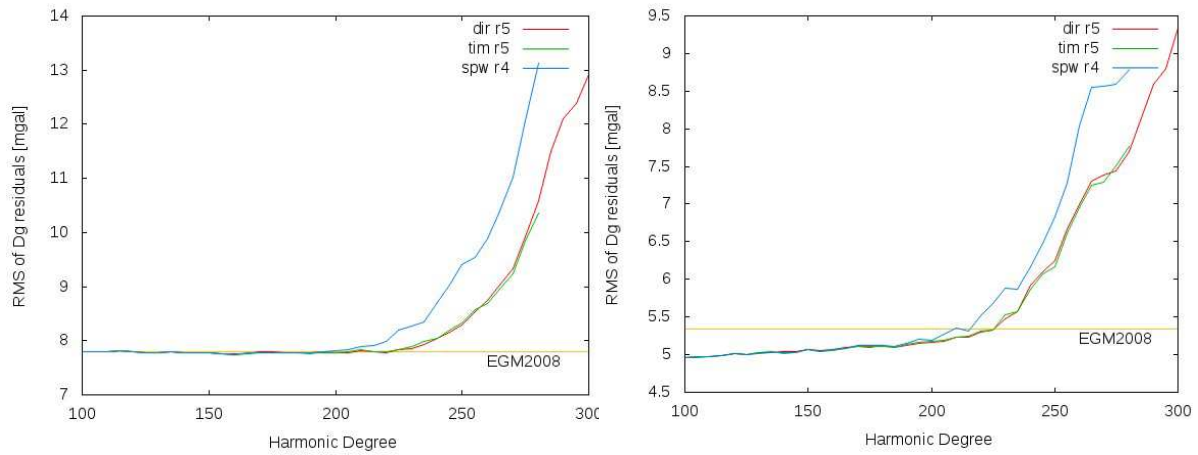


Figure 17: The r.m.s. of gravity residuals vs last released models (Italy – left panel; Greece – right panel)

When Italian GPS/levelling observations are considered, the same remarks given for the gravity data hold. Also in this case, there are no significant improvements with respect to EGM2008 (see Figures 8-10 and Table 4). The only remarkable improvement is in the mean values of the residuals that are half the value that is obtained using EGM2008. As it is for the gravity data, the best model over Italy, at full resolution, is TIM-R5, particularly if St.Dev. is considered (the corresponding value is also slightly better than the one referring to EGM2008). This can be clearly seen in Figure 18 (left panel) in which the green line corresponding to this solution is below the other two curves at degree 280. On the other hand, The SPW-R4 is better than the DIR-R5 and TIM-R5 up to degree 220.

With respect to the evaluation of the GPS/Levelling data over Greece, when satellite only models are evaluated to their maximum degrees without any spectral enhancement from EGM2008 and RTE effects, then, as expected, their differences are quite large (38.1 cm to 42.0 cm) due to the omission error (Vergos et al., 2014). When they are evaluated to their maximum degrees and then spectrally enhanced from EGM2008 and RTE effects then their differences reach the 15-27 cm level (see Table 6). On the other hand, when fill-in information from EGM2008 along with the computed RTE effects are taken into account for the intermediate degrees of expansion, then their performances are comparable and better than that of EGM2008. This is evidenced from Figures 14-16, which depict the variation of the St. Dev. of the geoid height differences between the enhanced GOCE/GRACE GGMs and GPS/Levelling. The useful spectral range, i.e., with errors smaller than EGM2008 is up to d/o 225 for DIR-R5, while the smallest St. Dev. at 12.3 cm is achieved at d/o 169. For TIM-R5 this spectral band is similar to d/o 224, while in the band between d/o 190 to 225 it provides slightly worse St. Dev. compared to DIR-R5. The overall smallest St. Dev. for TIM-R5 is reached at d/o 166 being at the 12.1 cm level. For the SPW-R4 model the useful spectral range is up to d/o 216, given that it contains only 26 months of GOCE data, while the R5 version of DIR and TIM contain the lower orbit GOCE SSG data. This is evidenced in the spectral band between d/o 190-225, that SPW-R4 deviates from DIR-R5 and TIM-R5 (see

Figure 18). It is interesting to notice that the St. Dev. of DIR-R4/R5, TIM-R4/R5 and SPW-R4 is smaller and larger than that of EGM2008 in the band between d/o 110 and 130 (see Figure 18). This consistent behaviour is a matter of further research and can be seen, to a smaller extent, in the comparison with the Italian GPS/Leveling data (notice the peak around 110-120 in Figure 18). In comparing GPS/Leveling data, similar results with the gravity data can be drawn as far as the progress with the addition of more GOCE data is concerned. The increased amount of data in the latest releases manage to boost the useful spectral range by 50 degrees for the DIR models, 60 degrees for the TIM GGMs and 45 degrees for the SPW ones, showing the improved representation of the shorter scales of the Earth's gravity field with the addition of more GOCE and of the late-stage lower orbit observations.

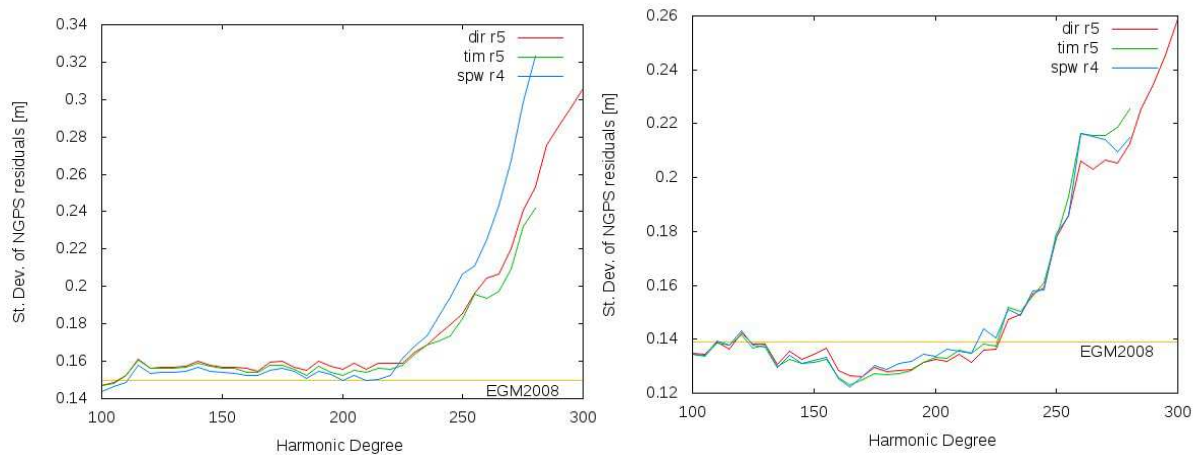


Figure 18: The St. Dev. of undulation residuals vs last released models (Italy – left panel; Greece – right panel)

5 Conclusions

The GOCE models, in their different releases, have been compared in the Mediterranean area with the Italian and the Greek gravity and GPS/levelling data. The two test areas include the Central Mediterranean (the Italian database) and the area of the Aegean Sea (the Greek database). Both areas are characterized by strong variations of the gravity field related to topography and/or geodynamical signals. Thus, due to the roughness of the gravity field in the two test areas, this can be considered as a valuable test for the evaluation of GOCE models. EGM2008 has been considered as well, as a benchmark solution. In estimating the residuals, EGM2008 has been used to account for the high frequency components for both gravity and geoid undulation to degree and order 2159. Furthermore, RTE has been computed to smooth the high frequencies related to the topography. The final residuals have been compared to those obtained using EGM2008. RTE effect has been computed also in this case. When Greek data are considered, the results show improvements w.r.t. EGM2008 up to d/o 230. This is a standard result that is frequently obtained when using GOCE models. Furthermore, clear improvements are visible while moving from the first to the last model release: this is (again) an expected result. In this respect, the best solution over the Greek area is the DIR-R5 model. However, the TIM-R5 is very close to this best fit model in terms of statistics. The SPW-R4 is worse than these two models but it must be mentioned that it doesn't include the last GOCE data collected at lower altitudes.

The comparisons in the Central Mediterranean area based on the Italian gravity and GPS/levelling data cannot be interpreted so clearly. The GOCE models/releases residuals have statistics that are always equivalent (or worse) to those obtained using EGM2008, either considering gravity and GPS/levelling. So, nearly no improvements are obtained up to d/o 230 as it is for the Greek database. The DIR-R5 and the TIM-R5 models are practically equivalent if gravity data are considered. SPW-R4 is, also in this case, the poorest solution, especially at full resolution. Same conclusions can be stated in case of GPS/levelling Italian data (but for the slightly better performance of SPW-R4 w.r.t. DIR-R5 and TIM-R4 around degree 210). The only remarkable reduction is in the mean of the geoid undulation and gravity residuals w.r.t. EGM2008 (e.g. in GPS/levelling data, the GOCE model residuals have mean values that are roughly half the EGM2008 value.) These critical results are possibly due to the quite poor quality of the Italian data (particularly of gravity data that have been measured over a large time span and are quite old). However, in the whole, these comparisons show how valuable the GOCE models are and how effective they are in properly reducing the ground based data by providing a reliable estimate of the low frequency component of the gravity field of the Earth.

References

- Andersen, O.B., 2010. The DTU10 Gravity field and Mean sea surface (2010). Second international symposium of the gravity field of the Earth (IGFS2), Fairbanks, Alaska.
- Barzaghi, R., Borghi, A., Carrion, D., Sona G., 2007. Refining the estimate of the Italian quasi-geoid. *Bollettino di Geodesia e Scienze Affini*, n° 3.
- Borghi, A., Carrion, D., Sona, G., 2007. Validation and fusion of different databases in preparation of high-resolution geoid determination. *GJI*, col. 171, Issue 2, 539-549.
- Brockmann, J.M., Zehentner, N., Höck, E., Pail, R., Loth, I., Mayer-Gürr, T., Schuh, W.D., 2014. EGM TIM RL05: An Independent Geoid with Centimeter Accuracy Purely Based on the GOCE Mission. *Geophysical Research Letters*, DOI:10.1002/2014GL061904.
- Bruinsma, S.L., Foerste, C., Abrikosov, O., Marty, J.M., Rio, M.H., Mulet, S., Bonvalot, S., 2013. The new ESA satellite-only gravity field model via the direct approach. *Geophys. Res. Lett.*, DOI:10.1002/grl.50716.
- Bruinsma, S.L., Foerste, C., Abrikosov, O., Lemoine, J.M., Marty, J.C., Mulet, S., Rio, M.H., Bonvalot, S., 2014. ESA's satellite-only gravity field model via the direct approach based on all GOCE data. *Geophys. Res. Lett.*, DOI:10.1002/2014GL062045.
- Ekman, M., 1989. Impacts of Geodynamic Phenomena on Systems for Height and Gravity. *Bull Geod* 63(3), pp 281–296.
- European Space Agency, 1999. Gravity field and Steady-State Ocean Circulation Mission. Report for mission selection of the four candidate Earth Explorer missions. Tech. Rept. European Space Agency , SP-1233(1), Noordwijk.
- Floberghagen, R., Fehringer, M., Lamarre, D., Muzi, D., Frommknecht, B., Steiger, C., Piñeiro, J., da Costa, A., 2011. Mission design, operation and exploitation of the gravity field and steady-state ocean circulation explorer mission. *Journal of Geodesy* , 85, 749-758.
- Forsberg, R., 1984. A Study of Terrain Reduction, Density Anomalies and Geophysical Inversion Methods in Gravity Field Modelling. Reports of the Department of Geodetic Science and Surveying, No 355, The Ohio State University, Columbus, Ohio.
- Gatti, A., Reguzzoni, M., Migliaccio, F., Sansò, F., 2014. Space-wise grids of gravity gradients from GOCE data at nominal satellite altitude. Presented at the 5th International GOCE User Workshop, 25-28 November 2014, UNESCO, Paris, France.
- Gianniou, M., 2008. HEPOS: Designing and implementing an RTK network. *Geoinformatics* 11(1): 10-13.
- Gruber, T., Visser, P. N. A. M., Ackermann, C., Hosse, M., 2011. Validation of GOCE gravity field models by means of orbit residuals and geoid comparisons; *Journal of Geodesy*, 85, Nr. 11, 845-860, Springer, ISSN 0949-7714, DOI: 10.1007/s00190-011-0486-7, 2011.
- Kotsakis, C. and Katsambalos, K., 2010. Quality analysis of global geopotential models at 1542 GPS/levelling benchmarks over the Hellenic mainland. *Surv Rev* 42(318), 327-344.

- Migliaccio, F., Reguzzoni, M., Sansò, F., 2004. Space-wise approach to satellite gravity field determination in the presence of coloured noise. *Journal of Geodesy*, 78, No. 4-5, 304-313.
- Pail, R., Goiginger, H., Schuh, W.-D., Höck, E., Brockmann, J.M., Fecher, T., Gruber, T., Mayer-Gürr, T., Kusche, J., Jäggi, A., Rieser, D., 2010. Combined satellite gravity field model GOCO01S derived from GOCE and GRACE. *Geophysical Research Letters*, 37, EID L20314, American Geophysical Union, ISSN 0094-8276, DOI: 10.1029/2010GL044906.
- Pail, R., Bruinsma, S., Migliaccio, F., Förste, C., Goiginger, H., Schuh, W.-D., Höck, E., Reguzzoni, M., Brockmann, J.M., Abrikosov, O., Veicherts, M., Fecher, T., Mayrhofer, R., Krasbutter, I., Sansò, F., Tscherning, C.C., 2011. First GOCE gravity field models derived by three different approaches. *Journal of Geodesy*, 85, No. 11, 819-843.
- Pavlis, N. K., Holmes, S. A., Kenyon, S. C. and Factor, J. K., 2012. The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). *Journal of Geophysical Research: Solid Earth*, 117, Issue B4, DOI: 10.1029/2011JB008916.
- Schall, J., Eicker, A., Kusche, J., 2014. The ITG-Goce02 gravity field model from GOCE orbit and gradiometer data based on the short arc approach. *Journal of Geodesy*, 88, 403–409, DOI 10.1007/s00190-014-0691-2.
- Smith, W.H.F. and Sandwell, D.T., 1997. Global seafloor topography from satellite altimetry and ship depth soundings. *Science* 277:1957-1962.
- Šprlák, M., Gerlach, C., Pettersen, B.R., 2012. Validation of GOCE global gravity field models using terrestrial gravity data in Norway, *Journal of Geodetic Science* 01/2012; 2(2):134-143. DOI: 10.2478/v10156-011-0030-y.
- Surace, L., 1997. La nuova rete geodetica nazionale IGM95: risultati e prospettive di utilizzazione. *Bollettino di Geodesia e Scienze Affini* - n. 3.
- Tscherning, C.C., Knudsen, P., and Forsberg, R., 1994. Description of the GRAVSOFIT package -Geophysical Institute, University of Copenhagen, Technical Report, 1991, 2. Ed. 1992, 3. Ed. 1993, 4. Ed. 1994.
- Tocho, C., Vergos, G.S., Pacino, M.C., 2014. Evaluation of the latest GOCE/GRACE derived Global Geopotential Models over Argentina with collocated GPS/Leveling observations. In: Marti U (ed) *Gravity, Geoid and Height Systems*, International Association of Geodesy Symposia 141, Springer International Publishing Switzerland, 75-83. doi: 10.1007/978-3-319-10837-7_10.
- Tziavos, I.N., Vergos, G.S., Grigoriadis, V.N., 2010. Investigation of topographic reductions and aliasing effects to gravity and the geoid over Greece based on various digital terrain models. *Surv Geophys* 31(3):23-67. doi: 10.1007/s10712-009-9085-z.
- Tziavos, I.N., Vergos, G.S., Grigoriadis, V.N., Andritsanos, V.D., 2012. Adjustment of collocated GPS, geoid and orthometric height observations in Greece. Geoid or orthometric height improvement? In: Kenyon S, Pacino C, Marti U (eds) *Geodesy for Planet Earth*, International Association of Geodesy Symposia 136, Springer Berlin Heidelberg New York, 481-488.
- Tziavos, I.N., Vergos, G.S., Mertikas, S.P., Daskalakis, A., Grigoriadis, V.N., Tripolitsiotis, A., 2013. The contribution of local gravimetric geoid models to the calibration of satellite altimetry data and an outlook of the latest GOCE GGM performance in GAVDOS. *Adv Space Res* 51(8): 1502-1522, doi: 10.1016/j.asr.2012.06.013.
- Vergos, G.S., Grigoriadis, V.N., Tziavos, I.N., Kotsakis, C., 2014. Evaluation of GOCE/GRACE Global Geopotential Models over Greece with collocated GPS/Levelling observations and local gravity data. In: Marti U (ed) *Gravity, Geoid and Height Systems*, International Association of Geodesy Symposia 141, Springer International Publishing Switzerland, pp. 85-92. doi: 10.1007/978-3-319-10837-7_11.
- Wessel, P., Smith, W.H.F., 1998. New improved version of Generic Mapping Tools released. *EOS Trans Amer Geophys U* 79(47): 579.
- Yi, W., 2012. An alternative computation of a gravity field model from GOCE. *Advances in Space Research* 50(3), 371-384, DOI 10.1016/j.asr.2012.04.018.
- Yi, W., Rummel, R., 2014. A comparison of GOCE gravitational models with EGM2008, *Journal of Geodynamics*, 73, January 2014, 14-22, ISSN 0264-3707, <http://dx.doi.org/10.1016/j.jog.2013.10.004>.

Evaluation of Recent GOCE Geopotential Models in South America

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Abstract

Several global geopotential models based on Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite have been published in the last few years. Some of these models use combinations of different satellite missions, while others use only GOCE data. This paper presents the evaluation and analysis of six Global Gravity Models (GGMs) using GOCE data, in South America.

1 Introduction

Nowadays, with dedicated satellite gravity missions as Challenging Minisatellite Payload (CHAMP), Gravity Recovery and Climate Experiment (GRACE) and Gravity Field and Steady-State Ocean Circulation (GOCE) are allowing the best knowledge of the long and medium wavelength components of the Earth gravitational field.

This paper focuses on GOCE GGMs. Table 1 shows the characteristics of the models considered: name, year of GGMs publication, maximum spherical harmonic degree and input data information. GO_CONS_GCF_2_DIR_R5 (DIRR5) is a satellite-only model based on a full combination of GOCE-SGG with GRACE and LAGEOS. It was produced by GFZ German Research Centre (GFZ) for Geosciences Potsdam and *Groupe de Recherche de Géodésie Spatiale* (GRGS)/CNES, Toulouse (Bruinsma et al, 2013). GO_CONS_GCF_2_TIM_R5 (TIMR5) is the 5th release of the GOCE gravity field model computed by time-wise approach. It was produced by Graz University of Technology, Institute for Theoretical and Satellite Geodesy University of Bonn, Institute of Geodesy and Geoinformation TU München, Institute of Astronomical and Physical Geodesy (IAPG) (Pail et al, 2011). GFZ and GRGS/CNES produced EIGEN-6C4, which is a global combined gravity field model (Shako et al, 2014; Förste et al, 2014). The others satellite-only models studied are GOGRA04S and JYY_GOCE04S, produced by IAPG, TU München (Yi et al, 2013). Finally, GOCO03S model has been produced by the Gravity Observation Combination (GOCO) in 2012. It is an initiative of TU München, Institute of Astronomical and Physical Geodesy; Univ. Bonn, Institute of Geodesy and Geoinformation; TU Graz, Institute of Theoretical

and Satellite Geodesy; Austrian Academy of Sciences, Space Research Institute; Univ. Bern, Astronomical Institute. It is a satellite-only model and uses GOCE and GRACE satellites, as well as geodetic laser satellite data (Mayer-Gürr et al., 2012).

Geoidal heights derived from GPS/BM and terrestrial gravity data are used to evaluate these models for South America. The EGM2008 was used too for comparison of GOCE GGMs. It is a combined solution based on ITG-GRACE03S (Mayer-Guerr, 2007), surface gravity and altimeter data over the ocean. It was calculated and made available to the scientific community by the development team from the Earth Gravitational Model (EGM), NASA (National Aeronautics and Space Administration) / NGA (Pavlis et al, 2008; Pavlis et al, 2012). The model is completed to degree and order 2159 and contains additional spherical harmonic coefficients up to degree 2190 and order 2159. The GGMs are tide free system and in this study no zero degree term on the height anomaly was added.

This paper shows also the comparison of the geoidal heights derived from GPS/BM with the geoidal model GEOID2014 (Blitzkow et al, 2014).

Table 1: GGMs used

Model	Year	Degree	Data
EIGEN-6C4	2014	2190	S(Goce,Grace,Lageos),G,A
TIMR5	2014	280	S(Goce)
DIRR5	2014	300	S(Goce,Grace,Lageos)
JYY_GOCE04S	2014	230	S(Goce)
GOGRA04S	2014	230	S(Goce,Grace)
GOCO03S	2012	250	S(Goce,Grace,...)
EGM2008	2008	2190	S(Grace),G,A

Source: International Centre for Global Earth Models (ICGEM) - Satellite (S); airborne and terrestrial gravity (G); Altimetry (A) survey.

2 Geoid model

The Laboratory of Surveying and Geodesy (LTG-EPUSP) computed recently GEOID2014 (Blitzkow et al, 2014). The area limited by 15° N and 57° S in latitude and 30° W and 95° W in longitude is involved by the model. The terrestrial gravity data for the continent have been updated with the most recent surveys. A total of 892,604 gravity points in South America (Figure 1) were collected. The complete Bouguer and Helmert gravity anomalies have been derived through the Canadian package SHGEO (Ellmann and Vaníček, 2007). The oceanic area was completed with the mean free-air gravity anomalies derived from a satellite altimetry model by the Danish National Space Center, called DTU10 (Andersen, 2010). The short wavelength component was estimated via FFT with the modified Stokes kernel proposed by Featherstone (2003). The model was based on EIGEN-6C3stat up to degree and order 200 as a reference field (Shako et al, 2014). A zero degree term of -0.41 m was added, see Figure 2. This converts geoid undulations that are intrinsically referred to an ideal mean-Earth ellipsoid into undulations that are referred to WGS 84.

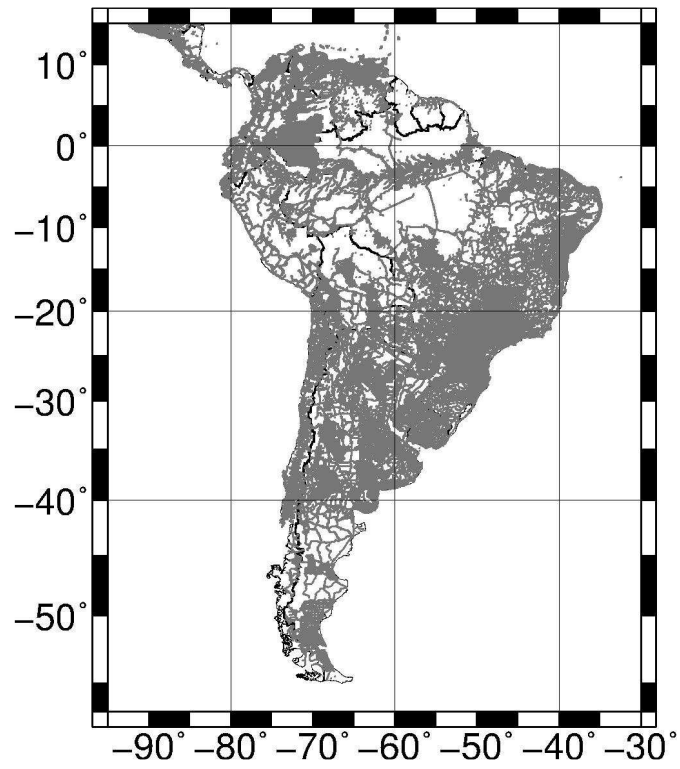


Figure 1: Gravity data in South America.

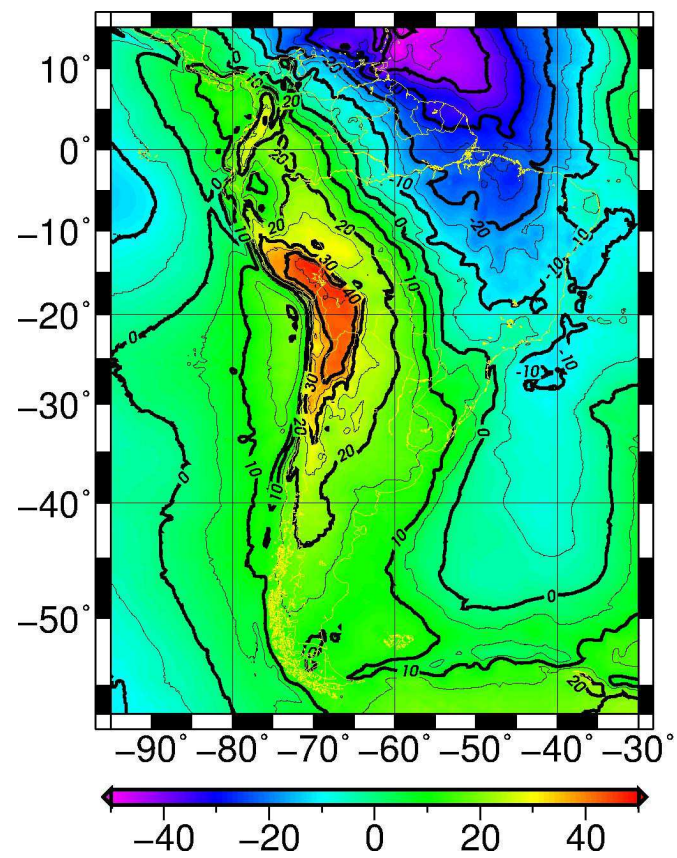


Figure 2: Model GEOID2014 (meter)

3 GPS data on benchmark

GPS observations carried out on benchmarks of the spirit levelling network in South America, which have been delivered under the SIRGAS (Geocentric Reference System for Americas) project (Hoyer et al, 1998; SIRGAS, 1997), were used for testing the selected GGMs and the geoid model. At the moment there are GPS/BM data available from the following countries: Argentina, Brazil, Chile, Ecuador, Uruguay and Venezuela, in a total of 1,861 points (Figure 7). Table 2 shows this information for each country: number of points; vertical and horizontal datum; and web site data.

The geoidal heights associated with GPS/BM have their inaccuracies due to the error of the spirit levelling as well as of the GPS. Figure 3 shows the standard deviation of the ellipsoidal and the orthometric heights in 673 points in Brazil, as a function of the latitude. This result was derived from the last vertical network adjustment undertaken by IBGE. The results of these points are on the decimetre level accuracy for most of the country as shown by Figure 3. The standard deviation of ellipsoidal and orthometric heights of the GPS/BM is only provided by IBGE. The institutions of other countries do not provide this information.

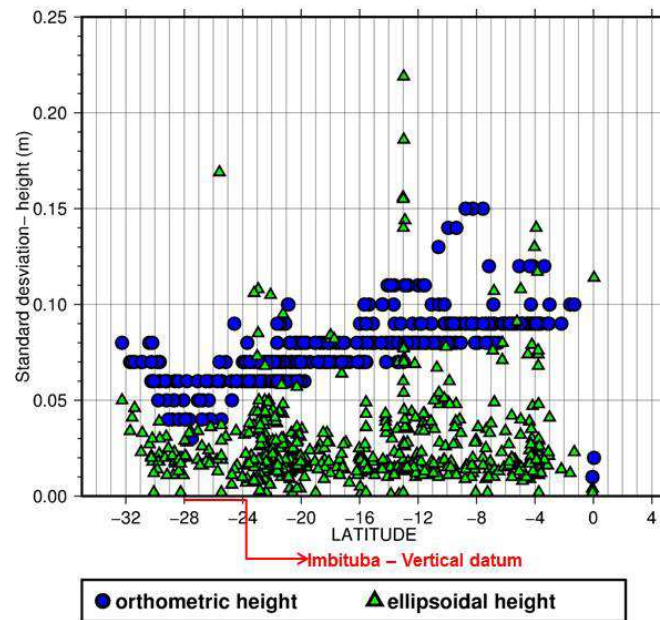


Figure 3: Standard deviation of ellipsoidal and orthometric heights as a function of latitude.

The mentioned comparison is very much useful to look after the consistency between the two heights. The original ellipsoidal heights derived from the GPS measurements refer in principle to a tide-free (*tf*) system in terms of the treatment of the permanent tide effect (Poutanen et al, 1996). However, as no tidal correction was applied to the height observations of the levelling network, the available normal orthometric heights refer, in principle, to a mean-tide system (*mt*) (Ferreira et al, 2013).

For the present analysis, these values were transformed into the tide-free system by using the formula (Tenzer et al, 2010):

$$H_{tf} = H_{mr} + \left\{ (1 + k - h) \left[-0.198 \left(\frac{3}{2} \sin^2 \varphi - \frac{1}{2} \right) \right] \right\} \quad (1)$$

where k and h are the tidal Love numbers and their values are 0.3 and 0.62, respectively, and φ is the geocentric latitude. This was necessary because the GPS and the applied GGMs are related to a tide-free system.

Table 3 shows the results in terms of mean value, RMS difference, standard deviation (σ) difference, extreme values of the differences among height anomalies of several GGMs (maximum degree) and GEOID2014 geoidal heights with GPS/BM geoidal heights.

Figures 4 and 5 show the histograms of the discrepancies between GGMs (EIGEN6C4 and DIRR5) and GPS/BMs, respectively. EIGEN6C4 is more consistent with GPS/BM than the other GGMs, due to the inclusion of terrestrial gravity data in its computation. Figures 7 and 8 show the GPS/BM distribution with a color palette for differences between GPS/BM geoidal heights and EIGEN6C4 and DIRR5 height anomalies, respectively. Figures 6 and 9 show the histogram and the map of the discrepancies between GPS/BM and GEOID2014 model, respectively. Almost 50% of the discrepancies in absolute terms are around 0.2 meters, which is within the GPS/BM points inaccuracies (Figure 3).

Table 4 shows RMS differences among GPS/BM geoidal heights with GGMs height anomalies (max degree) and GEOID2014 geoidal heights for each country. It is possible to observe that the zero degree term added in the geoid model shows a worse result for Argentina and Ecuador, not for other countries. For example, in Argentina (Figure 9 and Table 4), the RMS difference between GPS/BM and GEOID2014 is 0.60 m (Table 4). But, RMS difference with respect to GEOID2014, without zero degree term, is 0.30 m and, just in the Buenos Aires province, is 0.21 m. The vertical datum is not the same for different countries (Table 2). For example, the vertical datum discrepancy between Brazil and Argentina is higher than 20 cm, and Brazil and Ecuador is higher than 80 cm (Sánchez and Brunini, 2009; Sánchez, 2005). The height difference of each country was not corrected for the discrepancies. Although zero degree term has no relation with the difference between the vertical datum of each country, it emphasizes eventually these differences.

The GPS/BM information is still sparse, without a homogeneous distribution, so that this result is geographically limited, but Figure 10 shows the graphical differences for Argentina (296 points), Brazil (1,112 points), Chile (173 points), Ecuador (60 points), Uruguay (11 points) and Venezuela (187 points).

The GPS/BM for Argentina are concentrated in Buenos Aires province where the GGMs show good agreement up to degree 200. Out of that, TIMR5 GGM presents the best agreement up to 260. The GGMs EGM2008 and EINGEN6C4, to which terrestrial gravity data are included, show best agreement above degree 260.

For Brazil (Figure 10), most of these points are concentrated in the Southeast and South and all GGMs show good agreement up to 250 degree. Out of that, the complete GGMs are the best. Many differences are in the border between Roraima, Amazonas and Rondônia states (Figure 7 to 9, black North-South profile) probably there is a leveling bias on the benchmarks. Some points in Piauí state show high differences too. These points need to be reviewed.

In the same analysis for Chile, Ecuador and Uruguay, the GOCE GGMs only-satellites (TIMR5, DIRR5, JYY_GOCE04S, GOGRA04S) shows good agreement with GPS/BM. The EGM2008 presents better result than EIGEN6C4 for Chile and Uruguay. Figure 10 shows that all GGMs are good agreement with GPS/BM up to 230 in Venezuela. Out of that, the complete GGMs are the best too.

Table 2: GPS/BM information

	Number points GPS/BM	Institution	Datum horizontal	Datum vertical tide gauge	Web Site Data
Argentina	296	Instituto Geográfico Nacional/IGN and Universidade Nacional de Rosário/UNR	POSGAR07, ITRF 2005 época 2006.632 ⁽¹⁾	Mar del Plata, Province Buenos Aires, 1949 (Lauría et al, 2002)	No
Brazil	1112	IBGE, LTG, Instituto de Astronomia, Geofísica e Ciências Atmosféricas/IAG-USP, Universidade Estadual Paulista "Júlio de Mesquita Filho"/UNESP and Universidade Federal do Paraná/UFPR	SIRGAS2000, ITRF 2000, epoch 2000.4 ⁽²⁾	Imbituba, Santa Catarina state, 1958 ⁽³⁾	Yes ⁽⁴⁾ (IBGE)
Chile	173	Instituto Geográfico Militar/IGM	SIRGAS2000, ITRF 2000, epoch 2002.0 (Sánchez and Brunini, 2009)	Arica, Antofagasta, Valparaíso (mainly), San Antonio, Talcahuano, Puerto Montt and Punta Arenas (Sánchez, 2005)	No
Ecuador	60	Instituto Geográfico Militar/IGM	SIRGAS 95 ITRF1995.4 (Sánchez and Brunini, 2009)	La Libertad, Province del Guayas, 1959 (Sánchez, 2005)	No
Uruguay	11	Servicio Geográfico Militar/SGN	SIRGAS 95, epoch 1995.4 (Sánchez and Brunini, 2009)	Montivideo, Capital, 1948 (Piña et al, 2002)	No
Venezuela	187	Instituto Geográfico de Venezuela Simón Bolívar/IGVSB and Escuela de Ingeniería Geodésica (Facultad de Ingeniería, Universidad del Zulia)	SIRGAS 95, epoch 1995.4 (Sánchez and Brunini, 2009)	La Guaira, 1953 (Hernández et al, 2002)	No

(1) <http://www.ign.gob.ar/NuestrasActividades/Geodesia/Posgar07>;

(2) http://www.ibge.gov.br/home/geociencias/noticia_sirgas.shtm ;

(3) http://www.ibge.gov.br/home/geociencias/geodesia/rmpg/default_rmpg_int.shtm?c=10;

(4) <http://www.visualizador.inde.gov.br>

Table 3: Statistics of the differences between GPS/BM geoidal heights and height anomalies of the GGMs (max degree) for South America in meters.

	EGM2008	GOCO03S	JYY_GOCE04S	GROGA04S	TIMR5	DIRR5	EIGEN6C4	GEOID2014
Mean	-0.31	-0,28	-0,29	-0,29	-0,32	-0,32	-0,32	0,17
σ diff	0.46	0,61	0,59	0,58	0,54	0,54	0,44	0,52
RMS diff	0.55	0,67	0,65	0,65	0,63	0,63	0,55	0,55
Max.	2.10	2,57	2,46	2,47	2,48	2,58	2,09	2,24
Min.	-3.42	-2,80	-2,88	-2,88	-2,91	-2,94	-3,74	-2,55

Table 4: RMS difference between GPS/BM geoidal heights and height anomalies of the GGMs (max degree) for each country in meters.

	EGM2008	GOCO03S	JYY_GOC04S	GROGA04S	TIMR5	DIRR5	EIGEN6C4	GEOID2014
Argentina	0.30	0.34	0.34	0.34	0.32	0.33	0.29	0.60
Brazil	0.57	0.64	0.64	0.63	0.64	0.64	0.57	0.44
Chile	0.65	0.94	0.64	0.79	0.70	0.68	0.76	0.76
Ecuador	0.80	1.158	1.12	1.125	1.06	1.07	0.72	1.18
Uruguay	0.63	0.65	0.58	0.59	0.63	0.63	0.65	0.67
Venezuela	0.49	0.82	0.85	0.85	0.77	0.76	0.49	0.47

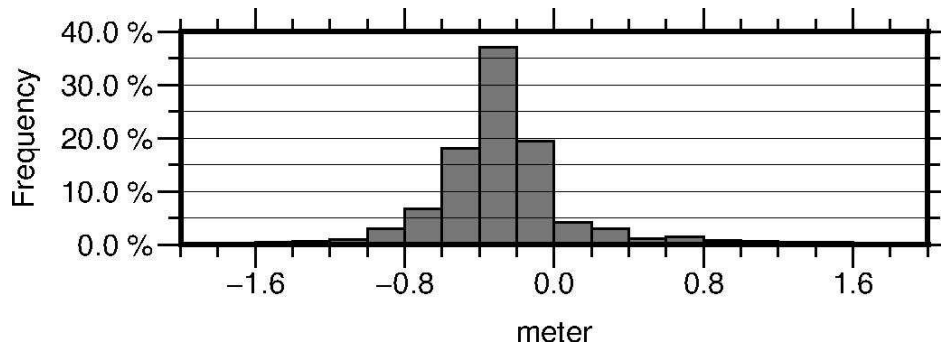


Figure 4: Histogram of the discrepancies between GPS/BM geoidal heights and EIGEN6C4 (max. degree) height anomalies.

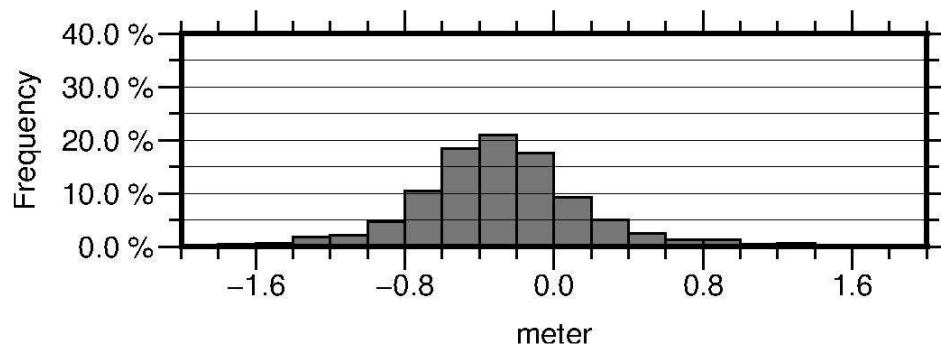


Figure 5: Histogram of the discrepancies between GPS/BM geoidal heights and DIRR5 (max. degree) height anomalies.

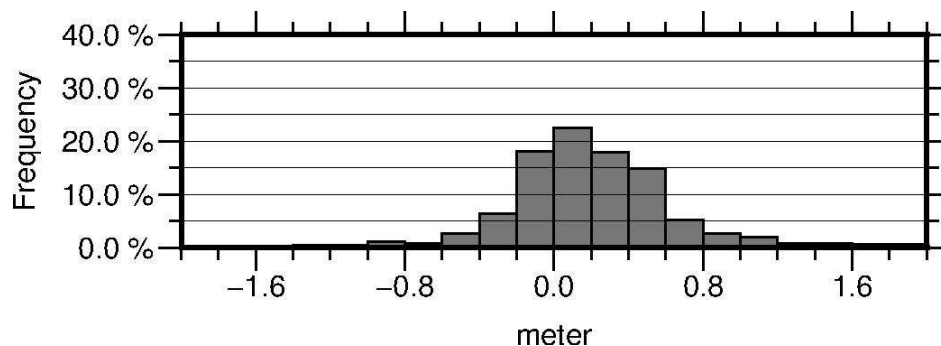


Figure 6: Histogram of the discrepancies between GPS/BM and GEOID2014 geoidal heights.

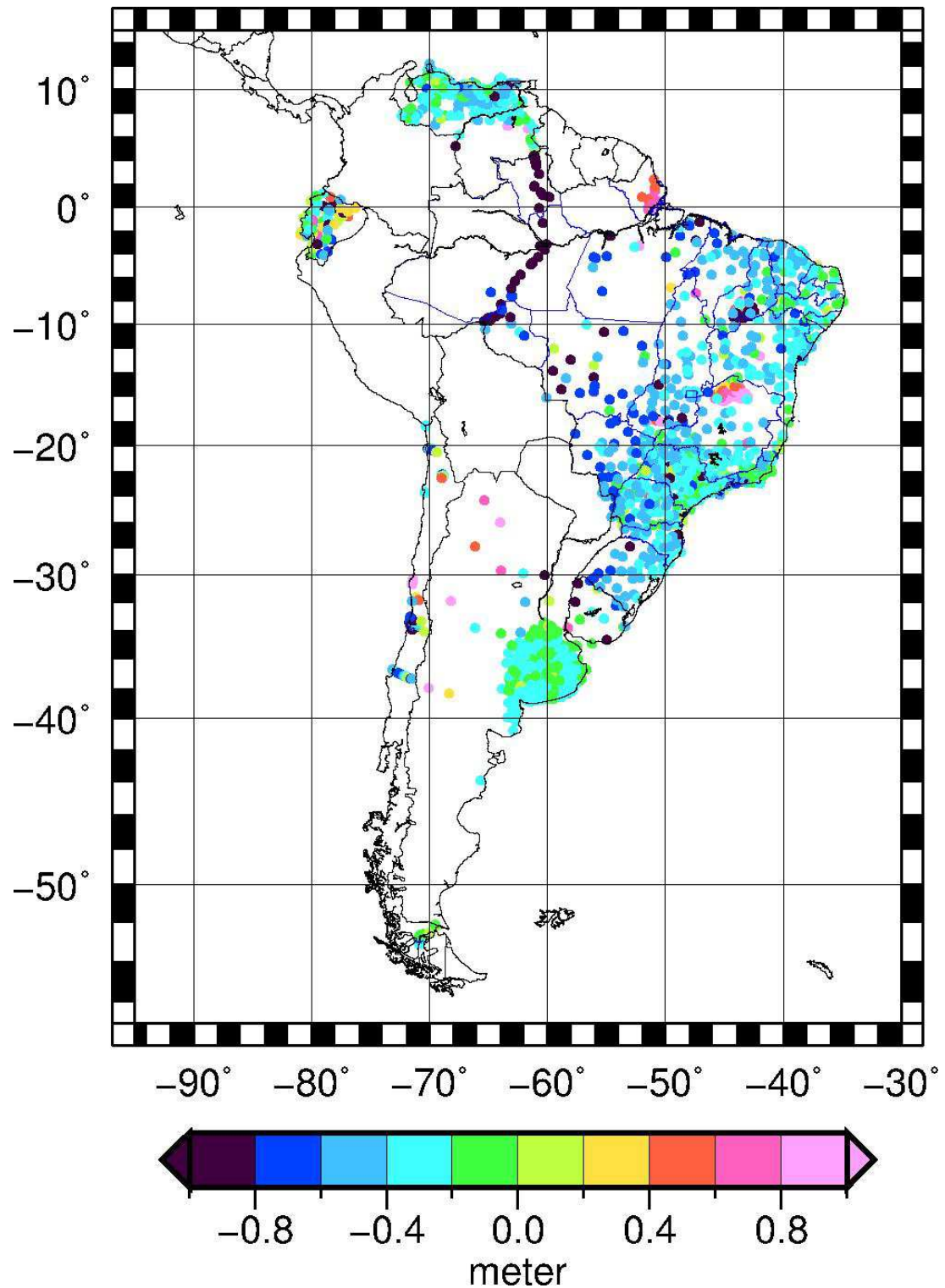


Figure 7: Distribution of the GPS/BMs and illustration of the differences between GPS/BM geoidal heights and EIGEN6C4 (max. degree) height anomalies.

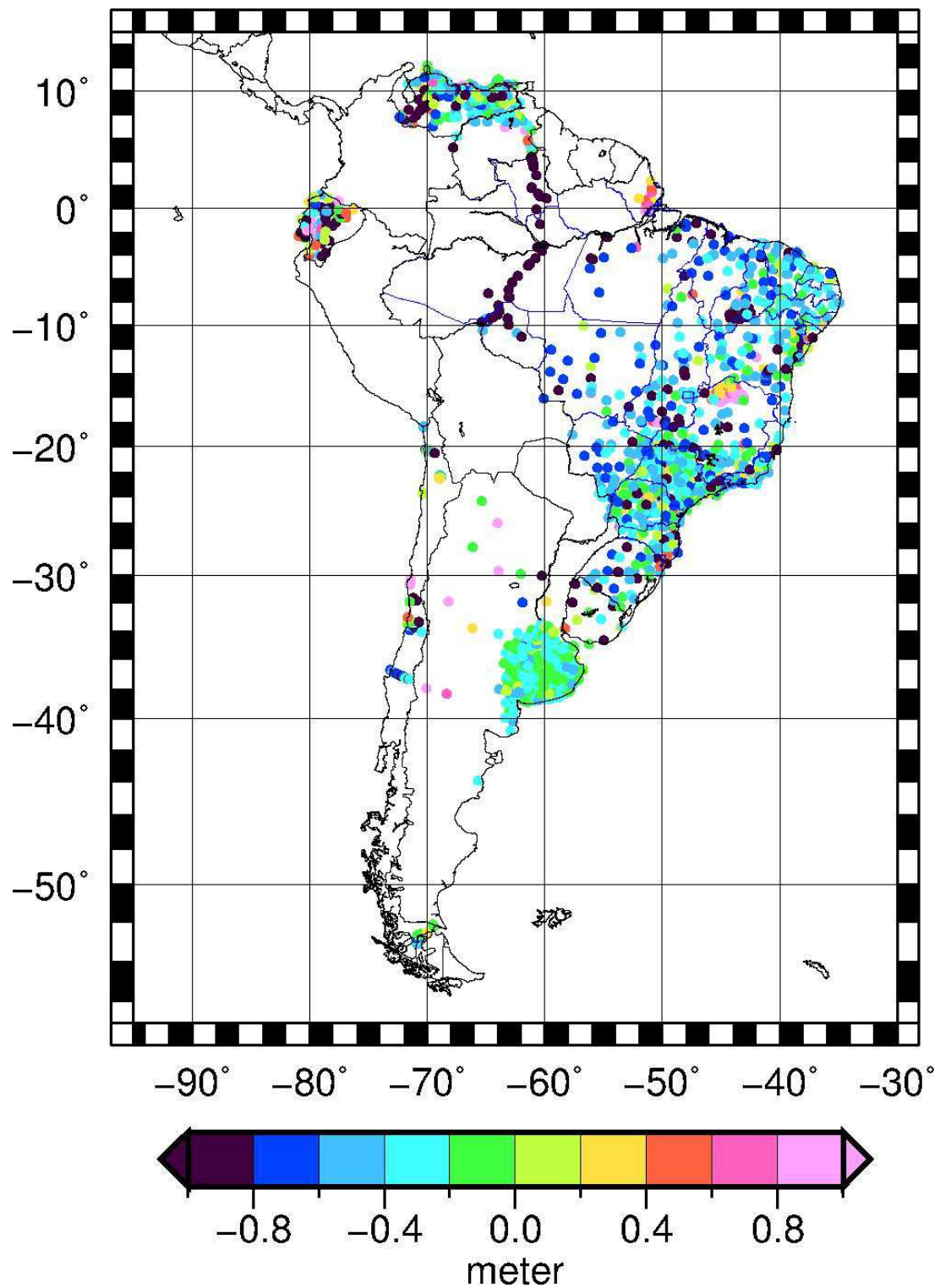


Figure 8: Distribution of the GPS/BMs and illustration of the differences between GPS/BM geoidal heights and DIRR5 (max. degree) height anomalies.

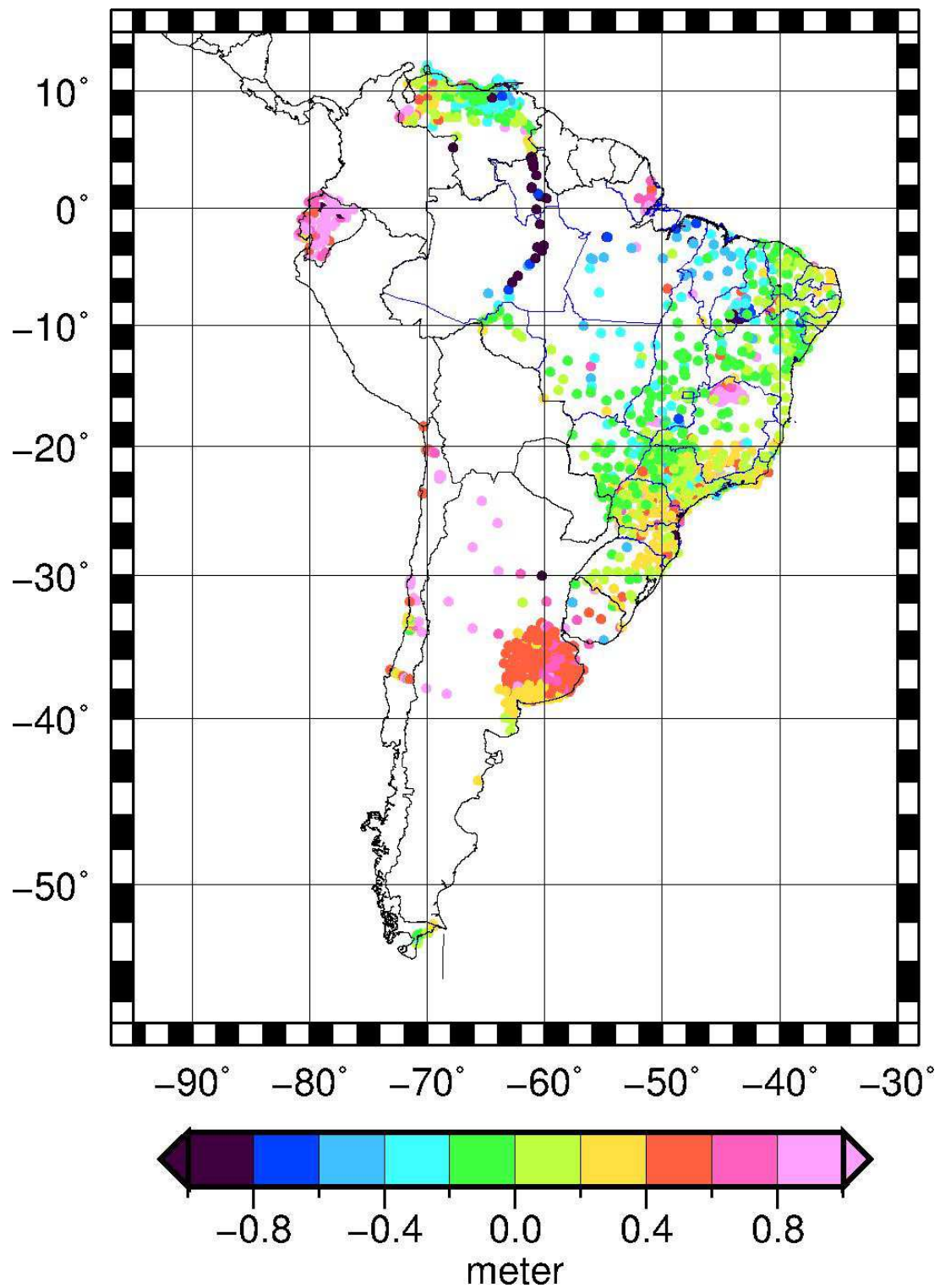


Figure 9: Distribution of the GPS/BMs and illustration of the differences between GPS/BM and GEOID2014 geoidal heights.

4 Terrestrial gravity data

South American Gravity Project (Green and Fairhead, 1991) was the first great effort in collecting and validating gravity data over the continent. This initiative was important to indicate the terrestrial and marine gravity distribution and to identify the major gaps. In 1991, the Anglo-Brazilian Gravity Project (ABGP) started some new efforts to infill the gaps in Brazil. This project was a cooperation program between LTG/EPUSP, IBGE and Geophysical Exploration Technology (GETECH), supported by U.S. National Geospatial-Intelligence Agency (NGA). After seven years of activities this project was responsible for an outstanding improvement on the gravity point distribution, mainly in the Amazon region, including rivers and airstrips along small villages. The activities of ABGP were extended to other countries in the continent in 2000 as South America Gravity Studies (SAGS). Presently a total of 892,604 terrestrial gravity points are available in South America.

The gravity anomalies derived from terrestrial gravity data are compared with gravity disturbances derived from GGMs. Table 5 shows the results in terms of mean value, standard deviation (σ) difference, RMS difference and extreme values of the differences between gravity anomalies derived from terrestrial gravity data and gravity disturbances derived from GGMs. Figures 11 and 12 show the histograms of the discrepancies between terrestrial gravity anomalies and gravity disturbances derived from EIGEN6C4 and DIRR5, respectively. One can see that EIGEN6C4 is better adjusted to the terrestrial gravity data than the other GGMs.

Figures 13 and 14 show the discrepancies between terrestrial gravity anomalies and gravity disturbances derived from EIGEN6C4 and DIRR5 in map of color palette, respectively. Nevertheless, the main discrepancies are correlated with high and rough topography, especially over Andes Mountains. In Brazil, the Minas Gerais, Rio de Janeiro and Bahia states (mountainous regions) are worse. The rain forest area that is located next to the coast of Paraná and Santa Catarina also shows high differences.

Figure 15 shows the RMS difference between terrestrial gravity anomalies and gravity disturbances derived by GGMs (180 to 360 degree) for South America. All GGMs present similar result up to 190 degree. After that up to 240 degree, the GOCE GGMs only-satellites (TIMR5, DIRR5, JYY_GOCE04S, GOGRA04S) are those with smallest RMS differences. The EIGEN6C4 shows smaller RMS differences than EGM2008 up to 320 degree.

Figure 16 shows in detail the discrepancies between terrestrial gravity anomalies and gravity disturbances derived by GGMs for Argentina (123,944 gravity points), Bolivia (99,733 gravity points), Brazil (444,608 gravity points), Chile (35,392 gravity points), Colombia (69,101 gravity points), Ecuador (13,222 gravity points), Paraguay (7,464 gravity points), Peru (39,999 gravity points), Uruguay (2,297 gravity points), and Venezuela (56,712 gravity points).

Among the countries, Chile, Colombia, Ecuador, Peru and Venezuela have the highest RMS differences. Brazil, Chile, Colombia and Venezuela all GGMs up to 200 are similar adjusted. Out of that, the complete GGMs present smallest RMS differences; the behavior is similar with Figure 15. EGM2008's RMS difference is the smallest for Argentina. GGMs only-satellite show smallest RMS differences to Bolivia, Ecuador and Paraguay. This analysis for Peru shows smallest with the EIGEN4C6 up to 230, after that GGMs only-satellite show smallest results.

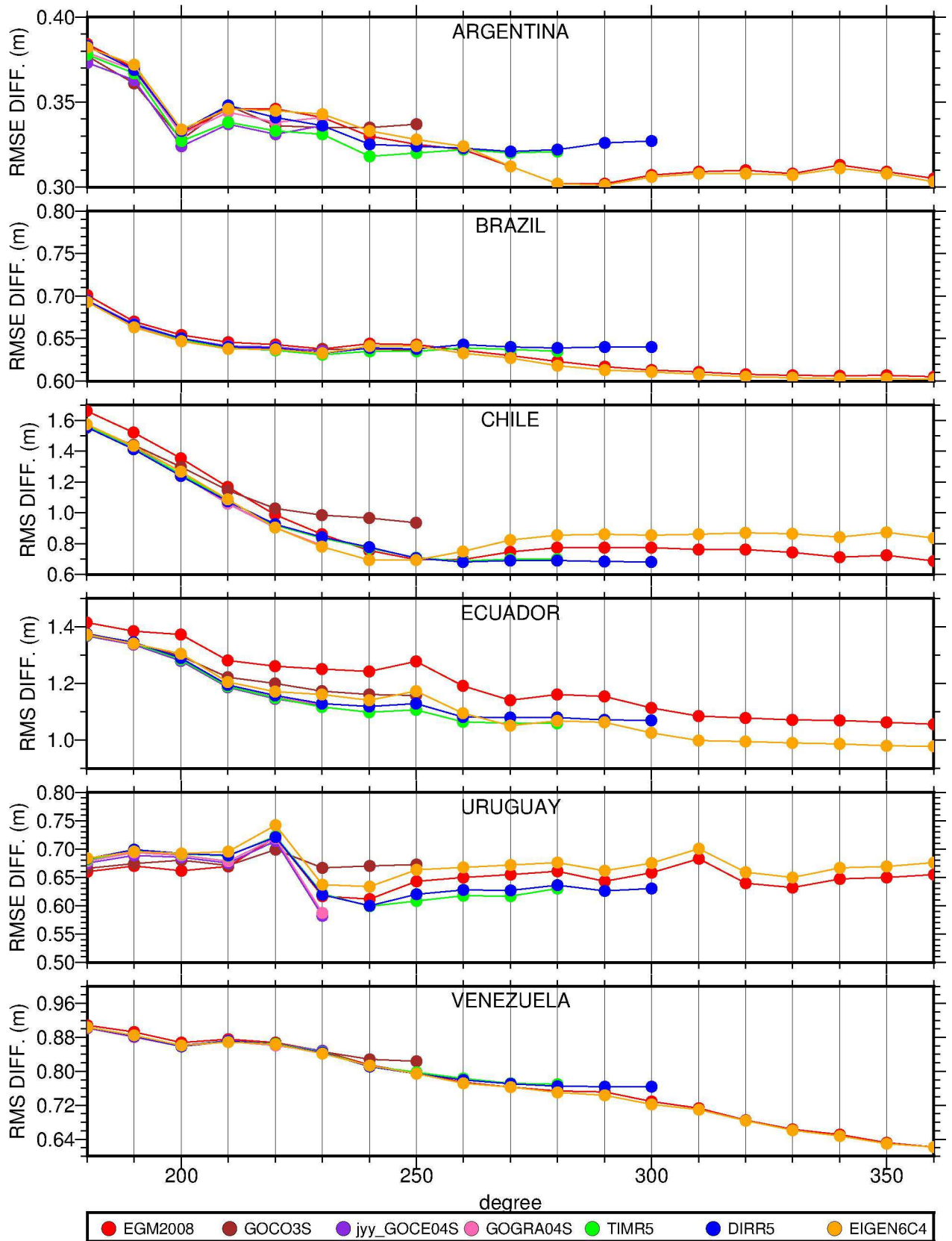


Figure 10: RMS difference between the geoid height (GPS/leveling) minus height anomalies of the GGMs (180 to 360 degree) for Argentina (296 points), Brazil (1,112 points), Chile (173 points), Ecuador (60 points), Uruguay (11 points) and Venezuela (187 points) in meter.

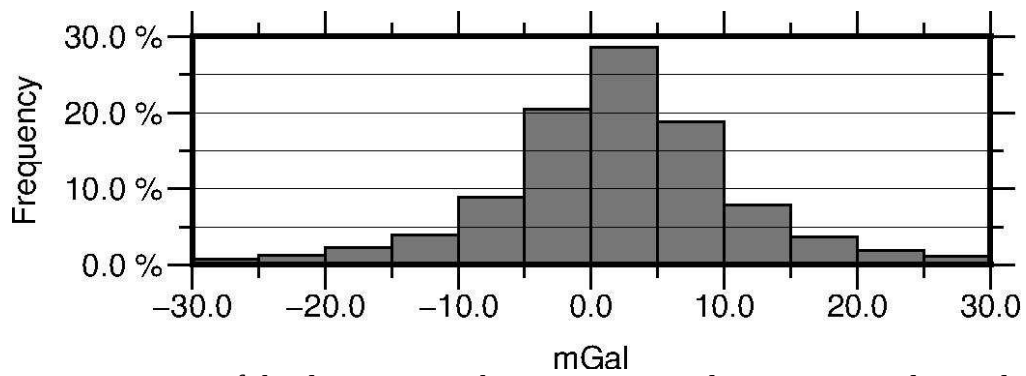


Figure 11: Histogram of the discrepancies between terrestrial gravity anomalies and gravity disturbances derived from EIGE6C4 (max. degree).

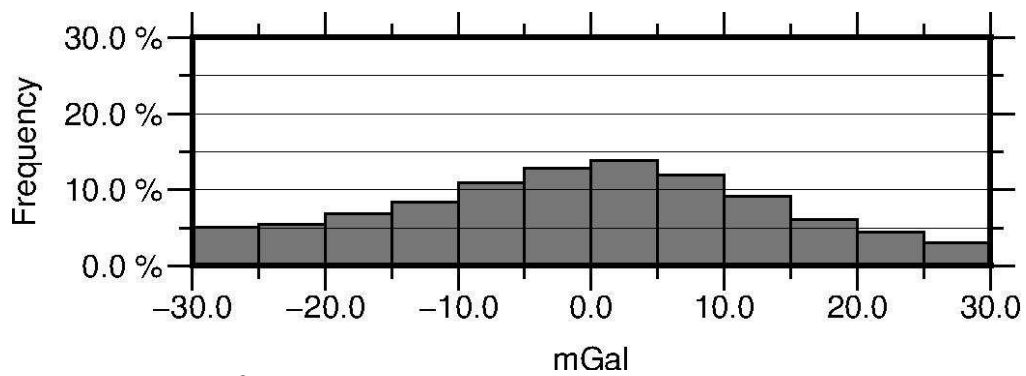


Figure 12: Histogram of the discrepancies between terrestrial gravity anomalies and gravity disturbances derived from DIRR5 (max. degree).

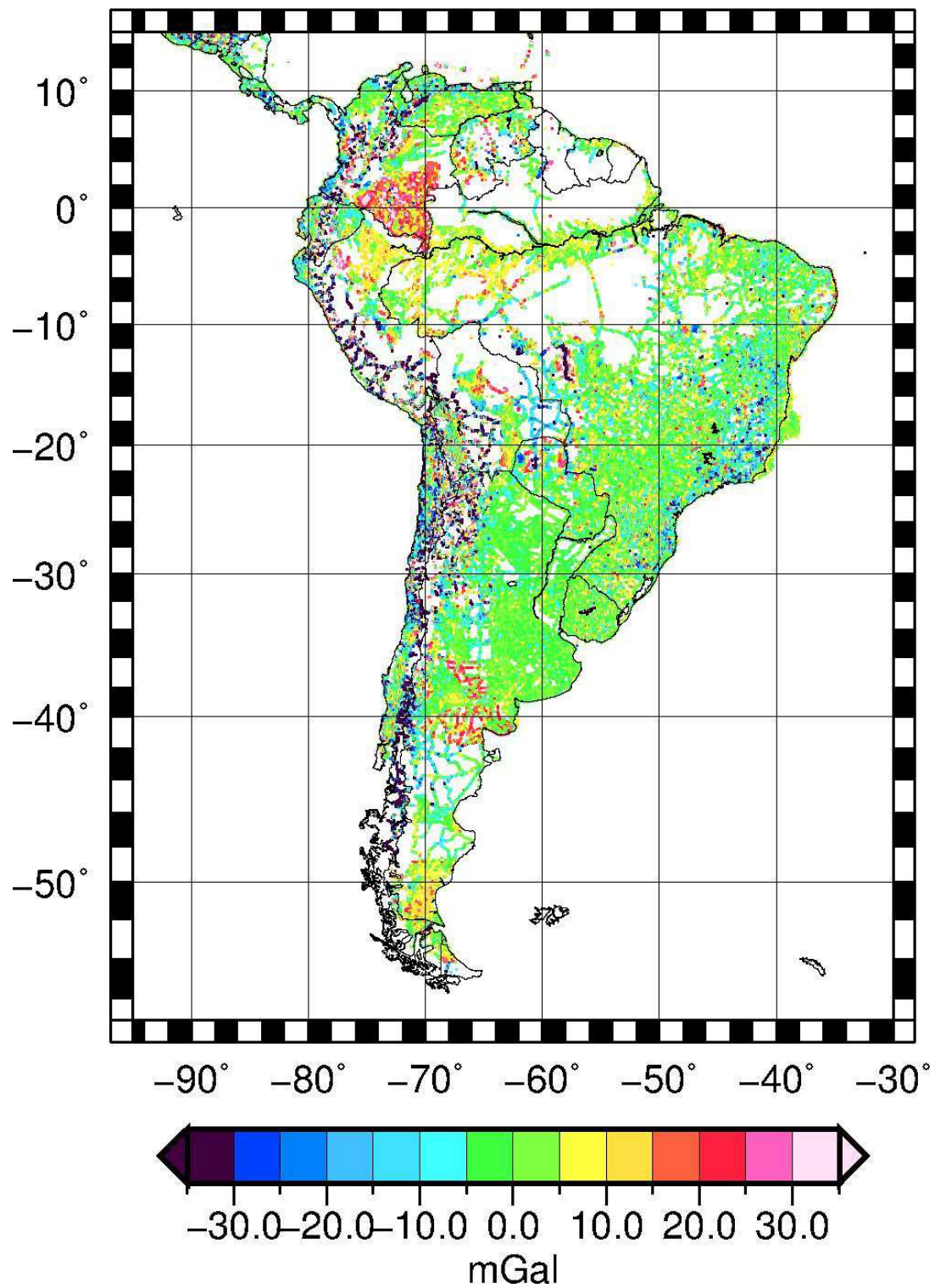


Figure 13: Discrepancies between terrestrial gravity anomalies and gravity disturbances derived from EIGEN6C4 (max. degree).

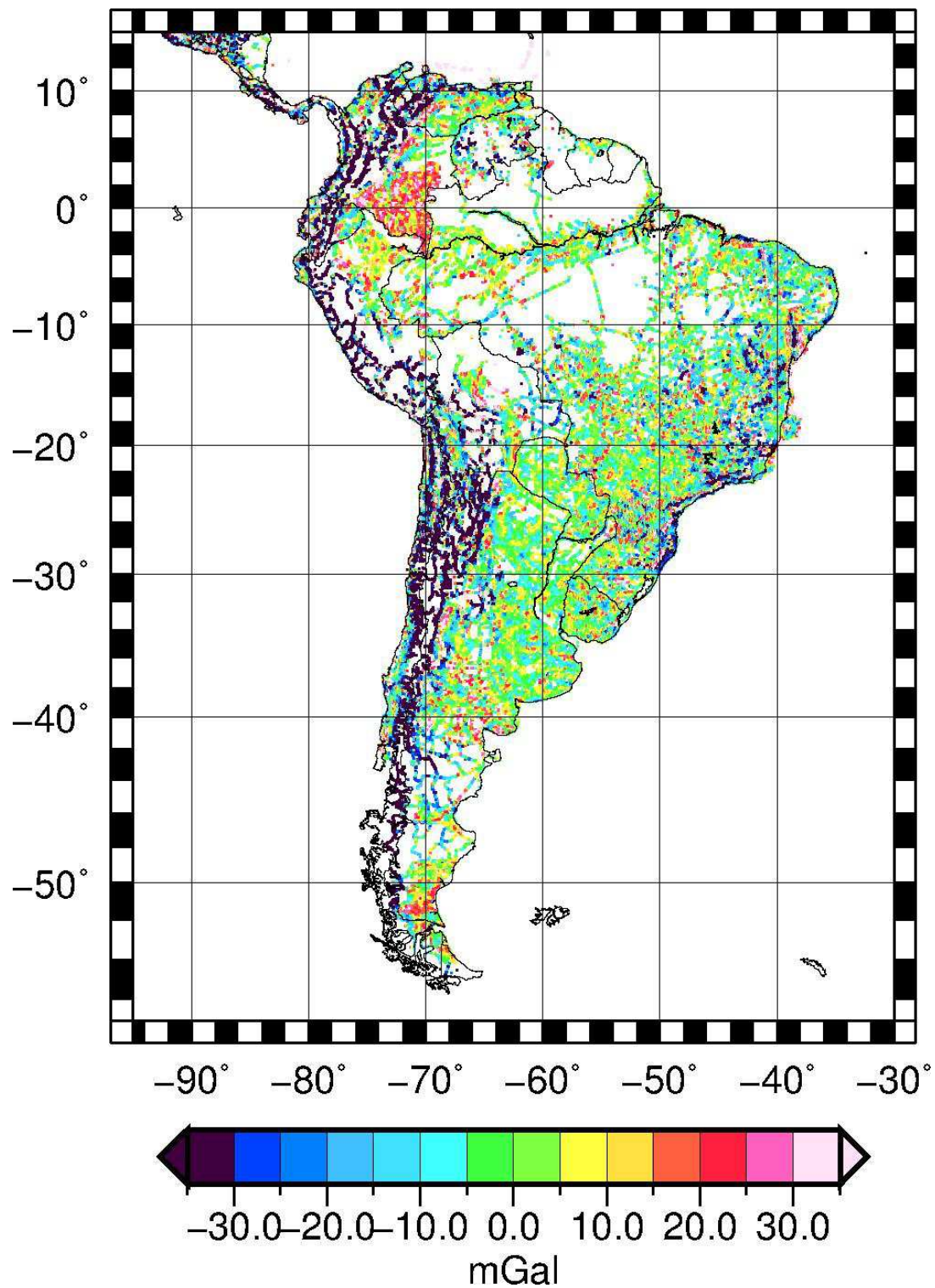


Figure 14: Discrepancies between terrestrial gravity anomalies and gravity disturbances derived from DIRR5 (max. degree).

Table 5: Statistics for the discrepancies between terrestrial gravity anomalies and gravity disturbances derived by GGMs (max degree) in mGal.

	EGM2008	GOCO03S	JYY_GOCE04S	GROGA04S	TIMR5	DIRR5	EIGEN6C4
Mean	0.97	-5.82	-5.72	-5.73	-5.14	-5.19	1.81
σ diff	14.38	25.83	25.53	25.53	24.71	24.51	14.48
RMS diff	14.41	26.48	26.17	26.17	25.24	25.06	14.59
Max.	301.59	282.20	284.27	284.39	285.42	286.53	304.81
Min.	-369.09	-369.18	-360.03	-360.21	-358.51	-351.16	-518.32

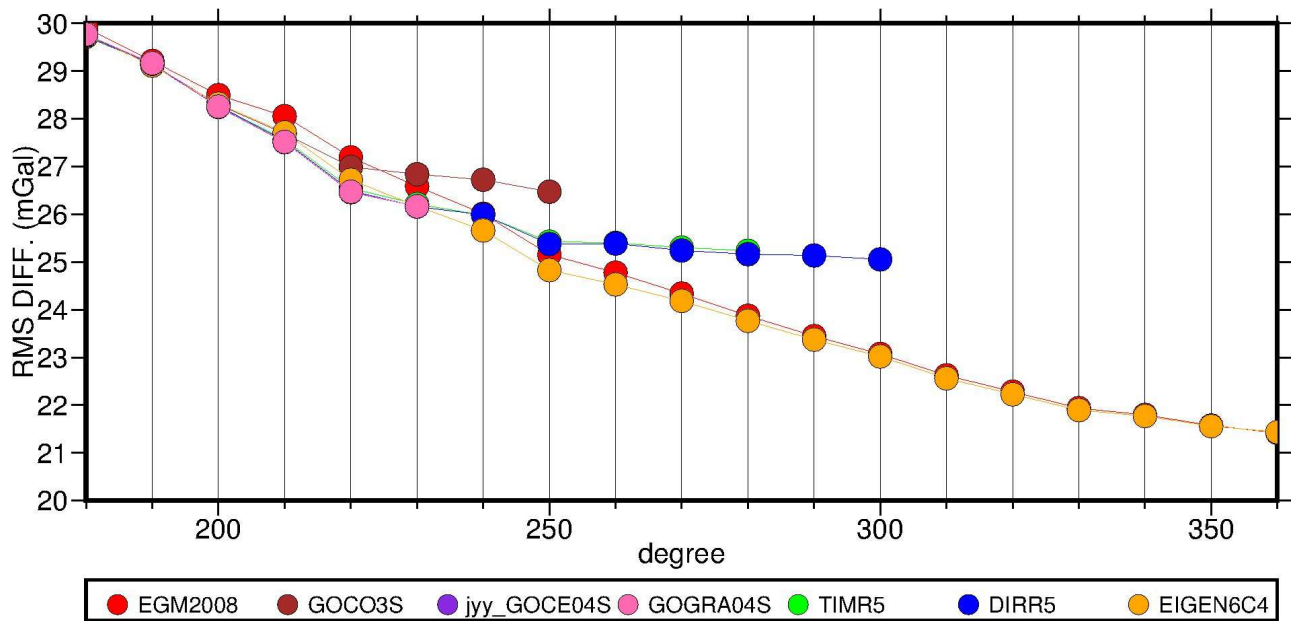
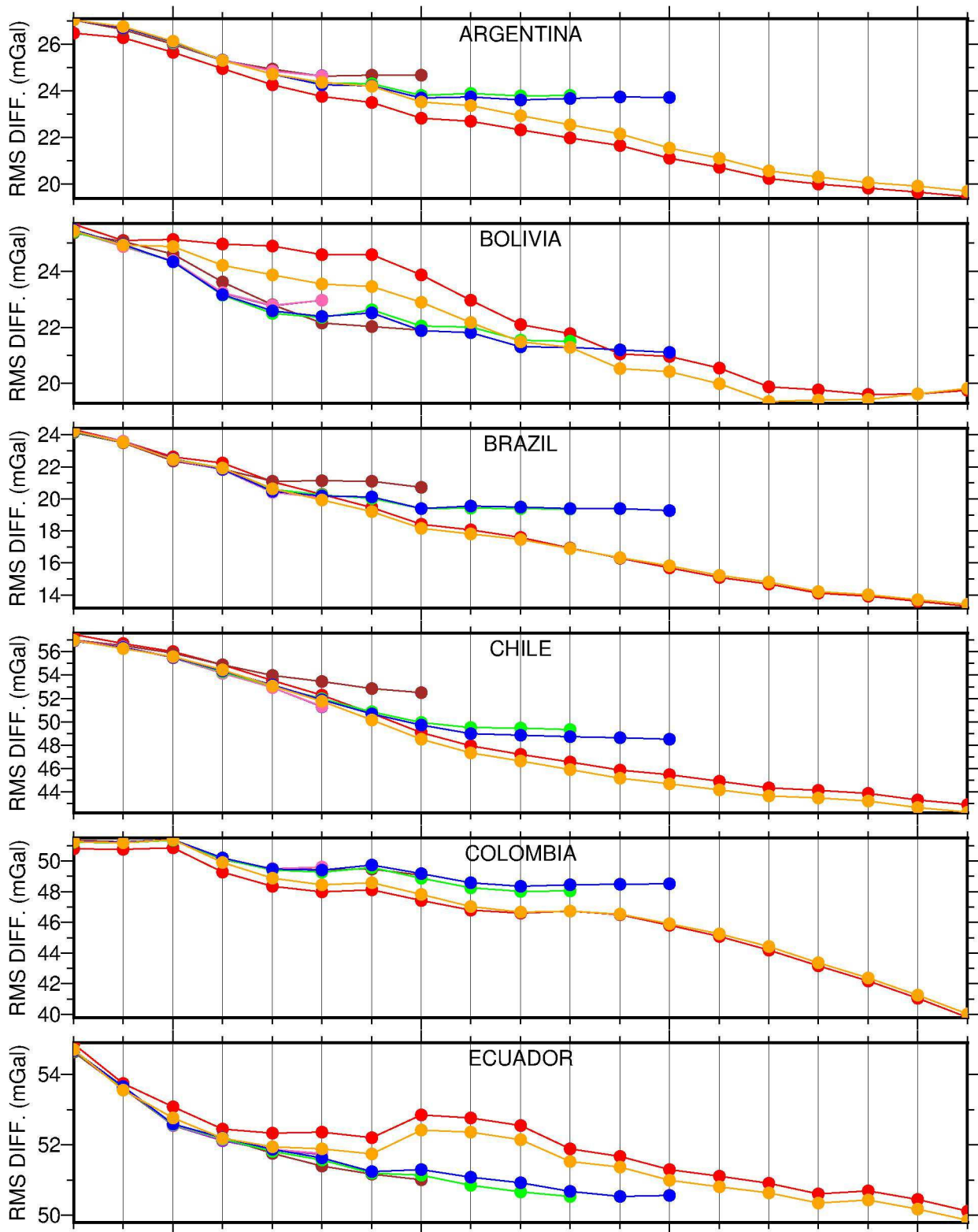


Figure 15: The discrepancies between terrestrial gravity anomalies and gravity disturbances derived by GGMs (180 to 360 degree) for South America in mGal.



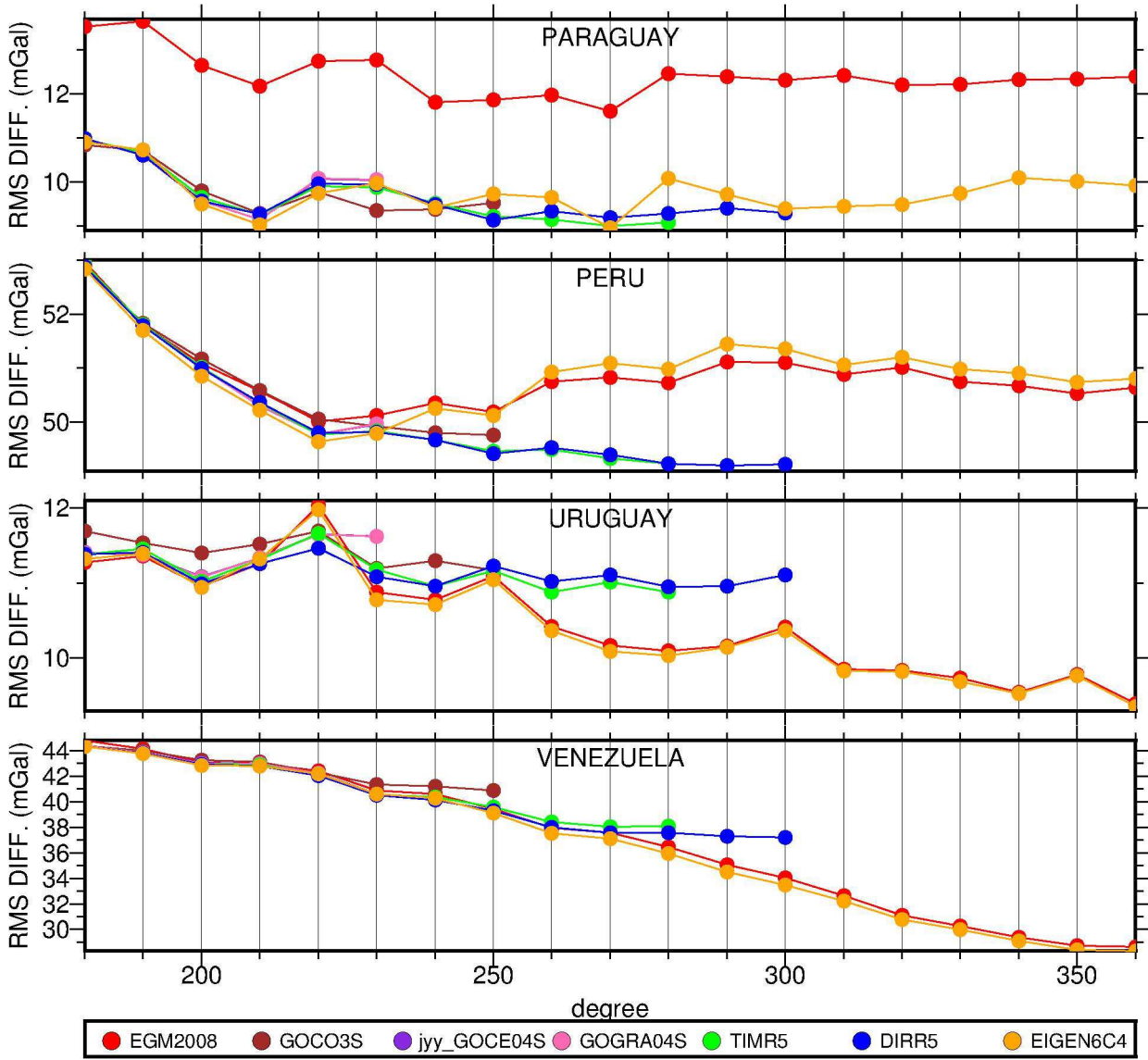


Figure 16: The discrepancies between terrestrial gravity anomalies and gravity disturbances derived by GGMs (180 to 360 degree) for Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay nad Venezuela in mGal.

5 Conclusions

The geoid undulation (height anomaly) derived from GGMs have two types of errors:

- 1- Commission error: due to the implied error of the coefficients of the GGMs;
- 2- Omission error: it is defined as neglecting harmonic coefficients higher than the highest degree in in the reference model and also due the discreteness of, or a lack of resolution, the gravimetric data (Jekeli et al, 2009; Yang, 2013).

Today's instruments are quite accurate and different sources of data are generally integrated to yield the geoid undulation, thus reducing the impact of the commission error. On the other hand, the omission error tells the resolution of gravity data (spacing between points) in a region and the

inherent accuracy. The gravity data of South America have a non-homogeneous distribution and spacing of 10 km or greater between points, out of São Paulo State (5 or 8 km) and some regions with airborne gravity surveys (Colombia). The ideal would be to have more gravity data in rough areas than smooth areas, but it is exactly the opposite that occurs due to the difficult access and high cost for such campaigns. In the Andes, aerial gravimetry is the only possibility which implies in a high cost for research institutions. The Amazon region, flat area, the difficulty is due to very dense tropical forest and the restriction to access indigenous and forest reserves. Due to all these difficulties, South America has large areas without information or few data, so it is expected a quite high omission error difficult to estimate.

This paper shows the validation of the GGMs over South America, but the errors mentioned above were disregarded. The selected GGMs are evaluated for various degrees and orders.

The statistical analysis of the differences between GPS/BM geoid heights and height anomalies of the EGM2008 and EIGEN6C4 in the Table 3 show close results. The same is observed between TIMR5 and DIRR5 and between JYY_GOCE04S and GOGA04S, respectively. The GEOID2014 has the same RMS difference that EGM2008 and EIGEN6C4 but a lower mean value.

EGM2008 shows the best fit for Chile and Uruguay (Table 4). For Argentina and Ecuador, the same occurs for EIGEN6C4. Figure 10 shows in more detail the evolution of these differences for various order and degree of GGMs studied in this paper. The GEOID2014 shows the best results for Brazil and Venezuela.

Section 4 addressed the attention to the study of discrepancies between terrestrial gravity anomalies and gravity disturbances derived by GGMs. EGM2008 has better results than EIGEN6C4 (Table 5 and Figure 15). TIMR5 and DIRR5 have similar results and as well as GOCO03S, JYY_GOCE04S and GROGA04S. Figure 16 shows the same discrepancies but in greater detail to the degrees and orders ranging from 180 to 360 degree for Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay and Venezuela. It is also observed that Andes show the highest differences (Figures 13 and 14). Colombia shows over 20 mGal differences in the region with data obtained from aerial gravimetry.

The general conclusion is that the recent geopotential models with GOCE/GRACE information represent an important improvement on the knowledge of the gravitational potential for South America.

References

- Andersen, O.B. (2010). *The DTU10 Gravity field and Mean sea surface*. Second International Symposium of the Gravity Field Service – IGFS2 20–22 September 2010 Fairbanks, Alaska.
- Blitzkow, D.; Matos, A. C. O. C.; Costa, D. S.; Guimarães, G. N.; Pacino, M. C.; Lauria, E. A.; Castro JR., C. A. C. E.; Mesquita, A. R. (2014). *Gravity surveys and quasi-geoid model for South America*. In: The 3rd International Gravity Field Service (IGFS) General Assembly, June 30-July 6, 2014, Shanghai, China.
- Bruinsma, S.; Foerste, C.; Abrikosov, O.; Marty, J.-C.; Rio, M.-H.; Mulet, S.; Bonvalot, S. (2013). *The new ESA satellite-only gravity field model via the direct approach*, Geophysical Research Letters, 40, 14:3607-3612. doi.org/10.1002/grl.50716.

- Ellmann, A.; Vaníček, P. (2007). *UNB applications of Stokes-Helmert's approach to geoid computation*. Journal of Geodynamics, 43, p. 200-213.
- Featherstone, W.E. (2003) Software for computing five existing types of deterministically modified integration kernel for gravimetric geoid determination, Computers and Geosciences 29(2): 183-193, doi: 10.1016/S0098-3004(02)00074-2.
- Ferreira, V. G.; Zhang, Y.; de Freitas, S. R. C. (2013). *Validation of GOCE gravity field models using GPS-leveling data and EGM08: a case study in Brazil*. Journal of Geodetic Science. 3(3):209–218, ISSN (Online) 2081-9943, ISSN (Print) 2081-9919, DOI: 10.2478/jogs-2013-0027.
- Förste, Ch.; Bruinsma, S.L.; Abrikosov, O.; Lemoine, J.- M.; Schaller, T.; Götze, H.- J.; Ebbing, J.; Marty, J.C.; Flechtner, F.; Balmino, G.; Biancale, R. (2014). *EIGEN-6C4 The latest combined global gravity field model including GOCE data up to degree and order 2190 of GFZ Potsdam and GRGS Toulouse*. 5th GOCE User Workshop, November, 25–28.11.2014, Paris.
- Green, C. M.; Fairhead, J. D. (1991) *The South American Gravity Project*. In: Torge, W. (Ed.). Recent geodetic and gravimetric research. [S.l.]: Springer-Verlag, p. 82–94.
- Hernández, J. N.; Blitzkow, D.; Luz, R. T.; Sánchez, L.; Sandoval, P.; Drewes, H. *Connection of the Vertical Control Networks of Venezuela, Brazil and Colômbia*. In: Drewes, H.; Dodson, A. H.; Fortes, L. P. S.; Sánchez, L.; Sandoval, P. (Ed.). Vertical Reference Systems. IAG Symposium 124, Cartagena, Colômbia. Berlin: Springer-Verlag, 2002. p. 324-327.
- Hoyer, M.; Arciniegas, S. ; Pereira, K.; Fagard, H.; Maturana, R.; Torchetti, R.; Drewes, H.; Kumar, M.; Seeber, G. (1998). *The definition and realization of the reference system in the SIRGAS project*, Springer; IAG Symposia; No. 118, 167–173.
- Jekeli, C.; Yang, H. J.; Kwon, J. H. (2009). Using gravity and topography-implied anomalies to assess data requirements for precise geoid computation, Journal of Geodesy, 83, 12, 1193
- Lauría, E. A.; Galbán, F. M.; Brunini, C.; Font, G.; Rodríguez, R.; Pacino, C. (2002). *The Vertical Reference System in the Argentine Republic*. In: Drewes, H.; Dodson, A. H.; Fortes, L. P. S.; Sánchez, L.; Sandoval, P. (Ed.). Vertical Reference Systems. IAG Symposium 124, Cartagena, Colômbia. Berlin: Springer-Verlag, 2002. p. 11-15.
- Mayer-Gürr, T. and the GOCO consortium (2012). *The new combined satellite only model GOCO03s*. Presented at International Symposium on Gravity, Geoid and Height Systems GGHS 2012, October 9-12, 2012, Venice.
- Mayer-Gürr, T. (2007). *ITG-Grace03s: The latest GRACE gravity field solution computed in Bonn*. Joint International GSTM and DFG SPP Symposium, 15-17 Oct 2007, Potsdam.
- Pail, R.; Bruinsma, S.; Migliaccio, F.; Foerste, C.; Goiginger, H.; Schuh, W.-D.; Hoeck E.; Reguzzoni, M.; Brockmann, J.M; Abrikosov, O.; Veicherts, M.; Fecher, T.; Mayrhofer, R.; Krasbutter, I.; Sanso, F.; Tscherning, C.C. (2011). *First GOCE gravity field models derived by three different approaches*. Journal of Geodesy, 85, 11: 819-843.
- Pavlis, N.K.; Holmes, S.A.; Kenyon, S.C.; Factor, J.K. (2008) *An Earth Gravitational Model to Degree 2160: EGM2008*- European Geosciences Union General Assembly, Vienna, Austria, April 13-18, 2008. <http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008>.
- Pavlis, N.K.; Holmes, S.A.; Kenyon, S.C.; Factor, J.K. (2012). *The development and evaluation of the Earth Gravitational Model 2008 (EGM2008)*. Journal of Geophysical Research: Solid Earth, 117: 2156-2202, B04406. doi:10.1029/2011JB008916.
- Piña, W. H. S.; Di Landro, H. R.; Turban, L. (2002). *The Vertical datum and Local Geoid Models in Uruguay*. In: Drewes, H.; Dodson, A. H.; Fortes, L. P. S.; Sánchez, L.; Sandoval, P. (Ed.). Vertical Reference Systems . IAG Symposium 124, Cartagena, Colômbia. Berlin: Springer-Verlag, 2002. p. 169-175.

- Poutanen, M.; Vermeer, M.; Mäkinen, J. (1996). *The permanent tide in GPS positioning*. J. Geod., 70, 8, 499–504.
- Sánchez, L.; Brunini, C. (2009) *Achievements and challenges of SIRGAS*. In: Drewes H. (Ed.): Geodetic Reference Frames, IAG Symposia 134: 161-166, Springer, 10.1007/978-3-642-00860-3_25.
- Sánchez, L. (2005). *GTIII SIRGAS: Datum Vertical – Reporte 2005*. Caracas, Venezuela, November 17 and 18, 2005. 37p.
- Shako, R.; Förste, C.; Abrykosov, O.; Bruinsma, S.; Marty, J.-C.; Lemoine, J.-M.; Flechtner, F.; Neumayer, K.-H.; Dahle, C. (2014). *EIGEN-6C: A High-Resolution Global Gravity Combination Model Including GOCE Data* - In: Flechtner, F., Sneeuw, N., Schuh, W.-D. (Eds.), *Observation of the System Earth from Space - CHAMP, GRACE, GOCE and future missions*, (GEOTECHNOLOGIEN Science Report; No. 20; Advanced Technologies in Earth Sciences), Berlin [u.a.]: Springer, 155-161. DOI 10.1007/978-3-642-32135-1_20, Print ISBN 978-3-642-32134-4 Online ISBN 978-3-642-32135-1
- SIRGAS Project Committee: *SIRGAS Final Report* (1997); Working Groups I and II, IBGE, Rio de Janeiro, 96 pp.
- Tenzer, R.; Vattré, V.; Abdalla, A.; Dayoub, N. (2010). Assessment of the LVD offsets for the normal-orthometric heights and different permanent tide systems - a case study of New Zealand. *Appl. Geom.*, 3(1): 1–8.
- Yang, H. J. (2013). Geoid Determination Based on a Combination of Terrestrial and Airborne Gravity Data in South Korea, report No. 507, Geodetic Science, v+98 pp, December 2013.
- Yi, W.; Rummel, R.; Gruber, Th. (2013). *Gravity field contribution analysis of GOCE gravitational gradient components*; *Studia Geophysica et Geodaetica*, 57(2):174-202, Springer Netherlands, ISSN 0039-3169, ISSN (Online) 1573-1626, DOI: 10.1007/s11200-011-1178-8.

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Assessment of different-generation GOCE-only and GOCE/GRACE Earth Global Gravity Models over Argentina using terrestrial gravity anomalies and GPS/Levelling data

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Abstract

The Gravity field and steady-state Ocean Circulation Explorer (GOCE) dedicated satellite gravity field mission was launched by the European Space Agency (ESA) on March 17, 2009. Since then, several Global Geopotential Models (GGMs) have been released based on data collected by GOCE.

This paper evaluates different GOCE-only and GOCE/GRACE GGMs using 567 available GPS/Levelling points and terrestrial free-air gravity anomalies in Argentina. EGM2008 and EIGEN-51C models are also included in the evaluation procedure, even though they are not based on GOCE data. The idea of using these models is to identify any improvements of the new GOCE-only or GOCE/GRACE GGMs in Argentina. The truncation of the Stokes coefficients at a certain spherical harmonic degree n_l produces an omission error. In order to reduce this omission error, synthetic GGMs are evaluated by adding signal from EGM2008 and topographic effects through a Residual Terrain Model (RTM) to the satellite GGMs models. The evaluation is performed with an incremental step of one in harmonic degree, so that the most detailed possible evaluation of the GOCE-only and GOCE/GRACE GGMs will be performed. The results show that EGM2008 is better than all GGMs, used for evaluation in this study, in terms of the standard deviation of the geoid heights are concerned. This superiority is marginal and statistically insignificant, being at the 3-2 mm level. GOCE/GRACE GGMs are significantly better than EGM2008 in terms of the range of the differences with the GPS/Levelling data, since they reduce the 1.964 m of the EGM2008 range by as much as 0.21 m for DIR_R5.

Contrary to the results for the validation with the GPS/Levelling data, all the GOCE and GOCE/GRACE GGMs are better at the 0.1 mGal level for the gravity anomaly differences.

Keywords: Global Earth gravity field models, geoid heights, gravity anomalies, GOCE.

1. Introduction

Since the launch of the GOCE (Gravity field and steady-state Ocean Circulation Explorer) satellite mission in 2009, ESA (European Space Agency) has started delivering a great variety of Global Geopotential Models (GGMs) based on different volumes of GOCE data. The latter refers to effective volumes of approximately two months, six to eight months, twelve months, twenty-seven months, and the complete mission lifetime, including the lower orbit data up to the re-entry of the satellite in November 2013, corresponding to the first release (R1), second release (R2), third release (R3), fourth release (R4) and fifth generation solutions (R5), respectively. Three different strategies have been applied for the determination of the Earth's gravity field, based on GOCE data. They are denoted as direct (DIR) solution, time-wise (TIM) solution and space-wise (SPW) solution. In addition to ESA's solutions, several combined models based on the combination of GOCE data with complementary gravity-field related information from other satellite missions like GRACE (Gravity Recovery and Climate Experiment), and terrestrial data have been developed. We will refer to these models, as GOCE/GRACE GGMs. GRACE and GOCE are complementary in terms of spectral sensitivity. EIGEN (European Improved Gravity model of the Earth by New techniques) solutions, GOCO (Gravity Observation Combination) solution and GOGRA (a combined gravity field model using GOCE and GRACE) are some examples of the GOCE/GRACE GGMs used in this study. The present paper assesses the accuracy of GOCE-only and GOCE/GRACE GGMs through comparisons with independent data like terrestrial gravity anomalies and geoid undulations derived by GPS and spirit levelling. Within that scheme, the focus is put on Argentina, where the evaluation of all available GOCE, GOCE/GRACE and combined GGMs is carried out with GPS/Levelling and gravity anomaly data.

2. Methodology for GGM evaluation

The evaluation of the GOCE, GOCE/GRACE and combined GGMs was carried out in terms of geoid undulations and gravity anomalies differences against local datasets. Geoid heights and gravity anomalies from several GGMs (N^{GGM} and Δg^{GGM} , respectively) have been compared against (a) “geometric” geoid heights represented by collocated GPS/Levelling observations on BMs ($N^{GPS/Levelling}$) and (b) point land free-air gravity anomalies (Δg) over Argentina. The residual geoid heights and residual gravity anomalies have been evaluated as:

$$\Delta N = N^{GPS / Levelling} - N^{GGM} \Big|_2^{n_1} - N^{EGM 2008} \Big|_{n_1+1}^{2160} - N^{RTM} - N_0, \quad (1)$$

$$\Delta g_{res} = \Delta g_f - \Delta g^{GGM} \Big|_2^{n_1} - \Delta g^{EGM 2008} \Big|_{n_1+1}^{2160} - \Delta g^{RTM}, \quad (2)$$

where, ΔN denotes the geoid heights differences at the GPS/Levelling BMs between the GPS-derived geoid heights ($N^{GPS / Levelling}$) and those derived by the GGM under investigation, generally denoted as (N^{GGM}).

The computation of GGM geoid undulations (N^{GGM}) has been carried out as (Heiskanen and Moritz 1967, Eqs. 8.100-8.102):

$$N^{GGM} = \zeta + \frac{\Delta g_B}{\gamma} H, \quad (3)$$

where, H is the orthometric height, Δg_B is the Bouguer gravity anomaly and ζ represents the height anomaly. The height anomaly has been computed from spherical harmonic series expansions based on the spherical harmonic coefficients of each model and the Geodetic Reference System 1980 (GRS80) normal gravity field parameters by the following expression:

$$\zeta(r, \theta, \lambda) = \frac{GM}{\gamma r} \sum_{n=2}^{n_1} \sum_{m=0}^n \left(\frac{a}{r} \right)^n \left(\overline{\Delta C}_{nm} \cos m\lambda + \overline{\Delta S}_{nm} \sin m\lambda \right) \overline{P}_{nm}(\cos \theta), \quad (4)$$

where, n_1 is some maximum degree of expansion of the GGM, $\overline{P}_{nm}$ denotes the fully normalized associated Legendre functions and $\overline{\Delta C}_{nm}$ and $\overline{\Delta S}_{nm}$ are the differences of the fully normalized potential coefficients of the gravitational potential minus the corresponding coefficients of the normal gravity potential. The second term in Eq. (3) is to convert the height anomaly to a geoid height. The Bouguer correction is determined within the *harm_synth* software (Pavlis et al., 2012) using the spherical harmonics expansion of the DTM 2006.0 model (Pavlis et al., 2012) to represent Earth's topography.

For the GGMs in Eq. (1) the evaluation is carried to some maximum degree of expansion n_1 ($N^{GGM} \Big|_2^{n_1}$), while EGM2008 (Pavlis et al., 2012) is used as a fill-in information for the rest of the geoid signal from degree n_1+1 to degree 2160 ($N^{EGM 2008} \Big|_{n_1+1}^{2160}$). The truncation of the GGM model coefficients at spherical harmonic degree 2160 produces an omission error (Torge 2001, p 273). Residual Terrain Modelling (RTM) is one approach that is suitable to compute and reduce this omission error (Hirt et al., 2010). Residual Terrain Model (RTM) effects on geoid heights (N^{RTM}) represent the topographic signal above degree 2160.

In Eq. (1) the zero-degree geoid term (N_0) is evaluated as in Heiskanen and Moritz (1967, Eq. 2.182).

$$N_0 = \frac{GM - GM_0}{R\gamma} - \frac{W_0 - U_0}{\gamma}, \quad (5)$$

where the parameters GM_0 and U_0 correspond to the geocentric gravitational constant of the reference ellipsoid and the normal gravity potential, respectively. The GRS80 ellipsoid is used as the reference ellipsoid for all numerical computations (Moritz, 2000), while the Earth's geocentric gravitational constant GM and the gravity potential at the geoid W_0 is set to $GM=398600.4415 \cdot 10^9 \text{ m}^3\text{s}^{-2}$ and $W_0=62636856.0 \text{ m}^2\text{s}^{-2}$, as given by Petit and Luzum (2010). The mean Earth radius R is taken equal to 6378136.3 m and the normal gravity γ at the surface of the ellipsoid is computed by the closed formula of Somigliana (Moritz, 2000). The same spectral enhancement approach is used for the analysis of the free-air gravity anomaly data Eq. (2).

The RTM effects on both geoid heights and gravity anomalies are estimated from an SRTM (Shuttle Radar Topography Mission) based on 3 arc-second resolution Digital Terrain Model (Tocho et al., 2012; Tziavos et al., 2010). As far as the tide system is concerned, all computations were carried out in the Tide Free (TF) system, so when a given GGM refers to the Zero Tide (ZT) system, the $\bar{C}_{20}$ coefficient is converted to TF using the following formula (Rapp et al., 1991):

$$C_{2,0}^{Tide-free} = C_{2,0}^{Zero-free} + 3.1108 \times 10^{-8} \frac{0.3}{\sqrt{5}}. \quad (6)$$

Geometric geoid undulation on land can be determined in an absolute sense according to the following equation:

$$N^{GPS / Levelling} = h - H, \quad (7)$$

where, h is the ellipsoidal height from GPS and H is the orthometric height. Eq. (7) is evaluated, in this study, including levelled heights instead of orthometric heights. As most countries, Argentina does not make any luni-solar correction for precise levelling, so that their orthometric heights refer to the Mean Tide system (MT). Therefore, orthometric heights needed to be converted from the MT to the TF with the expression (Ekman, 1989):

$$H^{TF} = H^{MT} - 0.68(0.099 - 0.296 \sin^2 \varphi). \quad (8)$$

Both the geoid height and gravity anomaly differences are evaluated with an incremental step of one harmonic degree, so that the most detailed possible evaluation of the GGMs will be achieved. Finally, it should be pointed out that the computed RTM effects represent a

maximum harmonic degree of 216,000, i.e., the omission error is at the mm-level. A more detailed discussion of the followed methodology and conventions is given in Tocho et al., (2014), Tziavos et al., (in press) and Vergos et al., (2014).

3. Global Geopotential Models, Gravity, and GPS/Levelling data over Argentina

3.1 Global Geopotential Models

Twenty one GGMs, up to their maximum degree and order (d/o), have been used in this study (Table 1). These models were released for public use via the International Centre for Global Earth Models (ICGEM) <http://icgem.gfz-potsdam.de/ICGEM/ICGEM.html>. EGM2008 complete to degree and order 2160 is used as the reference GGM against all GOCE-only and GOCE/GRACE based ones which are evaluated. It is used to fill-in medium and high frequency content for the rest of the geoid signal above the maximum degree and order (d/o) of expansion of the GOCE/GRACE models.

Some information on these GGMs and the amount of data they include, can be summarized as follows:

- EIGEN (European Improved Gravity model of the Earth by New techniques models):
 - EIGEN-51C is a combined gravity field model, complete to degree and order 360 from GRACE, LAGEOS and surface gravity data, released on September 29, 2008. This model is pre GOCE era.
 - EIGEN-6C was the first combined gravity field model complete to degree and order 1420 computed including GOCE Gravity Gradiometry (SGG) data, LAGEOS and GRACE data, augmented with the DTU10 surface gravity data (Andersen, 2010). It is the result of the collaboration of GFZ-Potsdam and GRGS-Toulouse and it was released on June 27, 2011.
 - EIGEN-6C2 is the first upgrade of EIGEN-6C which has been published in 2012.
 - EIGEN-6C3stat is a static pre-version of the future upgrade EIGEN-6C4 to d/o 1949.
- The satellite-only DIR models (DIR_R1, DIR_R2, DIR_R3, DIR_R4, and DIR_R5): The first, second, third, fourth and fifth generation of GOCE gravity field solution by the Direct (DIR) methodology, respectively. The fifth generation solutions span the complete GOCE mission lifetime, including the lower orbit data up to the re-entry of the satellite in November 2013. The time span covered is thus November 2009 up to November 2013.

Table 1: Pre GOCE-era GGMs: EGM2008 and EIGEN-51C, GOCE-only and GOCE/GRACE GGMs used for evaluation.

Models	Max d/o	Data	ICGEM name	References
EIGEN-51C	360	S(GRACE, LAGEOS),G,A	EIGEN-51C	Bruinsma et al., 2010
EIGEN-6C	1420	S(GOCE, GRACE, LAGEOS),G,A	EIGEN-6C	Förste et al., 2011
EIGEN-6C2	1949	S(GOCE, GRACE, LAGEOS),G,A	EIGEN-6C2	Förste et al., 2012
EIGEN-6C3stat	1949	S(GOCE, GRACE, LAGEOS),G,A	EIGEN-6C3stat	Förste et al., 2012
DIR_R1	240	S(GOCE)	GO_CONS_GCF_2_DIR_R1	Bruinsma et al., 2010
DIR_R2	240	S(GOCE)	GO_CONS_GCF_2_DIR_R2	Bruinsma et al., 2010
DIR_R3	240	S(GOCE, GRACE, LAGEOS)	GO_CONS_GCF_2_DIR_R3	Bruinsma et al., 2010
DIR_R4	260	S(GOCE, GRACE, LAGEOS)	GO_CONS_GCF_2_DIR_R4	Bruinsma et al., 2013
DIR_R5	300	S(GOCE, GRACE, LAGEOS)	GO_CONS_GCF_2_DIR_R5	Bruinsma et al., 2013
TIM_R1	224	S(GOCE)	GO_CONS_GCF_2_TIM_R1	Pail et al., 2010
TIM_R2	250	S(GOCE)	GO_CONS_GCF_2_TIM_R2	Pail et al., 2011
TIM_R3	250	S(GOCE)	GO_CONS_GCF_2_TIM_R3	Pail et al., 2011
TIM_R4	250	S(GOCE)	GO_CONS_GCF_2_TIM_R4	Pail et al., 2011
TIM_R5	280	S(GOCE)	GO_CONS_GCF_2_TIM_R5	Pail et al., 2011
GOCO01S	224	S(GOCE gradiometry, GRACE)	GOCO01S	Pail et al., 2010
GOCO02S	250	S(GOCE gradiometry and GOCE GPS-SST, GRACE, CHAMP, SLR)	GOCO02S	Goinginger et al., 2011
GOCO03S	250	S(GOCE gradiometry and GOCE GPS-SST, GRACE, CHAMP, SLR)	GOCO03S	Mayer-Gürr et al., 2012
ITG-GOCE02	240	S (GOCE)	ITG-GOCE02	Schall et al. 2014
GOGRA02S	230	S(GOCE, GRACE)	GOGRA02S	Yi et al., 2013
JYY-GOCE02S	230	S (GOCE)	JYY-GOCE02S	Yi et al., 2013
EGM2008	2160	S(GRACE),G,A	EGM2008	Pavlis et al., 2012

(Data: S = Satellite Tracking Data, G = Gravity Data, A = Altimetry Data
 GRACE (Gravity Recovery And Climate Experiment)
 CHAMP (CHAllenging Mini-satellite Payload)
 GOCE (Gravity field and steady state Ocean Circulation Explorer)
 LAGEOS (Laser GEodynamics Satellite)
 SLR (Satellite Laser Ranging)
 GPS (Global Position System)
 SST (Sea Surface Topography)

- The GOCE-only solutions TIM models (TIM_R1, TIM_R2, TIM_R3, TIM_R4 and TIM_R5): The first, second, third, fourth and fifth generation of GOCE gravity field solution by the Time-wise (TIM) approach.
- The satellite-only GOCO (Gravity Observation Combination) models (GOCO01S, GOCO02S, and GOCO03S). They are global gravity field models based on GOCE

gradiometry and GOCE GPS data with complementary gravity field from other satellite data like GRACE, SLR, and CHAMP.

- ITG-GOCE02 gravity field model which was computed from 7.5 months of GOCE gradiometer and orbit data from November 2009 up to June 2010.
- GOGRA02S a GOCE/GRACE combined gravity field model estimated by Yi et al., (2013).
- JYY-GOCE02S is a GOCE-only GGM developed by Yi et al., (2013) through the analysis of GOCE gravitational gradient components.

3.2 Gravity data

The gravity database used in this study has been compiled using different data sources that have been were acquired using different procedures. Most of the data have been supplied by Instituto Geográfico Nacional (IGN) of Argentina. In the whole, 180,660 point gravity values are available as displayed in Figure 1. Most of the gravity values in the network originally referred to the old Potsdam datum, but today they have been converted to IGSN71 through the application of a shift of -14.93 mGal to the measured values. This conversion formula has been tested on more than 800 points that have been measurements in both systems which results in a mean difference of 0.2 mGal. Apart from the methodology and instrumentation, the overall accuracy for the gravity measurements is better than 0.5 mGal. Free-Air gravity anomalies were calculated in the classical sense as "gravity on the geoid minus normal gravity on the ellipsoid".

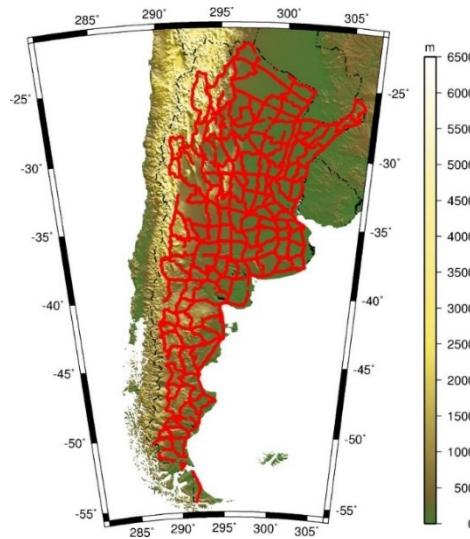


Figure 1. The gravity data base in Argentina

3.3 GPS/Levelling data

Many institutions in Argentina have established geodetic networks, mainly for cadastral purposes. Some of these points are coincident with levelling benchmarks, so they offer collocated GPS and Levelling information that can be used for the validation of GGMs. To this extent, GPS/Levelling height information on 567 points across Argentina has been supplied by the National Geographic Institute of Argentina. The geodetic coordinates (ϕ , λ , h) are framed to the POSgAR 07 (POSiciones Geodesicas ARGentinas) datum. POSgAR 07 is Argentina's official geodetic system and it was established through GPS measurements to realize the WGS84 (G1150) reference system in the country. The geocentric Cartesian coordinates of all stations were determined in ITRF2005 (epoch: 2006.632) and the ellipsoidal heights are given in the Tide Free system. The heights of the benchmarks are simple levelling heights without gravity related corrections. Thus, they are neither orthometric nor normal heights. Figure 2 depicts the distribution of the GPS/Levelling network that has been used in the following comparisons. As one can see in Figure 2, data are unevenly distributed, with the Buenos Aires plain being densely surveyed, while the Andes region is poorly covered.

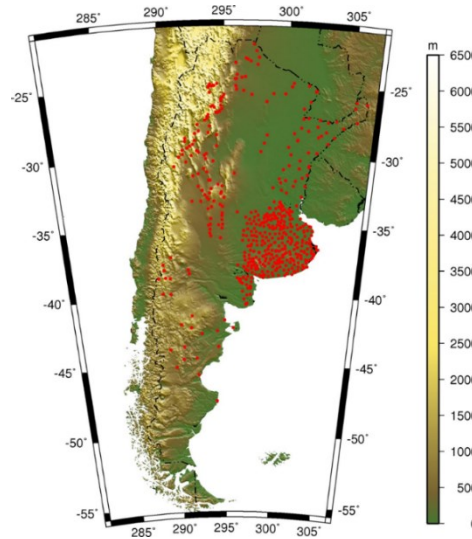


Figure 2. The GPS/Levelling database over the continental part of Argentina

4. Validation procedure

The external evaluation of GOCE-only and GOCE/GRACE GGMs is carried out with GPS/Levelling data on BMs and free-air gravity anomalies. The synthesis of the GOCE GGMs signal as outlined in Eq. (1) and (2) is evaluated per degree of the spherical harmonics expansion, through a combined use of *geocol17* (Tscherning et al., 1992) and *harm_synth_v02* (Pavlis et al., 2012). The former is used to compute the contribution of the GOCE-only and

GOCE/GRACE GGMs to a maximum degree n_l and the latter for the contribution of EGM2008 from degree n_l+1 to 2160. Finally, the RTM effects are computed with a modified version of the *tc* software, being a module of the GRAVSOFTE package (Tscherning et al., 1992). Tables 2 and 3 present the statistics of the available GPS/Levelling and gravity anomaly data, respectively, along with the RTM contribution to both geoid heights and gravity.

Table 2: Statistics of the ellipsoidal, orthometric, GPS/Levelling geoid heights and RTM effects on the BMs. Units: [m].

	max	min	mean	rms	std
h	3386.681	17.373	291.446	546.259	± 462.016
H	3347.687	2.293	272.559	532.636	± 457.617
$N^{\text{GPS/Levelling}}$	40.732	5.116	18.887	19.640	± 5.386
N^{RTM}	0.649	-0.647	-0.031	0.113	± 0.109

Table 3: Statistics of the available free-air gravity anomalies and RTM effects. Units: [mGal].

	max	min	mean	rms	std
Δg_f	498.16	-136.57	4.815	99.512	± 99.39
Δg^{RTM}	77.37	-124.38	-7.55	17.493	± 15.78

4.1 GGM spectral evaluation and external validation with GPS/Levelling data

Table 4 presents the statistics in terms of range, mean value, and standard deviation (std) of the absolute differences between the GPS/Levelling derived geoid heights available in the area under study and the synthesised GGM geoid heights enhanced with EGM2008 and RTM contributions. Note that in Table 4, we report the best GGM d/o, i.e., the n_l (see Eq. 1) that provides the overall best results w.r.t. the GPS/Levelling data in terms of the standard deviation (std) of their differences. In the same Table, the results for EGM2008 ($n_l=2160$) are used as reference for the other GGMs.

Table 4 shows that, EGM2008 with $n_l=2160$ has the overall best agreement with the GPS/Levelling-derived geoid for Argentina, with a standard deviation of ± 0.216 m and a mean value of 0.288 m. EGM2008 is superior to all GGMs used for evaluation, even from the latest fourth and fifth-generation GOCE Earth gravity field models, as far as the standard deviations of the differences are concerned. This superiority is marginal and statistically insignificant, being at the 3-2 mm level for DIR_R5 and TIM_R5, respectively, but it indicates that EGM2008 cannot be outperformed by the GOCE-only or GOCE/GRACE GGMs over Argentina. This can be attributed to the fact that most of the Argentinian gravity database has been used during the development of EGM2008; hence, the latter represents very well the

gravity field even over the remote Andes region. Moreover, the distribution of the available GPS/Levelling BMs is such that it follows the gravity survey traverses (see Figure 2) and are located mostly in lowland areas. Therefore, during the external evaluation they do not provide an independent GGM quality check, as would for instance happen if GPS/Levelling BMs over un-surveyed areas would be available.

On the other hand, the other GGMs are significantly better than EGM2008 in terms of the range of the differences with the GPS/Levelling data, since they reduce the 1.964 m of the EGM2008 range by as much as 0.21 m (DIR_R5). This is a good indication that even though the GOCE GGMs do not manage to reduce the standard deviation of the differences compared to EGM2008; they indeed manage to provide more homogeneous geoid information hence reducing the range of the differences.

Table 4: Statistics of the differences between GPS/Levelling derived geoid heights and geoid heights from the GGMs (n_1 denotes the maximum d/o that the GGMs are used, whilst above that they are complemented with EGM2008 and RTM). Units: [m].

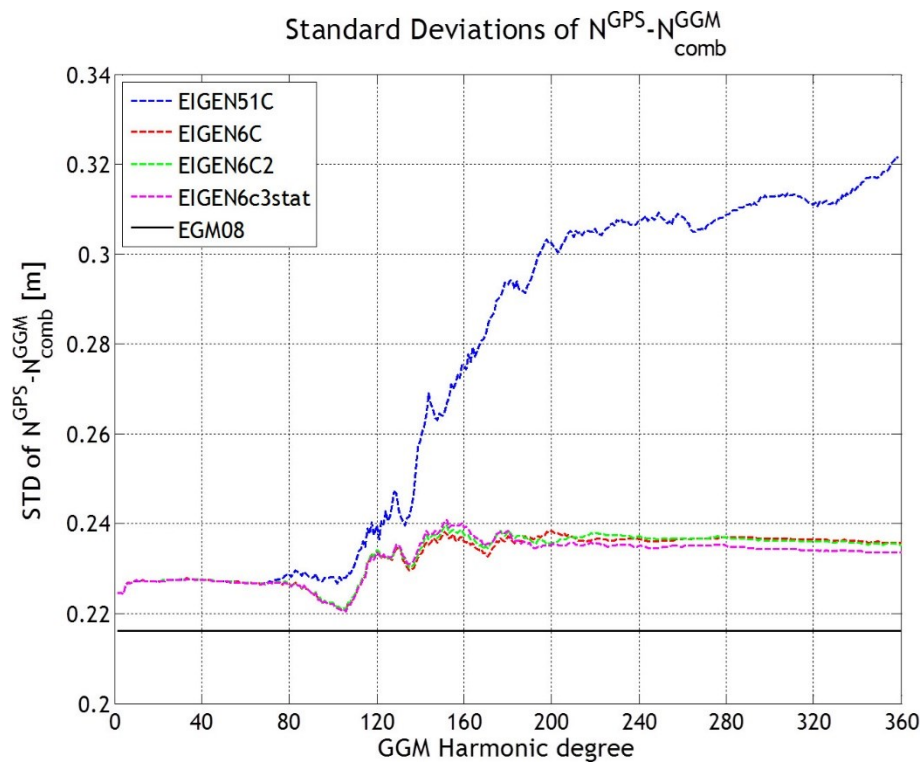
	n₁	range	mean	std
EGM2008	2160	1.964	0.288	±0.216
EIGEN-51C	64	1.955	0.289	±0.227
EIGEN-6C	104	1.854	0.286	±0.221
EIGEN-6C2	107	1.773	0.283	±0.221
EIGEN-6C3stat	107	1.794	0.283	±0.220
DIR_R1	106	1.878	0.297	±0.223
DIR_R2	102	1.819	0.289	±0.222
DIR_R3	105	1.814	0.287	±0.220
DIR_R4	106	1.791	0.286	±0.220
DIR_R5	107	1.754	0.284	±0.219
TIM_R1	103	1.774	0.288	±0.220
TIM_R2	104	1.780	0.275	±0.224
TIM_R3	103	1.777	0.279	±0.221
TIM_R4	107	1.765	0.286	±0.219
TIM_R5	107	1.764	0.286	±0.218
GOCO01S	107	1.770	0.283	±0.221
GOCO02S	107	1.767	0.283	±0.221
GOCO03S	107	1.771	0.283	±0.221
ITG-GOCE02S	103	1.773	0.283	±0.218
GOGRA02S	107	1.768	0.283	±0.221
JYY-GOCE02S	105	1.763	0.294	±0.220

Moreover, the improved performance for the GOCE-only and GOCE/GRACE GGMs with the progression of their releases (R1 to R5) is clearly noticeable. For the DIR models, the standard deviation improves from 0.223 m for R1 to 0.219 cm for R5, while the range of the differences reduces by 0.124 m. The same holds for the TIM models, for which the standard deviation

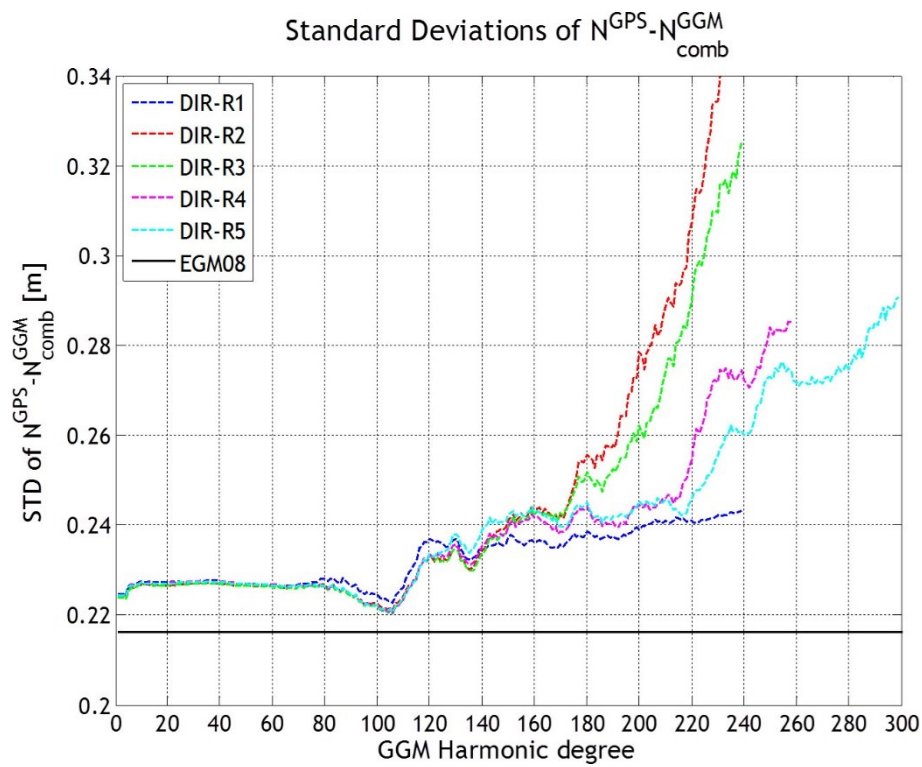
reduces by 0.002 m between the R1 and R5 versions. For the TIM GGMs, the dramatic improvement in the range of the differences, even for R1 is noticeable, since it is lower by 0.190 m compared to EGM2008. This can be attributed to the fact that the TIM GGMs are pure GOCE ones, while the DIR models incorporate GRACE data as well as some a-priori information (e.g., EIGEN-51C in DIR_R1, ITG-GRACE2010S in DIR_R2, etc.).

The evolution of the GOCE-only and GOCE/GRACE GGMs can be seen as well from Figure 3, where the standard deviation of the differences per harmonic degree is depicted for the EIGEN GGMs (Figure 3a), the DIR GGMs (Figure 3b), and TIM GGMs (Figure 3c) and for other versions of GOCE-only and GOCE/GRACE GGMs (Figure 3d). Figure 3e shows the results of the newest GGMs evaluated in this study. All EIGEN GGMs have provided quite similar results, except for the combined gravity field model EIGEN-51C which has not contained GOCE data. All the DIR models have provided quite similar results up to ~80 d/o (Figure 3b), which reflects the consistency of the different releases in this spectral range. From 180 d/o onward the standard deviations have increased rapidly for all the DIR releases. For the TIM models, even though they are marginally worse than EGM2008, their evolution with the increasing number of GOCE data used in their development is evident. If we set an arbitrary std limit at the 0.24 m, this is met at d/o 151, 147, 152, 198, and 219 for R1, R2, R3, R4 and R5, respectively (see Figure 3c). Given that the difference between the R4 and R5 versions of DIR relies on the lower-orbit GOCE data acquired during the last stages of the mission, their value is prominent at the higher bands of the GGM spectrum. The DIR_R5 GGMs start to differentiate from the R4 ones at about d/o 190-195, while after d/o 215 they boost the geoid spectrum by about 10-20 harmonic degrees. The latter is viewed in terms of acquiring the same std as that of the R4 release in higher degrees of harmonic expansion.

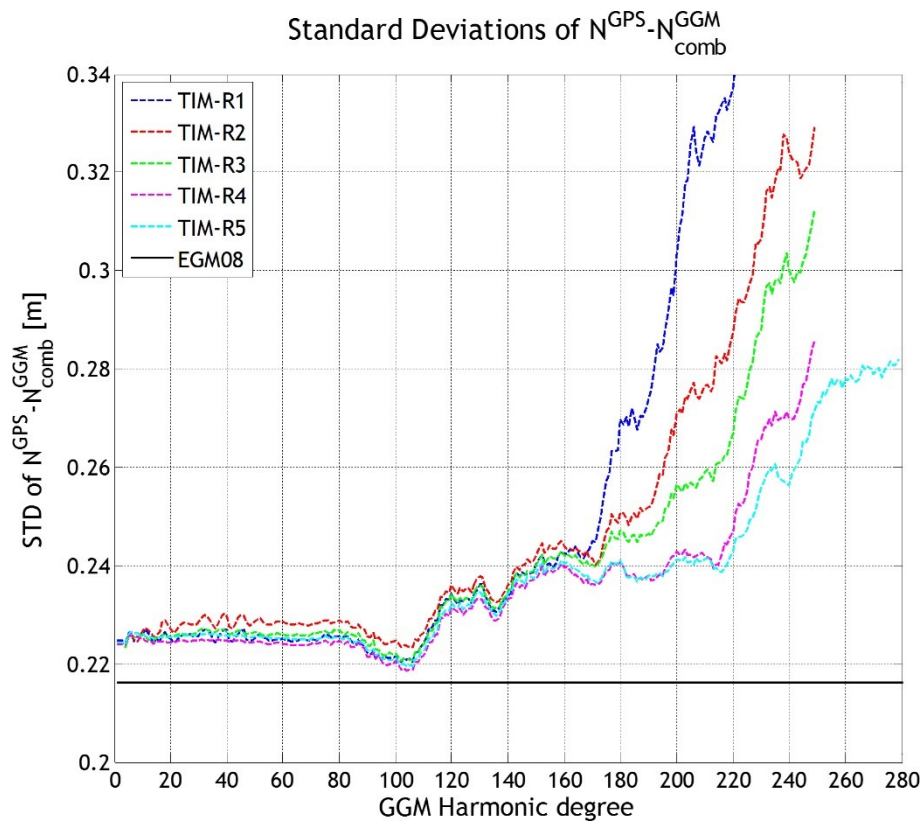
Before completing the evaluation with the GPS/Levelling data it is worth noting the performance of the latest entries in the GOCE/GRACE GGM family, i.e., GOGRA02S (see Figure 3d). Even though this model are based only on the second release of GOCE data, they provide up to some d/o comparable and slightly better results than the R5 GGMs. ITG-GOCE02S, being a pure GOCE-only model, is better than TIM_R5 and DIR_R5 up to d/o 105, while it follows TIM_R4 to d/o 172. This is indeed a very promising result for the followed short-arc approach during its development. GOGRA02S is slightly worse than ITG-GOCE02S and follows DIR_R5 up to d/o 215, but in any case, the results acquired are quite promising for the R4 and R5 versions of these new GGMs.



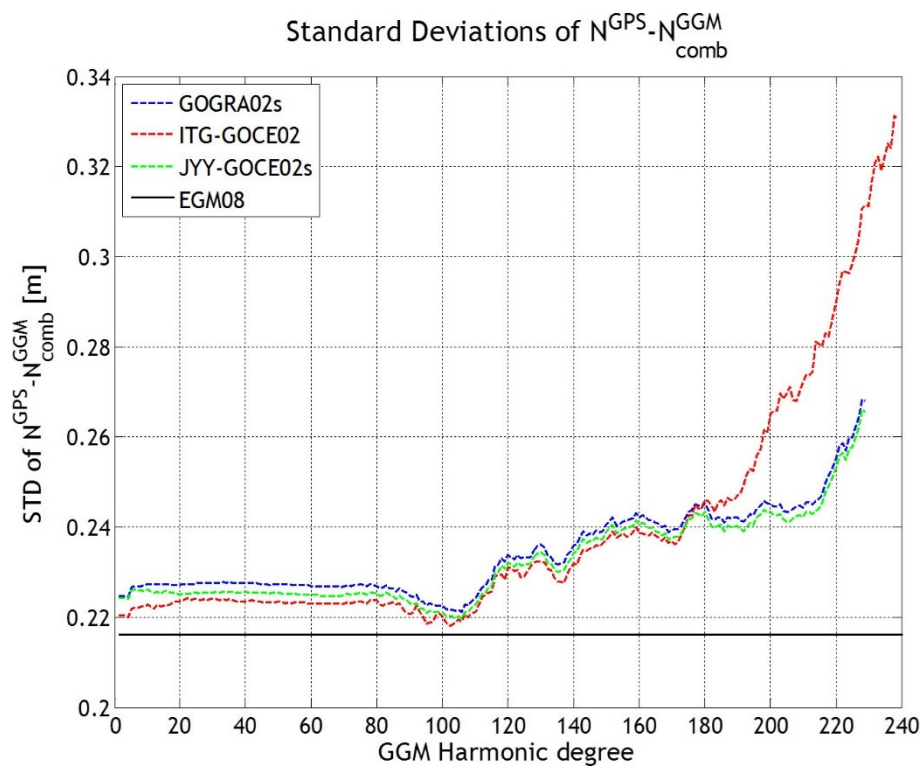
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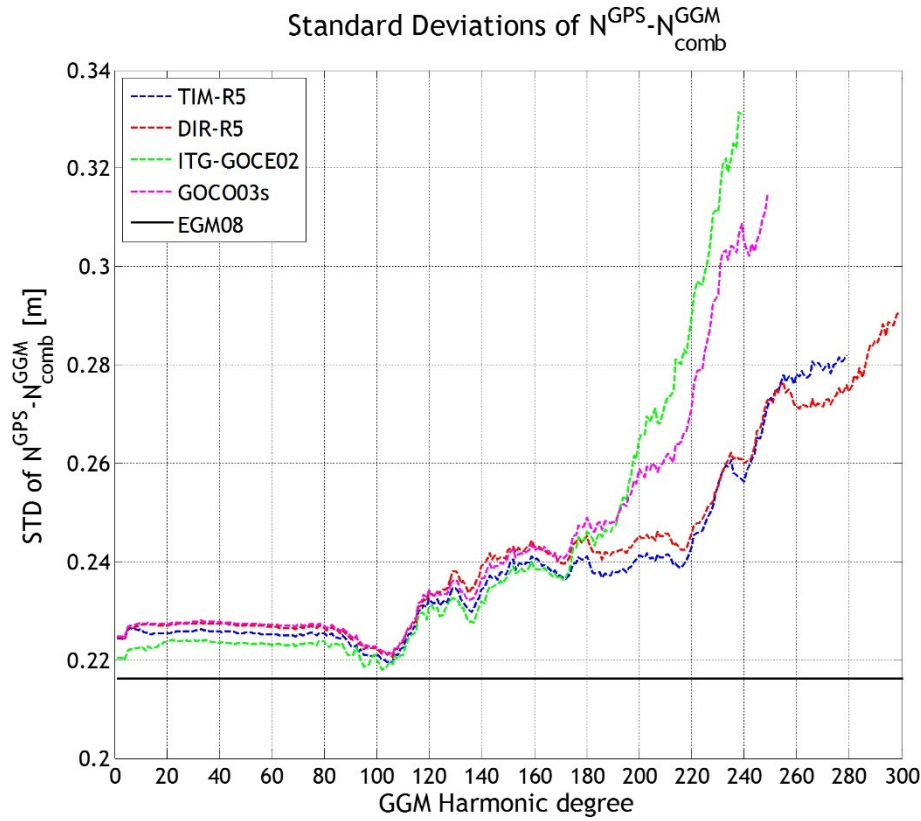
(b)



(c)



(d)



(e)

Figure 3. Standard deviations for the differences between the GOCE-only, GOCE/GRACE and combined GGMs with the GPS/Levelling geoid heights for various degrees of expansion. (a) various versions of the EIGEN models; (b) DIR_R1, DIR_R2, DIR_R3, DIR_R4 and DIR_R5; (c) TIM_R1, TIM_R2, TIM_R3 TIM_R4 and TIM_R5; (d) GOGA, JYY and ITG models; (e) comparison between the latest versions of the models studied.

4.2 GGM spectral evaluation and external validation with gravity data

Following the same validation procedure, Table 5 presents the statistics of the differences between the available local gravity data and the synthesised GGM and RTM contribution. Contrary to the results for the validation with the GPS/Levelling data, the GOCE and GOCE/GRACE GGMs manage to provide a slight improvement for the gravity anomaly differences. This improvement is marginal at the 0.1 mGal level and clearly statistically insignificant, given the accuracy of the gravity data themselves, but in any case, it is a good proof that the GOCE and GOCE/GRACE-based models perform equally well than EGM2008. Given that most, if not all, of the gravity data over Argentina have been incorporated in the EGM2008 development.

This is more clearly seen in terms of the range of the differences, which are ~ 3 mGal lower than those of EGM2008 for DIR_R4, TIM_R4, TIM_R5, ITG-GOCE02S and GOGRA02S. Figure 4a and Figure 4b shows the differences between EGM2008 and TIM_R4 with the local free-air gravity data, respectively.

Geographically, the larger differences with the local data are found over the highest peaks of the Andes with heights between 2500 m and 5000 m. It should be noted that this local gravity database has been compiled from an earlier version after a 3 rms blunder detection test. On the other hand some large free-air gravity anomaly values still exist over the highest Andes peaks (Figure 4a and 4b), therefore a more careful quality check is needed along with an investigation of the original gravity records (wherever possible).

Table 5: Statistics of the differences between the local and GGM-derived gravity anomalies. n_l denotes the maximum d/o that the GOCE-only, GOCE/GRACE, EIGEN-51C GGMs are used, whilst above that they are complemented with EGM2008 and RTM. Units: [mGal].

	n_l	range	Mean	Std
EGM2008	2160	652.00	3.34	± 23.99
EIGEN-51C	99	651.55	3.33	± 23.91
EIGEN-6C	153	649.98	3.24	± 23.89
EIGEN-6C2	152	649.42	3.22	± 23.90
EIGEN-6C3stat	156	649.17	3.22	± 23.86
DIR_R1	151	650.94	3.26	± 23.93
DIR_R2	153	650.66	3.21	± 23.89
DIR_R3	153	650.48	3.21	± 23.90
DIR_R4	154	649.62	3.23	± 23.87
DIR_R5	155	650.42	3.20	± 23.89
TIM_R1	151	650.87	3.23	± 23.91
TIM_R2	154	650.30	3.21	± 23.89
TIM_R3	154	650.01	3.22	± 23.89
TIM_R4	154	649.87	3.23	± 23.87
TIM_R5	155	649.96	3.21	± 23.88
GOCO01S	155	650.53	3.22	± 23.88
GOCO02S	155	649.59	3.22	± 23.88
GOCO03s	156	649.89	3.22	± 23.87
ITG-GOCE02S	154	649.37	3.24	± 23.89
GOGRA02S	155	649.85	3.22	± 23.87
JYY-GOCE02S	155	650.10	3.22	± 23.89

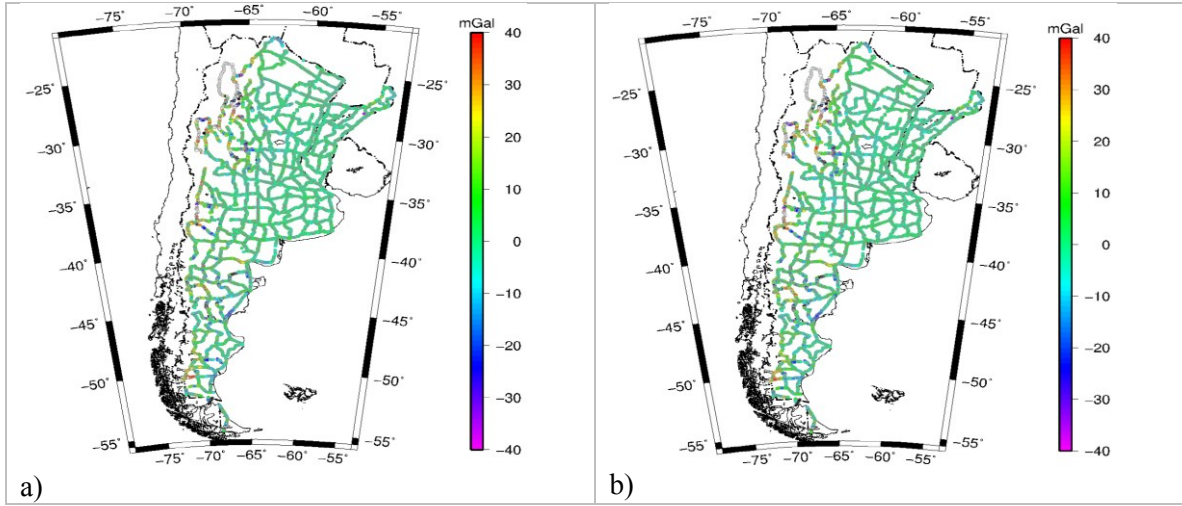
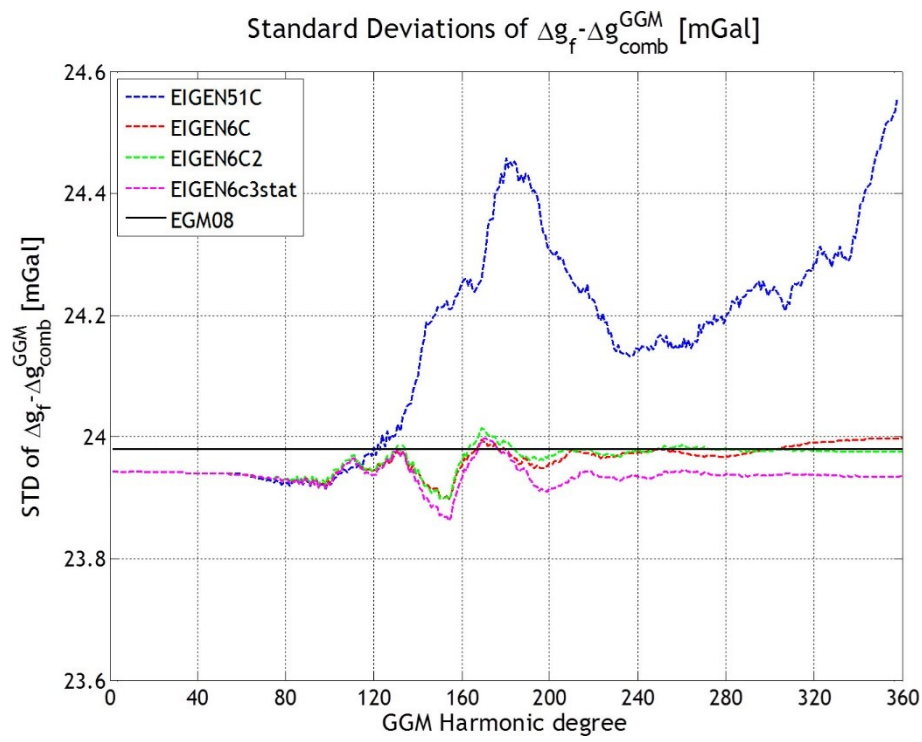
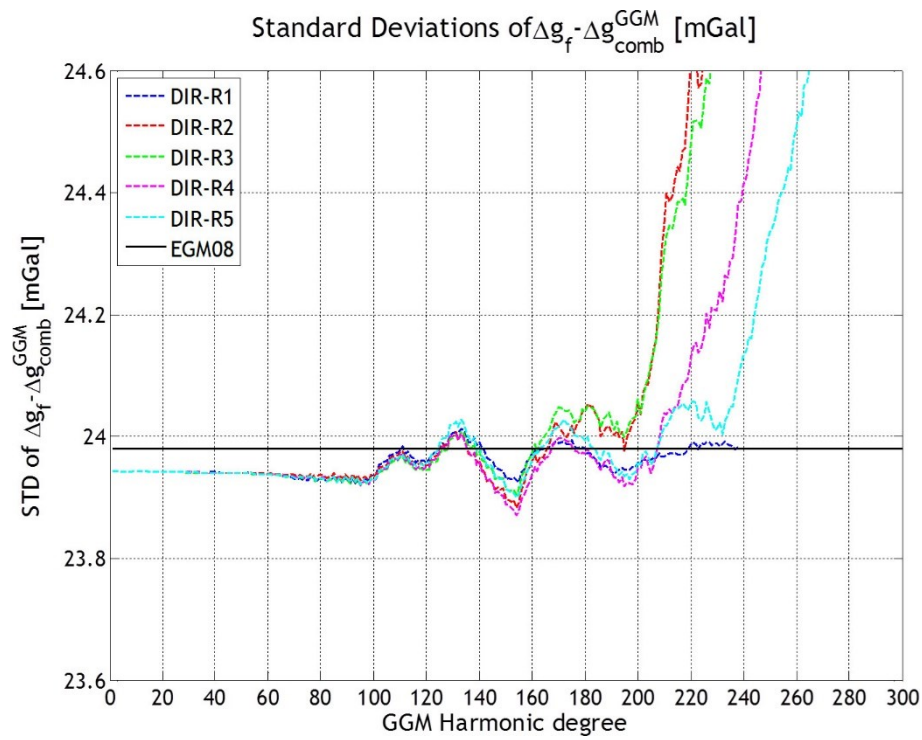


Figure 4. Differences between EGM2008 (left, d/o=2160, std=±24.0 mGal), and TIM_R4 (right, d/o=155, std=±23.7 mGal) with the local free-air gravity data.

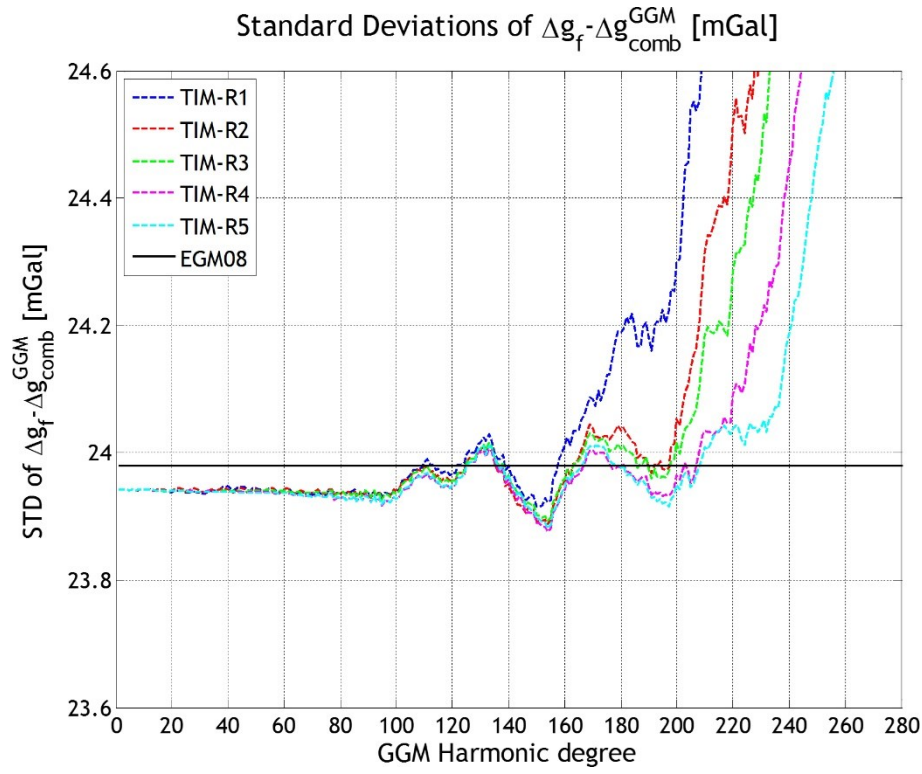
Figure 5 depicts the standard deviation of the differences between gravity anomalies computed by the different GGMs and the terrestrial gravity anomalies per harmonic degree. Figure 5a shows the differences when the EIGENs models are used, Figure 5b and 5c for the different releases of DIR and TIM GGMs, respectively. Figure 5d for the latest versions of the various GGMs. All EIGEN GGMs have provided quite similar results up to $\sim$ d/o 120 (Figure 5a), which reflects the consistency of the EIGEN solutions in this spectral range. Figure 5a also shows the big discrepancy for EIGEN-51C beyond d/o 120 due to this solution is not based on GOCE data. The EIGEN-6C combined GGM gives a similar fit to the EGM2008 beyond d/o 200, which can be expected because of the terrestrial gravity data included in that model. TIM_R1 is better than EGM2008 to d/o 158, which is boosted to d/o 166,167, 208 and 211 for TIM_R2, TIM_R3, TIM_R4 and TIM_R5, respectively (Figure 5c). ITGGOCE02S and GOGRAA02S do not show the same good performance as in the GPS/Levelling case unexpectedly. This behavior when evaluating a GGM against different external data can be attributed to the different spectral content between geoid heights and gravity anomalies. Gravity anomalies containing significant power to the medium to high frequencies, while geoid heights have most of their energy to the low to medium frequencies (Hirt et al., 2011; Schwarz 1985).



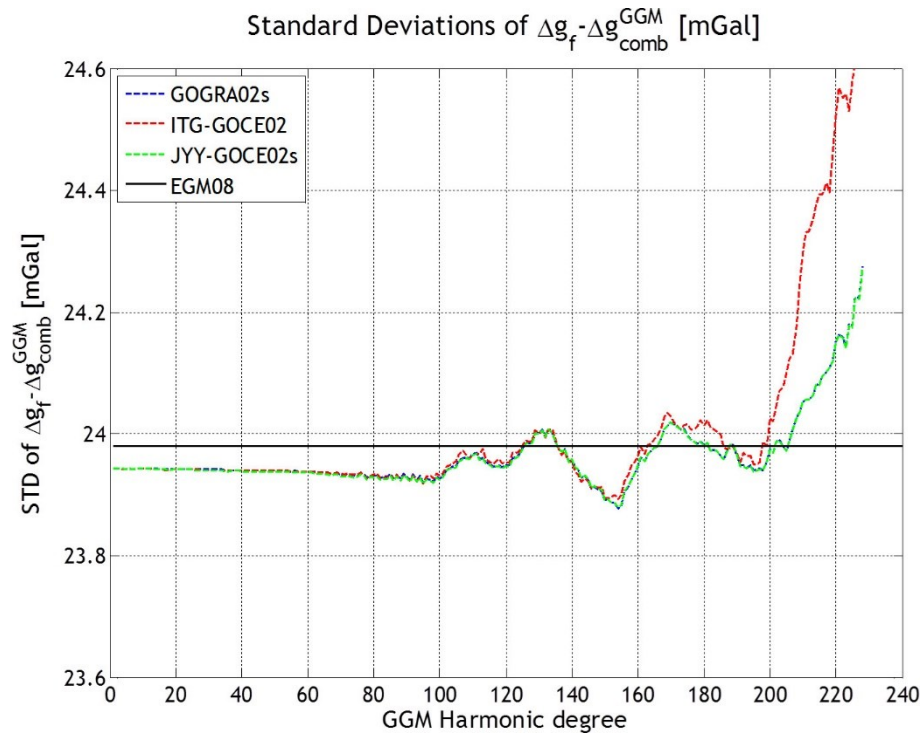
(a)



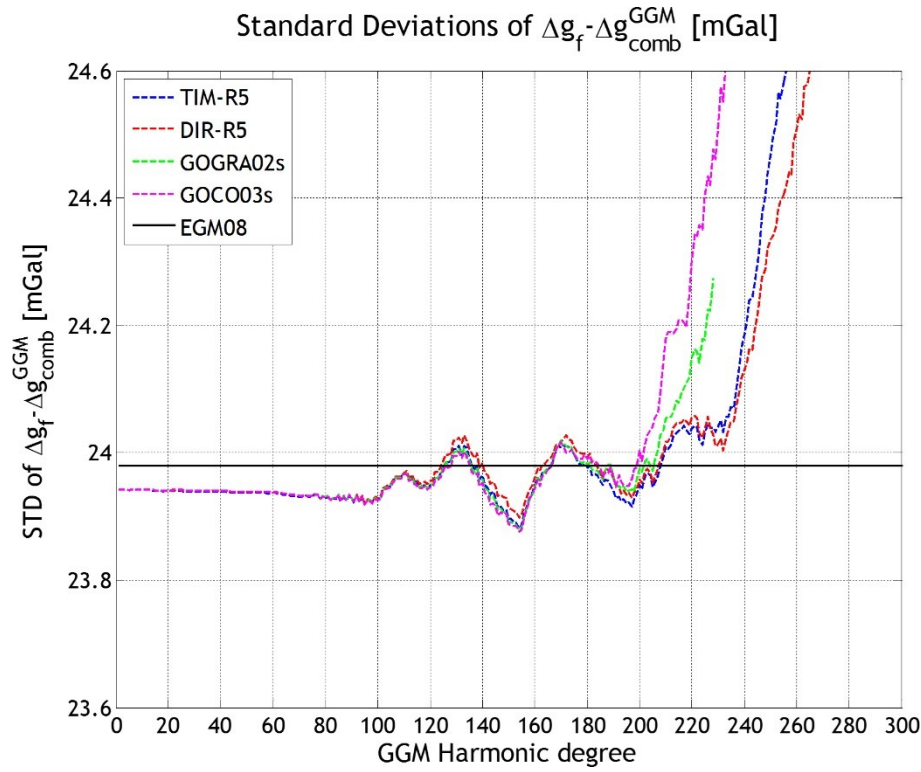
(b)



(c)



(d)



(e)

Figure 5. Standard deviations for the differences between the combined GOCE-only and GOCE/GRACE GGMs and local free-air gravity anomalies. (a) various versions of the EIGEN models; (b) DIR_R1, DIR_R2, DIR_R3, DIR_R4 and DIR_R5; (c) TIM_R1, TIM_R2, TIM_R3, TIM_R4 and TIM_R5; (d) GOGA, JYY and ITG models; (e) comparison between the latest versions of the models studied.

Conclusions

In this study, an evaluation of GOCE-only and GOCE/GRACE combined Global Geopotential Models have been carried out by comparing all of the models released by the European Space Agency High-level Processing Facility and some other GOCE and GRACE models with GPS/Levelling data and gravity observations in Argentina. The evaluation of the GGMs was also focused on their spectral comparison.

Considering the standard deviation as the main indicator of the agreement; EGM2008 is the best, by few mm, Global Geopotential Model that represents the long wavelength gravity field in Argentina as far as the geoid heights are concerned. Contrary, GOCE/GRACE GGMs are better at the sub-mGal level when gravity anomalies are considered.

A significant reduction of the range of the differences with the GPS/Levelling data was found, reaching 0.21 m for DIR_R5. For the validation with gravity anomalies a 3 mGal reduction of

the range was reached for several of the latest GOCE GGMs, while TIM_R5 and DIR_R5 are better, compared to EGM2008, all the way up to d/o 210. Finally, it can be concluded that the lower-orbit GOCE data, during the mission end, are of significant value since they boost the spectrum by 20-40 harmonic degrees compared to the earlier releases of the GGMs.

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References

- Andersen B (2010) The DTU10 Gravity field and mean sea surface –improvements in the Arctic, 2nd International Symposium of the Gravity Field of the Earth (IGFS2), Fairbanks, Alaska, 20–22 September 2010.
- Bruinsma SL, Marty JC, Balmino G, Biancale R, Förste C, Abrikosov O, Neumayer H (2010) GOCE gravity field recovery by means of the direct numerical method. In: Lacoste-Francis H (ed), Proceedings of the ESA living planet symposium, ESA Publication SP-686. ESA/ESTEC. ISBN: 978-92-9221-250-6; ISSN: 1609-042X.
- Bruinsma SL, Förste C, Abrikosov O, Marty JC, Rio M-H, Mulet S and Bonvalot S (2013) The new ESA satellite-only gravity field model via the direct approach. *Geophys Res Let* 40(14): 3607-3612. doi.org/10.1002/grl.50716.
- Ekman M (1989) Impacts of Geodynamic Phenomena on Systems for Height and Gravity. *Bull Géodésique* 63(3): 281–296.
- Förste C, Bruinsma S, Shako R., Marty JC, Flechtner F, Abrikosov O, Dahle C, Lemoine JM, Neumayer KH, Biancale R, Barthelmes F, König R, Balmino G (2011). EIGEN-6 - A new combined global gravity field model including GOCE data from the collaboration of GFZ-Potsdam and GRGS-Toulouse; *Geophysical Research Abstracts*, Vol. 13, EGU2011-3242-2, EGU General Assembly.
- Förste C, Bruinsma SL, Flechtner F, Marty JC, Lemoine JM, Dahle C, Abrikosov O, Neumayer KH, Biancale R, Barthelmes F, Balmino G (2012) A preliminary update of the Direct approach GOCE Processing and a new release of EIGEN-6C presented at the AGU Fall Meeting 2012, San Francisco, USA, 3-7 Dec, Abstract No. G31B-0923, 2012.
- Goiginger H, Rieser D, Mayer-Guerr T, Pail R, Schuh W-D, Jäggi A, Maier A, GOCO Consortium (2011) The combined satellite-only global gravity field model GOCO02S. *European Geosciences Union General Assembly 2011*, Wien, 04.04.2011.
- Heiskanen WA and Moritz H (1967) *Physical Geodesy*, W.H. Freeman and Company, San Francisco.
- Hirt C., Featherstone W.E and Marti U. (2010): Combining EGM2008 and SRTM/DTM2006.0 residual terrain model data to improve quasigeoid computations in mountainous areas devoid of gravity data, *Journal of Geodesy* 84(9), pp 557-567, DOI 10.1007/s00190-010-0395-1.
- Hirt C, Gruber T and Featherstone WE (2011) Evaluation of the first GOCE static gravity field models using terrestrial gravity, vertical deflections and EGM2008 quasi geoid heights. *J Geod* 85(10): 723-740.
- ICGEM (2014) International Centre for Global Earth Models.
<http://icgem.gfz-potsdam.de/ICGEM/>.

- Mayer-Guerr T, Rieser D, Höck E, Brockmann JM, Schuh W-D., Krasbutter I, Kusche J, Maier A, Krauss S, Hausleitner W, Baur O, Jäggi A, Meyer U, Prange L, Pail R, Fecher T, Gruber T (2012) The new combined satellite only model GOCO03S. Presented at the IAG Commission 2 “Gravity, Geoid and Height Systems GGHS2012” conference, October 9th-12th, Venice, Italy.
- Moritz H (2000) Geodetic Reference System 1980. *Journal of Geodesy*. Vol. 74, Issue 1, pp 128-133. <http://dx.doi.org/10.1007/s001900050278>.
- Pail R, Goiginger H, Schuh W-D, Höck E, Brockmann JM, Fecher T, Gruber T, Mayer-Gürr T, Kusche J, Jäggi A, Rieser D (2010) Combined satellite gravity field model GOCO01S derived from GOCE and GRACE. *Geophysical Research Letters*, Vol. 37, EID L20314, American Geophysical Union, ISSN 0094-8276, DOI: 10.1029/2010GL044906.
- Pavlis NK, SA Holmes, SC Kenyon, and JK Factor (2012) The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). *J. Geophys. Res.*, 117, B04406. <http://dx.doi.org/10.1029/2011JB008916>.
- Petit G and B Luzum (eds.) (2010) IERS Conventions 2010. IERS Technical Note 36: Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt a. M. 179 pp., ISBN 3-89888-989-6.
- Rapp RH, Nerem RS, Shum CK, Klosko SM, Williamson RG (1991) Consideration of Permanent Tidal Deformation in the Orbit Determination and Data Analysis for the Topex/Poseidon Mission. NASA TM 100775, Goddard Space Flight Center, Greenbelt, MD, 1991.
- Schall J, Eicker A, Kusche J (2013) The ITG-Goce02 gravity field model from GOCE orbit and gradiometer data based on the short arc approach, *Journal of Geodesy* April 2014, Volume 88, Issue 4, pp 403-409 DOI 10.1007/s00190-014-0691-2.
- Schwarz KP (1985) Data types and their spectral properties. In: *Proceedings of the International Summer School on Local Gravity Field Approximation*, Beijing, China, UCSE Report #60003, Division of Surveying Engineering, University of Calgary, Calgary, Alberta.
- Tocho C, Vergos GS, Pacino MC (2014) Evaluation of the latest GOCE/GRACE derived Global Geopotential Models over Argentina with collocated GPS/Levelling observations. In: Marti U (ed) *Gravity, Geoid and Height Systems*, International Association of Geodesy Symposia Vol. 141, Springer International Publishing Switzerland. doi: 10.1007/978-3-319-10837-7_10.
- Tocho C, Vergos GS, Sideris MG (2012) Investigation of topographic reductions for marine geoid determination in the presence of an ultra-high resolution reference geopotential model. In: Kenyon S, Pacino C, Marti U (eds) *Geodesy for Planet Earth*, International Association of Geodesy Symposia Vol. 136, Springer Berlin Heidelberg New York, pp. 419-426. doi:10.1007/978-3-642-20338-1_50.
- Torge W (2001) *Geodesy*, 3rd edition. Walter de Gruyter.
- Tscherning CC, Forsberg R, Knudsen P (1992) The GRAVSOFTE package for geoid determination. In: Holota P, Vermeer M (eds) *1st Continental Workshop on the geoid in Europe*, pp. 327-334.
- Tziavos IN, Vergos GS, Grigoriadis VN, Tzanou EA, Natsiopoulos DA (in press) Validation of GOCE/GRACE satellite only and combined global geopotential models over Greece, in the frame of the GOCESaComb Project. Accepted for Publication to the IAG Scientific Assembly 2013, International Association of Geodesy Symposia Vol. 143, Springer International Publishing Switzerland.
- Tziavos IN, Vergos GS, Grigoriadis VN (2010) Investigation of topographic reductions and aliasing effects to gravity and the geoid over Greece based on various digital terrain models. *Surveys in Geophysics* 31(3):23-67. doi: 10.1007/s10712-009-9085-z.

- Yi W, Rummel R, Gruber T (2013) Gravity field contribution analysis of GOCE gravitational gradient components. *Studia Geophysica et Geodaetica* pp 174-202, DOI: 10.1007/s11200-011-1178-8.
- Vergos GS, Grigoriadis VN, Tziavos IN, Kotsakis C (2014) Evaluation of GOCE/GRACE Global Geopotential Models over Greece with collocated GPS/Levelling observations and local gravity data. In: Marti U (ed) *Gravity, Geoid and Height Systems*, International Association of Geodesy Symposia Vol. 141, Springer International Publishing Switzerland. doi: 10.1007/978-3-319-10837-7__11.

Assessments of Recent GRACE and GOCE Release 5 Global Geopotential Models in Canada

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Abstract

The objective of this study is to assess the recent GRACE and GOCE release 5 (R5) global geopotential models (GGM) in Canada. For the evaluation of the GGM against GPS-Levelling data and deflections of the vertical, the satellite models need to be combined with terrestrial gravity data to determine high-resolution geoid models. This process allows a significant reduction of the omission error in the satellite gravity models. The geoid computation is founded on the remove-compute-restore Stokes-Helmert scheme, in which the Stokes kernel function modification is used to constrain the regional geoid models to the spectral bands of the satellite model to be assessed. The resulting geoid models are directly comparable to the GPS-Levelling data, and these same geoid models can be used to derive deflections of the vertical which are compared to astronomic deflections. The data analysis indicates that the GOCE R5 models provide better precision than the GOCE release 4 (R4) models beyond degree and order 180. The accuracy of the GOCE R5 models is estimated to be better than 4-5 cm up to spherical harmonic degree ~ 200 . The astronomic deflections appear not accurate enough to measure improvements in the GOCE R5 models with respect to the GOCE R4 models. For the validation of GGM against terrestrial gravity data over land, EIGEN-6C4, which includes a GOCE R5 model, is assessed in contrast to EGM2008. Our analysis infers that the GOCE contribution in EIGEN-6C4 is more accurate than the corresponding wavelength components in EGM2008, which includes the Canadian terrestrial gravity data.

1 Introduction

The Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite by European Space Agency (ESA) was launched on March 17th, 2009, and re-entered the Earth's atmosphere falling into the ocean on November 11th, 2013. Its objectives were to measure the Earth's gravity field with an accuracy of 1 mGal (one millionth of the Earth's gravity) and geoid with an accuracy of 1-2 cm at a spatial resolution of 100 km. Since the first release of GOCE models in 2010, four more generations of GOCE-only and GOCE-based satellite global geopotential models (GGM) have been made available publically. This paper will look into the latest two releases. Simultaneously, geodesists resumed the development of GGM from the ongoing twin-satellite Gravity Recovery And Climate Experiment (GRACE) mission. The paper will also investigate recent GRACE models that are now derived from more than 10 years of data. As these satellite-only models only provide the long and medium wavelength components of the gravity field, the analysis includes an extra-high degree model. EIGEN-6C4 is complete to degree/order 2190 and combines GRACE and GOCE data with terrestrial and altimetry-derived gravity data to improve the determination of the complete Earth's gravity field.

The first three releases of GOCE models were assessed using the GPS-Levelling data in Canada (Ince et al. 2012; Huang and Véronneau 2014). It was suggested that the third release of GOCE models were consistent with the Canadian terrestrial gravity data up to spherical harmonic degree 180 showing evident improvement over the first and second releases of models. Similar assessments have been made in other regions and globally using 1) GPS-Levelling data (Gruber et al. 2011; Janák and Pitoňák 2011; Guimarães et al. 2012; Odera and Fukuda 2013; Godah et al. 2014; Ince et al. 2014; Li et al. 2014; Šprlák

et al. 2014; Tocho et al. 2014; Vergos et al. 2014; Voigt and Denker 2014), 2) terrestrial gravity data (Hirt et al. 2011; Guimarães et al. 2012; Rexer et al. 2013; Šprlák et al. 2014; Vergos et al. 2014; Voigt and Denker 2014), 3) deflections of the vertical (Hirt et al. 2011; Voigt and Denker 2014), and 4) topographic forward modelling (Hirt et al. 2012b; Tsoulis and Patlakis 2013).

Assessments of the new releases of GRACE- and GOCE-based models are to understand what new and improved gravity information these models have brought in; what unique contribution each mission has made; how accurate these models are; and how combined models like EIGEN-6C4 have improved determination of the full Earth's gravity field. Answers to these questions are important in order to improve geoid modelling as Canada adopted officially the geoid-based Canadian Geodetic Vertical Datum of 2013 (CGVD2013) in November 2013. This study attempts to address these questions through assessing the recent GRACE and GOCE Release 5 (R5) geopotential models using GPS-Levelling data, astronomic deflections of the vertical and terrestrial gravity data in Canada. Following this section, Section 2 describes the methods followed for the assessments. Section 3 lists the GRACE- and GOCE-based global geopotential models assessed in this report. Section 4 provides details about the independent datasets used in the validation of the GGM. Analysis of the results is presented in Section 5. Finally, Section 6 summaries the study.

2 Methods

2.1 Comparison of Geoid Heights

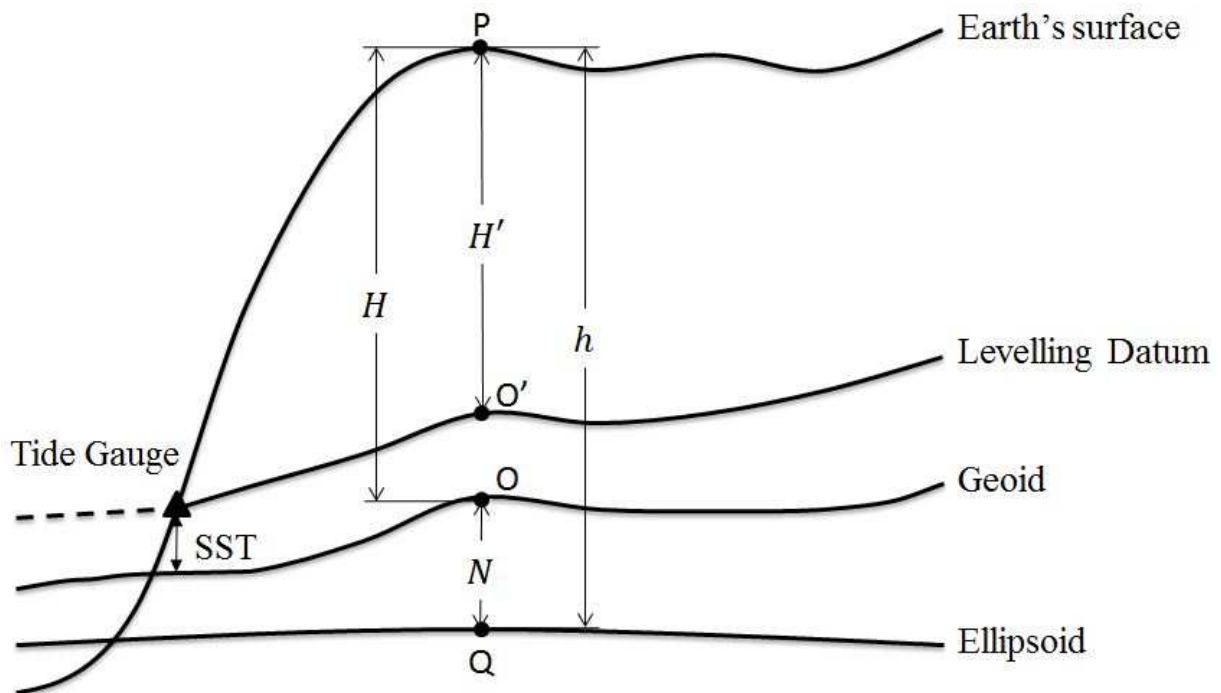


Figure 2.1 Geoid, orthometric and ellipsoidal heights.

Geoid heights N can be calculated by the GPS-measured ellipsoidal heights h and spirit-levelled orthometric heights H at benchmarks. These geometrically-determined geoid heights are independent of the gravimetric-determined geoid heights (see Figure 2.1), providing an ideal method to validate precision of geoid models, i.e.,

$$\epsilon = h - H - N \quad (2.1)$$

The first two terms on the right side of equation (2.1) gives the GPS-Levelling geoid height. Strictly speaking, the determination of precise orthometric heights requires gravity measurements along the leveling line. If we assume that all three heights are errorless, the residual ϵ is negligible, being generally smaller than 1 mm (Jekeli 2000). This is the basic equation for the comparison of GPS-Levelling and gravimetric geoid heights. Considering measurement and modelling errors, the actual residual ϵ can be expressed as

$$\epsilon = \epsilon_h - \epsilon_H - \epsilon_N \quad (2.2)$$

The three terms on the right side of equation (2.2) are errors of the corresponding heights. The ellipsoidal height error ϵ_h is considered mostly random while the orthometric height and geoid height often consists of both random and inhomogeneous systematic errors (ϵ_H , ϵ_N). Figure 2.1 shows that the levelling-determined orthometric height H' can also be biased with respect to the geoid by the mean sea surface topography (SST) as levelling datums are generally defined by the mean sea level at a specific tide gauge. These errors are usually impossible to obtain at individual GPS-Levelling data stations. Instead the error propagation by the least-squares principle is normally used to estimate their standard deviations. The combined GPS-Levelling standard deviation errors provide the base level of residuals for assessment of a geoid model. If they are known, the geoid standard deviation errors can be estimated. Otherwise the comparison can only show relatively statistical geoid improvement from model to model. The latter case applies to this study as the systematic errors of the orthometric heights in Canada are not well known.

The geoid can be determined from regional and global approaches. In regional geoid determination, the geoid height at a point is computed by the remove-compute-restore (RCR) Stokes-Helmert scheme (Huang and Véronneau 2013):

$$N(\Omega) = N_0(\Omega) + N_1(\Omega) + N_{\text{GGM}}(\Omega) + \frac{R}{4\pi\gamma_E} \iint_{\sigma_0} S_M(\psi) [\Delta g(\Omega') - \Delta g_{\text{GGM}}(\Omega')] d\sigma + \delta N \quad (2.3)$$

where Ω and Ω' are the geocentric angles denoting the geodetic longitude and latitude pairs (λ, φ) and (λ', φ') of the computation and integration points, respectively. The term N_0 accounts for mass and potential differences between the Earth and the reference ellipsoid (see Equation 2-182, Heiskanen and Moritz 1967). The term N_1 corrects for misalignment between the Earth's centre of mass and the origin of the reference coordinate system (see Equation 2-176b, Heiskanen and Moritz 1967). N_{GGM} and Δg_{GGM} represent the Helmert geoid height and gravity anomaly synthesized from a GGM and spherical harmonic forms of the digital elevation model (DEM). The spherical harmonic DEM is used to transform the two parameters above from real space to Helmert's space to realize the RCR scheme in Helmert's space (Huang and Véronneau 2013). S_M is the modified degree-banded kernel function. ψ is the spherical angle between the point of computation and an integration point. Δg is the surface Helmert gravity anomaly on the geoid derived from ground and airborne gravity and topographical data. R is the mean radius of the Earth. γ_E is the normal gravity on the reference ellipsoid. The symbols σ_0 and $d\sigma$ stand for the local domain and the surface area element on a unit sphere, respectively. The Stokes integral gives the geoid residual in a spherical approximation, which is accurate enough to achieve centimeter accuracy when a GRACE and GOCE satellite GGM model is used in the RCR scheme. Finally, the last term δN is the primary indirect effect which transforms the Helmert co-geoid height to the geoid height.

The modified degree-banded Stokes kernel function ($S_M(\psi)$) can be expressed as (Huang and Véronneau 2013):

$$S_M(\psi) = \sum_{n=2}^{nx} \alpha_n(L) \frac{2n+1}{n-1} P_n(\cos\psi) \quad (2.4)$$

where nx is the upper limit of the spherical harmonic degree and corresponds to the spectral content of the terrestrial gravity data. α_n are the spectral transfer coefficients of spherical harmonic degree n , and P_n are the Legendre's polynomials. Figure 2.2 shows α_n for three modification degrees L (180, 210 and 240) which determine how the GGM and terrestrial gravity anomalies are combined together. Figure 2.2 (left) shows the low spherical harmonic degrees of α_n . The spectral transition has a 60-degree bandwidth, where α_n increase from 0 at degree $L - 60$ to 1 at degree L . The higher is the modification of degree L , the more satellite gravity data is introduced into the solution, replacing the corresponding components of the terrestrial gravity anomalies. This substitution can improve a geoid model when the GGM components are more accurate than the terrestrial gravity components replaced, and vice versa (Huang and Véronneau 2015). Figure 2.2 (right) shows the high spherical harmonic degrees of α_n . The spectral transition bandwidth is 120 degrees, for which α_n decrease from 1 at degree 5400 to 0 at degree 5520 for the three cases. Degree 5400 corresponds to the 2' by 2' spatial resolution of the terrestrial gravity data. Thus, for the spherical harmonic degrees between degrees L and 5400, the terrestrial gravity data contribute entirely to the geoid model as $\alpha_n = 1$.

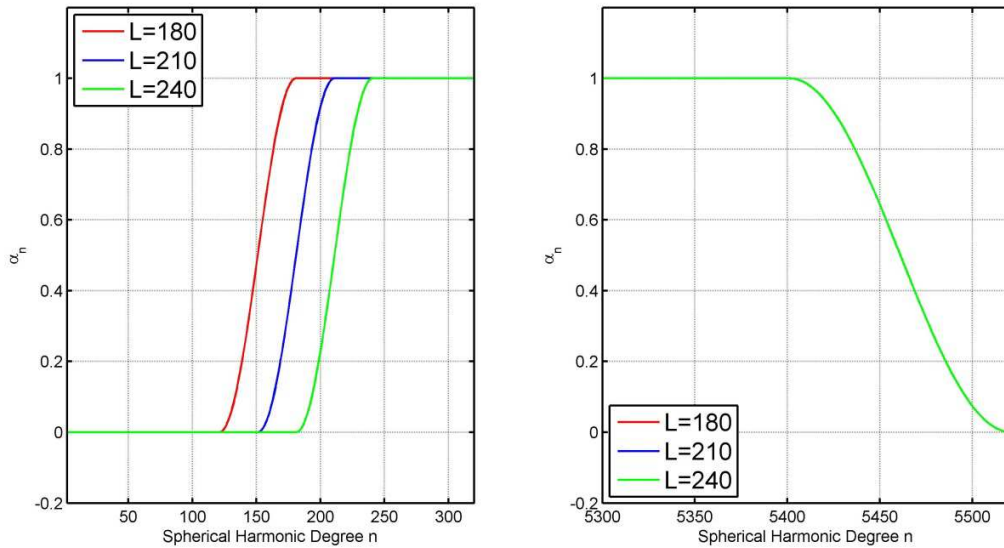


Figure 2.2 The spectral transfer coefficients α_n of the low (left) and high (right) spherical harmonic degrees for modification degrees $L = 180, 210, 240$. Note: the curves for $L = 180$ and 210 are the same as $L = 240$ on the right graph.

At the global scale, the Earth's gravity field is generally depicted by a spherical harmonic expansion. The geoid height can then be computed from a GGM as

$$N_{n_{\max}}(\Omega) = N_0(\Omega) + N_1(\Omega) + \frac{GM}{r_E \gamma_E} \sum_{n=2}^{n_{\max}} \left(\frac{a}{r_E} \right)^n \sum_{m=0}^n \bar{C}_{nm} \bar{Y}_{nm}(\Omega) + C_T(\Omega) \quad (2.5)$$

The third term represents the sum of the spherical harmonic components of the geoid synthesized from the GGM. The pair of (GM, a) are the scaling geocentric gravitational constant and radius of the GGM, respectively. $\bar{C}_{nm}$ are the fully normalized spherical harmonic geopotential coefficients that have been reduced by the even harmonic coefficients of the reference field. $\bar{Y}_{nm}$ are the fully normalized spherical harmonic functions of degree n and order m. The last term is a correction for the topographical effect (see Appendix A).

2.2 Comparison of Astronomic Deflections of the Vertical

A deflection of the vertical according to Helmert's projection is the angle at point P between the gravity vector and the normal to the reference ellipsoid. The deflection is composed of a north-south component (ξ) and east-west component (η). They can be determined by astronomic and geodetic observations to the 2nd-order term (Jekeli 1999):

$$\begin{aligned}\xi &= \Phi - \phi + \frac{1}{2}\eta^2 \tan(\phi) \\ \eta &= (\Lambda - \lambda) \cos \phi\end{aligned}\quad (2.6a \text{ and } 2.6b)$$

where the pair (Φ, Λ) are the astronomic latitude and longitude, and the pair (ϕ, λ) are the geodetic latitude and longitude.

In this study, astronomic deflections of the vertical are compared to the corresponding deflections derived from global and regional geoid models. Given gravimetric height anomalies, we can compute the deflections of the vertical according to Helmert's projection by (see 8-9, Heiskanen and Moritz 1967):

$$\begin{aligned}\xi &= -\frac{1}{R} \frac{\partial \zeta}{\partial \phi} - \frac{\Delta g}{\gamma} \frac{1}{R} \frac{\partial H}{\partial \phi} + 0.17'' H_{\text{km}} \sin 2\phi \\ \eta &= -\frac{1}{R \cos \phi} \frac{\partial \zeta}{\partial \lambda} - \frac{\Delta g}{\gamma} \frac{1}{R \cos \phi} \frac{\partial H}{\partial \lambda}\end{aligned}\quad (2.7a \text{ and } 2.7b)$$

where ζ is the height anomaly on the Earth's surface, and can be computed from the geoid height by

$$\zeta = N - \frac{\Delta g_B}{\gamma} H \quad (2.8)$$

Δg is the free-air gravity anomaly, H is the orthometric height, and Δg_B is the Bouguer gravity anomaly. The height anomaly ζ needs be transferred to the observation point level for evaluating deflections of vertical. The first terms of Equations (2.7a and 2.7b) only give approximate deflection values, and the second terms of Equations (2.7a and 2.7b) are corrections for the transfer to the observation point level to meet the theoretical requirement. The third term in Eq. (2.7a) is the correction for the normal curvature of the plumb line which converts the north-south component to the corresponding component defined in Equation (2.6a). The deflection at a point is numerically computed from the derivative of the closest nine grid points of a geoid model and the DEM. In Canada, geoid models have a standard resolution of 2' by 2' (~3.6 km in the north-south direction). This results in

having modelled deflections of the vertical that do not contain spectral components at the scale less than 2'. Therefore, the differences between the observed and modelled deflections are affected by the omission errors in the geoid models. In this study, we do not estimate this omission error as all regional geoid models are subject to the same one. The objective of study is to assess relative improvement of GOCE models from one release to next one. However, the omission error could be taken into consideration using the residual terrain modelling technique in future studies as demonstrated by Hirt et al (2010) on an European dataset.

2.3 Comparison of Gravity Anomalies

The gravity anomalies can be computed from a GGM by the following formula (Heiskanen and Moritz, 1967):

$$\Delta g(\Omega, r_s) = -\frac{\partial T(\Omega, r)}{\partial h} \Big|_{r=r_E} + \frac{1}{\gamma} \frac{\partial \gamma}{\partial h} T(\Omega, r_E) + UC \quad (2.9)$$

where

$$T(\Omega, r) = \frac{GM}{r} \sum_{n=2}^{\infty} \left(\frac{a}{r} \right)^n \sum_{m=0}^n \bar{C}_{nm} \bar{Y}_{nm}(\Omega) \quad (2.10)$$

These synthesized anomalies can be compared to the measured gravity anomalies. The routine 'Harmonic_synth.f' (version 05/01/2006, isw=50, 03 and 06) provided by the National Geospatial-intelligence Agency (NGA) was used to compute the free-air gravity anomaly on the Earth's surface at the observed gravity points.

In the computation, the ellipsoidal height at each point is computed by adding the CGG2013 geoid height to the orthometric height, which is corrected by a bias of -8 cm, representing the mean separation between Canada's old datum (CGVD28) and new datum (CGVD2013). In a second step, the ellipsoidal height is used to compute the second-order upward continuation correction UC to the free-air anomaly evaluated on the reference ellipsoid. The zero-degree term due to the difference between the geopotential constants GM of GGM and GRS80 is 0.144 mGal in absolute value and is added to the synthesized free-air anomalies. Input parameters were set to produce point values in the tide-free system with reference to GRS80 (Moritz 1980).

3 Global Geopotential Models

Table 3.1 Global geopotential models.

Model	Max Degree	Data Sources	Authors
GGM05S	180	GRACE (2003-2013) and SLR	Tapley et al. 2013
ITSG-Grace2014s	200	GRACE (2003-2013)	Mayer-Gürr et al. 2014
TIM-R4	250	GOCE	Pail et al. 2011
DIR-R4	260	Lageos, GRACE, GOCE	Bruinsma et al 2013
TIM-R5	280	GOCE	Brookmann et al. 2014
DIR-R5	300	Lageos, GRACE, GOCE	Bruinsma et al. 2014
EGM2008	2190	GRACE, Gravity, Altimetry	Pavlis et al. 2012
EIGEN-6C4	2190	GRACE, GOCE, Gravity, Altimetry	Förste et al. 2014

In this study, we assess seven GRACE and GOCE GGMs. These models are listed in Table 3.1. They include two recent GRACE models: GGM05S (Tapley et al. 2013) and ITSG-Grace2014s (Mayer-Gürr et al 2014); two GOCE R5 models: TIM-R5 (Brockmann et al. 2014) and DIR-R5 (Bruinsma et al. 2014); two GOCE R4 models: TIM-R4 (Pail et al. 2011) and DIR-R4 (Bruinsma et al. 2013); and one extra-high spherical harmonic model: EIGEN-6C4 (Förste et al. 2014). EIGEN-6C4 combines the four main types of gravity data (GRACE, GOCE, Terrestrial and altimetry). EGM2008 (Pavlis et al. 2012) is also included as a baseline for the comparisons. Among these GGMs, TIM-R5, DIR-R5 and EIGEN-6C4 include GOCE data for its entire mission.

4 Data

4.1 GPS and Levelling on Benchmarks

There are 2,668 benchmarks (BMs) observed by spirit levelling and GPS spreading through five independent levelling networks for this study. These networks encompass the Canadian mainland (CA) with 2449 BMs, the provinces of Newfoundland (NFLD) with 113 BMs and Prince Edward Island (PEI) with 18 BMs, as well as Anticosti Island (AI), located in the Gulf of St-Lawrence, with 15 BMs, and Vancouver Island (VI) with 73 BMs on the west coast. The mainland network includes few benchmarks in Alaska as a levelling loop in the Yukon Territory goes within the USA. The orthometric heights are from the Sept12 adjustments. These are minimum constraint adjustments. For example, the mainland network is constrained to a single benchmark in Halifax, Nova Scotia. The datum at this station is the equipotential surface $W_0 = 62636856m^2s^{-2}$ (definition of CGVD2013), determined by $(h - N) * \bar{g}$ where N is from CGG2010 transformed to the above mentioned equipotential surface. The GPS ellipsoidal heights are from two national adjustments: version 3.3 for the GPS survey between 1986 and 1993 and version 5.3.1 for the GPS survey after 1993 (Craymer personal communication 2012). All the ellipsoidal heights are in ITRF2008 and transformed to epoch 2010.0.

4.2 Astronomic Deflections of the Vertical

In Canada, the astronomic observations were collected between 1910 and 1975. The geodetic coordinates were derived by traditional angular and distance measurements, and transformed into ITRF93. Figure 4.1 shows the distribution of the 939 astronomical deflections of the vertical in Canada while Table 4.1 provides some statistical information. These deflections are the same ones that were used in the evaluation of EGM2008 (Huang and Véronneau 2009). They have estimated accuracy between 0.3 and 0.5 arcsec. The second order term in Equation (2.6a), which is smaller than 0.005 arcsec for all the stations, is negligible.

Table 4.1 Statistics of deflections of the vertical in arcsec.

	Number	Min	Max	Mean	StdDev	R.M.S.
ξ (north-south)	939	-23.41	17.88	0.21	4.50	4.51
η (east-west)	939	-22.39	24.35	-0.23	6.14	6.14

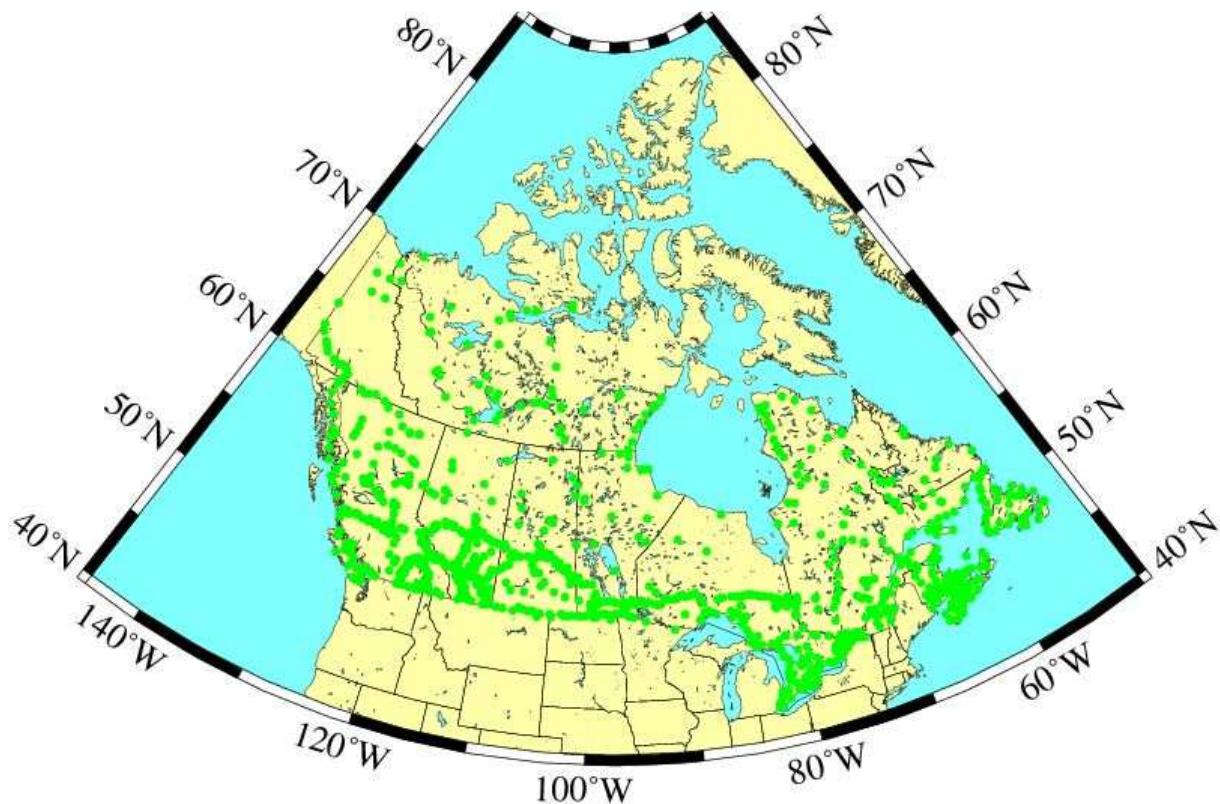


Figure 4.1 Location of the 939 astronomic deflections of the vertical in Canada.

4.3 Gravity Anomalies

In Canada, gravity data include a collection of gravity observations on land, ice caps, sea and lake surfaces (ship and ice), sea and lake bottoms, and in the air (airborne). About 98 percent of the observations were collected over the last 50 years covering entirely Canada and neighboring oceans. There are some 750,000 Canadian gravity measurements in the gravity database (CGDB). Each record essentially contains the station unique number, latitude, longitude, gravity, error estimate, observation year, etc. The accuracy of the derived free-air gravity anomalies (GRS80) varies across Canada depending on the type of instruments, platforms, height reductions, etc. The estimates of their errors range from 0.01 to 10.01 mGal with a mean of 1.88 mGal. Among these observations, the overall accuracy of land gravity observation is the best. Table 4.2 shows a statistical description of the free-air gravity anomalies along their error estimates and elevations. The error for the anomalies is the combination of the errors coming from gravity and elevation measurements, the elevation being the dominant error source. Figure 4.2 depicts the error of the gravity anomalies in Canada. One can observe that the error estimates are smaller than 1 mGal over most of the Canadian territory. The larger errors can be seen over Baffin Island, Northwest Territories, northern Quebec and southern British Colombia. The same land gravity data set was used for the evaluation of EGM2008 (Huang and Véronneau 2009); though, the gravity database now includes an additional ~15,000 measurements.

Table 4.2 Statistical description of the 231,079 free-air gravity anomalies over land.

Data	Min	Max	Mean	StdDev	R.M.S.
Free-air anomalies (mGal)	-183.62	393.31	-9.99	28.73	30.42
Error standard deviations (mGal)	0.00	9.26	0.83	0.72	1.10

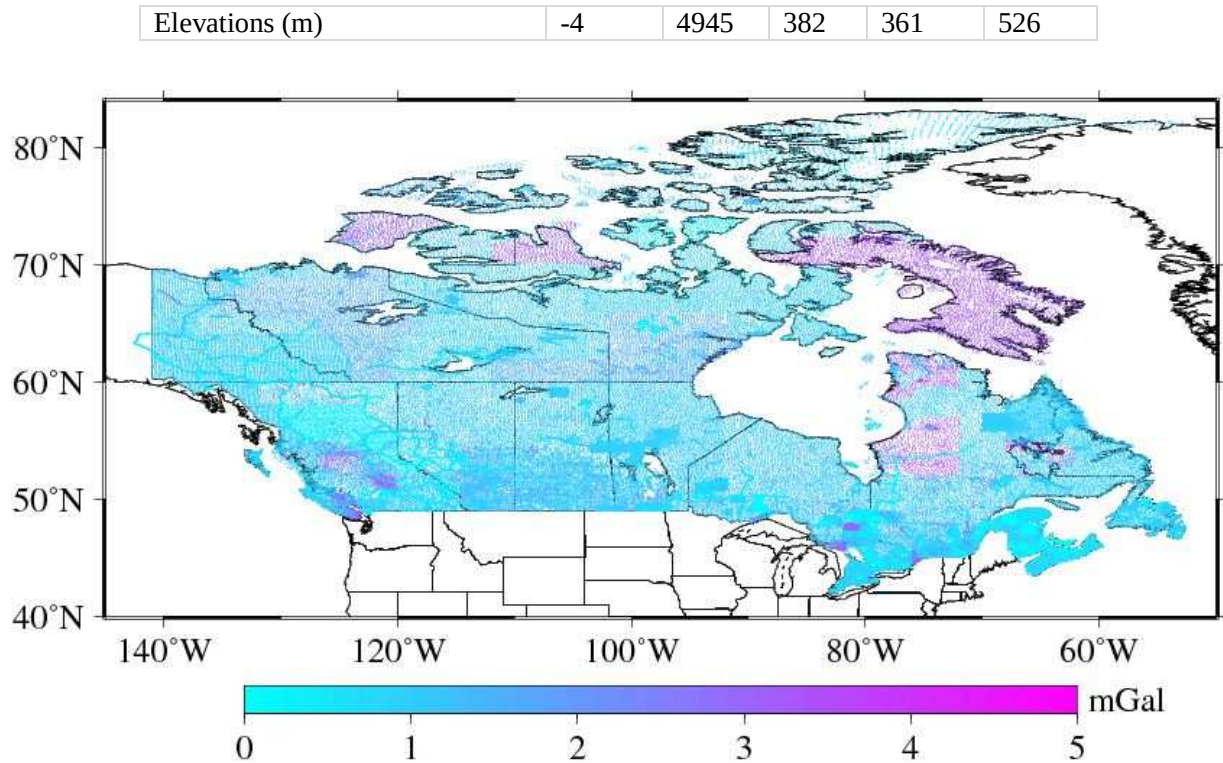


Figure 4.2 Distribution of 231,079 land gravity points. The colour scale indicates the magnitude of the error estimates. Note: The upper limit of the colour scale does not represent the maximum error estimate; the error values greater than 5 mGal are shown as the upper limit color.

The atmospheric correction in GRS80 (Moritz 1980) was applied to the free-air anomalies using the following formula:

$$Dg_A = 0.87e^{-0.116H_{\text{km}}^{1.047}}$$

where H_{km} is the orthometric height in kilometer. The atmospheric correction is in mGal.

5 Assessments and Results

5.1 Using GPS and Levelling Data

The Canadian Geodetic Survey computed a series of gravimetric geoid models according to Equations (2.3) and (2.4) using a range of modification degrees starting at degree $L=120$. The gravimetric geoid models used the same terrestrial gravity data and Digital Elevation Models as CGG2013 so that the resulting models differ only by the underlying satellite model and the degree of modification. Geoid heights are interpolated at the GPS-Levelling stations from each gravimetric geoid model using the bi-linear method. The gravimetric geoid heights are compared with the GPS-Levelling geoid heights according to Equation (2.1). The standard deviation of the residuals ($h - H - N$) is used to characterize the level of the residuals because it is not affected by the datum bias of the levelling network. The results are shown in Figures 5.1 and 5.2 for mainland Canada (CA) and five sub-regions: the Yukon Territory (YK), northern British Columbia (NBC), the Great Lakes (GL), the Maritimes (MT) and Newfoundland (NFLD). These five sub-regions correspond to relatively large geoid updates from GRACE and GOCE models as shown in Figures 5.3 and 5.4. In addition, EIGEN-6C4 has also been used to compute a geoid model according to Equation (2.5). The C_T term is computed to degree/order 2190 using the spherical

harmonic DEM models complete to degree/order 2700 provided by the US National Geodetic Survey. They are based on a mean 1 arcmin grid averaged from the 30 arcsec SRTM grid (Wang 2009). The GPS-Levelling comparisons are also done against EIGEN-6C4 and CGG2013 (see Figures 5.1 and 5.2).

A progressive improvement can be seen from GRACE-only, GOCE-based R4 and R5 models in terms of the GPS-Levelling comparisons. Firstly, both GRACE models improve from $L = 120$ to 150, and deteriorate from $L = 150$ to 180. GGM05S deteriorates more rapidly than the ITSG-Grace2014s. The fact that both GRACE models are un-constrained, and use the approximately same data period suggests that the latter is better than the former beyond degree 150. Secondly, GOCE-only model TIM-R4 performs significantly better than ITSG-Grace2014s for $L = 180$ and higher. This improvement over the GRACE model can be attributed to GOCE contribution, and partly to Kaula's regularization applied to TIM-R4 beyond degree 180. The DIR-R4 model gives similar results, and further confirms the GOCE contribution. Thirdly, GOCE-only model TIM-R5 performs significantly better than TIM-R4 beyond degree 180, and maintains the same level of residuals until degree 240. The better and steady performance of TIM-R5 from $L = 180$ can be attributed to the last stage of GOCE observation at the lower orbits, and partly due to Kaula's regularization applied to TIM-R5 beyond degree 200. The DIR-R5 model again confirms the improvement from the last stage of GOCE observation. One exception is found in Newfoundland where DIR-R4 (also CGG2013) outperforms DIR-R5 being likely attributed to the striping error when combining the GRACE models in the DIR solutions (see more discussions later in this section). Note that the levelling lines in Newfoundland extend from 150 to 380 km in the north-south direction and from 150 to 350 km in the east-west direction. These levelling lines are long enough in assessing GOCE models.

Furthermore comparing the performances of TIM-R5 and DIR-R5 suggests that the GOCE-only model is almost equivalent to the combined GRACE and GOCE model DIR-R5 in terms of the residual levels of the GPS-Levelling comparisons. DIR-R5 performs better for mainland Canada, the Yukon Territory, northern British Columbia, the Great Lakes region, but worse for the Maritimes and Newfoundland than TIM-R5. These results do not allow us draw a simple and general conclusion on which of the two R5 models is better in Canada. Overall, we can conclude that the best modification degree is $L = 150$ for the GRACE-only models and $L = 200$ for the GOCE-based models (R5).

CGG2013 is included in the analysis to serve as a baseline to assess improvements in the R5 models. CGG2013 uses the low-degree components of EIGEN-6C3stat ($L = 180$), which is based on a GOCE-based R4 model by the DIR approach (Förste et al., 2013). For $L = 180$ in Figures 5.1 and 5.2, CGG2013 maintains the same level of residuals as the geoid models based on TIM-R5 and DIR-R5 except for the Maritimes region where a smaller standard deviation is observed for both TIM-R4 and TIM-R5. The two geoid models using TIM-R5 and DIR-R5 for $L = 200$ show slightly lower residual levels than CGG2013. This indicates that these two GOCE models bring slightly more precise signal components into the two resulting geoid models than EIGEN-6C3stat in CGG2013. The GOCE signals allow improvement over the terrestrial gravity data for the frequency band between 120 and 200 ($L = 180$ to 200). For instance, TIM-R5 and DIR-R5 based geoid models modified to degree $L = 200$ outperform CGG2013 by about 0.5 cm along the GPS-Levelling line (26 BMs) that crosses the vertical stripes in the central Quebec (see Figures 5.3 and 5.4).

The geoid updates to CGG2013 by both TIM-R5 and DIR-R5 display a pattern of the GRACE-like striping error as shown in Figures 5.3 and 5.4 over eastern Canada. We have plotted differences between a number of TIM-4 and TIM-5 based regional geoid models (not shown here). They do not show a striping pattern like Figures 5.3 and 5.4 as Brockmann et al. (2014) have shown. This suggests that the GRACE model is the source of the striping pattern. The difference map between DIR-R4 and DIR-R5 by Bruinsma et al. (2014) has also shown the trace of the striping pattern. Thus the striping pattern in Figure

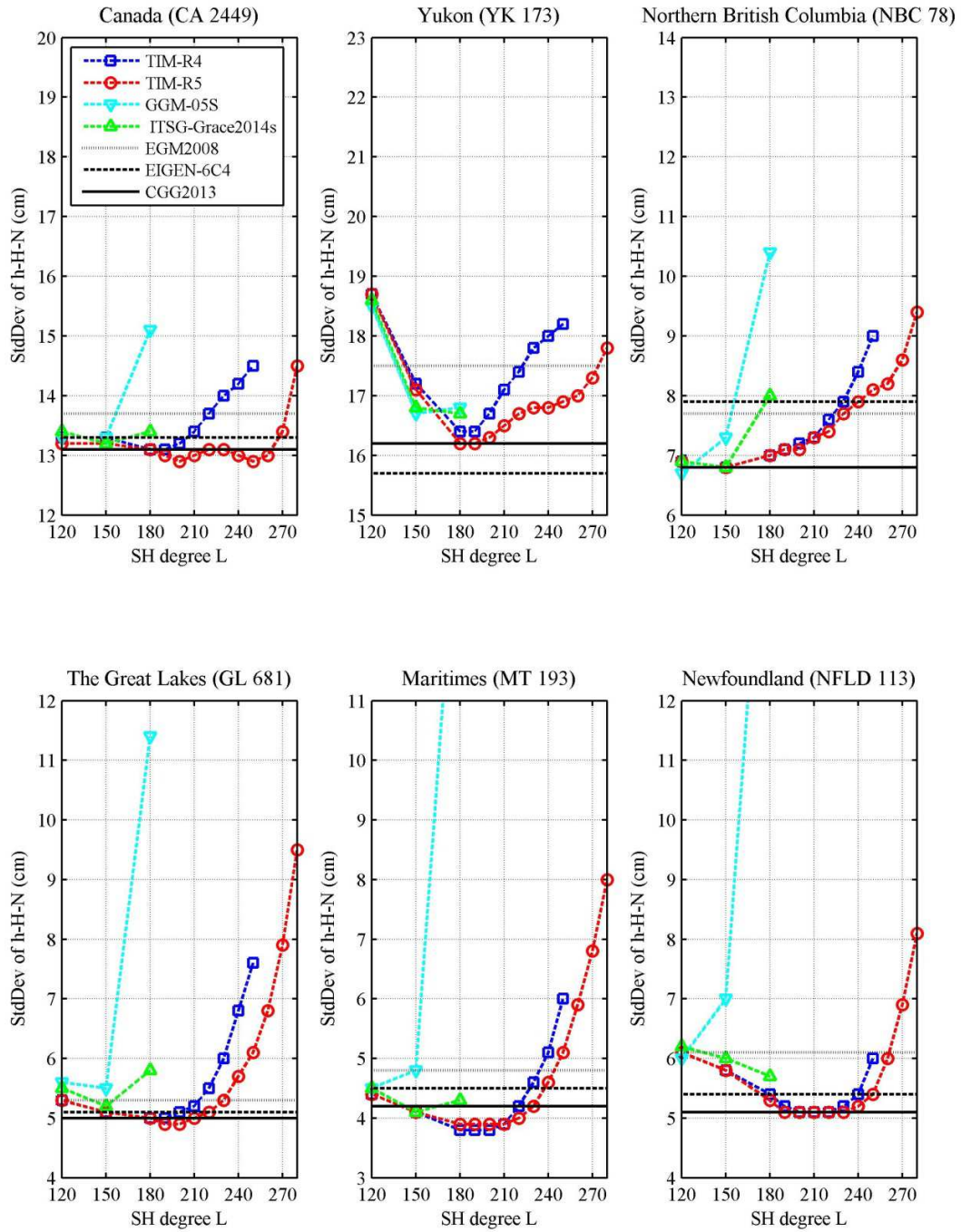


Figure 5.1 The standard deviations of $(h - H - N)$ for mainland Canada, and five sub-regions using recent GRACE and **GOCE-only** (TIM-R4 and -R5) GGMs (Unit: cm). The number of GPS-Levelling points for each region is given between parentheses. The range of the vertical axis is 8 cm.

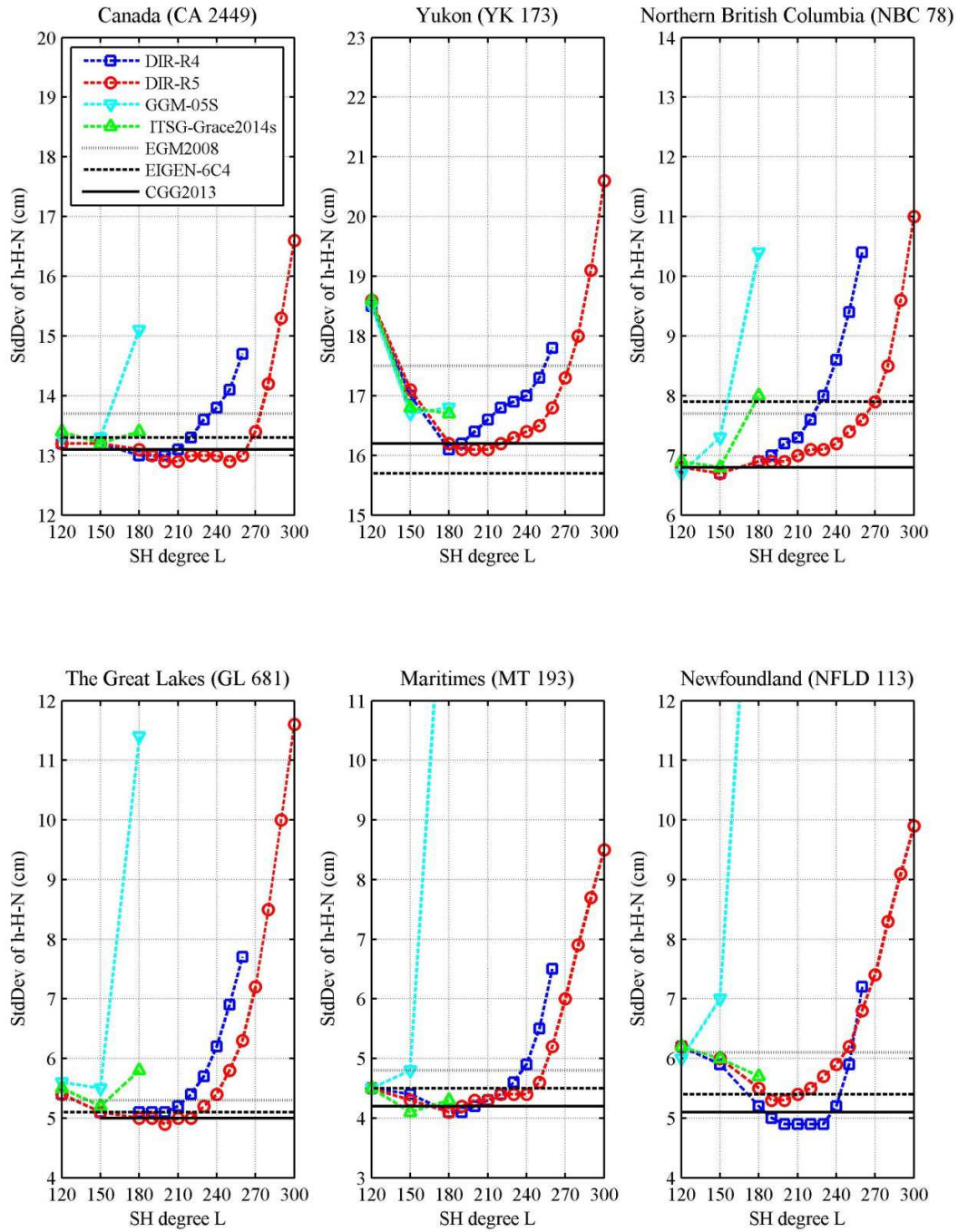


Figure 5.2 The standard deviations of $(h - H - N)$ for mainland Canada, and five sub-regions using recent GRACE and **combined GRACE and GOCE** (DIR-R4 and -R5) GGMs (Unit: cm). The number of GPS-Levelling points for each area is given between parentheses. The range of the vertical axis is 8 cm.

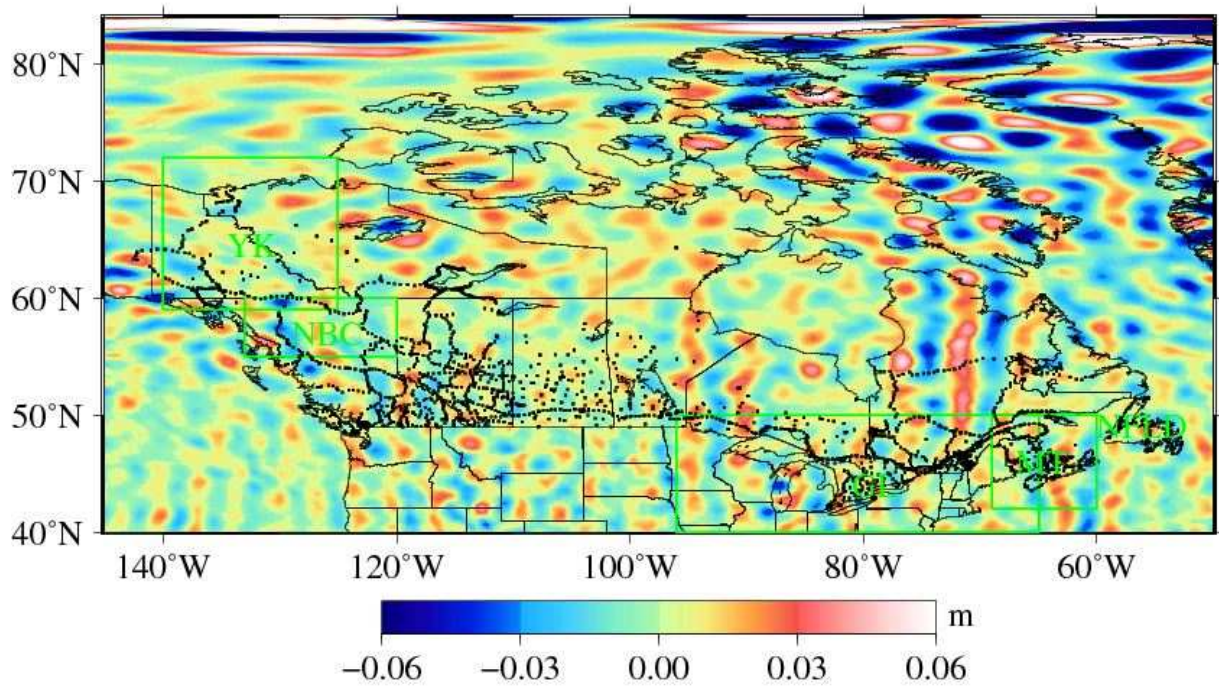


Figure 5.3 The geoid differences between M023 (TIM-R5, $L = 200$) and CGG2013. The black squares mark the GPS-Leveling stations.

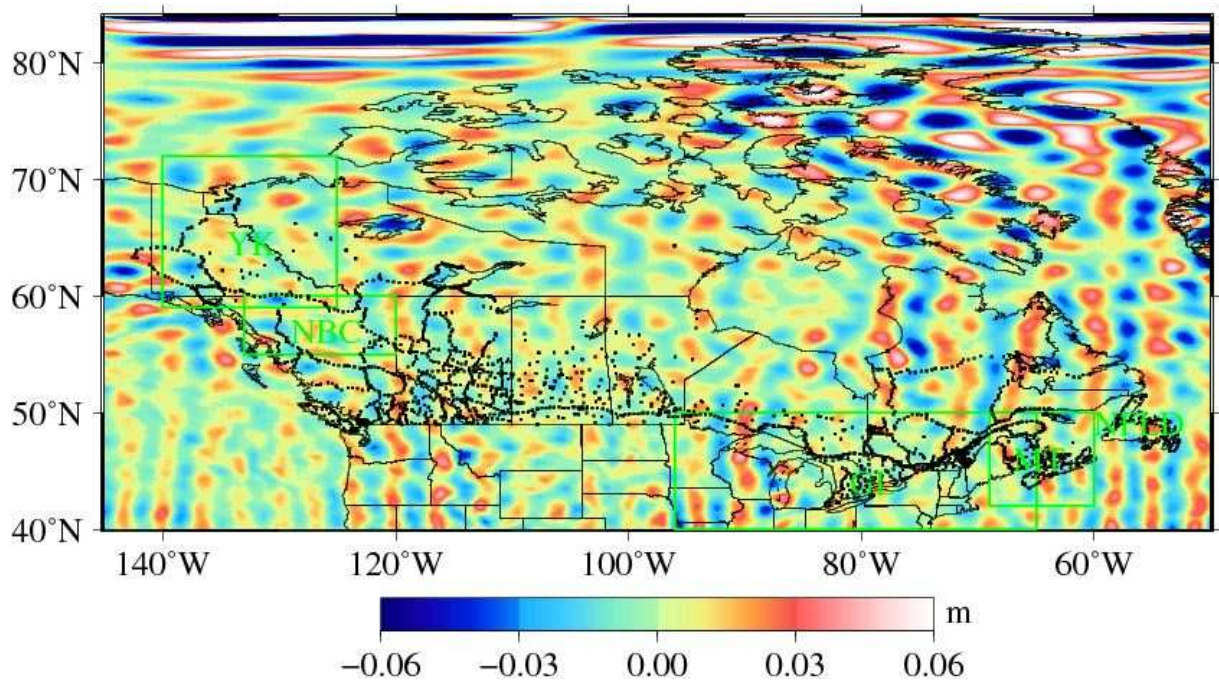


Figure 5.4 The geoid differences between M035 (DIR-R5, $L = 200$) and CGG2013. The black squares mark the GPS-Leveling stations.

5.3 is considered from CGG2013 which indirectly uses the GRACE model via EIGEN-6C3stat, while the striping pattern in Figure 5.4 comes from both CGG2013 (indirectly based on DIR-R4) and DIR-R5. The update from DIR-R5 improves CGG2013 in central Quebec on one hand, but worsens CGG2013 in Newfoundland on the other hand. This inconsistent performance appears due to the method for combination of GRACE models into the DIR models.

CGG2013 outperforms EIGEN-6C4 in mainland Canada and for four out of five sub-regions mostly due to its higher spatial resolution. This suggests that the omission error is still a limitation factor for EIGEN-6C4 in modelling the geoid in Canada regardless that it combines the latest gravity information from all sources. The residual levels of EGM2008 are also shown in Figures 5.1 and 5.2, and are generally higher than the ones for the EIGEN-6C4 geoid. Over the Canadian land, both EGM2008 and EIGEN-6C4 are based on the same terrestrial gravity data. The improvement from EIGEN-6C4 is considered primarily due to the use of the GOCE model. Note that we have used the EGM2008 GRS80 geoid undulation grid for this study, which is transformed from the 1 by 1 arcmin WGS84 geoid undulation grid by the NGA (http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/egm08_wgs84.html). In the meantime, we have computed an EGM2008 geoid undulation grid using the same spherical harmonic DEM as the one for EIGEN-6C4. The statistical results of the GPS-Levelling comparison only differ slightly (0 mm for GL, 1 mm for CA, NBC and MT, and 2 mm for YK in standard deviation) for the two EGM2008 geoid undulation grids even though the differences between them can reach decimeters at the extreme cases, mostly over high mountains where there are no GPS-Levelling data.

The residual levels vary from region to region with the lowest level in the Maritimes and the highest level in the Yukon Territory reflecting the sum of errors from the geoid models and GPS-Levelling data. The GPS ellipsoidal heights generally have a precision better than 2 cm at most of the stations, but the error can be larger than 10 cm for the surveys conducted before 1994. The levelling orthometric heights are as precise as a few millimeters within a few kilometers, but contain a systematic error slope of about 30 cm from the eastern to western coasts. A simple four-parameter fit to remove the error slope reduces the residual level of CGG2013 in mainland Canada from 13.1 cm to 7.3 cm. The smaller a region is, the less the effect of the error slope. For instances, the levels of residuals in the Great Lakes and Maritimes regions are about 4-5 cm, which are less affected by the error slope and more reflect the total random errors. A similar level of residuals is also observed in Newfoundland as well as other regions of similar sizes not included in this study. These results imply that the GOCE components of the geoid models are accurate to better than 4-5 cm. The high level of residuals in the Yukon Territory is mostly related to the poor closure of the large levelling loops and instability of the benchmarks in this remote region.

5.2 Using Deflections of the Vertical Data

Deflections of the vertical have been determined according to the method described in Section 2.2 from eight geoid models. The results of the comparison between the model-derived deflections and the astronomic deflections are shown in Table 5.1. The two global models (EGM2008 and EIGEN-6C4) are chosen to validate the GOCE contribution to the global geopotential modelling while four regional geoid models (M04, M13, M23 and M35) with modification degree $L = 200$ are selected to validate the improvement of the R5 models over the R4 models. The M58 model is selected to determine if EIGEN-6C4 performs better than EIGEN-6C3stat which underlies CGG2013 ($L = 180$).

The EGM2008 model gives a slightly lower residual level than the EIGEN-6C4 model for both the north-south and east-west components (see Table 5.1). The six regional geoid models show the almost same levels of residuals, a standard deviation of 1.23 arcsec for the north-south component and 1.58 arcsec for the east-west component. The standard deviations represent geoid slopes of 6.0 cm and 7.7 cm over a 10-k m distance. Error slopes of this magnitude are not observed in the geoid models when compared to

GPS/Levelling data. This indicates that the astronomical deflections may not be as accurate as estimated, the transfer from the geoid to the topography may introduce errors and/or the resolution of the models is not high enough. The residual levels could be significantly reduced by the residual terrain modelling (RTM) technique as it is shown in Hirt et al. (2010).

To help understand these results, differences of the model-predicted deflections have also been computed from four pairs of geoid models and shown in Table 5.2. They represent deflection corrections of the R5 models to the previous release. The level of the corrections is lower than 0.3 arcsec for the two global models and 0.1 arcsec for the six regional models. It suggests that the deflections must be accurate to better than 0.1 arcsec to validate improvement from the R5 GOCE models. The accuracy of the astronomic deflections is about 0.3 to 0.5 arcsec, and is not accurate enough to validate the improvement from the R5 models. In Table 5.1, the two global models give larger residual levels than the six regional models most likely due to the omission errors of the global models.

Table 5.1 Differences between the geoid model-predicted and astronomic deflections of the vertical at 939 stations (Unit: arcsec).

Geoid Model	GGM	L	ξ (north-south)				η (east-west)			
			Min	Max	Mean	StdDev	Min	Max	Mean	StdDev
EGM2008			-9.56	9.94	0.03	1.51	-11.63	7.98	0.17	1.81
EIGEN6C4			-8.51	9.98	0.01	1.55	-11.38	8.38	0.17	1.87
M04	TIM-R4	200	-5.21	9.80	0.05	1.23	-12.94	7.54	0.21	1.58
M23	TIM-R5	200	-5.22	9.75	0.06	1.22	-12.93	7.45	0.22	1.58
M13	DIR-R4	200	-5.23	9.80	0.06	1.23	-12.90	7.54	0.21	1.58
M35	DIR-R5	200	-5.26	9.76	0.06	1.23	-12.87	7.46	0.22	1.58
CGG2013	EIGEN-6C3stat	180	-5.23	9.85	0.06	1.23	-12.92	7.46	0.21	1.58
M58	EIGEN6C4	200	-5.24	9.85	0.06	1.23	-12.89	7.38	0.22	1.58

Table 5.2 Differences of the geoid model-predicted deflections of the vertical at 939 stations (Unit: arcsec).

Model Pair	ξ (north-south)				η (east-west)			
	Min	Max	Mean	StdDev	Min	Max	Mean	StdDev
EIGEN-6C4 - EGM2008	-1.38	1.40	-0.02	0.24	-1.71	2.00	0.00	0.29
M23 - M04	-0.16	0.16	0.00	0.05	-0.22	0.23	0.00	0.07
M35 - M13	-0.15	0.15	0.00	0.05	-0.22	0.26	0.01	0.08
M58 - CGG2013	-0.18	0.25	0.00	0.05	-0.24	0.27	0.00	0.08

Note that the residual values for EGM2008 in Table 5.1 are smaller than the previous estimated values (Huang and Véronneau 2009). This is mainly because of the use of the Canadian Digital Elevation Data (<http://www.nrcan.gc.ca/earth-sciences/geography/atlas-canada/free-data/16894#geobase>) which replaced the spherical harmonic DEM provided by NGA for EIGEN-6C4 and EGM2008. In addition, the two additional terrain-related terms in Equation (2.7) are now considered. These two terms can reach up to 2 arcsec with an RMS of 0.2 arcsec at the 939 stations. Also, the statistics presented in 2009 excluded nine stations that did not have proper station identification.

5.3 Using Gravity Data

Gravity comparisons are only limited to the two extra high degree models EGM2008 and EIGEN-6C4 which have significantly smaller omission errors than the satellite-only models due to the use of terrestrial

gravity data. Both models directly or indirectly use the same land gravity data in Canada for high-degree components beyond the satellite signal. The latter contains upgraded GRACE signals with respect to the GRACE signals that are included in EGM2008, and GOCE signals to higher spherical harmonic degree and order, and may improve over the former if the new satellite signals are more accurate than the corresponding terrestrial components in EGM2008.

The free-air gravity anomalies have been synthesized from EGM2008 and EIGEN-6C4, and compared to the free-air gravity anomalies at the land gravity points, respectively. The differences are given in Table 5.3 and Figures 5.5 and 5.6. Difference levels for both models are similar. In other words, these gravity comparisons do not show the improvement from EIGEN-6C4 over EGM2008. However they have confirmed that the GOCE components in EIGEN-6C4 agree with the corresponding terrestrial components in EGM2008 to the error level of the land data. The differences of the free-air anomalies synthesized from EIGEN-6C4 and EGM2008 are also shown in Table 5.3 and Figure 5.7. The RMS of the differences is 0.71 mGal that is close to the mean error 0.82 mGal of the land data shown in Table 4.2. In other words, the error level in the land data is too high to resolve the improvement of EIGEN-6C4 over EGM2008. Furthermore, both GGMs are dependent of the land gravity data. EGM2008 depends more than EIGEN-6C4 on the land gravity data, therefore tends to agree better with them.

Table 5.3 Differences between the free-air gravity anomalies and the gravity anomalies synthesized from EGM2008 and EIGEN-6C4 at 231,079 land points, respectively (the first two rows). Differences between free-air anomalies synthesized from the two GGMs are also included (the third row). Unit: mGal.

Model	Min	Max	Mean	StdDev
EGM2008	-176.85	175.62	-1.58	13.33
EIGEN-6C4	-177.15	175.53	-1.60	13.37
EIGEN-6C4 – EGM2008	-12.48	10.78	0.02	0.71

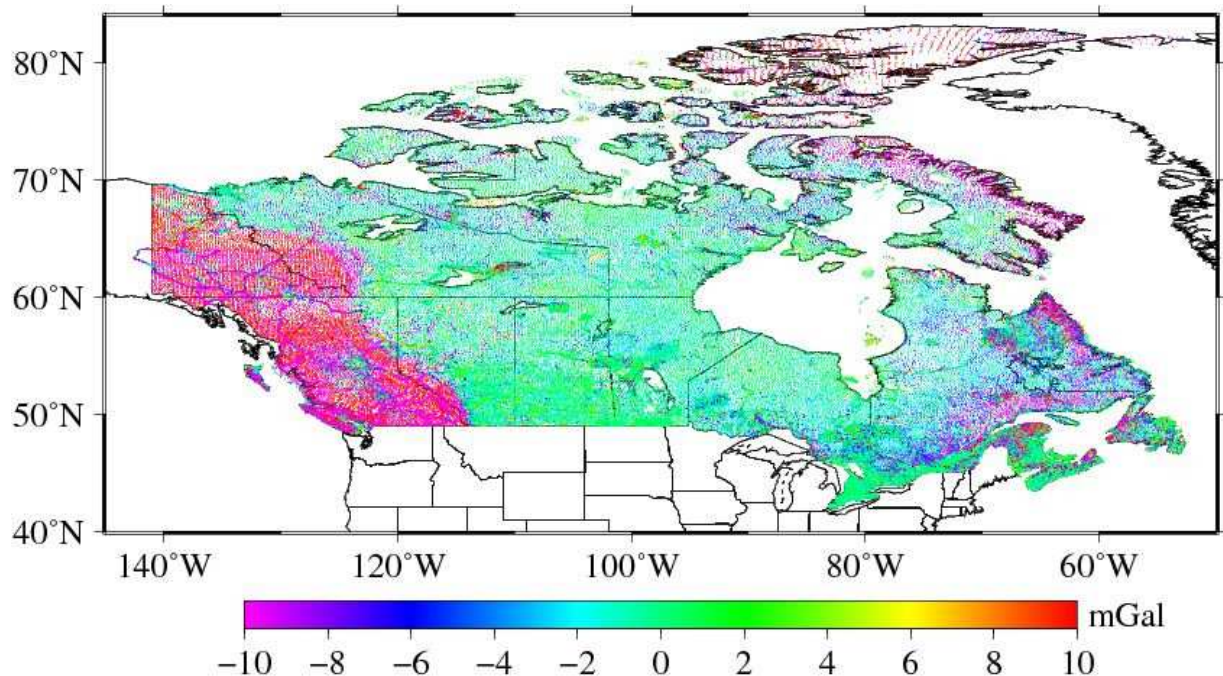


Figure 5.5 Differences between the free-air gravity anomalies and the gravity anomalies synthesized from EGM2008 at 231,079 land points.

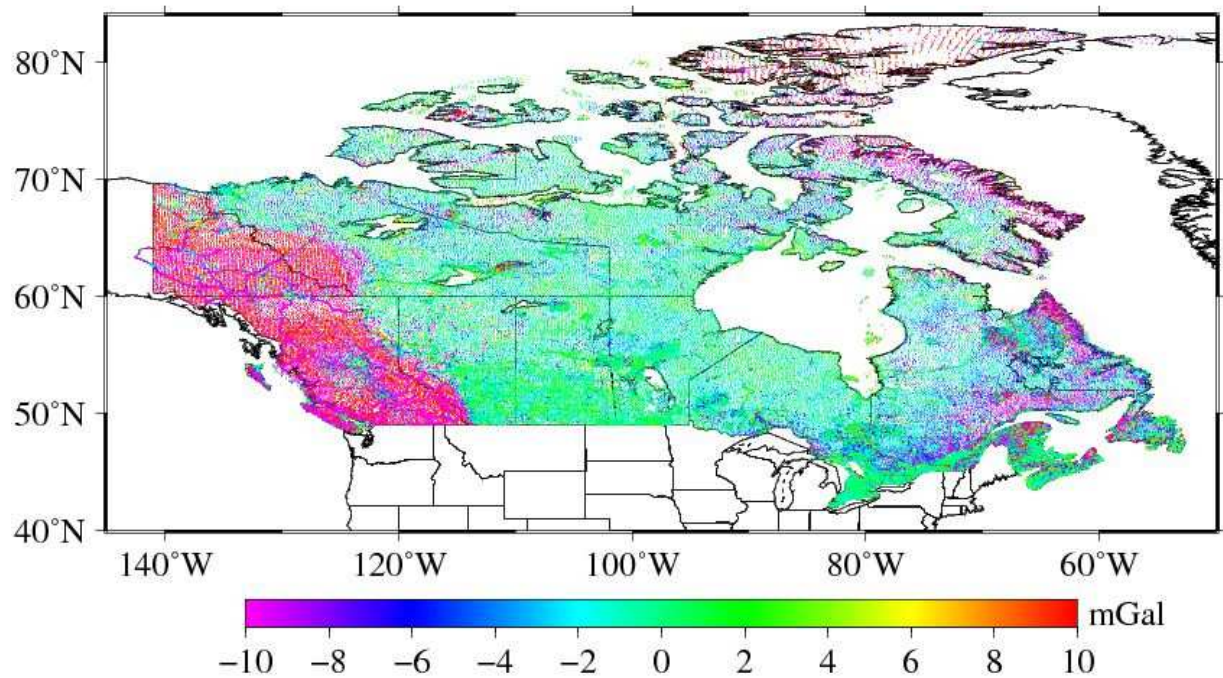


Figure 5.6 Differences between the free-air gravity anomalies and the gravity anomalies synthesized from EIGEN-6C4 at 231,079 land points.

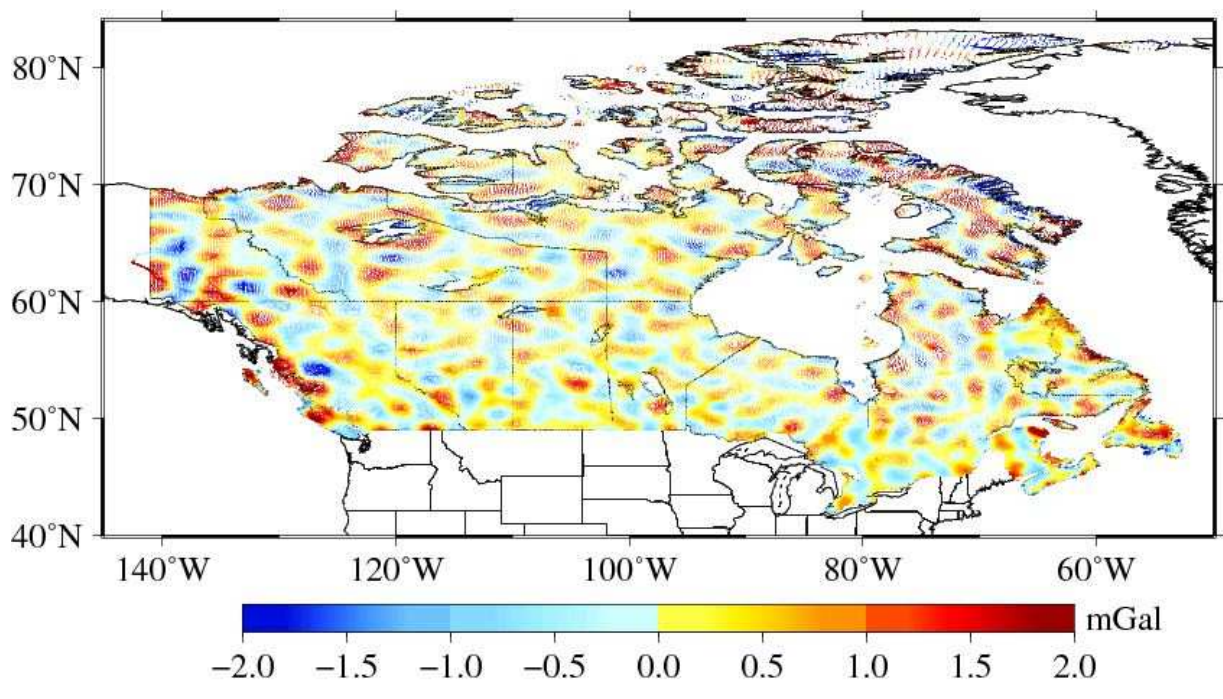


Figure 5.7 Differences between the free-air gravity anomalies synthesized from EIGEN-6C4 and EGM2008 at 231,079 land points.

On the other hand the better performance of EIGEN-6C4 than EGM2008 in the GPS-Levelling validation suggests that the GOCE components in EIGEN-6C4 are slightly better than the corresponding terrestrial

components in EGM2008. Figure 5.7 also shows that significant differences generally correlate with relatively sparse and erroneous land gravity data coverage in the western and northern Canada as Figure 4.2 shows.

6 Conclusions

In this study, we analysed seven global geopotential models that are founded on GRACE or/and GOCE observations. The models comprise two recent GRACE-only models (GGM05S and ITSG-Grace2014), two GOCE-only models (TIM-R4 and TIM-R5), two combined GRACE and GOCE models (DIR-R4 and DIR-R5), and one extra high degree model (EIGEN-6C4) that includes the integration of terrestrial and altimetry-derived gravity data. The analysis also includes CGG2013, the geoid model realizing the new vertical datum in Canada, and EGM2008 as baselines. These nine models were validated against three types of datasets in Canada: GPS-Levelling data, astronomic deflections of the vertical and terrestrial land gravity data. We conclude:

1. The GRACE-only models (GGM05S and ITSG-Grace2014) start to deteriorate from spherical harmonic degree 150 in terms of GPS-Levelling validation. However, ITSG-Grace2014 can still perform significantly better than GGM05S up to degree 180 (being the maximum expansion).
2. The GOCE-only models (TIM-R4 and TIM-R5) perform as well as the GRACE-only models below degree 150 in the GPS-Levelling validation. This indicates that the GRACE advantage over GOCE for the lower degrees is not captured by the GPS-Levelling data.
3. The GGMs that include the fifth release of GOCE data (TIM-R5 and DIR-R5) outperform the corresponding R4 models for degrees higher than 180 except in Newfoundland where DIR-R4 outperforms DIR-R5. Most importantly, the R5 models perform steadily beyond degree 200 with an estimated cumulative error smaller than 4-5 cm in terms of GPS-Levelling validation.
4. EGM2008 and EIGEN-6C4 provide similar statistical comparison (13 mGal) in terms of validation against the Canadian terrestrial gravity data over land. The two models directly or indirectly makes use of the Canadian data in their development. The only difference is that EIGEN-6C4 uses less terrestrial gravity data than EGM2008 in the frequency band that includes GOCE measurements. On the other hand, the GOCE contribution in EIGEN-6C4 can be measured against the GPS-Levelling data. EIGEN-6C4 better results than EGM2008 indicates that the GOCE components are more accurate than the corresponding components of the terrestrial gravity data.
5. The regional geoid models based on the R5 models perform slightly better than CGG2013 ($L = 180$) in the GPS-Levelling validation. It suggests that the R5 models could improve geoid modelling in Canada, allowing a higher degree of modification of the Stokes kernel function (e.g., $L = 210$). This means a more homogenous solution across Canada and reduction of possible regional systematic errors in the terrestrial gravity data.
6. For the GGMs that include GRACE and GOCE data, we can observe striping patterns indicating possibly that the GRACE data carry too much weight in the models. The striping patterns may be the cause of poorer performance of DIR-R5 than DIR-R4 in Newfoundland.

As for the astronomic deflections, they contain higher frequency components than the regional geoid models causing the omission errors in the comparisons. They compared better with regional geoid models than GGMs such as EGM2008 and EIGEN-6C4 because the former includes relatively higher frequency components. The integration of different GRACE and/or GOCE models in the development of regional geoid models does not influence the statistics of the comparison to astronomic deflections because the GOCE updates are below the error level of the deflections data. It may be feasible to make use of astronomic deflections in evaluating satellite models with a regional geoid model, but they would need to be much more accurate (< 0.1 arcsec).

Acknowledgements: We would like to thank the two anonymous reviewers for their constructive comments and suggestions, and Editor, Dr. Thomas Gruber.

Appendix A: Topographical Term C_T for the Geoid Computation from a Global Geopotential Model (GGM)

The geoid can be computed according to Bruns's theorem (Heiskanen and Moritz 1967):

$$N(\Omega) = \frac{T^*(\Omega)}{\gamma_E} \quad (A1)$$

$T^*(\Omega)$ is the disturbing potential on the geoid inside the topography, and γ_E is normal gravity on the geoid.

The disturbing potential $T^*(\Omega)$ on the geoid cannot be computed directly by the spherical harmonic synthesis from a GGM because of the existence of topographical mass above the geoid, which does not meet the harmonic condition. To deal with the topography, we have developed a parallel approach to the Stokes-Helmert scheme which uses terrestrial gravity data for the determination of the disturbing potential on the geoid (Vaníček and Martinec 1994). It conceptually consists of two steps. First the disturbing potential $T_{\text{GGM}}(r, \Omega)$ from the GGM is transformed into the Helmert disturbing potential $T_{\text{HGGM}}(r, \Omega)$ above and on the Earth's surface (Eq. 8, Huang and Véronneau 2013) as follows:

$$T_{\text{HGGM}}(r, \Omega) = T_{\text{GGM}}(r, \Omega) - \delta V_{\text{DTE}}(r, \Omega) \quad (A2)$$

where $\delta V_{\text{DTE}}(r, \Omega)$ is the direct topographical effect on geopotential (Eq. 28, *ibid*). The Helmert disturbing potential can be directly computed downwards on the geoid as follows:

$$T_{\text{HGGM}}(\Omega) = T_{\text{GGM}}(\Omega) - \delta V_{\text{DTE}}(\Omega) \quad (A3)$$

where $T_{\text{GGM}}(\Omega)$ alone is the fictional disturbing potential on the geoid inside the topography, and is given in (Eq. 9, *ibid*). Second the disturbing potential $T^*_{\text{GGM}}(\Omega)$ on the geoid is computed by adding the primary indirect topographical effect, which restores the topography from the Helmert layer condensation layer, as degree-0 and degree-1 terms as follows:

$$T^*_{\text{GGM}}(\Omega) = T_0(\Omega) + T_1(\Omega) + T_{\text{HGGM}}(\Omega) + \delta V_{\text{PITE}}(\Omega) \quad (A4)$$

$$\delta V_{\text{PITE}}(\Omega) = 2\pi G \rho R^2 \sum_{n=0}^{nx} \frac{1}{2n+1} \sum_{m=-n}^n \bar{I}_{nm} \bar{Y}_{nm}(\Omega) \quad (A5)$$

$$\bar{I}_{nm} = -(n+1)(t^2)_{nm} - \frac{(n+1)(n-2)}{3}(t^3)_{nm} - \frac{(n+1)n(n-1)}{12}(t^4)_{nm} \quad (A6)$$

Combining Equations (A3) and (A4), we get

$$T^*_{\text{GGM}}(\Omega) = T_0(\Omega) + T_1(\Omega) + T_{\text{GGM}}(\Omega) - \delta V_{\text{DTE}}(\Omega) + \delta V_{\text{PITE}}(\Omega) \quad (A7)$$

By Bruns's theorem, we get

$$N_{\text{GGM}}(\Omega) = N_0(\Omega) + N_1(\Omega) + N_{\text{GGM}}(\Omega) + C_T(\Omega) \quad (\text{A8})$$

where the C_T is given by

$$C_T(\Omega) = \frac{-\delta V_{\text{DTE}}(\Omega) + \delta V_{\text{PITE}}(\Omega)}{\gamma_E} \quad (\text{A9})$$

The sum of the DTE and PITE terms is derived as follows:

$$-\delta V_{\text{DTE}}(\Omega) + \delta V_{\text{PITE}}(\Omega) = 2\pi G \rho R^2 \sum_{n=0}^{nx} \sum_{m=-n}^n \bar{\Lambda}_{nm} \bar{Y}_{nm}(\Omega) \quad (\text{A10})$$

For the fourth order of approximation, we have

$$\bar{\Lambda}_{nm} = -(t^2)_{nm} - \frac{2}{3}(t^3)_{nm} - \frac{(n+1)n}{12}(t^4)_{nm} \quad (\text{A11})$$

where $t = H/R$, and

$$(t^k)_{nm} = \frac{1}{4\pi} \int_{\Omega} t^k \bar{Y}_{nm}(\Omega) d\Omega \quad (\text{A12})$$

Sjöberg (Eq. 23, 2007) derived an equivalent equation to (A9) to the 3rd order approximation, and called this term as the topographic bias.

It should be pointed that Rapp (1997) first derived equations for this correction by upward continuing the height anomaly from the reference ellipsoid to the Earth's surface followed by a conversion from the height anomaly to the geoid. In Rapp's upward continuation, only the first-order gradient of the height anomaly was used. Hirt (2012a) improved Rapp's approach by considering higher order gradient terms of the height anomaly with radius. One advantage of equation (A9) is that it is expressed in the spherical harmonic form, and can match the spectral content of GGM with the digital topographic models exactly. A comparison of the two approaches is theoretically and practically interesting but out of the scope of this study.

References:

- Bruinsma, S. L., C. Förste, O. Abrikosov, J. C. Marty, M. H. Rio, S. Mulet and S. Bonvalot (2013) The new ESA satellite-only gravity field model via the direct approach. *Geophys. Res. Lett.*, 40, 3607–3612, doi:10.1002/grl.50716
- Bruinsma, S. L., C. Förste, O. Abrikosov, J.-M. Lemoine, J.-C. Marty, S. Mulet, M.-H. Rio and S. Bonvalot (2014) ESA's satellite-only gravity field model via the direct approach based on all GOCE data. *Geophys. Res. Lett.*, 41, 7508–7514, doi:10.1002/2014GL062045
- Brockmann, J. M., N. Zehentner, E. Höck, R. Pail, I. Loth, T. Mayer-Gürr and W.-D. Schuh (2014) EGM_TIM_RL05: An independent geoid with centimeter accuracy purely based on the GOCE mission. *Geophys. Res. Lett.*, 41, doi:10.1002/2014GL061904
- Förste, Ch., F. Flechtner, Ch. Dahle, O. Abrikosov, H. Neumayer, Franz Barthelmes, R. König, S.L. Bruinsma, J.C. Marty, J.-M. Lemoine and R. Biancale (2013) EIGEN-6C3 - the newest High Resolution Global Combined Gravity Field Model based on the 4th Release of the GOCE Direct Approach. Potsdam/Toulouse, Sept. 2013

- Förste, Ch., S. L. Bruinsma, O. Abrikosov, J.-M. Lemoine, T. Schaller, H.-J. Götze, J. Ebbing, J.C., Marty, F. Flechtner¹, G. Balmino and R. Biancale (2014) EIGEN-6C4 The latest combined global gravity field model including GOCE data up to degree and order 2190 of GFZ Potsdam and GRGS Toulouse. 5th GOCE User Workshop, Paris, 25. – 28.11.2014
- Godah, W., M. Szelachowska and J. Krynski (2014) Accuracy assessment of GOCE-based geopotential models and their use for modelling the gravimetric quasigeoid – A case study for Poland. *Geodesy and Cartography*, 63(1), 3-24, doi:10.2478/geocart-2014-0001
- Gruber, Th., P. N. A. M. Visser, Ch. Ackermann and M. Hosse (2011) Validation of GOCE gravity field models by means of orbit residuals and geoid comparisons. *J. Geod.*, 85:845-860, doi:10.1007/s00190-011-0486-7
- Heiskanen, W. A. and H. Moritz (1967) *Physical geodesy*. W.H. Freeman, San Francisco
- Guimarães, G., A. Matos and D. Blitzkow (2012) An evaluation of recent GOCE geopotential models in Brazil. *Journal of Geodetic Science*, 2:144–155, doi:10.2478/v10156-011-0033-8
- Hirt, C., U. Marti, B. Bürki, and W. E. Featherstone (2010) Assessment of EGM2008 in Europe using accurate astrogeodetic vertical deflections and omission error estimates from SRTM/DTM2006.0 residual terrain model data. *J. Geophys. Res.*, 115, B10404, doi:10.1029/2009JB007057
- Hirt, C., Th. Gruber and W. E. Featherstone (2011) Evaluation of the first GOCE static gravity field models using terrestrial gravity, vertical deflections and EGM2008 quasigeoid heights. *J. Geod.*, 85:723–740, doi:10.1007/s00190-011-0482-y
- Hirt, C. (2012a) Efficient and accurate high-degree spherical harmonic synthesis of gravity field functionals at the Earth's surface using the gradient approach. *J. Geod.*, 86:729–744, doi:10.1007/s00190-012-0550-y
- Hirt, C., M. Kuhn, W. E. Featherstone and F. Göttl (2012b) Topographic/isostatic evaluation of new-generation GOCE gravity field models. *J. Geophys. Res.*, 117, B05407, doi 10.1029/2011JB008878
- Huang, J. and M. Véronneau (2009) Evaluation of the GRACE-Based Global Gravity Models in Canada. *Newton's Bulletin*, n. 4, 66-72
- Huang, J. and M. Véronneau (2013) Canadian gravimetric geoid model 2010. *J. Geod.*, 87:771–790, doi:10.1007/s00190-013-0645-0
- Huang, J. and M. Véronneau (2014) A Stokesian approach for the comparative analysis of satellite gravity models and terrestrial gravity data. In U. Marti (ed.), *Gravity, Geoid and Height Systems*, International Association of Geodesy Symposia 141, doi:10.1007/978-3-319-10837-7_13, Springer
- Ince E. S., M. G. Sideris, J. Huang and M. Véronneau (2012) Assessment of the GOCE global gravity models in Canada. *Geomatica*, 66(2):125-140
- Ince, E. S., B. Erol and M. G. Sideris (2014) Evaluation of the GOCE-Based Gravity Field Models in Turkey. In U. Marti (ed.), *Gravity, Geoid and Height Systems*, International Association of Geodesy Symposia 141, doi:10.1007/978-3-319-10837-7_12, Springer
- Janák, J. and M. Pitoňák (2011) Comparison and testing of GOCE global gravity models in Central Europe. *Journal of Geodetic Science*, 1:333–347
- Jekeli, C. (1999) An analysis of vertical deflections derived from high-degree spherical harmonic models. *J. Geod.*, 73: 10 – 22
- Jekeli, C. (2000) Heights, the Geopotential, and Vertical Dautms. Report No. 459, *Geodetic Science and Surveying*, Dept. of Civil and Environmental Engineering and Geodetic Science, The Ohio State Univ., Columbus, Ohio
- Li, J., X. Zou, X. Xu and W. Shen (2014) Evaluation of Recent GRACE and GOCE Satellite Gravity Models and Combined Models Using GPS/Leveling and Gravity Data in China. In U. Marti (ed.), *Gravity, Geoid and Height Systems*, International Association of Geodesy Symposia 141, doi 10.1007/978-3-319-10837-7_9, Springer
- Moritz, H (1980) Geodetic Reference System 1980. *Bull Geod*, 62(2): 187-192
- Mayer-Gürr, T., N. Zehentner, B. Klinger and A. Kvas (2014) ITSG-Grace2014: a new GRACE gravity field release computed in Graz. - in: GRACE Science Team Meeting (GSTM). Potsdam
- Odera, P. A. and Y. Fukuda (2013) Towards an improvement of the geoid model in Japan by GOCE data: A case study of the Shikoku area. *Earth Planets Space*, 65, 361–366
- Pail, R., et al. (2011) First GOCE gravity field models derived by three different approaches. *J. Geod.*, 85, 819–823, doi:10.1007/s00190-011-0467-x
- Pavlis, N. K., S. A. Holmes, S. C. Kenyon and J. K. Factor (2012) The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). *J. Geophys. Res.*, 117, B04406, doi:10.1029/2011JB008916
- Rapp, R. H. (1997) Use of potential coefficient models for geoid undulation determinations using a spherical harmonic representation of the height anomaly/geoid undulation difference. *J. Geod.*, 71: 282-289
- Rexer, M., C. Hirt, R. Pail and S. Claessens (2013) Evaluation of the third- and fourth-generation GOCE Earth gravity field models with Australian terrestrial gravity data in spherical harmonics. *J. Geod.*, 88(4), 319-333, doi:10.1007/s00190-013-0680-x

- Sjöberg, L. E. (2007) The topographic bias by analytical continuation in physical geodesy. *J. Geod.* (2007) 81:345–350, doi:10.1007/s00190-006-0112-2
- Šprlák, M., B. R. Pettersen, O. C. D. Omang, D. I. Lysaker, M. Sekowski and P. Dykowski (2014) Comparison of GOCE Global Gravity Field Models to Test Fields in Southern Norway. In U. Marti (ed.), *Gravity, Geoid and Height Systems*, International Association of Geodesy Symposia 141, doi:10.1007/978-3-319-10837-7_8, Springer
- Tocho, C., G. S. Vergos, and M. C. Pacino (2014) Evaluation of GOCE/GRACE Derived Global Geopotential Models over Argentina with Collocated GPS/Levelling Observations. In U. Marti (ed.), *Gravity, Geoid and Height Systems*, International Association of Geodesy Symposia 141, doi:10.1007/978-3-319-10837-7_10, Springer
- Tapley, B. D., F. Flechmer, S. V. Bettadpur and M. M. Watkins (2013) The status and future prospect for GRACE after the first decade. *Eos Trans. Fall Meet. Suppl.*, abstract G22A-01
- Tsoulis, D. and K. Patlakis (2013) A spectral assessment review of current satellite-only and combined Earth gravity models. *Rev. Geophys.*, 51, 186–243, doi:10.1002/rog.20012
- Vaníček P. and Z. Matinec (1994) The Stokes–Helmert scheme for the evaluation of a precise geoid. *Man Geod.* 19:119–128
- Vergos, G. S., V. N. Grigoriadis, I. N. Tziavos and C. Kotsakis (2014) Evaluation of GOCE/GRACE Global Geopotential Models over Greece with Collocated GPS/Levelling Observations and Local Gravity Data. In U. Marti (ed.), *Gravity, Geoid and Height Systems*, International Association of Geodesy Symposia 141, doi:10.1007/978-3-319-10837-7_11, Springer
- Voigt, C. and H. Denker (2014) Regional validation and combination of GOCE gravity field models and terrestrial data. In: Flechtner, F., et al. (eds), *Observation of the System Earth from Space - CHAMP, GRACE, GOCE and Future Missions*, Advanced Technologies in Earth Sciences, 139-145, doi:10.1007/978-3-642-32135-1_18, Springer
- Wang, Y. M. (2009) Investigation of the topographic effect by using high degree spherical harmonic expansion. IAG 2009 Scientific Assembly, Buenos Aires, Argentine, August 31-September 4, 2009

Validation of GOCE Models in Africa

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Abstract

In modern geodesy, the geoid computation is carried out using the so-called remove-restore technique. In this technique, the effect of the topography and its isostatic compensation as well as the effect of a global reference field are removed from the gravimetric quantities being used in the geoid computation. The quality of the reference geopotential model used in the framework of the remove-restore technique plays a great role in estimating the accuracy of the computed geoid. In the last decade, the GOCE gravity field dedicated satellite mission has taken place in order to enhance the gravity field recovery worldwide. Numerous GOCE geopotential models have already been released. Each geopotential model depends on the strategy of the solution and the inclusion of terrestrial gravity data. The main aim of this paper is to validate the recently released GOCE geopotential models in Africa. The results show that the EIGEN-6C4 and GO_CONS_GCF_2_DIR_R5 models give the smallest standard deviation and range of the reduced isostatic anomalies, respectively. However, the range and the standard deviation of the reduced isostatic anomalies are relatively too high, which shows that none of the GOCE released geopotential models ideally fits the African gravity field.

Keywords: Harmonic synthesis, geopotential models, Africa, gravity anomaly.

1. Introduction

The global geopotential models are widely used in practice in many geodetic applications, such as gravity reduction, gravity smoothing, gravity interpolation and geoid computation. In the frame of the remove-restore geoid determination technique, the global geopotential models play an important role by introducing the effect of the long wavelength component of the gravity field. Hence, the proper choice of a global geopotential model in a geodetic application depends on how such a geopotential model fits the gravity field of the area of interest. The main aim of the current investigation is to examine how suitable the recently released GOCE global geopotential models are to the geodetic applications in Africa.

A number of recently available GOCE global geopotential models are considered for the current study. The local point free-air gravity anomaly data set for Africa is illustrated along with the available Digital Height Models necessary for the gravity reduction computations. The used formulas to compute the synthesized gravity anomalies from high-degree geopotential models are given. The used window remove-restore technique (Abd-Elmotaal and Kühtreiber, 2003) is outlined. The synthesized free-air gravity anomalies for Africa using the newly released GOCE global geopotential models are

computed. The isostatic reduced gravity anomalies for Africa using the newly released GOCE global geopotential models are computed and widely discussed.

2. Used Geopotential Models

Table 1 illustrates the recently released GOCE global geopotential models used in the current investigation. For the sake of completeness, the EGM2008 global geopotential model is also used. Table 1 shows the models, their available maximum degree as well as the data used to develop these models. The following abbreviations are adopted for the used type of data in developing the geopotential models:

S = Satellite Tracking Data
G = Gravity Data
A = Altimetry Data

A wide range of geopotential models from satellite-only models with low maximum degree to combined models with ultra high-degree are considered for the current study.

Table 1: Used global geopotential models

Model	Year	Degree	Used Data	Reference
EGM2008	2008	2160	S(Grace),G,A	Pavlis et al., 2008, 2012
EIGEN-6C2	2012	1949	S(Goce,Grace,Lageos),G,A	Förste et al., 2012
EIGEN-6C4	2014	2190	S(Goce,Grace,Lageos),G,A	Förste et al., 2014
GO_CONS_GCF_2_TIM_R3	2011	250	S(Goce)	Pail et al., 2011
GO_CONS_GCF_2_TIM_R5	2014	280	S(Goce)	Brockmann et al., 2014
GO_CONS_GCF_2_DIR_R5	2014	300	S(Goce,Grace,Lageos)	Bruinsma et al., 2014
GOGRA02S	2013	230	S(Goce,Grace)	Yi et al., 2013
GOGRA04S	2014	230	S(Goce,Grace)	Yi et al., 2013
JYY_GOCE04	2014	230	S(Goce)	Yi et al., 2013
ITG-GOCE02	2013	240	S(Goce)	Schall et al., 2014

3. The Data

3.1. Point Free-Air Gravity Anomalies

All currently available sea and land point free-air gravity anomalies for Africa are used in the current investigation. Figure 1 shows their distribution. The distribution of the point free-air gravity anomaly stations on land is very poor. Many areas are empty. The distribution of the data points on sea is much better. More detailed information about the free-air data for Africa, the technique used for the needed gross-error detection and the merging technique can be found in (Abd-Elmotaal et al., 2015).

A total number of 1,186,032 free-air gravity anomaly values are available (cf. Fig. 1). The point free-air gravity anomalies range between -409.67 mgal and 452.80 mgal with an average of -4.37 mgal and a standard deviation of about 39.61 mgal.

In order to plot the free-air anomalies, they have been gridded on a $5' \times 5'$ grid using Kriging interpolation technique. Figure 2 shows the gridded $5' \times 5'$ free-air gravity anomalies for Africa used for the current investigation.

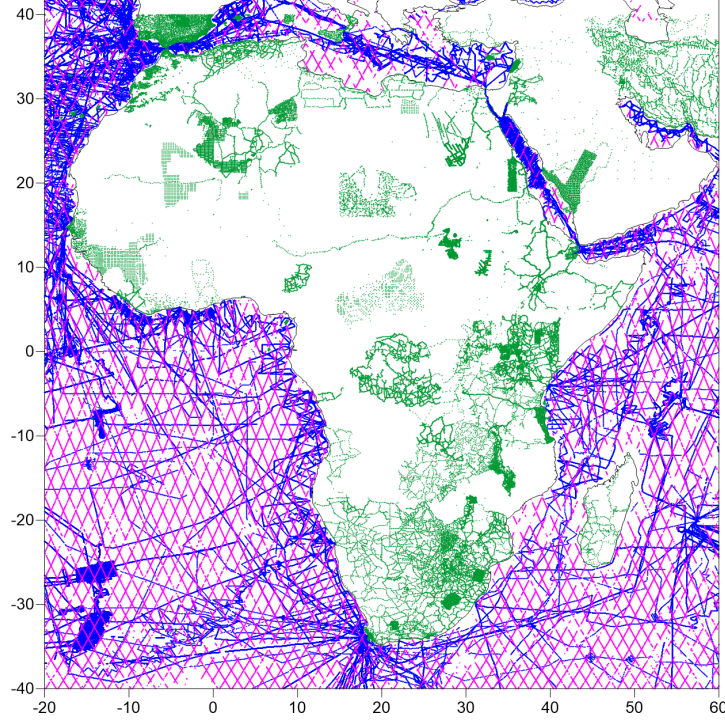


Figure 1: Distribution of the point free-air land (green), shipborne (blue) and altimetry derived (magenta) gravity anomalies in Africa.

3.2. Digital Height Models

For the terrain reduction computation, a set of fine and coarse Digital Height Models (DHM's) is needed. The $30'' \times 30''$ SRTM30+ (Farr et al., 2007), which includes topography and bathymetry, is employed as fine DHM, and the $3' \times 3'$ SRTM is used as coarse DHM. Figure 3 illustrates the $30'' \times 30''$ SRTM30+ fine DHM.

4. Basic Equations

The gravitational potential V can be expressed in spherical harmonic expansion as (Torge, 1989, p. 28; Dragomir et al., 1982, p. 53)

$$V(r, \theta, \lambda) = \frac{GM}{r} \left[1 + \sum_{n=2}^{\infty} \left(\frac{a}{r} \right)^n \sum_{m=0}^n (\bar{C}_{nm} \cos m\lambda + \bar{S}_{nm} \sin m\lambda) \bar{P}_{nm}(\cos \theta) \right], \quad (1)$$

where GM is the geocentric gravitational constant, r is the geocentric radius, θ is the polar distance, λ is the geodetic longitude, a stands for the equatorial radius of the mean earth's ellipsoid, $\bar{P}_{nm}$ denotes the associated fully normalized Legendre functions and $\bar{C}_{nm}$ and $\bar{S}_{nm}$ are the fully normalized potential coefficients. The polar distance θ can simply be expressed in terms of the geocentric latitude ψ as:

$$\theta = 90^\circ - \psi, \quad (2)$$

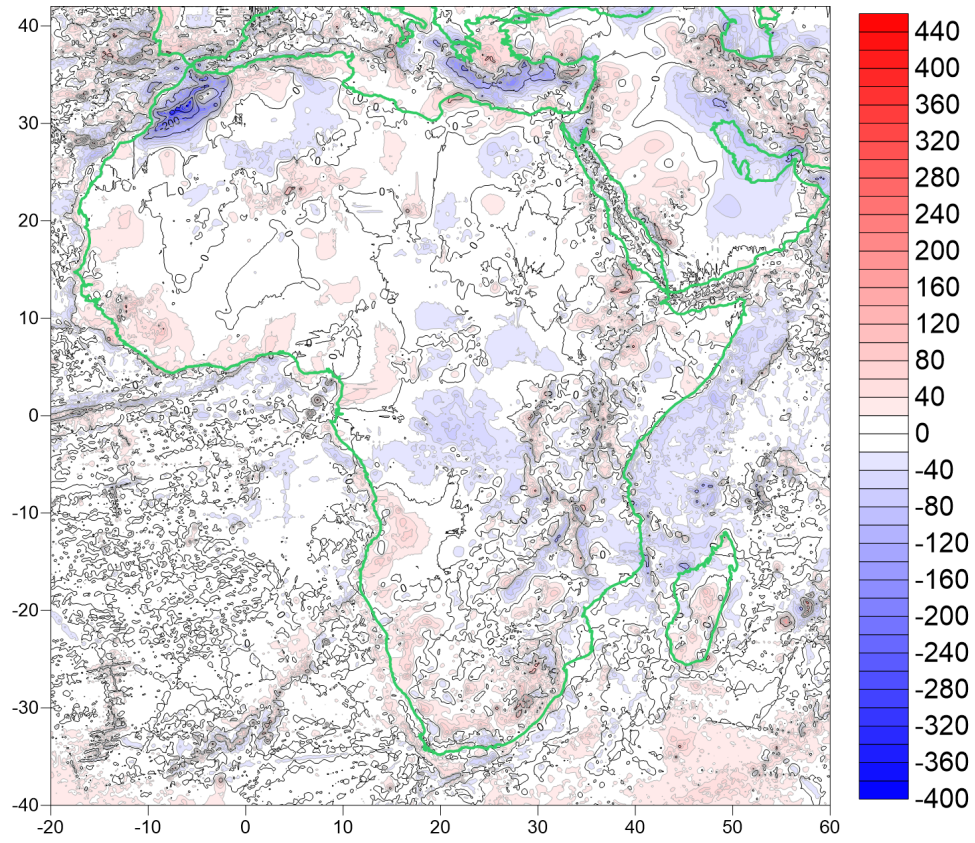


Figure 2: Gridded $5' \times 5'$ free-air gravity anomalies for Africa using the point gravity anomalies. Contour interval: 20 mgal.

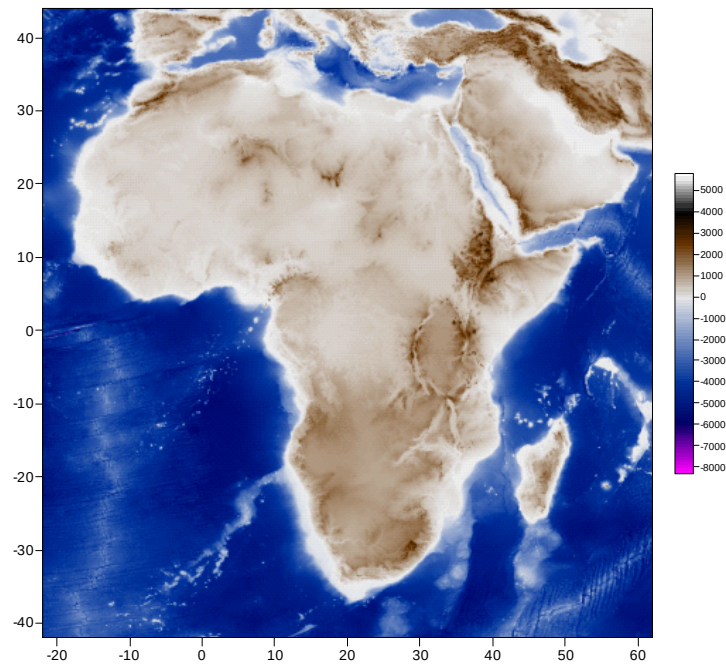


Figure 3: The fine $30'' \times 30''$ SRTM30+ DHM. Units in [m].

where ψ is related to the geodetic latitude ϕ through the following expression (Torge, 1980, p. 50):

$$\tan \psi = (1 - f)^2 \tan \phi, \quad (3)$$

where f is the flattening of the earth's ellipsoid.

The disturbing potential T is defined by

$$T(r, \theta, \lambda) = V(r, \theta, \lambda) - U(r, \theta) \quad (4)$$

where U is the normal gravitational potential of the mean earth's ellipsoid, given by (Torge, 1989, p. 37)

$$U(r, \theta) = \frac{GM}{r} \left[1 + \sum_{n=2}^{\infty} \left(\frac{a}{r} \right)^n \bar{C}_{n0}^u \bar{P}_{n0}(\cos \theta) \right]. \quad (5)$$

Here $\bar{C}_{n0}^u$ denotes the fully normalized harmonic coefficients implied by the reference equipotential ellipsoid. Because of the rotational symmetry of the mean earth's ellipsoid, there will be only zonal terms. And because of the symmetry with respect to the equatorial plane, there will be only even zonal harmonics $\bar{C}_{2n,0}^u$ (Heiskanen and Moritz, 1967, p. 72). The even degree zonal harmonic coefficients $\bar{C}_{2n,0}^u$ converge quickly toward zero, so that (5) may safely be truncated after $n = 6$.

Thus inserting (1) and (5) into (4), the disturbing potential T can be expressed as (Torge, 1989, p. 43)

$$T(r, \theta, \lambda) = \frac{GM}{r} \sum_{n=2}^{\infty} \left(\frac{a}{r} \right)^n \sum_{m=0}^n \left(\bar{C}_{nm}^* \cos m\lambda + \bar{S}_{nm} \sin m\lambda \right) \bar{P}_{nm}(\cos \theta), \quad (6)$$

where $\bar{C}_{nm}^*$ is the difference between the actual coefficients $\bar{C}_{nm}$ and those implied by the reference equipotential ellipsoid $\bar{C}_{nm}^u$.

The gravity anomaly Δg can be expressed, using the spherical approximation, by (Moritz, 1980)

$$\Delta g(r, \theta, \lambda) = \frac{GM}{r^2} \sum_{n=2}^{\infty} (n-1) \left(\frac{a}{r} \right)^n \sum_{m=0}^n \left(\bar{C}_{nm}^* \cos m\lambda + \bar{S}_{nm} \sin m\lambda \right) \bar{P}_{nm}(\cos \theta). \quad (7)$$

5. The Window Technique

The traditional way of removing the effect of the topographic-isostatic masses faces a theoretical problem. A part of the influence of the topographic-isostatic masses is removed twice as it is already included in the global reference field. This leads to some double consideration of that part of the topographic-isostatic masses. Figure 4 sketches the traditional gravity reduction for the effect of the topographic-isostatic masses. The short-wavelength part, depending on the topographic-isostatic masses, is computed for a point P for the masses inside the circle denoted by TC . Removing the effect of the long-wavelength part by a global earth's gravitational potential field normally implies removing the influence of the global topographic-isostatic masses, shown as the big rectangle in Fig. 4 denoted by EGM (here EGM stands for Global Geopotential Model).

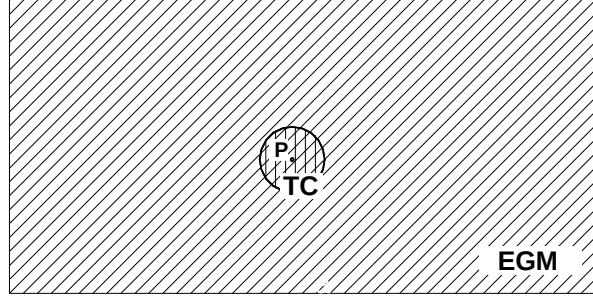


Figure 4: The traditional remove-restore technique.

The double consideration of the topographic-isostatic masses inside the circle (double hatched) is thus seen.

A possible way to overcome this difficulty is to adapt the used reference field to the effect of the topographic-isostatic masses for a fixed data area (Abd-Elmotaal and Kühtreiber, 2003). Figure 5 shows the advantage of the window remove-restore technique. Consider a measurement at point P ; the short-wavelength part, depending on the topographic-isostatic masses, is now computed by using the masses of the whole data area (the small rectangle in Fig. 5). The adapted reference field is created by subtracting the effect of the topographic-isostatic masses of the data window, in terms of potential coefficients, from the reference field coefficients. Thus, removing the long-wavelength part by using this adapted reference field does not lead to a double consideration of a part of the topographic-isostatic masses (as there is no double hatched area in Fig. 5).

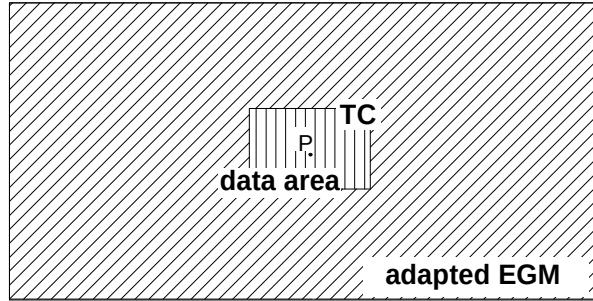


Figure 5: The window remove-restore technique.

The remove step of the window remove-restore technique can then mathematically be written as

$$\Delta g_{iso\ win} = \Delta g_F - \Delta g_{TI\ win} - \Delta g_{GM\ Adapt} , \quad (8)$$

where $\Delta g_{iso\ win}$ stands for the isostatic anomalies computed using the window technique, $\Delta g_{GM\ Adapt}$ is the contribution of the adapted reference field and $\Delta g_{TI\ win}$ is the effect of topography and its compensation for the fixed data window on the gravity anomalies employing the fine and coarse DHM's described in sec. 3.2. Equation (8) can be written more explicitly as

$$\begin{aligned} \Delta g_{iso\ win} &= \Delta g_F - \Delta g_{TI\ win} - (\Delta g_{GM} - \Delta g_{wincof}) \\ &= \Delta g_F - \Delta g_{TI\ win} - \Delta g_{GM} + \Delta g_{wincof} , \end{aligned} \quad (9)$$

where Δg_{GM} is the contribution of the original global reference field and Δg_{wincof} is the contribution of the harmonic coefficients of the topographic-isostatic masses of the data window (for our case it is the African data window $-40^\circ \leq \phi \leq 42^\circ$, $-20^\circ \leq \lambda \leq 60^\circ$) computed to the maximum degree of the used geopotential model.

The computation of the potential harmonic coefficients of the topographic-isostatic masses within the data window is carried out using (Abd-Elmotaal and Kühtreiber, 1999, Eq. (11)). The contribution Δg_{wincof} is computed from the potential harmonic coefficients of the topographic-isostatic masses within the data window (for our case it is the African data window). For more details on the window remove-restore technique, the reader is kindly invited to refer to (Abd-Elmotaal and Kühtreiber, 1999, 2003).

Let us define a couple of terms. The first term is called “the long-medium wavelength free-air anomalies” $\Delta g_{F \text{ long-med}}$, which is defined as

$$\Delta g_{F \text{ long-med}} = \Delta g_F - \Delta g_{TI \text{ win}} + \Delta g_{wincof} . \quad (10)$$

The second term is called “the reduced free-air anomalies” $\Delta g_{F \text{ red}}$, which is defined as

$$\Delta g_{F \text{ red}} = \Delta g_F - \Delta g_{GM} . \quad (11)$$

6. The Results

Table 2 shows the statistics of the point free-air gravity anomalies as well as of the free-air anomalies produced by the used global geopotential models. The program GRVHRM (Abd-Elmotaal, 1998) has been used to compute the free-air gravity anomalies at the gravity data points produced by the used geopotential models Δg_{GM} .

Table 2: Statistics of the free-air gravity anomalies produced by the used global geopotential models (1,186,032 stations). Units in [mgal]

gravity anomalies	N_{max}	min.	max.	mean	st. dev.
Point free-air (Δg_F)	—	−409.67	452.80	−4.37	39.61
$\Delta g_{F \text{ long-med}}$	—	−237.16	322.42	−3.28	36.30
EGM2008	2160	−234.72	578.21	−2.51	38.14
EIGEN-6C2	1949	−237.06	573.60	−2.52	37.97
EIGEN-6C4	2190	−233.70	579.57	−2.50	37.96
GO_CONS_GCF_2_TIM_R3	250	−191.72	176.16	−0.86	28.26
GO_CONS_GCF_2_TIM_R5	280	−185.04	190.75	−0.96	29.11
GO_CONS_GCF_2_DIR_R5	300	−182.12	190.64	−1.02	29.35
GOGRA02S	230	−197.34	176.59	−0.93	28.27
GOGRA04S	230	−196.16	176.96	−0.81	28.24
JYY_GOCE04S	230	−196.06	176.90	−0.81	28.24
ITG-GOCE02	240	−190.47	175.88	−0.69	27.97

According to Eq. (9), in order to get as much smaller reduced anomalies as possible, the term “the long-medium wavelength free-air anomalies” $\Delta g_{F \text{ long-med}}$ should compensate with the term Δg_{GM} . Accordingly, Table 2 may give the sign that none of the examined geopotential models would satisfy this criterion. The range of the long-medium wavelength free-air anomalies $\Delta g_{F \text{ long-med}}$ is only 65% of that of the free-air anomalies and the standard deviation is about 92% of that of the free-air anomalies (which signalizes that the short wavelength are mostly removed from the free-air anomalies). Table 2 shows that the ultra high-degree models have generally greater range than that of the long-medium wavelength free-air anomalies $\Delta g_{F \text{ long-med}}$ with slightly higher standard deviation. In contradictory, the satellite-only models (which have low upper maximum degree) have generally much smaller range than that of the long-medium wavelength free-air anomalies $\Delta g_{F \text{ long-med}}$ with significantly smaller standard deviation.

Table 3 shows the statistics of “the reduced free-air anomalies” $\Delta g_{F \text{ red}}$ for all used global geopotential models. No topographic-isostatic reduction has been made at this stage. Table 3 shows that the range of the reduced free-air gravity anomalies $\Delta g_{F \text{ red}}$ for all models is at the same order of magnitude as that of the point free-air gravity anomalies. It shows also that the standard deviation of the reduced free-air anomalies $\Delta g_{F \text{ red}}$ for the ultra high-degree models is dramatically smaller than that of the satellite-only models. This is simply because the satellite-only models could not remove the medium wavelength from the free-air anomalies having a relatively low upper maximum degree. This may also come from the possible inclusion of some of the gravity measurements over Africa in the creation of the ultra-high geopotential models. Table 3 also shows that the mean value of the reduced free-air anomalies $\Delta g_{F \text{ red}}$ for the ultra high-degree models is smaller than that of the satellite-only models.

Table 3: Statistics of the reduced free-air gravity anomalies $\Delta g_{F \text{ red}}$ computed by Eq. (11) for the used global geopotential models (1,186,032 stations). Units in [mgal]

used geopotential model	N_{max}	min.	max.	mean	st. dev.
EGM2008	2160	-457.03	271.53	-1.86	13.24
EIGEN-6C2	1949	-473.32	272.07	-1.85	13.47
EIGEN-6C4	2190	-456.51	270.80	-1.88	13.35
GO_CONS_GCF_2_TIM_R3	250	-525.32	313.08	-3.51	29.10
GO_CONS_GCF_2_TIM_R5	280	-527.16	294.74	-3.41	27.94
GO_CONS_GCF_2_DIR_R5	300	-525.37	295.34	-3.35	27.68
GOGRA02S	230	-515.18	323.29	-3.44	29.22
GOGRA04S	230	-510.40	320.69	-3.56	29.09
JYY_GOCE04S	230	-510.44	320.57	-3.56	29.09
ITG-GOCE02	240	-518.39	316.61	-3.68	29.41

Figure 6 shows the free-air reduced gravity anomalies $\Delta g_{F \text{ red}}$ for the EIGEN-6C4 geopotential model, being one of the best models to generate the reduced free-air anomalies for Africa. It should be noted that EGM2008 model gives nearly the same statistics of the reduced free-air gravity anomalies. Figure 6 shows that most of the area has

free-air reduced gravity anomalies less than 20 mgal in magnitude (the white pattern). More than 91.4% of the points have reduced free-air anomalies less than 20 mgal in magnitude. The higher values are located at the high mountainous area of Morocco, which is likely due to vertical datum inconsistency. Deeper investigation for this area is essentially needed (cf. Abd-Elmotaal et al., 2015).

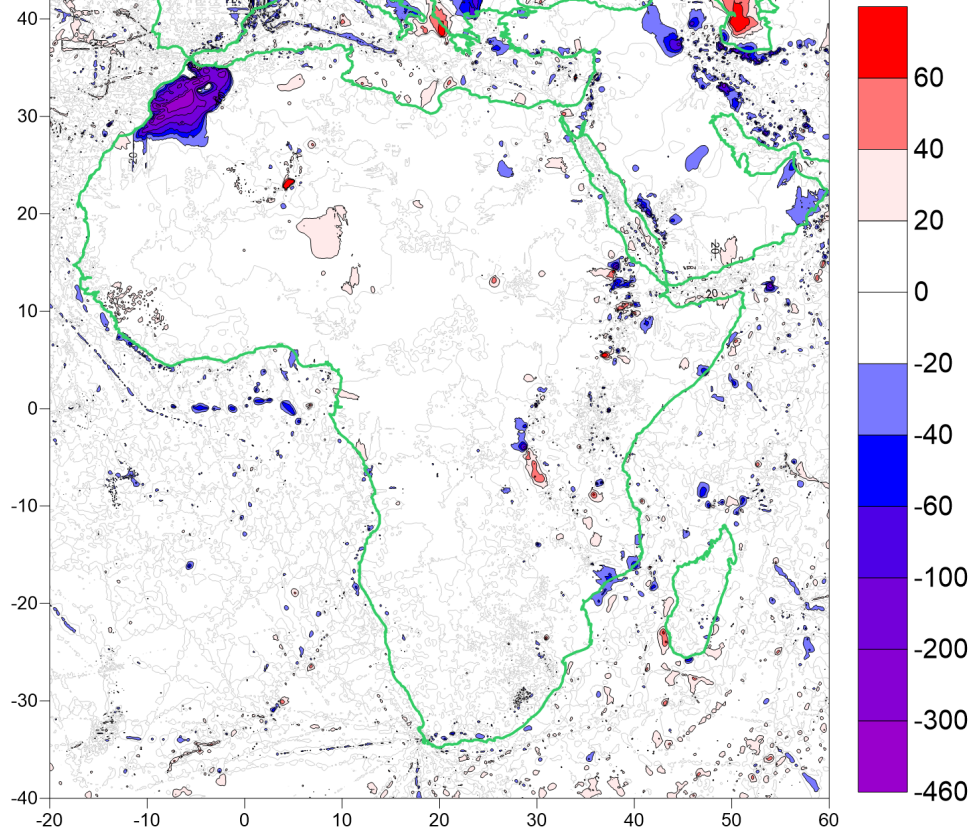


Figure 6: The EIGEN-6C4 reduced free-air anomalies $\Delta g_{F\ red}$ for Africa (computed by Eq. (11)).

Table 4 shows the statistics of the isostatic anomalies computed using the window technique $\Delta g_{iso\ win}$ for the used geopotential models. The Airy-Heiskanen isostatic model has been used with the following parameters:

$$\begin{aligned} T_o &= 30 \text{ km}, \\ \rho_o &= 2.67 \text{ g/cm}^3, \\ \Delta\rho &= 0.4 \text{ g/cm}^3. \end{aligned} \tag{12}$$

Table 4 shows that the standard deviation and the mean values of the Airy window isostatic gravity anomalies for the ultra high-degree models are slightly smaller than those of the satellite-only models. The range of the Airy window isostatic gravity anomalies for the ultra high-degree models is, however, significantly larger than that of the satellite-only models. Generally, the range and the standard deviation of the Airy window isostatic anomalies are relatively too high for such kind of gravity anomalies, which may signalize that none of these models is ideal for geodetic applications in Africa.

More interesting is the significant drop of the standard deviation of the the Airy window isostatic gravity anomalies for the satellite-only models. This already indicates an improvement, but perhaps not to the desired extent.

Table 4: Statistics of the isostatic anomalies computed using the window technique $\Delta g_{iso\ win}$ using Eq. (9) for the used global geopotential models (1,186,032 stations). Units in [mgal]

used geopotential model	N_{max}	min.	max.	mean	st. dev.
EGM2008	2160	-423.93	270.86	-0.77	20.09
EIGEN-6C2	1949	-409.02	271.40	-0.77	20.03
EIGEN-6C4	2190	-423.59	270.13	-0.79	20.00
GO_CONS_GCF_2_TIM_R3	250	-202.96	282.96	-2.42	22.86
GO_CONS_GCF_2_TIM_R5	280	-207.79	281.82	-2.33	21.55
GO_CONS_GCF_2_DIR_R5	300	-205.08	276.98	-2.26	21.22
GOGRA02S	230	-212.28	281.00	-2.35	23.10
GOGRA04S	230	-210.06	284.15	-2.47	23.02
JYY_GOCE04S	230	-209.96	284.10	-2.47	23.02
ITG-GOCE02	240	-207.72	285.43	-2.59	23.33

In order to distinguish between the case on land and on sea regions, two tables are established. Tables 5 and 6 show the statistics of the isostatic anomalies computed using the window technique $\Delta g_{iso\ win}$ for the used geopotential models on land and sea, respectively. Generally, the Airy window isostatic anomalies on land have slightly higher standard deviation and range than those on sea for all models.

Table 5: Statistics of the isostatic anomalies on land computed using the window technique $\Delta g_{iso\ win}$ using Eq. (9) for the used global geopotential models (94,838 stations). Units in [mgal]

used geopotential model	N_{max}	min.	max.	mean	st. dev.
EGM2008	2160	-423.93	270.86	-0.39	23.65
EIGEN-6C2	1949	-409.02	271.40	-0.34	23.59
EIGEN-6C4	2190	-423.59	270.13	-0.19	23.70
GO_CONS_GCF_2_TIM_R3	250	-202.96	282.96	-0.27	25.38
GO_CONS_GCF_2_TIM_R5	280	-207.79	281.82	-0.52	23.96
GO_CONS_GCF_2_DIR_R5	300	-205.08	276.98	-0.53	23.62
GOGRA02S	230	-212.28	281.00	-0.14	25.81
GOGRA04S	230	-210.06	284.15	-0.14	25.68
JYY_GOCE04S	230	-209.96	284.10	-0.14	25.68
ITG-GOCE02	240	-207.72	285.43	-0.16	25.77

Table 6: Statistics of the isostatic anomalies on sea computed using the window technique $\Delta g_{iso\ win}$ using Eq. (9) for the used global geopotential models (1,091,194 stations). Units in [mgal]

used geopotential model	N_{max}	min.	max.	mean	st. dev.
EGM2008	2160	-187.90	142.50	-0.81	19.75
EIGEN-6C2	1949	-186.05	145.02	-0.80	19.69
EIGEN-6C4	2190	-187.65	143.68	-0.84	19.65
GO_CONS_GCF_2_TIM_R3	250	-152.32	159.09	-2.61	22.62
GO_CONS_GCF_2_TIM_R5	280	-140.64	159.21	-2.48	21.32
GO_CONS_GCF_2_DIR_R5	300	-140.02	151.68	-2.41	21.00
GOGRA02S	230	-149.29	167.32	-2.55	22.84
GOGRA04S	230	-149.01	168.93	-2.67	22.76
JYY_GOCE04S	230	-149.08	168.99	-2.68	22.76
ITG-GOCE02	240	-153.41	170.45	-2.80	23.09

Figure 7 shows the Airy window isostatic gravity anomalies $\Delta g_{iso\ win}$ for the EIGEN-6C4 geopotential model, being the best model giving the smallest standard deviation of the Airy window isostatic anomalies. Figure 7 shows that most of the area has Airy window isostatic gravity anomalies less than 20 mgal in magnitude (the white pattern). More than 78.5% of the points have Airy window isostatic anomalies less than 20 mgal in magnitude.

Figure 8 shows the Airy window isostatic gravity anomalies $\Delta g_{iso\ win}$ for the satellite-only GO_CONS_GCF_2_DIR_R5 geopotential model, which have a significantly better range than that of EIGEN-6C4 model (more than 210 mgal less) and a slightly larger standard deviation (1.2 mgal higher). The advantage of the GO_CONS_GCF_2_DIR_R5 geopotential model is that its upper maximum degree is only 300, which saves a tremendous amount of CPU time for computing the synthesized gravity anomalies Δg_{GM} . Figure 8 shows that most of the area has Airy window isostatic gravity anomalies less than 20 mgal in magnitude (the white pattern). More than 75.2% of the points have Airy window isostatic anomalies less than 20 mgal in magnitude.

7. Conclusion

Different recent GOCE geopotential models are tested to produce reduced isostatic gravity anomalies for Africa. The reduction of the gravity anomalies follows the window remove-restore technique employing the Airy floating hypothesis. A wide range of geopotential models are tested from satellite-only models, having low upper degree, to combined models having ultra high upper degree.

The results show that the GOCE-GRACE-LAGEOS combined geopotential model EIGEN-6C4 gives the smallest standard deviation of the Airy window isostatic anomalies for Africa. The GOCE satellite-only model GO_CONS_GCF_2_DIR_R5 gives the smallest range of the Airy window isostatic anomalies for Africa, with only 1 mgal higher in the

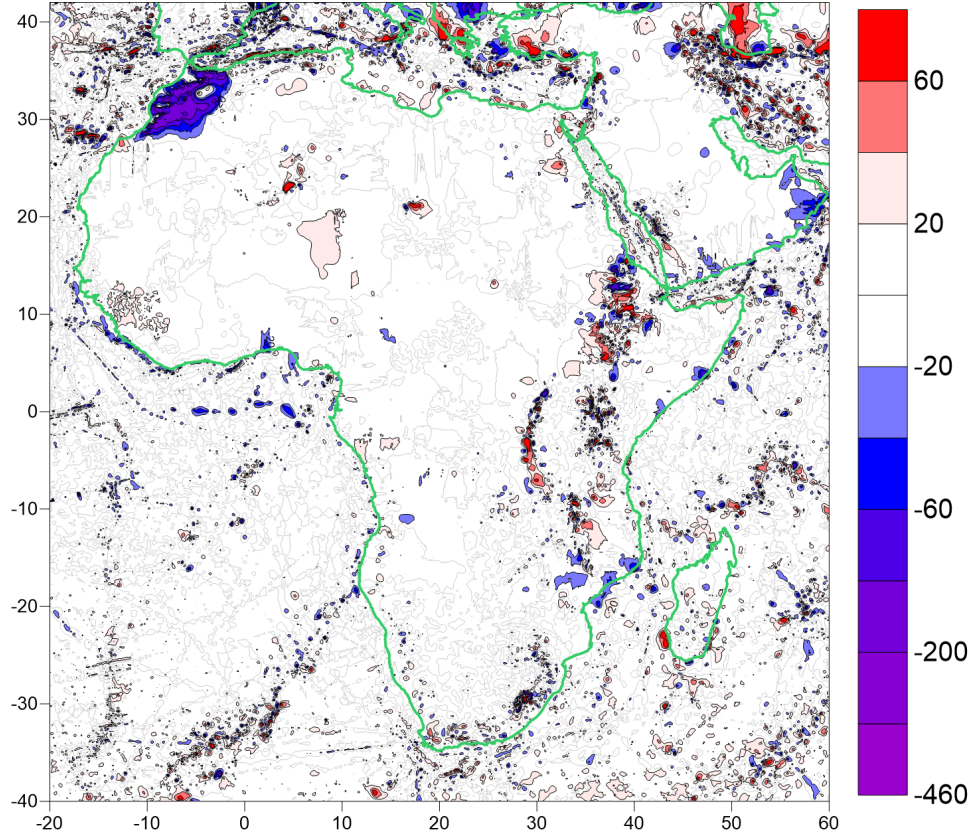


Figure 7: The EIGEN-6C4 Airy window isostatic anomalies $\Delta g_{iso\ win}$ for Africa (computed by Eq. (9)).

standard deviation compared to that of the EIGEN-6C4 model. Both the range and standard deviation of the Airy window isostatic anomalies generated by all tested models are relatively high.

It has been shown that most of the points on land in Africa have Airy window isostatic anomalies below 20 mgal in magnitude. There are still some spots, like in the high mountainous area of Morocco, that they still have large values of the Airy window isostatic anomalies. This needs, however, a deeper investigation. We believe that using some of the African land gravity measurement in the scaling process of the satellite-only models would definitely increase their fit to the African gravity field.

References

- Abd-Elmotaal, H. (1998) An Alternative Capable Technique for the Evaluation of Geopotential from Spherical Harmonic Expansions, *Bollettino di Geodesia e Scienze Affini*, **57**, 25–38.
- Abd-Elmotaal, H. and Kühtreiber, N. (1999) Improving the Geoid Accuracy by Adapting the Reference Field. *Physics and Chemistry of the Earth*, **24**(1), 53–59, DOI: 10.1016/S1464-1895(98)00010-6.
- Abd-Elmotaal, H. and Kühtreiber, N. (2003) Geoid Determination Using Adapted Refer-

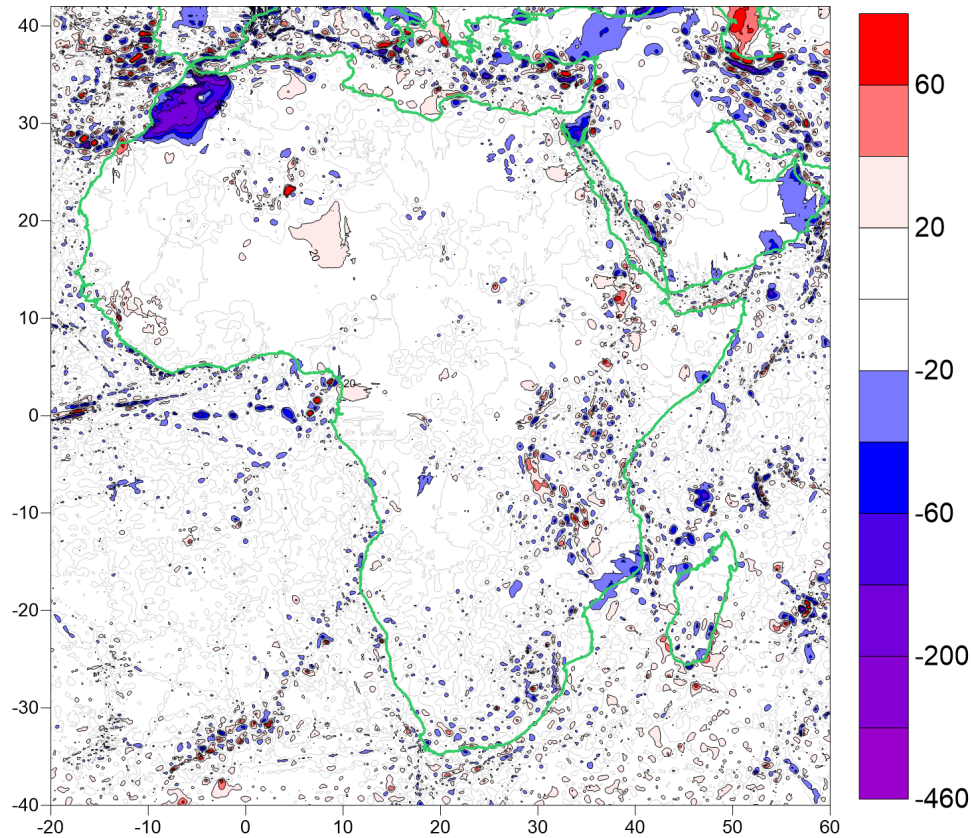


Figure 8: The GO_CONS_GCF_2_DIR_R5 Airy window isostatic anomalies $\Delta g_{iso\ win}$ for Africa (computed by Eq. (9)).

- ence Field, Seismic Moho Depths and Variable Density Contrast, *Journal of Geodesy*, **77**, 77–85.
- Abd-Elmotaal, H., Seitz, K., Kühtreiber, N. and Heck, B. (2015) Establishment of the Gravity Database for the African Geoid. *International Association of Geodesy Symposia Journal*, **144**, DOI: 10.1007/1345.2015_51.
- Brockmann, J.M., Zehentner, N., Höck, E., Pail, R., Loth, I., Mayer-Gürr, T., and Schuh, W.-D. (2014) EGM_TIM_RL05: An independent geoid with centimeter accuracy purely based on the GOCE mission. *Geophysical Research Letters*, **41** (22), 8089–8099, DOI: 10.1002/2014GL061904.
- Bruinsma, S.L., Förste, C., Abrikosov, O., Lemoine, J.-M., Marty, J.C., Mulet, S., Rio, M.H. and Bonvalot, S. (2014) ESA’s Satellite-Only Gravity Field Model via the Direct Approach Based on all GOCE data. *Geophysical Research Letter*, **41** (21), 7508–7514, DOI: 10.1002/2014GL062045.
- Dragomir, V.C., Ghițău, D.N., Mikăilescu, M.S. and Rotaru, M.G. (1982) *Theory of the Earth’s Shape: Developments in Solid Earth Geophysics*, 13. Elsevier Scientific Publishing Company, Amsterdam, Oxford, New York.
- Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D. and Alsdorf, D. (2007) The Shuttle Radar To-

- pography Mission, *Reviews of Geophysics*, **45**, RG2004, DOI:10.1029/2005RG000183.
- Förste, C., Bruinsma, S.L., Flechtner, F., Marty, J.-C., Lemoine, J.-M., Dahle, C., Abrikosov, O., Neumayer, H., Biancale, R., Barthelmes, F. and Balmino, G. (2012) A New Release of EIGEN-6C. *American Geophysical Union, Fall Meeting, San Francisco, USA, December 3–7, 2012*.
- Förste C., Bruinsma, S.L., Abrikosov, O., Lemoine, J.-M., Schaller, T., Götze, H.-J., Ebbing, J., Marty, J.C., Flechtner, F., Balmino, G., Biancale, R. (2014) EIGEN-6C4 The Latest Combined Global Gravity Field Model Including GOCE Data Up to Degree and Order 2190 of GFZ Potsdam and GRGS Toulouse. *5th GOCE User Workshop, Paris, November 25–28, 2014*.
- Heiskanen, W.A., and Moritz, H. (1967) *Physical Geodesy*. Freeman, San Francisco.
- Moritz, H. (1980) *Advanced Physical Geodesy*. Wichmann, Karlsruhe.
- Pail, R., Bruinsma, S., Migliaccio, F., Förste, C., Goiginger, H., Schuh, W.-D., Höck, E., Reguzzoni, M., Brockmann, J.M., Abrikosov, O., Veicherts, M., Fecher, T., Mayrhofer, R., Krasbutter, I., Sansò, F. and Tscherning, C.C. (2011) First GOCE Gravity Field Models Derived by Three Different Approaches. *Journal of Geodesy*, **85** (11), 819–843, DOI: 10.1007/s00190-011-0467-x.
- Pavlis, N.K., Factor, J.K., Holmes, S.A. (2007) Terrain-Related Gravimetric Quantities Computed for the Next EGM, *Harita Dergisi; Özel Sayı: Gravity Field of the Earth, Proceedings of the 1st International Symposium of the International Gravity Field Service (IGFS), 28 August – 1 September, 2006, Istanbul, Turkey*, **18**, 318–323.
- Pavlis, N.K., Holmes, S.A., Kenyon, S.C., and Factor, J.K. (2008) An Earth Gravitational Model to Degree 2160: EGM2008, *General Assembly of the European Geosciences Union, Vienna, Austria, April 13–18, 2008*.
- Pavlis, N.K., Holmes, S.A., Kenyon, S.C., and Factor, J.K. (2012) The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). *Journal of Geophysical Research* **117**, B04406, doi:10.1029/2011JB008916.
- Schall J., Eicker, A., Kusche, J. (2014) The ITG-GOCE02 Gravity Field Model from GOCE Orbit and Gradiometer Data Based on the Short Arc Approach. *Journal of Geodesy*, **88**, 403–409, DOI: 10.1007/s00190-014-0691-2.
- Torge, W. (1980) *Geodesy*. Walter de Gruyter, Berlin, New York.
- Torge, W. (1989) *Gravimetry*. Walter de Gruyter, Berlin, New York.
- Yi, W., Rummel, R., Gruber, T. (2013) Gravity Field Contribution Analysis of GOCE Gravitational Gradient Components. *Studia Geophysica et Geodaetica*, **57** (2), 174–202, DOI: 10.1007/s11200-011-1178-8.

Topographic evaluation of fifth-generation GOCE gravity field models – globally and regionally

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Abstract

ESA (European Space Agency) has released a series of new-generation Earth gravity field models computed from gradiometry and GPS observations carried out aboard the GOCE (Gravity field and Ocean Circulation Explorer) satellite. In order to assess the quality of the new GOCE gravity fields, the sensitivity of satellite gravimetry to the gravitational attraction of the topographic masses can be exploited. This study uses topographic mass models to evaluate five generations of GOCE gravity models, both globally and regionally. As model representing Earth's topography, ice-sheet and water-body masses we use the new RET2014 rock-equivalent topography model by Curtin University (Perth). The gravitational potential of the RET2014 model is computed in spherical harmonics and in ellipsoidal approximation (ellipsoidal topographic potential, cf. Claessens and Hirt 2013, JGR Solid Earth, 118, 5991). We compare gravity from GOCE and from the RET2014 topography, whereby similar signal characteristics are taken as a sign of quality for the GOCE gravity fields. Our topographic evaluation shows a steadily improved agreement of the five model generations with topography-implied gravity, and increase in GOCE model resolution. For the fifth-generation GOCE gravity fields, full resolution is indicated to harmonic degree ~220 (90 km scales), and partially resolved gravity features are found to degree ~270 (time-wise approach, TIM) and degree ~290-300 (direct approach, DIR). As such, the 5th-generation GOCE models capture parts of the gravity field signal down to ~70 km spatial scales. This is a very significant improvement in satellite-only static gravity field knowledge compared to the pre-GOCE-era. Our comparisons show that models from the DIR approach improved relative to those from the TIM approach from the 2nd to the 5th generation, with DIR offering the best short-scale performance (from degree 240 and beyond). Considering the unprecedented gravity field resolution achieved, the GOCE gravity field mission performed beyond the expectations. The GOCE gravity fields will serve as a de-facto-standard in a range of applications encompassing geodesy, geophysics and oceanography.

Key words GOCE, gravity, topography, mass modelling, model evaluation

1. Introduction

Over a period of four years, European Space Agency (ESA)'s dedicated Gravity field and Ocean Circulation Explorer (GOCE) satellite mission has measured Earth's gravity field with unprecedented spatial resolution from space (e.g., van der Meijde et al. 2015). Launched in March 2009, the GOCE mission entered its operational phase in November 2009 and probed the gravity field till ~mid 2012 from a nearly circular orbit (altitude of ~255 km and inclination of 96.7°). Additional measurements were carried out during a low-flying mission phase at a lower altitude of ~255 to ~224 km (July 2012 to June 2013), and at ~224 km (June to October 2013).

The main instrument aboard the GOCE satellite was a satellite gradiometer for measurement of gravity gradients (second derivatives of the gravitational potential), complemented by GPS-based satellite-to-satellite tracking to enhance the gravity field recovery in the lower-frequency spectrum (Drinkwater et al. 2003, Rummel et al. 2011, Bock et al. 2014). ESA's GOCE-High-Level Processing Facility (HPF) was used to produce a series of spherical harmonic GOCE gravity field models using different data periods (first to fifth generation models), and processing strategies (e.g., Pail et al. 2011) known as time-wise approach (abbreviated as TIM) and direct computation approach (DIR), cf. Section 2.

The spatial resolution of any gravity model from satellite observations is governed by Newton's law of gravitation implying attenuation of gravity signals with the square of the satellite height. Thus, a particularly important constituent of the GOCE gravity observation is the gravity effect of those masses which are closest to the satellite – the uppermost layers of the lithosphere and hydrosphere, notably the topography, ocean water and ice masses.

The sensitivity of satellite gravimetry for the gravitational attraction of the topographic masses (e.g., Mahkloof and Ilk 2008, Janák and Wild-Pfeiffer 2010, Grombein et al. 2011, Hirt et al. 2012, Novák and Tenzer 2013) can be exploited to assess the quality of GOCE gravity fields. Good agreement among gravity computed from Earth's topography and measured by GOCE – e.g., in terms of signal correlation – is a quality indicator for the satellite model. This particularly holds at shorter spatial scales where the gravity field becomes strongly influenced by the topographic masses. Topographic evaluation techniques are often used to assess the quality of satellite-measured gravity fields of the terrestrial planets (e.g., Venus, Konopliv et al. 1999, Mars, Konopliv et al. 2011, and Moon, Lemoine et al. 2014), and were shown to be useful for gravity fields from the GOCE mission too (Hirt et al. 2012).

Over most areas of Earth, the global topography is known with much higher resolution than the resolution provided by the GOCE gravity models. Compared to model validation based on ground-truth observations (with often regionally limited coverage, see several other papers in this volume), topographic evaluation thus allows for a truly global feedback on GOCE from comparisons against the global topography. However, comparisons between GOCE and the topography can be done regionally too, which is useful e.g., over areas where ground-truth data is limited (e.g., Africa, South America or Antarctica), cf. Hirt et al. (2012).

Besides the model evaluation, there are further major areas of application where the topography is crucial for GOCE gravity applications. These include the computation of GOCE Bouguer gravity (e.g., Braitenberg 2013, Hirt 2014), and smoothing of GOCE gravity measurements (e.g., Janák and Wild-Pfeiffer 2010, Grombein et al. 2011, 2014). In both cases, gravity implied by the topography is subtracted from GOCE gravity in order to highlight effects associated with mass-density anomalies (Bouguer gravity), or to improve the quality of interpolation (smoothing). Topographic evaluation of GOCE gravity fields, as done here, uses differences between gravity from GOCE and from the

topography too, whereby a reduction in signal variability is taken as a sign of quality for the GOCE gravity fields.

This contribution focuses on the global and regional topographic evaluation of five GOCE model generations from the TIM and DIR approaches (Section 2). As model for the uppermost masses of the lithosphere and hydrosphere we use the newly developed RET2014 rock-equivalent topography model (<http://ddfe.curtin.edu.au/models/Earth2014>). This model represents the masses of Earth's topography, ice-sheets and water-bodies based on new or improved data sets (Section 3). The gravitational potential of the RET2014 model is computed using a recently developed gravity forward modelling technique (Claessens and Hirt 2013) that accounts for Earth's ellipsoidal shape (Section 4). It delivers the RET2014 gravitational potential in spherical harmonics and in ellipsoidal approximation, which is rigorously compatible with the mathematical representation of GOCE gravity field models.

In Section 5, gravity effects from the various GOCE models and from RET2014 are compared. This is done both in terms of cross-correlation, and signal reduction rates which quantify the amount of RET2014 gravity signals "observed" by GOCE. The comparisons are carried out as a function of the harmonic degree, and with geographic specificity over various regions (global, land, oceans, continents). This provides insight into (a) the spatial resolution of the GOCE models, (b) their sensitivity for short-scale gravity recovery, and (c) the relative performance of the DIR and TIM approaches over five model generations. Concluding remarks are given in Section 6.

Our paper builds upon the earlier study by Hirt et al. (2012) who evaluated the first three GOCE model generations using an initial version of Earth's RET (RET2011), and forward modelled gravity effects in spherical approximation (e.g., Rummel et al. 1988). Compared to our earlier study, recent progress includes (i) improved gravity forward modelling in ellipsoidal approximation, (ii) up-to-date mass modelling through RET2014, and (iii) inclusion of five GOCE model generations. In order to substantiate points (i) and (ii), earlier models of Earth's topographic potential are included in this study (cf. Section 3.2 and appendix A).

We acknowledge the many other studies concerned with evaluation of GOCE gravity field models using a range of complementary evaluation techniques, e.g., comparisons against ground gravity data (Gruber et al. 2011, Hirt et al. 2011, Voigt and Denker 2011, Tscherning and Arabelos 2011, Abdallah et al. 2012, Guimarães et al. 2012, Szucz 2012, Janák and Pitoňák 2011, Sprlák et al. 2011, 2012, Rexer et al. 2013, Gerlach et al. 2013, Godah et al. 2014), against global gravity models (e.g., Pail et al. 2011, Hirt et al. 2011), other satellite-collected data (Hashemi Farahani et al. 2013), and orbit comparisons (Gruber et al. 2011).

2. GOCE gravity models

ESA's GOCE satellite mission has triggered a new era of gravity observation from space. The reason for this advance is the sensitivity of GOCE's main gravity sensor (a gravity gradiometer) to signals at comparatively small spatial scales (up to ~ 80 km) w.r.t. to earlier satellite gravity missions such as GRACE (up to ~ 150 km) and CHAMP. Since the launch of the GOCE satellite a multitude of gravity field models incorporating GOCE gravity data have been published. Among the 26 listed models (<http://icgem.gfz-potsdam.de/ICGEM/>, accessed September 2014), the most important are ESA's official GOCE gravity field releases, which are based on three different processing approaches known as *direct* (DIR ; Bruinsma et al. 2010) , *space-wise* (SPW; Migliaccio et al. 2010) and *time-wise* (TIM; Pail et al. 2010) method. The models are the result of the joint effort of ESA's *High-Level Processing Facility* (HPF), involving ten European universities and research institutes under the management of Technische Universität München. For the details and further literature on the different processing

strategies we refer to Pail et al. (2011). The processing approaches follow different philosophies e.g. regarding outlier detection, stochastic modelling, constraining, a priori information and combination with other sources of gravity data (Table 1). Hence, the different models come with different features and the user should carefully consider the choice of model based on the intended application.

While the production of *space-wise* models has been abandoned after the release of the second model generation in 2011, five model generations exist from each of the two other processing approaches (DIR and TIM). The fifth generation models, released in mid-2014, are the final versions of ESA GOCE models, as they incorporate the data of the entire operational mission time (November 2009 - October 2013), cf. Table 1. Detailed descriptions of the fifth-generation models are given in Bruinsma et al. (2014) for DIR5 and in Brockmann et al. (2014) for TIM5.

The previous generation models (1st to 4th) may be regarded as intermediate models because of two reasons: (a) they incorporate only a certain period of GOCE observations and (b) the processing strategies have been improved and were adapted to the mission's circumstances in course of time. An overview over the processing changes from the 1st to the 4th generation DIR and TIM models is given in Rexer et al. (2013). The processing details for each release can be found in the respective model header information and the additional data sheet (the latter has been released continuously from the 3rd generation onwards). The 5th generation models incorporate 14 additional months of GOCE observations w.r.t. to the 4th generation models. The maximum degree and order has been increased from 260 to 300 (DIR) and 250 to 280 (TIM). The DIR5 processing has been subject to two major changes:

- (1) the Kaula regularization in DIR5 now already starts from degree 180, whereas this constraint was applied beyond 200 in DIR4;
- (2) the low harmonic degrees (up to degree 130) in DIR5 (apart from SLR contributions) now rely entirely on the ten years GRACE (release 3) normal equations of GRGS / CNES (Bruinsma et al. 2009). The GFZ GRACE release 05 (Dahle et al. 2012), present in DIR4 between degree 55 and 180, has been taken out.

In contrast to the rigorous GOCE-only gravity models of the TIM group, DIR models shall yield excellent performance over the entire spectrum. This is because they are full combinations of GOCE-SGG (beyond degree 130), GRACE (Tapley and Reigber 2001) and LAGEOS (Tapley et al. 1993). The latter two missions provide global gravity data of superior accuracy in the long wavelengths and are therefore highly complementary to the GOCE sensors. The TIM models rely on GOCE's GPS-SST (satellite-to-satellite) tracking data only in the lower frequencies, which cannot 'compete' with GRACE's Ka-band measurements. Therefore the TIM5 model, similar to the previous TIM releases, shows higher formal errors in the lower harmonic bands compared to DIR5. In the processing strategy of TIM5 two changes can be found:

- (1) an increased harmonic degree of the GPS-SST normal equations based on the short-arc integral approach (now 150 compared to 130 in TIM4);
- (2) the coefficients are now subject to Kaula regularization beyond degree 200 (previously beyond degree 180).

However, the largest difference between the 5th and the 4th generation models is not related to the nature of the processing strategies but in the orbit lowering of the GOCE satellite, commenced in late 2012. In its extended mission phase GOCE has been incrementally manoeuvred to an orbit altitude of 224 km (reached in June 2013) until the satellite's deorbiting in October 2013. The orbit lowering

resulted in higher sensitivity for short-scale gravity signals, as the gravity attenuation effect is mitigated (Bruinsma et al. 2013; Schack et al. 2014). Therefore (and because of additional data in general), both 5th release models show significantly lower errors in the high harmonic degrees as well as higher spherical harmonic resolutions. The evolution of the models from the 1st generation to the 5th generation shows a continuous improvement w.r.t to the respective predecessor model, e.g., in terms of cumulative geoid errors (Fig. 1), which are derived from the formal errors of the models' coefficients. Note that the magnitude of the formal error estimates of DIR releases (as provided along with the models in terms of the coefficients' standard deviation) tend to be too optimistic in general (pers. comm. Sean Bruinsma and Roland Pail). The observed magnitude of DIR errors (from external validation) is rather in the order of TIM formal error estimates (Rexer et al. 2013).

Table 1. Main characteristics of all five model generations of the time-wise (TIM) and the direct (DIR) method; GRACE: Gravity Recovery And Climate Experiment; SLR: Satellite Laser Ranging; GRGS: Groupes de Recherches de Géodésie Spatiale; CNES: Centre National d'Etudes; GFZ: GeoForschungszentrum Potsdam; SGG: Satellite Gravity Gradiometer; SST: Satellite-to-Satellite Tracking; DIR : GO_CONS_GCF_2_DIR (1,2,3,4,5) ; TIM : GO_CONS_GCF_2_TIM (1,2,3,4,5).

	Release date	Model acronym	Data period	Effective data [months]	Lmax	Auxilliary data used [years]	Release specific comment	Model specific comment
R1	2010	DIR1	2009/11/1 - 2010/01/11	2	240	EIGEN5C	-	Combined solution making use of terrestrial data at short scales
		TIM1	2009/11/1 - 2010/01/11	2	224	none		pure GOCE-only solution
R2	2011	DIR2	2009/11/1 - 2010/06/30	8	240	ITG-GRACE2010s	-	SGG: band pass filter 10-125 mHz GOCE-SST up to 130 Exclusion of terrestrial data
		TIM2	2009/11/1 - 2010/07/05	8	250	none		processing strategy unchanged w.r.t. previous release-
R3	2011	DIR3	2009/11/1 - 2011/04/19	11.5	240	GRACE: 6.5 SLR: 6.5	-	GRACE and SLR as normal equations
		TIM3	2009/11/1 - 2011/04/17	12	250	none		SGG: inclusion of V_{xz} -compo167nent
R4	2013	DIR4	2009/11/1 - 2012/08/01	28	260	GRACE: 9 SLR: 25	Increased accuracy on all scales due to new Level-1b processing (Stummer et al. 2012)	SGG: inclusion of V_{xz} -component GRACE: GRGS/CNES and GFZ solutions
		TIM4	2009/11/1 - 2012/06/19	26.5	250	none		SST: short-arc integral method up to 130 (Mayer-Gürr et al. 2006)
R5	2014	DIR5	2009/11/1 - 2013/10/20	42	300	GRACE: 10 SLR: 25	Increased accuracy and spatial resolution due to orbit lowering.	GRACE : only GRGS/CNES Kaula: starting at 180
		TIM5	2009/11/1 - 2013/10/20	42	280	none		SST: up to 150 Kaula: starting at 200

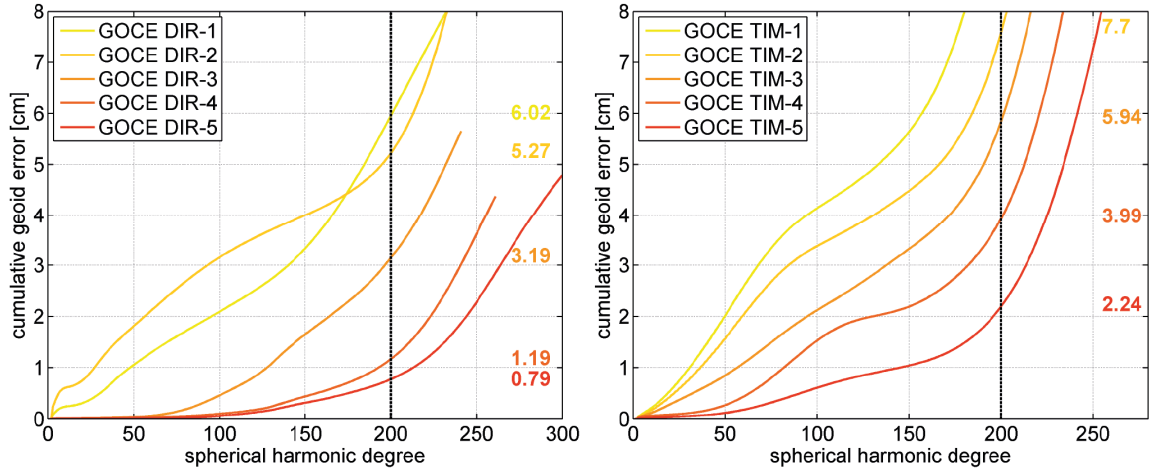


Fig. 1. Cumulative geoid height error of all generations of GOCE models of the direct (left) and the time-wise (right) approach with the numerical values of the error at degree 200 (= intersection of model with black dashed line) ; DIR: GO_CONS_GCF_2_DIR (1,2,3,4,5) ; TIM: GO_CONS_GCF_2_TIM (1,2,3,4,5).

3. Rock-equivalent topography (RET) and mass modelling

3.1 The new RET2014 model

To describe the masses of Earth's visible topography, ocean water, lake water and ice masses based on the newest data sets, the RET2014 model was developed as part of Curtin University's Earth2014 suite of global Earth topography models (Hirt and Rexer 2015). RET2014 is a composite model that represents ice and water masses as mass-equivalent layers of rock. RET2014 uses

- (i) The 250m (7.5 arc-sec) release of the SRTM V4.1 topography (Jarvis et al. 2008) over land areas between $\pm 60^\circ$ latitude,
- (ii) the 2014 version 9 release of the SRTM30_PLUS (Becker et al. 2009) bathymetry model over the oceans (30 arc-sec resolution)
- (iii) Bedmap2 (Fretwell et al. 2013) bedrock, bathymetry and ice thickness data over Antarctica (1 km resolution) and
- (iv) The 1km-resolution Greenland_Bedrock_Topography_V3 (GBT_V3) product (J.L. Bamber 2014, pers. comm., Bamber et al. 2013) over Greenland,

see Hirt and Rexer (2015) for full details. The RET2014 model is publically available via <http://ddfe.curtin.edu.au/models/Earth2014>, allowing replication of our study. The procedures applied to generate the RET2014 topography are largely similar to those used for the predecessor models RET2012 and RET2011 (cf. Hirt 2013, Hirt et al. 2012). We computed RET heights H_{RET} from SRTM30_PLUS, Bedmap2 and GBT_V3 by compressing water and ice masses into RET using

$$H_{RET} = H_{BED} + \frac{\rho}{\rho_R} \Delta H \quad (1)$$

where H_{BED} is the bedrock, lake bottom or seafloor height (reckoned negative if below the geoid), ΔH is the thickness of the ice or water body, ρ_R is the mass density of topographic rock, and ρ the mass density of the ice or water body (see Table 2 for density values used). Over ice-covered water bodies (e.g., ice shelves), ice and water are compressed and stacked via

$$H_{RET} = H_{BED} + \frac{\rho_W}{\rho_R} \Delta H_W + \frac{\rho_I}{\rho_R} \Delta H_I. \quad (2)$$

Anywhere over dry land, the heights of the topography are identical with RET heights. A spherical harmonic series expansion of the RET2014 topography grid to degree and order 2,160 was generated following the procedures outlined in Hirt (2013).

Table 2. Mass-density values used in RET2014

Mass body	Symbol	Mass density [kg m ⁻³]
Topography	ρ_R	2670
Ocean water	ρ_O	1030
Lake water	ρ_L	1000
Ice water	ρ_I	917

We acknowledge that even today the geometric knowledge of water bodies (bathymetry) is incomplete over areas devoid of direct depth measurements (see Becker et al. 2009), this equally holds for the lower boundaries of the ice-sheets (bedrock) over areas where direct ice thickness measurements are absent or scarce (Fretwell et al. 2013). Further, all data sets used may be subject to artefacts (e.g., spikes, data or interpolation errors), which are mostly of high-frequency nature. At the spatial scales observed by GOCE (say 70 km and larger), these imperfections are assumed to be rather uncritical for the topographic evaluation of the GOCE gravity fields.

3.2 Previous versions of RET models

As previous versions of Earth's rock-equivalent topography, we include Curtin University's RET2011 model (Hirt et al. 2012), and RET2012 (Hirt 2013) which were used in earlier topographic evaluations of GOCE gravity fields. Both RET models are based on 'older' ice and bathymetry data compilations. RET2011 relies on the DTM2006.0 spherical harmonic model of Earth's topography and bathymetry (Pavlis et al. 2007), while RET2012 as direct predecessor of RET2014 uses topography and bathymetry from SRTM V4.1 and SRTM30_PLUS (version 7). Both predecessors use RET computed from ETOPO1 (Amante and Eakins 2009) ice and bedrock data over Antarctica and Greenland (the data of which is now superseded by Bedmap2 and GBT_V3). As further differences between the three versions

- water masses of the major inland lakes are modelled in RET2014 and RET2012 (but not RET2011),
- ice-covered water bodies are modelled in RET2014 (but not RET2011 and RET2012).
- the RET-compression over ice-covered land is partially erroneous in RET2011 and RET2012 where bedrock heights are below the geoid. The error in RET2011 and RET2012 affects those fraction of the ice-sheets below the geoid which was incorrectly compressed by a factor of $(1 - \rho_I / \rho_R) \approx 0.65$ instead of $\rho_I / \rho_R \approx 0.35$. In RET2014, all ice masses (below and above the geoid) are compressed by ρ_I / ρ_R (Eqs. 1 and 2).

Table 3 summarises the data sets used to generate the three generations of RET models.

Table 3. Data sources and detail of modelling for three generations of RET models

Input data \ RET version	RET2014 (This work)	RET2012	RET2011
Land topography	SRTM V4.1 ^{&}		SRTM ~2004-release [*]
Ocean bathymetry	SRTM30_PLUS v9	SRTM30_PLUS v7	Smith and Sandwell (~2004) bathymetry [*]
Inland bathymetry	SRTM30_PLUS v9	SRTM30_PLUS v7	Not modelled
Antarctica – surface	Bedmap2	Bedmap1 ⁺	
Antarctica – bedrock	Bedmap2	Bedmap1 ⁺	
Greenland – surface	GBT_V3	GLOBE topography ⁺	
Greenland – bedrock	GBT_V3	NSDIC bedrock ⁺	
RET-modelling: ice	ice-sheets, ice-shelves,	ice-sheets	
RET-modelling: water	oceans, major lakes, water below ice (shelves, lake Vostok)	oceans, major lakes	oceans

[&] artefacts detected and removed over Asia and other areas, as described in Hirt et al. (2014)

^{*} as provided through the DTM2006.0 series expansion by Pavlis et al. (2007)

⁺ as provided through the ETOPO1 topography model by Amante and Eakins (2009)

3.3 Role of isostatic compensation

It is well known that at large spatial scales (say ~100s to 1000s of km) the limited rigidity of the Earth's crust cannot mechanically support the load of the topographic masses (e.g., Watts 2011). This phenomenon leads to isostatic compensation of the topography, i.e., a thickening of the Earth's crust below major mountain ranges. While the scientific foundation of isostasy is well established (see Watts 2011), accurate and detailed modelling of the isostatic compensation masses is not straightforward. Simplistic compensation models based on hypotheses such as Airy-Heiskanen or Pratt-Hayford are capable of describing isostatic compensation effects in coarse approximation only (Göttl and Rummel 2009). Observation-based crustal models describing the geometry of the crust-mantle interface (Moho) do not reach much higher resolution than 1 degree (about 110 km) globally, with lower resolution or dependence on gravity inversion over areas devoid of seismic Moho observations (e.g., Crust 1.0, Laske et al. 2013). Hirt et al. (2012) tested a range of isostatic compensation models, however, without improving the agreement between GOCE gravity and those implied by the uncompensated topography. This supports findings of an earlier study by Tsoulis and Stary (2005) who pointed out that *“Neither the long- nor the short-wavelength parts of the observed gravity field spectrum can be adequately explained by any of the existing isostatic models”*.

In the absence of the sufficiently detailed and accurate isostatic compensation models, Earth's topography is treated as uncompensated in this evaluation study. At the spatial scales which are of particular interest for the GOCE mission (say 100 km scales), surface topography should be in good approximation uncompensated *“beyond harmonic degree 200”* (Wieczorek 2007), suggesting that isostatic compensation is not too much of concern for our study.

While the main focus of our topographic evaluation study is not on isostatic compensation, we note that GOCE observations are now being used to improve crustal models (see e.g., van de Meijde et al. 2015 and Reguzzoni et al. 2013) through gravity inversion. However, using these new GOCE-dependent models to describe isostatic compensation masses for the purpose of GOCE evaluation is not considered useful because it would be a cyclic procedure.

4. Methods

4.1 Computation of gravity from topography

The effect of the rock-equivalent topography on the Earth's gravitational potential, i.e. the topographic potential, was modelled using the harmonic combination method (Claessens and Hirt 2013). This method applies forward modelling of the Earth's topographic potential in the spectral domain, and generates a set of spherical harmonic coefficients of the topographic potential. The major advantage of this method over earlier methods (e.g., Rummel et al. 1988) is that it does not rely on a spherical approximation of the Earth, but rigorously computes the gravitational potential generated by topography referenced to a geodetic reference ellipsoid. In the harmonic combination method, powers of the topographic heights are expanded into surface spherical harmonic series with coefficients $\bar{d}_{nm}^{(k)}$

$$\bar{d}_{nm}^{(k)} = \frac{1}{4\pi} \int_{\sigma} \left(\frac{d_{\Sigma}}{r_e} \right)^k \bar{Y}_{nm} d\sigma \quad (3)$$

where k is the power of the topography, σ is the unit sphere, d_{Σ} is the topographic height above the reference ellipsoid measured along the direction to the ellipsoid's origin, r_e is the ellipsoidal radius, and $\bar{Y}_{nm}$ is the fully normalised (4π -normalised) spherical harmonic function of degree n and order m . The integration in Eq. (3) is performed in a spherical coordinate frame, using geocentric co-latitude and longitude. Solid spherical harmonic coefficients of the topographic potential ($\bar{V}_{nm}^R$) are then computed from a summation over these surface spherical harmonic coefficients ($\bar{d}_{nm}^{(k)}$) of equal order m (Claessens and Hirt 2013)

$$\bar{V}_{nm}^R = \frac{4\pi\rho b^3}{M(2n+1)(n+3)} \left(\frac{b}{R}\right)^n \sum_{k=1}^{n+3} \binom{n+3}{k} \sum_{j=0}^{\infty} (-1)^j \left(-\frac{n+3}{2}\right)_j e^{2j} \sum_{i=-j}^j \bar{K}_{nm}^{2i,2j} \bar{d}_{n+2i,m}^{(k)} \quad (4)$$

where ρ is the mean density of the rock-equivalent topography (2670 kg m^{-3} used here), b and e are the semi-minor axis and first numerical eccentricity of the reference ellipsoid (GRS80 parameters used; Moritz 2000), M is the Earth's mass ($5.9725810 \times 10^{24} \text{ kg}$ used), R is the reference radius of the solid spherical harmonic series (6378137 m used), and $\bar{K}_{nm}^{2i,2j}$ are fully normalised sinusoidal Legendre weight functions. The latter can be computed recursively (see Claessens 2005, 2006, or Claessens and Hirt 2013 for details).

In this study, the RET2014 model of rock-equivalent topography was used as input in the harmonic combination method. The resulting model of the topographic potential was named dV_ELL_RET2014. Like EGM2008 (Pavlis et al. 2012), this model has a maximum spherical harmonic degree of 2190, containing (incomplete) coefficients beyond degree and order 2160 that are vital for accurate evaluation of the topographic potential at high resolution (Claessens and Hirt 2013). In the computation, the summation over k was truncated at $k = 10$, and the summation over j was truncated at $j = 30$. Claessens and Hirt (2013) have shown this to be sufficient, as both series converge fairly rapidly.

The gravitational attraction due to the topographic masses (in short: *topographic gravity*) can easily be evaluated anywhere on or above the Earth's surface from a topographic potential model such as dV_ELL_RET2014. This can be done in ellipsoidal approximation (e.g. Claessens 2006, Barthelmes 2009) or in spherical approximation. Spherical approximation was used here as it is sufficiently accurate for the purpose of this study. In spherical approximation, the topographic gravity δg_{TOPO} is given by

$$\delta g_{TOPO}(r, \theta, \lambda) = \frac{GM}{r^2} \sum_{n=0}^{n_{max}} \left(\frac{R}{r}\right)^{n+1} (n+1) \sum_{m=-n}^n \bar{V}_{nm}^R \bar{V}_{nm}(\theta, \lambda) \quad (5)$$

where GM is the geocentric gravitational constant of the Earth (GRS80 parameter used; Moritz 2000).

4.2 Methodology for GOCE model evaluation

Following Hirt et al. (2012), we evaluate the GOCE model generations by comparing synthesised gravity from (a) GOCE and (b) the dV_ELL_RET2014 topographic potential model that is based on the RET2014 topography. In all comparisons, gravity is computed in narrow spectral bands of 5 harmonic degrees (e.g., degrees 6 to 10, 11 to 15, ... 296 to 300, or lower, depending on the GOCE model) in terms of regularly spaced geocentric latitude-longitude grids of 10 arc-min spatial resolution. The computation height is set to 10,000 m above the surface of the GRS80 reference ellipsoid. This places the computation points safely outside the topographic masses where the field is non-harmonic.

The level of agreement between GOCE gravity δg_{GOCE} and topographic gravity δg_{TOPO} is quantified using cross-correlation coefficients (CCs)

$$CC = \frac{\sum (\delta g_{GOCE} - \bar{\delta g}_{GOCE}) \sum (\delta g_{TOPO} - \bar{\delta g}_{TOPO})}{\sqrt{\sum (\delta g_{GOCE} - \bar{\delta g}_{GOCE})^2 \sum (\delta g_{TOPO} - \bar{\delta g}_{TOPO})^2}} \quad (6)$$

and (signal) reduction rates (RRs)

$$RR = 100\% \left(1 - \frac{RMS(\delta g_{TOPO} - \delta g_{GOCE})}{RMS(\delta g_{TOPO})} \right) \quad (7)$$

where the symbols $\bar{\delta g}_{GOCE}$ and $\bar{\delta g}_{TOPO}$ denote mean values and RMS is the root-mean-square operator. CCs and RRs are computed as a function of (i) the GOCE model, (ii) the spectral band, and (iii) selected regions (the seven continents, all land and ocean areas, and the globe, cf. Fig. 2). In all cases we exclude

- all computation points located North of 83.3° and South of -83.3° latitude (these are areas not directly observed by GOCE due to the satellite's orbit inclination), as well as
- all computation points over Antarctica where bedrock elevations and ice-thicknesses depend on GOCE (see Fretwell et al. 2013 and Fig. 2). This ensures independence between GOCE and topographic gravity in our comparisons.

The two criteria CCs and RRs have the following testing power (after Hirt et al. 2012, Hirt 2014): CCs quantify the similarity between GOCE and topographic gravity, with strong correlation (say CCs of 0.7 or more) indicating good quality of the GOCE gravity fields. Complementary to CCs, signal reduction rates RRs quantify the portion of topographic gravity that is explained by the GOCE gravity observation. RRs of ~30% or higher indicate “*substantial topographic gravity signals explained by the GOCE observation*” (Hirt 2014), while lower but positive RRs demonstrate that parts of the (uncompensated) topographic gravity signal is observed by GOCE. Negative RRs occur when the difference δg_{TOPO} minus δg_{GOCE} possesses higher RMS signal strength than δg_{TOPO} alone (cf. Eq. 7), indicating that GOCE and topographic gravity signals are largely unrelated.

Fig. 3 gives an example of δg_{TOPO} , δg_{GOCE} and the difference δg_{TOPO} minus δg_{GOCE} over the Himalayas in spectral band of degrees 201 to 205 for three selected GOCE-TIM model releases. The

correlation and notable signal reduction are clearly visible, demonstrating a significant amount of GOCE-captured topographic gravity signals.

Note that the presence of mass-density anomalies (with respect to the reference density of 2670 kg m^{-3}) and any kind of modelling deficiency or observation error in δg_{GOCE} and δg_{TOPO} prevent RRs from approaching the theoretical maximum of 100 % (i.e., the GOCE-observed gravity signal δg_{GOCE} would be identical with the forward-modelled signal δg_{TOPO}). In practice, RRs do not exceed ~50% over continental areas and ~65% over very mountainous regions at the spatial scales observed by GOCE. CCs are capable of indicating the agreement between gravity signal patterns (lows and highs) only, which however does not provide information on the agreement between gravity signal magnitudes. The latter information is delivered by RRs.

Based on practical experiences, CCs and RRs are not computed for individual harmonic degrees. This is because the presence of correlations among the GOCE SHCs – and among the topographic potential SHCs (because of the underlying harmonic combination method, see Claessens and Hirt 2013) – would lower the mutual agreement between GOCE and topographic gravity. Computation of CCs and RRs over narrow spectral bands (here 5 degree band-width) reduces this effect as well as oscillations in the CCs and RR curves across the spectrum. Using spectral bands of few harmonic degrees band-width is also common in other validation studies, e.g., Gruber et al. (2011).

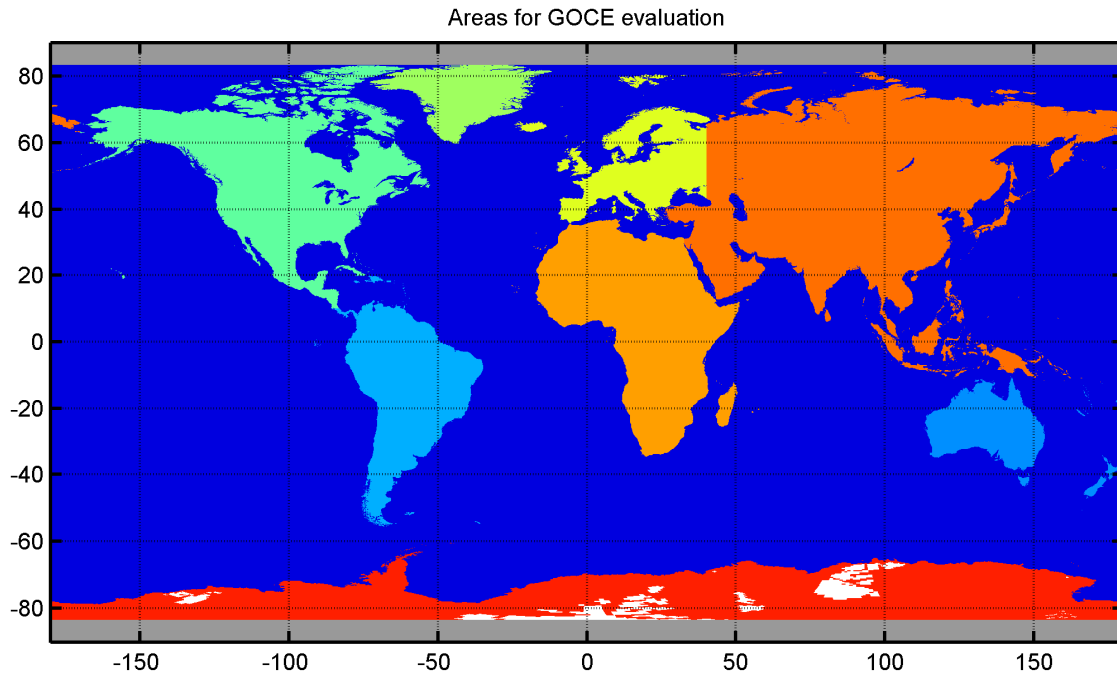


Fig. 2. Areas for evaluation of GOCE gravity field models. Oceans (dark blue), land/continental areas (various colours). Australia and New Zealand form the Oceania evaluation area. White areas over Antarctica indicate where Bedmap2 bedrock depends on earlier GOCE releases (excluded in all evaluations). Grey areas indicate the polar cap which is not directly observed by GOCE (excluded in all evaluations). Latitudes of this and all other maps are in terms of in geocentric coordinates.

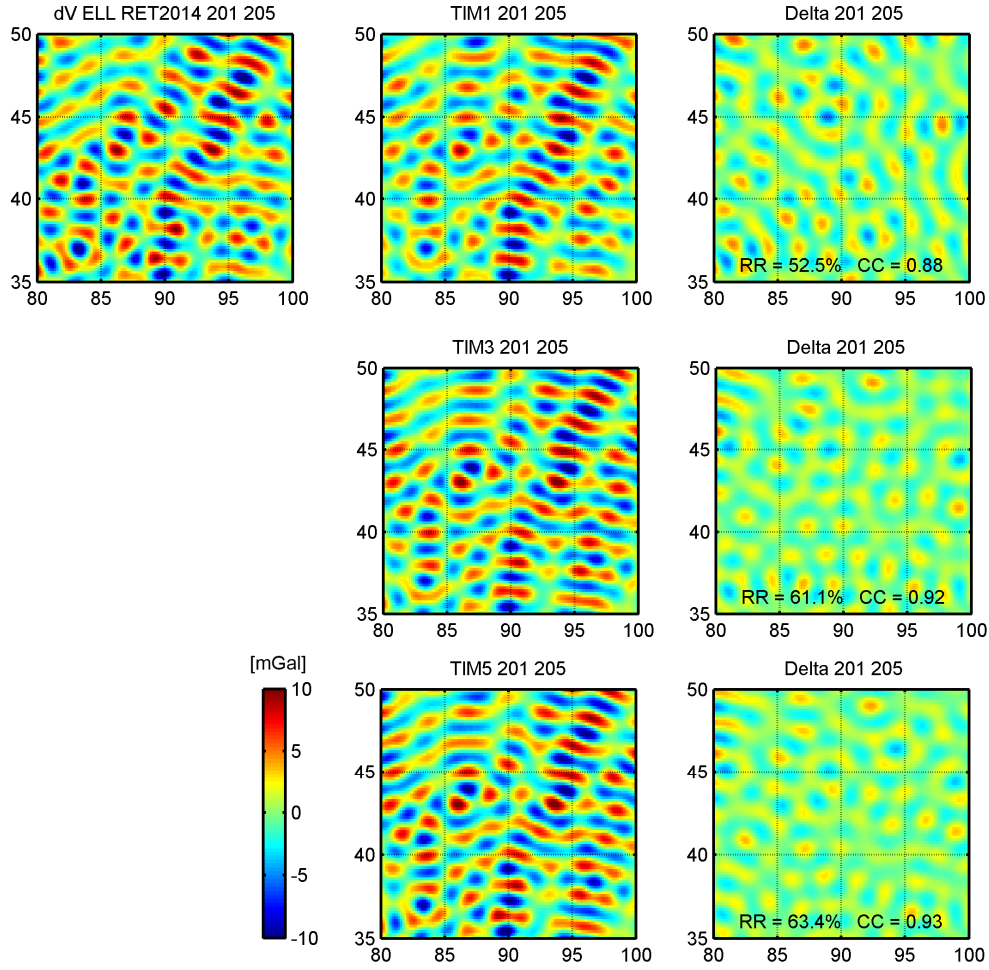


Fig. 3. Gravity effects implied by the RET2014 topography (left), and by GOCE TIM1, TIM3 and TIM5 models (middle column) in spectral band of degrees 201 to 205 over the Himalayas, differences between gravity from dV_ELL_RET2014 and GOCE (right column). Color range is ± 10 mGal for all panels. The agreement between dV_ELL_RET2014 and GOCE gravity is very good, with CCs in excess of 0.9 and signal reduction (RRs) larger than 60% over the most rugged area of Earth. From top to bottom, the improved agreement from TIM1 to TIM5 is demonstrated. Residuals (right column) can be interpreted as a result of mass-density anomalies, and any kind of modelling/measurement errors in both data sets.

5. Results

5.1 Global comparisons

General observations

Fig. 4 shows CCs and RRs computed globally for the five GOCE model generations from the DIR and TIM approach. Fig. 5 provides the same indicators, however, separately for land and ocean areas. For all models, RRs steadily increase to 30-35% around harmonic degree 150, showing that the GOCE gravity observations explain a larger fraction of the gravity signal generated by the uncompensated topography as the harmonic degree increases. Depending on the model generation (2nd to 5th), and computation approach (TIM vs. DIR), all models experience a drop in RR, the 2nd generation around degree $\sim 160-170$, the 3rd near degree ~ 180 , the 4th generation around degree ~ 190 and the 5th generation around degree 220 (seen in comparison to DIR1 which relies on terrestrial gravity data at short spatial scales). The drop in RR indicates that the respective model starts to “lose” the gravity signal, reflecting the effect of short-scale gravity signal attenuation at satellite height.

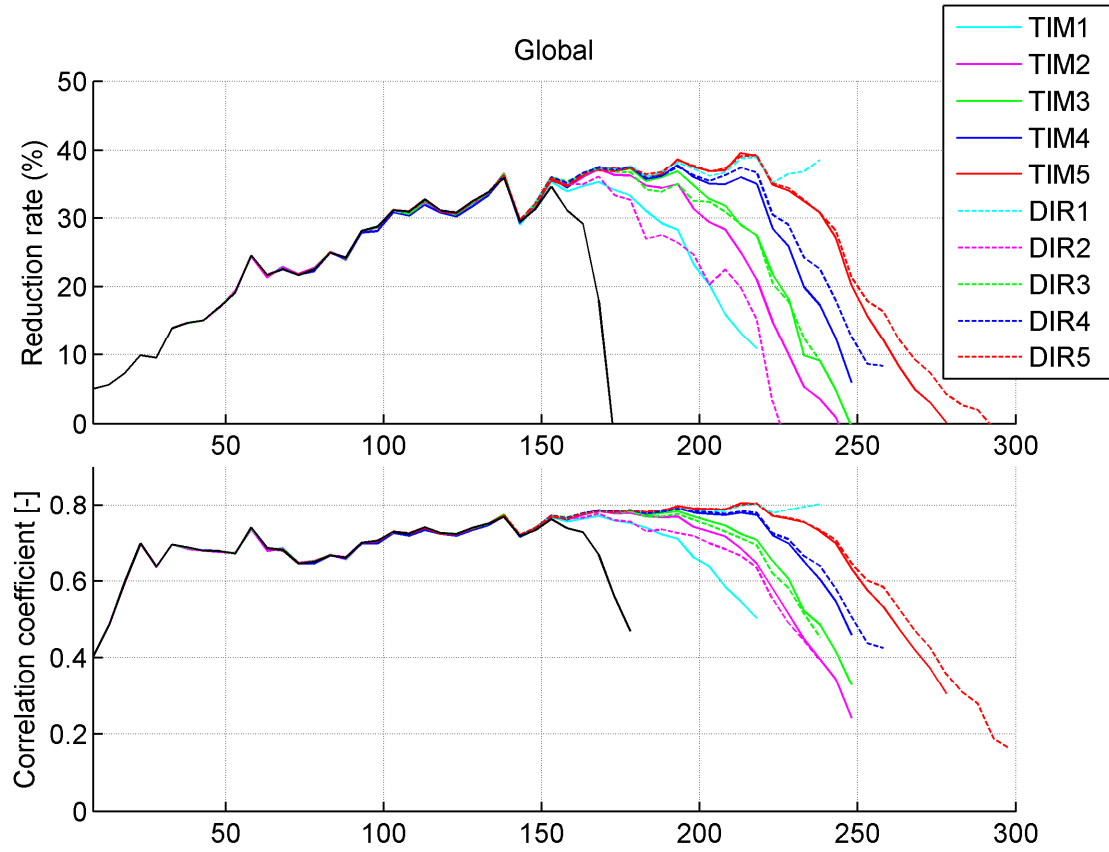


Fig. 4. RRs (top) and CCs (bottom) of 10 GOCE models and ITG-GRACE2010s (black curves) computed against dV_ELL_RET2014 near-globally (without polar regions and white areas shown in Fig 2). Indicators RR and CC are shown as a function of the harmonic degree (horizontal axes).

Notwithstanding, most of the models show positive RRs near or at their formal model resolution, showing that GOCE gravity captures topography-generated signals. Focussing on the 5th model generation which contains the 2012/2013 low-altitude observations, gravity from DIR5 (TIM5) reduces the RMS strengths of topographic gravity by $\sim 10\%$ at degree ~ 265 (~ 260), with RRs still being positive around degree ~ 275 (TIM5) and 285 (DIR5). This clearly demonstrates the presence of gravity signals at scales as short as ~ 70 km in the 5th-generation GOCE model releases, albeit in strongly attenuated form.

From Fig. 4 CCs are around $+0.7$ and larger over most of the spectrum, even at low degrees, and reach maximum values somewhat larger than $+0.8$ around degrees ~ 215 - 220 for the 5th generation GOCE releases. CCs start to drop around harmonic degrees ~ 160 - 170 (2nd), ~ 180 (3rd), ~ 200 (4th) and ~ 220 (5th generation), which reflects the increased quality of the GOCE models due to more observations, orbit lowering and improvements related to processing changes (see section 3). From a comparison between CCs and RRs, there is no one-to-one relation between both indicators. CCs are found to vary between $+0.2$ and $+0.4$ where RRs approach 0% in the high harmonic degrees. Conversely, for the low and medium harmonics, CCs are at the $+0.7$ level, while RRs show a steady increase (Fig. 4).

Comparison DIR vs. TIM

Both indicators allow discrimination between the short-scale performance of the DIR and TIM approaches for given model generations (Fig. 4). For the 2nd generation, TIM shows a better short-scale performance than DIR from degree 160 and higher, which is seen by RRs being up to 10%-points larger (e.g., around degree 200), likewise CCs being up to $+0.05$ larger. For the 3rd generation,

this behaviour is not so much pronounced anymore (RRs and CCs are close together, but with the indicators for TIM3 slightly better than for DIR3, also see results in Hirt et al. (2012). With the 4th model generation, there is a reversal in performance, with DIR4 offering the better short-scale agreement with topographic gravity: DIR4 is found to be around 3-5%-points (RRs) and 0.02-0.04 (CCs) above those of TIM4 beyond degree 200 (Fig. 4 and 5). For the 5th release, DIR5 and TIM5 offer a comparable performance against topographic gravity up to degree ~ 245 -250. At very short spatial scales (70-80 km, or harmonic degrees 250 to 290), however, gravity from the DIR5 model offers better agreement with topographic gravity (5% advantage in terms of RRs, about 0.05 in terms of CCs). Holistically, these observations suggest performance improvements of the DIR-approach relative to the TIM-approach from the 2nd to 5th model generation.

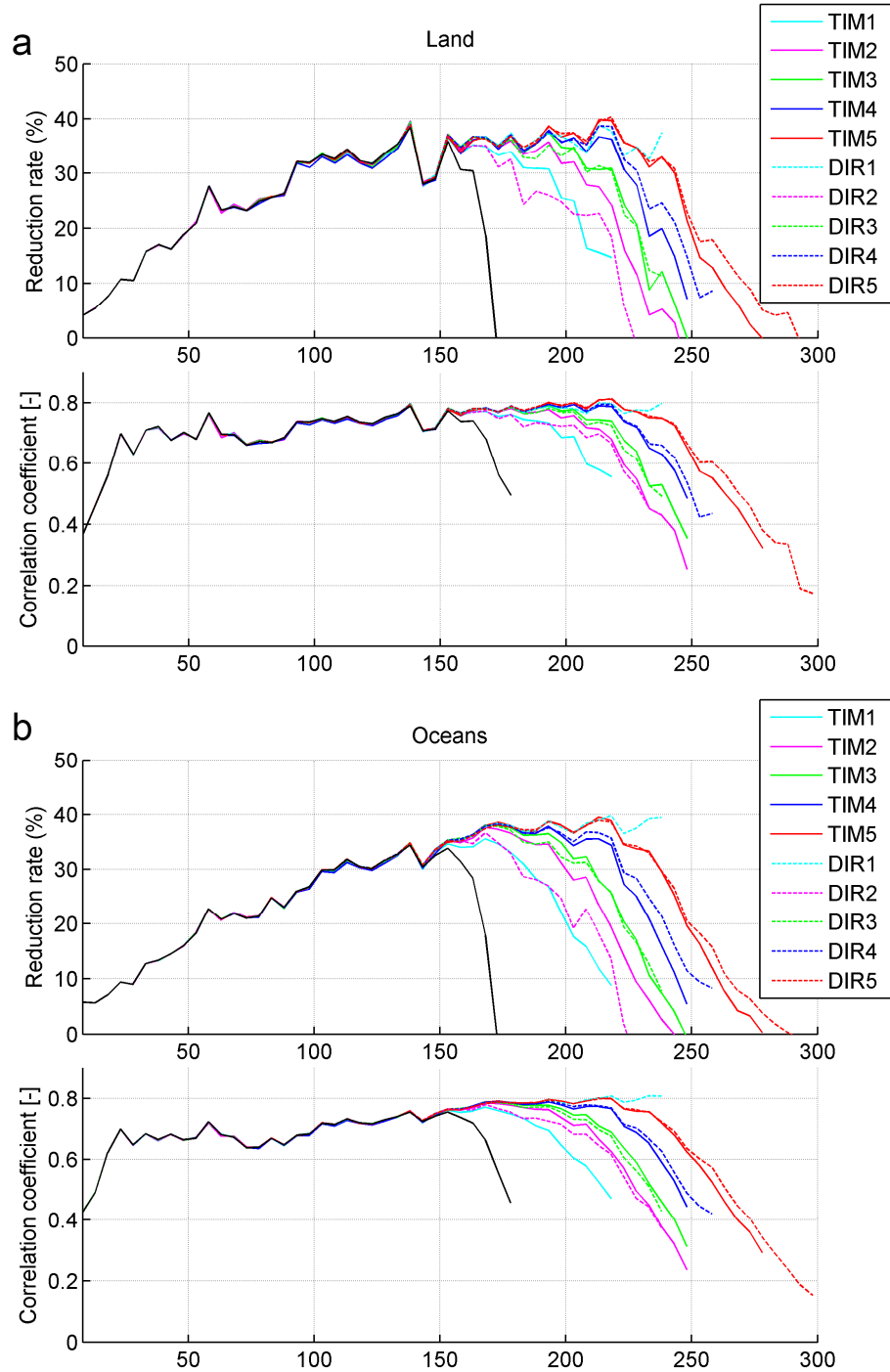


Fig. 5. As Fig. 4, but separate evaluations over the oceans (top panel), and land areas (bottom panel)

Comparison land vs. ocean

Fig. 5 essentially shows a comparable performance of the GOCE models over oceans and land areas (compare panel a with panel b), which suggests that the GOCE data quality is homogenous over land and oceans. The comparable performance also provides a feedback on the topographic gravity modelling, indicating similar quality of the RET2014 topography and dV_ELL_RET2014 topographic potential model over land and sea at the spatial scales observed by GOCE. RRs and CCs over land show somewhat more variability than over the oceans which is due to the smaller amount of computation points over land areas.

Comparison GOCE vs. GRACE

To demonstrate the steadily increased resolution of the GOCE gravity model generations, we have included the degree-180 ITG-GRACE2010s gravity model (Mayer-Gürr et al. 2010) as probably best satellite-only model of the pre-GOCE-era. From Fig. 4 and 5, ITG-GRACE2010s (black line) effectively resolves the gravity field to degree 160-165. Relative to the GRACE model, the 5th generation GOCE gravity fields provide new satellite-only gravity data to degree ~ 220 -230, with some information up to degree ~ 300 (DIR5). The GOCE short-scale gravity signal recovery is exemplified for the DIR5-release in Fig. 6 over the Himalayas. The GOCE gravity mission thus improves gravity maps (w.r.t GRACE) in spectral band of degrees ~ 165 up to ~ 290 , or at spatial scales of ~ 125 to ~ 70 -80 km, which is a very significant addition to our gravity field knowledge from satellite-only data.

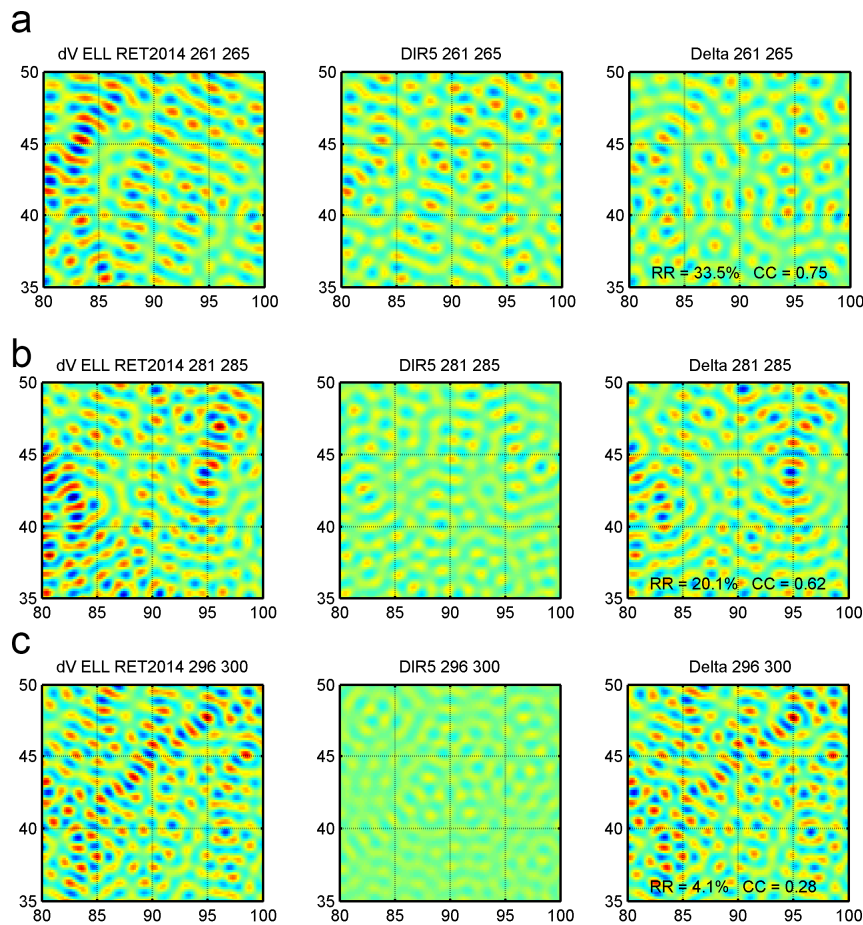


Fig. 6. Demonstration of DIR5 short-scale gravity signal capture over the Himalayas. Gravity from dV_ELL_RET2014 (left), gravity from DIR5 (middle), differences dV_ELL_RET2014 minus DIR5 gravity (right) in spectral bands 261 to 265 (a), 281-285 (b), and 296-300 (c). Color range is ± 10 mGal for all panels. Note that subtraction of DIR5 gravity from dV_ELL_RET2014 gravity reduces RMS signal variability to some extent, even in spectral band 296-300 (by 4.1 %).

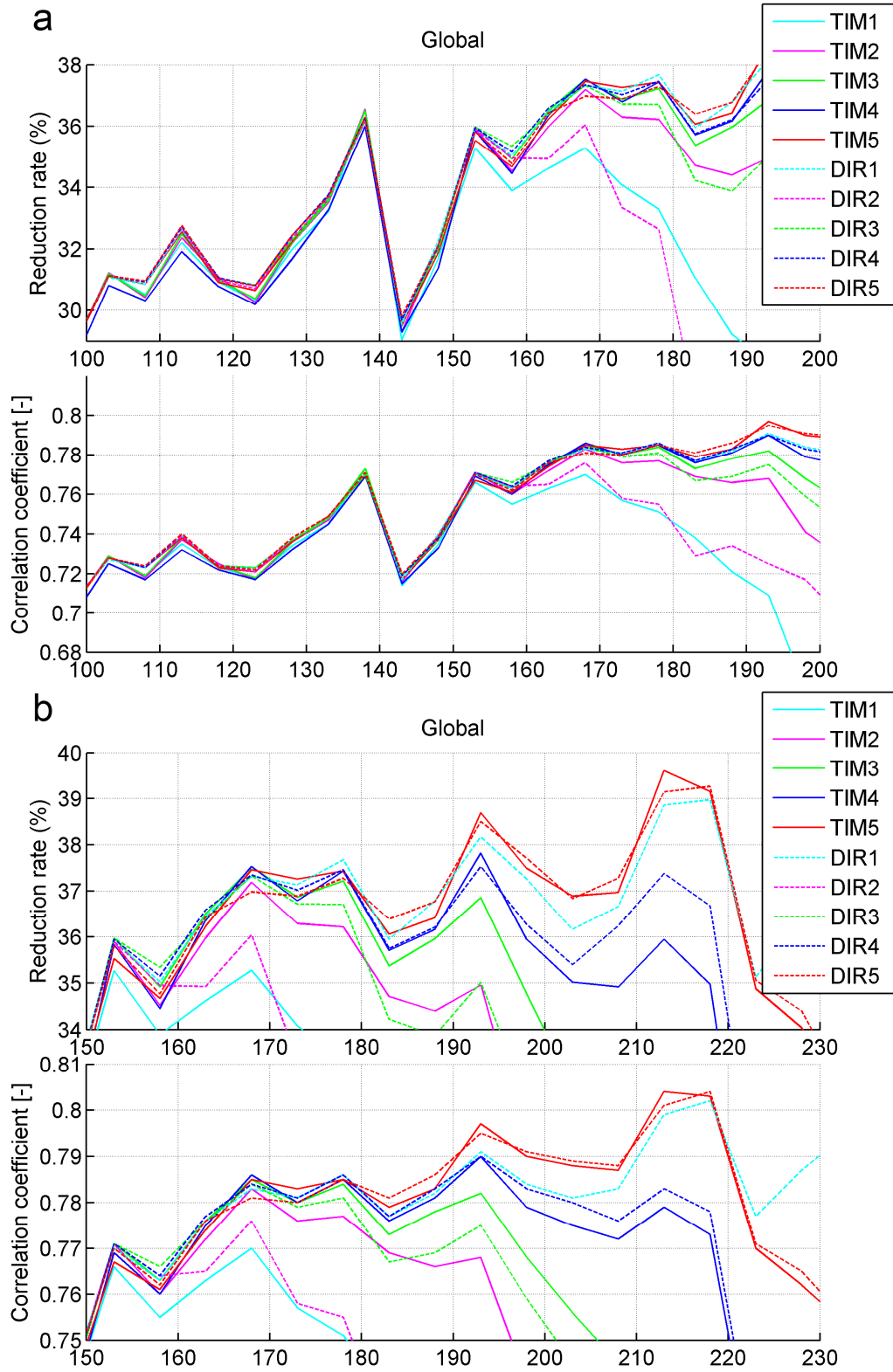


Fig. 7. As Fig. 4, but zoom into band of harmonic degrees 100 to 200 (a), and 150 to 250 (b). Note the behaviour of the 5th-generation models near degree 160. The RR and CC-agreement of the 5th-generation models DIR5 and TIM5 with the ground-gravity dependent DIR1-release (serving as a baseline) indicates full resolution of DIR5 and TIM5 to degree ~220.

Model performances in medium degrees

Fig. 7 shows the RRs and CCs over medium harmonic degrees (same data as in Fig. 4, but enlarged). From all models, the fifth model generation does not show the best performance over all harmonic degrees, despite incorporating the largest amount of GOCE observations from all models. This is evident in spectral window of degree ~ 150 to ~ 165 , where DIR3, TIM3 and DIR4 offer higher RRs and CCs with respect to the RET topography. This somewhat unexpected observation could suggest a slight deterioration in quality of the 5th model generation over the predecessor models in the mid degrees. We also note that the TIM4 model shows lower RRs and CCs from degrees ~ 100 to ~ 170 compared to DIR4, TIM3 and DIR3, which is again not within the expectations, given the increased amount of data used in the 4th releases of the models. The interpretation of the above detected degradation of the 5th model generations w.r.t. previous generations within the band ~ 150 to ~ 165 is not easy, as there is a great variety of possible reasons to explain such a behaviour. Referring to the model and release specific comments in table 1, we may say that

- in case of TIM5 no obvious explanation for the degradation exists, as processing changes did not affect the band ranging from degree 150 to 180 (the same can be stated for the changes of TIM4 w.r.t TIM3)
- in case of DIR5, the change to the CNES/GRGS GRACE solution from degree 55 to 150 may explain for the behaviour in the affected band.

Note that the apparent degradation of the 5th model generations is very small ($< 1\%$ RR) in general and does not limit the usability of the latest models.

5.2 Regional comparisons

Fig. 8 and 9 show the two indicators over six continents (Europe, Asia, North/South America, Africa, Antarctica,), the Oceania region (Australia, New Zealand and surrounding islands), and Greenland as a continent-like land mass. In comparison to the indicator curves over global areas (Fig. 4 and 5), there are larger oscillations which reflect the effect of smaller numbers of data points over regional areas. For better legibility, the performance of the 2nd- 5th GOCE model generation are shown only.

The regional comparisons largely confirm the reported GOCE model characteristics, in that, the fifth generation models seem to fully capture gravity field features to degree ~ 220 , while partially resolving the field to degree ~ 280 . Over Africa, Oceania, and South America, DIR5 shows slightly positive RRs towards degree 300, demonstrating the recovery of topography signals at ~ 70 km scales.

Over all of the regions, DIR5 and TIM5 show are mostly comparable performance to degree ~ 250 , with somewhat higher RRs over Greenland, Oceania, Antarctica and Europe for DIR5. Beyond degree 250, a better short-scale performance is observed over most regions for DIR5. Depending on the region and spatial scale, RRs reach peak values between 40-48% around degree ~ 220 (Asia, North America, Europe, South America, Oceania), indicating a very significant portion of topographic gravity signals that is explained by 5th-generation GOCE gravity. As for the prior global investigations, in some regions the third generation models show slightly higher reduction rates than their successor models in the spectral band of degree 150 to 180 (see e.g. Greenland, North America and Asia).

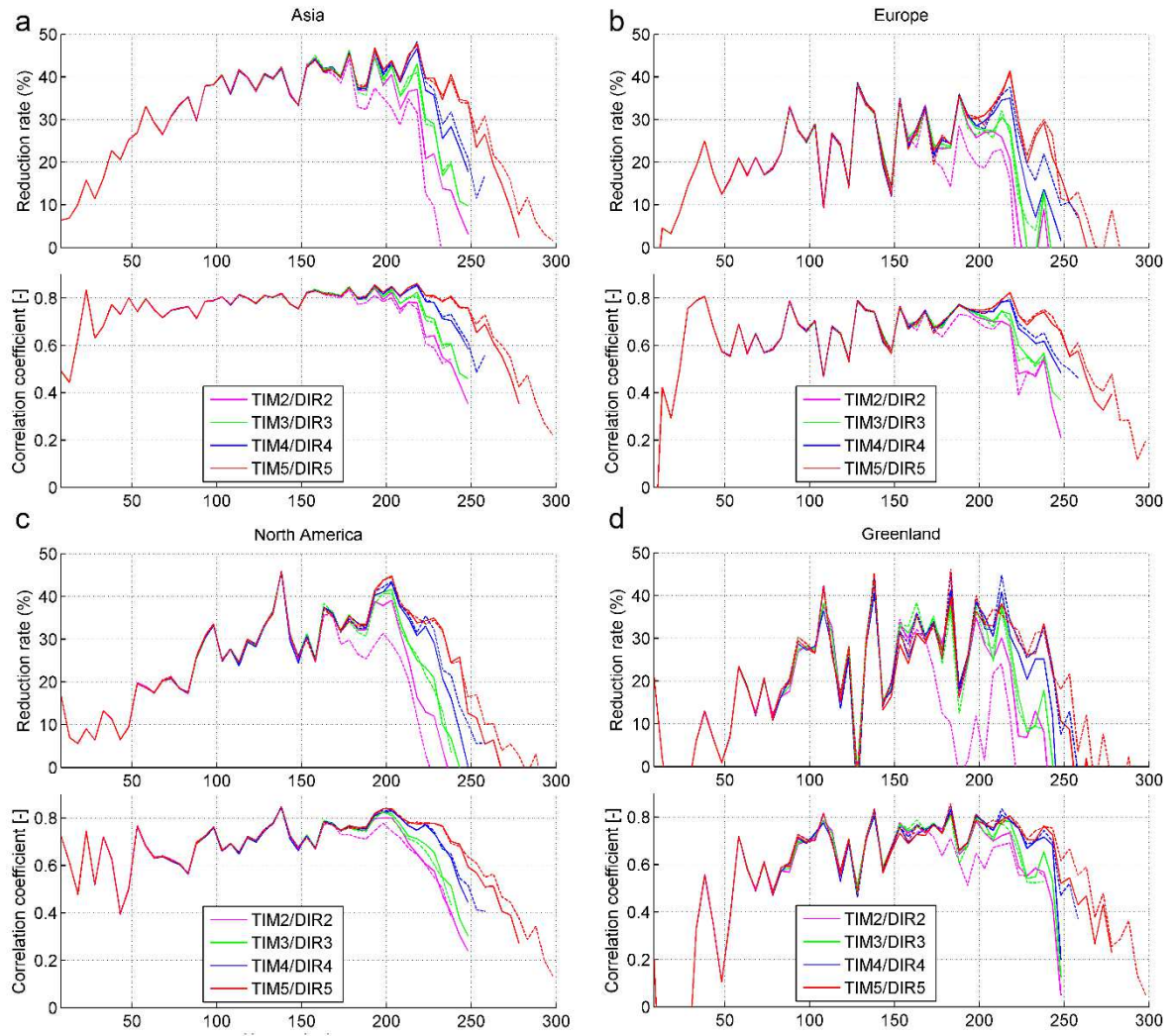


Fig. 8. GOCE evaluation results over the Northern Hemisphere continental areas. For better legibility, only the 2nd to 5th generation of DIR (dashed lines) and TIM (solid lines) approaches are shown.

6. Concluding remarks

The topographic evaluation technique was applied based on most recent topographic mass models and ellipsoidal gravity forward-modelling techniques to evaluate five generations of GOCE gravity field models from the DIR and TIM computation approach. The comparisons were performed over a range of narrow spectral bands using signal reduction rates and cross-correlation coefficients as key indicators. These indicate the level of agreement between gravity signal patterns and magnitudes from the topographic masses, and the GOCE mission. The topographic evaluation showed a steadily improved agreement of the five model generations with topography-implied gravity, and increase in GOCE model resolution.

For the fifth-generation GOCE gravity fields, our comparisons indicate full resolution of the DIR5 and TIM5 models to harmonic degree ~ 220 (90 km scales), and partially resolved gravity features to degree ~ 270 (TIM5) and degree ~ 290 –300 (DIR5), with variations from these values over some of the continental areas tested. As such, the new GOCE models capture parts of the gravity field signal down to ~ 70 km spatial scales. This is a very significant improvement in satellite-only static gravity field data compared to the pre-GOCE-era, where the resolution of gravity from the GRACE mission was limited to about ~ 125 km spatial scales (degree ~ 170).

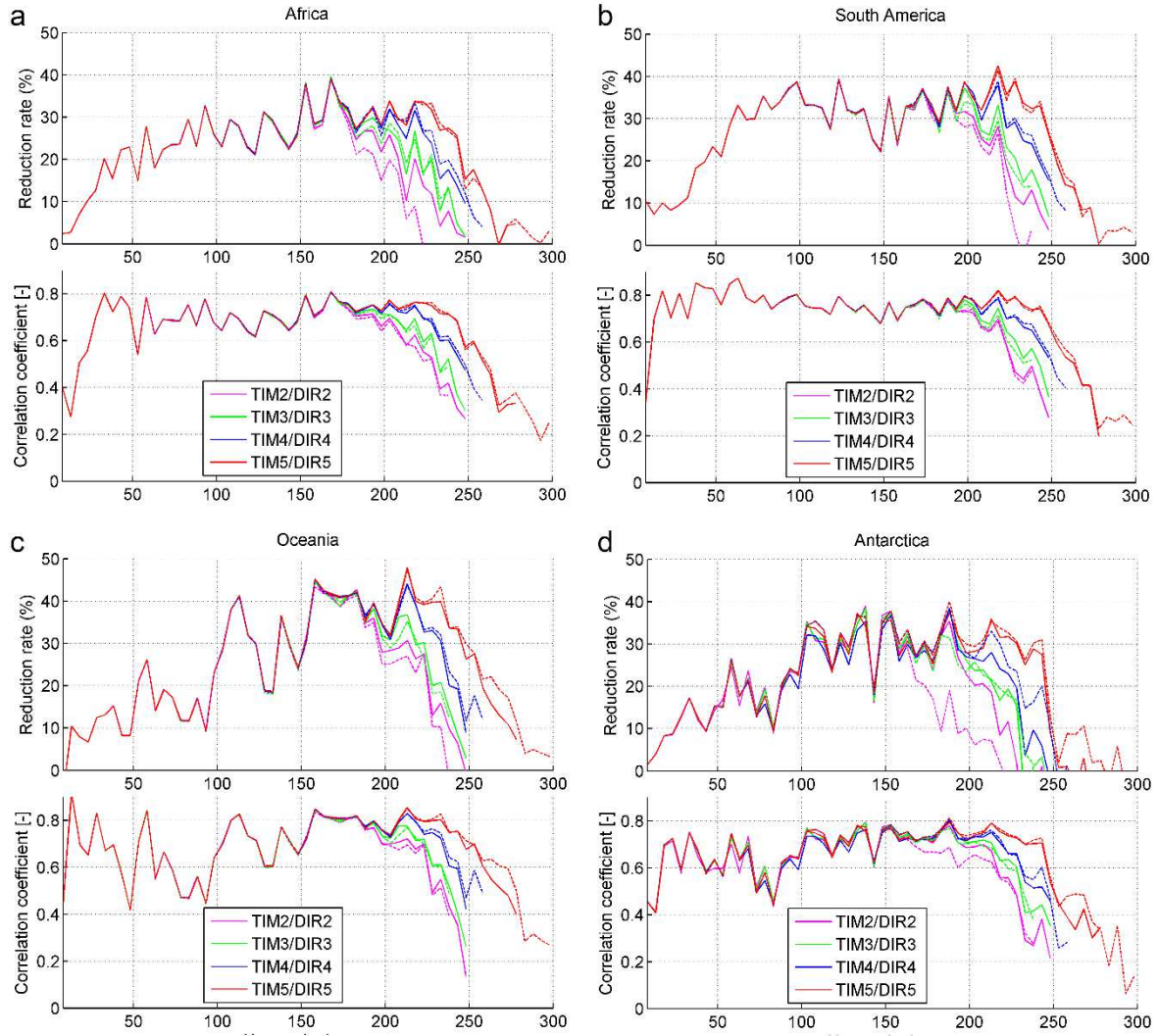


Fig. 9. GOCE evaluation results over the Southern Hemisphere continental areas. For better legibility, only the 2nd to 5th generation of DIR (dashed lines) and TIM (solid lines) approaches are shown.

Our comparisons showed that models from the DIR approach improved relative to those from the TIM approach from the 2nd to the 5th generation, with DIR5 offering the best short-scale performance (from degree 240 and beyond). At degrees less than 240, gravity from DIR5 and TIM5 is largely comparable.

Considering the unprecedented gravity field resolution achieved, the GOCE gravity field mission performed beyond the expectations. The GOCE gravity fields will continue to be used as a de-facto-standard in a range of applications encompassing geodesy, geophysics and oceanography.

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Appendix A

A1 Performance of various topography/ topographic potential models vs. GOCE

While the main scope of this paper is evaluation of the new GOCE gravity fields from latest topography, the evaluation technique can easily be ‘reversed’ by using GOCE gravity to provide feedback on different models of Earth’s topographic masses and gravity computation techniques. We use DIR5 as the highest-resolution GOCE model (cf. Section 5) to provide the reference in these comparisons. Gravity is computed from a total of six topographic potential models developed over the past years and used in different gravity field studies. The input topography models are summarised in Table 3 and the derived topographic potential models in Table 4. These are the (i) dV_SPH_RET2011, and (ii) dV_SPH_RET2012 topographic potential models, which are both based on spherical approximation (i.e., use a mass-sphere as a reference, Rummel et al. 1988). The more recently developed (iii) dV_ELL_ETOPO1, (iv) dV_ELL_RET2012 and (v) dV_ELL_RET2014 topographic potential models rely on the more advanced ellipsoidal approximation (i.e., use of a mass-ellipsoid as a reference, Claessens and Hirt 2013).

Also included are the topographic potential coefficients of the (vi) Karlsruhe Institute for Technology (KIT)’s Rock-Water-ICE model (Grombein et al. 2011, 2014) abbreviated here to dV_KIT_RWI. In contrast to (i) to (v), the dV_KIT_RWI model does not use the concept of rock-equivalent topography, but instead models the potential of topography, ocean water, lake water and ice masses via volumetric layers *without* condensation. This approach is more accurate than the RET-compression, because the geometry of mass bodies is not changed. The dV_KIT_RWI model was developed through Newtonian integration in the space domain, followed by a subsequent harmonic analysis to obtain solid SHCs of the topographic potential. While models (i) to (v) are based on spectral-domain forward modelling, (vi) deploys forward modelling in the space domain. Fig. 10 shows the RRs and CCs of the six models computed against the GOCE DIR5 release. While the indicators do not sense notable differences in performance in the low harmonics (say to degree 50), the RR and CC curves start to diverge around degree 100. For the two spherically approximated models RRs are clearly lower than of all models in ellipsoidal approximation. This clearly shows that the ellipsoidal approximation level (iii-vi) is more compatible than the spherical approximation with GOCE gravity field models (reflecting that the actual mass distribution is more ellipsoidal than spherical), particularly in the higher harmonic degrees. This effect is not so pronounced in the CC-curves, but still visible (cf. Fig. 10).

The inter-comparison of the four ellipsoidal models reveals that the agreement between topographic and GOCE gravity becomes increasingly better with the incorporation of newer topographic data sets (compare dV_ELL_RET2012 with dV_ELL_RET2014). The highest RRs against GOCE DIR5 are observed for the new dV_ELL_RET2014 model, which particularly reflects the use of recent Bedmap2 data over Antarctica. CCs sense these improvements too, with the differences between the CC curves less pronounced than for RRs. The ETOPO1-based ellipsoidal topographic potential model shows RR and CCs comparable to those of dV_ELL_RET2012, which reflects similar data sources used in the model construction (cf. Table 3, differences are over the oceans and the SRTM releases over land).

R Rs and CCs are mostly higher for the ETOPO1, RET2012 and RET2014-based ellipsoidal topographic potential models than for the dV_KIT_RWI model. This is most likely due to the use of newer data sets in RET2012 and RET2014 (KIT_RWI is based on the DTM2006.0 topography data base that include topography mass models available in or before 2006). It also suggests that the RET-compression in the dV_ELL_RET2012 and dV_ELL_RET2014 models little affects the RRs and CCs performance curves, so plays a minor role for the purpose of GOCE model evaluation. A detailed study on the role of the RET compression effect in topographic evaluation of satellite-observed

gravity fields would require the construction of “KIT-type” and RET-type” models from exactly the same data, which is not possible here, so remains as a future task. In summary, Fig. 10 shows the evolution of Curtin University’s topographic mass modelling, with notable improvements through (a) the development and adoption of ellipsoidal forward modelling techniques, and (b) updates of the mass models through use of most recent topography data sets.

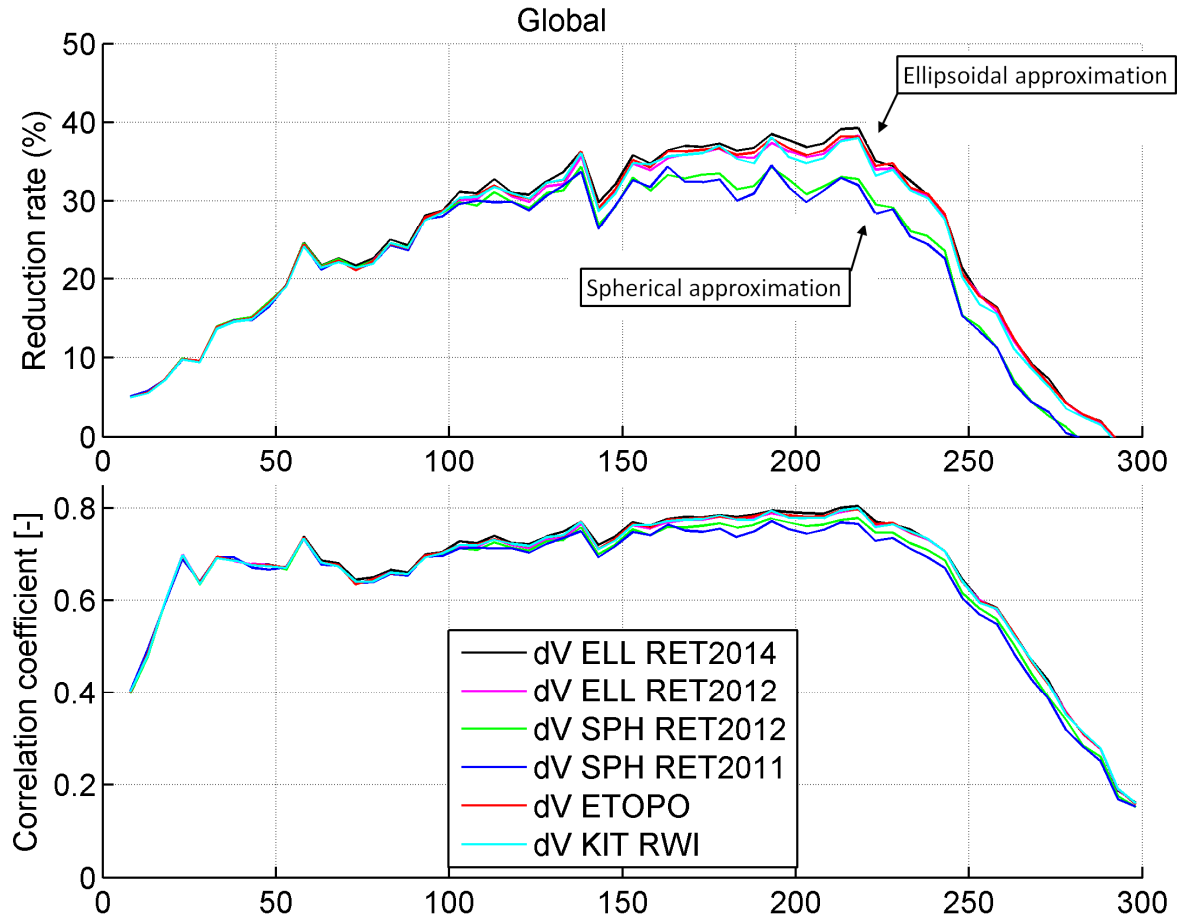


Fig. 10. Comparison of gravity from six topographic potential models against DIR5 over the near- global area (used in Fig. 6) in terms of signal reduction rates (top), and cross-correlation (bottom). Gravity from all models was evaluated in terms of geocentric coordinate grids 10,000 m above the reference surface (sphere for models dV_SPH_RET2011/2012, and the GRS80 ellipsoid for the other models).

Table 4. Topographic potential models – input data and computation details

Potential model	Input-Topography	Level of approximation	Rock-equivalent topography (RET)	Reference
dV_SPH_RET2011	RET2011	Spherical	Yes	Hirt et al. 2012
dV_SPH_RET2012	RET2012	Spherical	Yes	Hirt & Kuhn 2012
dV_ELL_RET2012	RET2012	Ellipsoidal	Yes	Claessens& Hirt 2013
dV_ELL_RET2014	RET2014	Ellipsoidal	Yes	This work
dV_ETOPO1	ETOPO1	Ellipsoidal	Yes	Amante & Eakins 2009
dV_KIT_RWI	DTM2006	Ellipsoidal	No – direct modelling	Grombein et al. 2014

References

- Abdalla, A., H. Fashir, A. Ali, and D. Fairhead (2012) Validation of recent GOCE/GRACE geopotential models over Khartoum state – Sudan, *Journal of Geodetic Science* 2:88–97, doi: 10.2478/v10156-011-0035-6.
- Amante, C. and B. W. Eakins (2009), ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24, 19 pp, March 2009.
- Bamber, J.L., J. A. Griggs, R. T. W. L. Hurkmans, J. A. Dowdeswell, S. P. Gogineni, I. Howat, J. Mouginot, J. Paden, S. Palmer, E. Rignot, and D. Steinhage (2013), A new bed elevation dataset for Greenland, *The Cryosphere*, 7, 499–510, doi:10.5194/tc-7-499-2013.
- Barthelmes, F. (2009), Definition of Functionals of the Geopotential and their Calculation from Spherical Harmonic Models. Scientific Technical Report STR09/02, GeoForschungsZentrum Potsdam, Germany.
- Becker, J.J., D.T. Sandwell, W.H.F. Smith, J. Braud, B. Binder, J. Depner, D. Fabre, J. Factor, S. Ingalls, S.-H. Kim, R. Ladner, K. Marks, S. Nelson, A. Pharaoh, R. Trimmer, J. Von Rosenberg, G. Wallace and P. Weatherall (2009), Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30_PLUS, *Marine Geodesy* 32(4): 355–371.
- Bock, H., A. Jäggi, G. Beutler and U. Meyer (2014), GOCE: precise orbit determination for the entire mission, *Journal of Geodesy* 88(11), 1047–1060, doi: 10.1007/s00190-014-0742-8.
- Braitenberg, C. (2013), Exploration of tectonic structures with GOCE in Africa and across-continent, *International Journal of Applied Earth Observation and Geoinformation* 35 (2015), 88–95, doi: 10.1016/j.jag.2014.01.013.
- Brockmann, J.M., N. Zehentner, E. Höck, R. Pail, I. Loth, T. Mayer-Gürr and W.-D. Schuh (2014), EGM_TIM_RL05: An independent geoid with centimeter accuracy purely based on the GOCE mission, *Geophysical Research Letters* 41(22), 8089–8099, doi: 10.1002/2014GL061904.
- Bruinsma S.L., J.M. Lemoine, R. Biancale, and N. Vales (2009), CNES/GRGS 10-day gravity field models (release 2) and their evaluation, *Adv. Space Res.* 45(4), 587–601, doi:10.1016/j.asr.2009.10.012.
- Bruinsma S., J. Marty, G. Balmino, R. Biancale, C. Förste, O. Abrikosov, and H. Neumayer (2010), GOCE gravity field recovery by means of the direct numerical method. In: Lacoste-Francis H (ed) Proceedings of the ESA living planet symposium, 28 June–2 July, Bergen, ESA, Publication SP-686.
- Bruinsma, S., J. Marty, C. Förste, O. Abrikosov, and S. Bonvalot (2013), Analysis of GOCE data after each orbit reduction - Abstracts, AGU 2013 Fall Meeting (San Francisco, USA 2013).
- Bruinsma, S.L., C. Förste, O. Abrikosov, J.-M. Lemoine, J.-C. Marty, S. Mulet, M.-H. Rio and S. Bonvalot (2014), ESA's satellite-only gravity field model via the direct approach based on all GOCE data, *Geophysical Research Letters* 41(21), 7508–7514, doi: 10.1002/2014GL062045.
- Claessens, S.J. (2005), New relations among associated Legendre functions and spherical harmonics, *Journal of Geodesy*, 79(6–7), 589–598, doi: 10.1007/s00190-005-0483-9.
- Claessens, S.J. (2006), *Solutions to Ellipsoidal Boundary Value Problems for Gravity Field Modelling*, PhD thesis, Curtin University of Technology, Department of Spatial Sciences, Perth, Australia.
- Claessens, S.J. and C. Hirt (2013), Ellipsoidal topographic potential – new solutions for spectral forward gravity modelling of topography with respect to a reference ellipsoid, *Journal of Geophysical Research - Solid Earth*, 118(11), 5991–6002, doi: 10.1002/2013JB010457.
- Dahle, C., F. Flechtner, C. Gruber, R. König, G. Michalak, and H. Neumayer (2012), GFZ GRACE Level-2 Processing Standards Document for Level-2 Product Release 0005, (Scientific Technical Report - Data, 12/02), Potsdam, 20 p, doi: 10.2312/GFZ.b103-1202-25.
- Drinkwater, M.R., R. Floberghagen, R. Haagmans, D. Muzi, and A. Popescu (2003), GOCE: ESA's first Earth Explorer Core mission, In *Earth Gravity Field from Space - from Sensors to Earth Sciences*. In the Space Sciences Series of ISSI, Vol. 18, 419–432, Kluwer Academic Publishers, Dordrecht, Netherlands.
- Fretwell, P., H.D. Pritchard, D.G. Vaughan, J.L. Bamber, et al. (2013), Bedmap2: improved ice bed, surface and thickness datasets for Antarctica, *The Cryosphere*, 7, 375–393, doi:10.5194/tc-7-375-2013, 2013.
- Gerlach C., M. Šprlák, K. Bentel, B. Pettersen (2013), Observation, Validation, Modeling - Historical Lines and Recent Results in Norwegian Gravity Field Research, *Kart og Plan* 73(2):128 – 150.
- Godah, W., M. Szelachowska, J. Krynski (2014), Accuracy assessment of GOCE-based geopotential models and their use for modelling the gravimetric quasigeoid – A case study for Poland, *Geodesy and Cartography* 63(1), 3–24, doi: 10.2478/geocart-2014-0001.
- Göttl, F. and R. Rummel (2009), A Geodetic View on Isostatic Models, *Pure Appl. Geoph.*, 890 166(8–9), 1247–1260, doi: 10.1007/s00024-004-0489-x.
- Grombein, T., K. Seitz, and B. Heck (2011), Smoothing GOCE gravity gradients by means of topographic-isostatic reductions, Proc. of '4th International GOCE User Workshop', Munich, Germany, 31 March – 1 April 2011 (ESA SP-696, July 2011).

- Grombein, T., X. Luo, K. Seitz, and B. Heck (2014), A wavelet-based assessment of topographic-isostatic reductions for GOCE gravity gradients, *Surveys in Geophysics* 35(4), 959-982 doi: 10.1007/s10712-014-9283-1.
- Gruber, T., P. Visser, C. Ackermann and M. Hosse (2011), Validation of GOCE gravity field models by means of orbit residuals and geoid comparisons, *Journal of Geodesy* 85(11):845–860, doi: 10.1007/s00190-011-0486-7.
- Guimarães, G., A. Matos and D. Blitzkow (2012), An evaluation of recent GOCE geopotential models in Brazil, *Journal of Geodetic Science* 2:144–155, doi: 10.2478/v10156-011-0033-8.
- Hashemi Farahani, H., P. Ditmar, R. Klees, J. Teixeira da Encarnacao, X. Liu, Q. Zhao and J. Guo (2013), Validation of static gravity field models using GRACE K-band ranging and GOCE gradiometry data, *Geophysical Journal International* 194:751–771, doi: 10.1093/gji/ggt149.
- Hirt, C., T. Gruber and W. Featherstone (2011), Evaluation of the first GOCE static gravity field models using terrestrial gravity, vertical deflections and EGM2008 quasigeoid heights, *Journal of Geodesy* 85:723–740, doi: 10.1007/s00190-011-0482-y.
- Hirt, C., M. Kuhn, W. Featherstone and F. Göttl (2012), Topographic/isostatic evaluation of new-generation GOCE gravity field models, *Journal of Geophysical Research - Solid Earth* 117(B05407), doi: 10.1029/2011JB008878.
- Hirt, C. (2013), RTM gravity forward-modeling using topography/bathymetry data to improve high-degree global geopotential models in the coastal zone, *Marine Geodesy* 36(2):1-20, doi: 10.1080/01490419.2013.779334.
- Hirt, C. (2014), GOCE's view below the ice of Antarctica: Satellite gravimetry confirms improvements in Bedmap2 bedrock knowledge, *Geophysical Research Letters*, 41(14), 5021-5028, doi: 10.1002/2014GL060636.
- Hirt, C., M. Kuhn, S.J. Claessens, R. Pail, K. Seitz, and T. Gruber (2014), Study of the Earth's short-scale gravity field using the ERTM2160 gravity model, *Computers & Geosciences*, 73, 71-80, doi: 10.1016/j.cageo.2014.09.00.
- Hirt, C. and M. Rexer (2015), Earth2014: 1 arc-min shape, topography, bedrock and ice-sheet models - available as gridded data and degree-10,800 spherical harmonics, *International Journal of Applied Earth Observation and Geoinformation* 39, 103-112, doi:10.1016/j.jag.2015.03.001. Available at: <http://ddfe.curtin.edu.au/models/Earth2014>.
- Janák, J., and F. Wild-Pfeiffer (2010), Comparison of various topographic-isostatic effects in terms of smoothing gradiometric observations. In (Sansò, F. and Mertikas, S. P. P., ed), Gravity, Geoid and Earth Observation, International Association of Geodesy Symposia 135, 377-381, doi:10.1007/978-3-642-10634-7-50.
- Janák, J. and M. Pitoňák (2011), Comparison and testing of GOCE global gravity models in Central Europe. *Journal of Geodetic Science* 1:333–347.
- Jarvis, A., H.I. Reuter, A. Nelson, and E. Guevara (2008), Hole-filled SRTM for the globe Version 4, Available from the CGIAR-SXI SRTM 90m database. Available at: <http://srtm.csi.cgiar.org>.
- Konopliv, A.S., W. B. Banerdt, and W. L. Sjogren (1999), Venus Gravity: 180th Degree and Order Model, *Icarus* 139, 3–18.
- Konopliv, A.S., S.W. Asmar, W.M. Folkner, Ö. Karatekin, D.C. Nunes, S.E. Smrekar, C.F. Yoder and M.T. Zuber (2011), Mars high resolution gravity fields from MRO, Mars seasonal gravity, and other dynamical parameters, *Icarus*, 211, 401–428.
- Laske, G., G. Masters, Z. Ma, and M. Pasyanos (2013), CRUST1.0 - A 1-degree Global Model of Earth's Crust, *Geophysical Research Abstracts* Vol. 15, EGU2013-2658, EGU General Assembly 2013.
- Lemoine, F.G., S. Goossens, T.J. Sabaka, J.B. Nicholas et al. (2014), GRGM900C: A degree-900 lunar gravity model from GRAIL primary and extended mission data, *Geophysical Research Letters*, 41(10), 3382-3388, doi: 10.1002/2014GL060027.
- Makhloof, A.A. and K.-H. Ilk (2008), Effects of topographic-isostatic masses on gravitational functionals at the Earth's surface and at airborne and satellite altitudes, *Journal of Geodesy* 82, 93-111, doi: 10.1007/s00190-007-0159-8.
- Mayer-Gürr, T., A. Eicker, and K.-H. Ilk (2006), Gravity field recovery from GRACE-SST data of short arcs. In: Flury J, Rummel R, Reigber C, Rothacher M, Boedecker G, Schreiber U (eds) *Observation of the Earth system from space*. Springer, Berlin, pp 131–148.
- Mayer-Gürr, T., E. Kurtenbach, and A. Eicker (2010), ITG-Grace2010 Gravity Field Model. URL: <http://www.igg.uni-bonn.de/apmg/index.php?id=itg-grace2010>, 2010.
- Migliaccio F., M. Reguzzoni, F. Sanso, C.C. Tscherning and M. Veicherts (2010), GOCE data analysis: the space-wise approach and the first space-wise gravity field model; presented at the ESA Living Planet Symposium 2010, Bergen, June 27 - July 2, Bergen, Norway, 2010

- Moritz, H. (2000), Geodetic Reference System 1980. *Journal of Geodesy* 74, 128-140.
- Novák, P. and R. Tenzer (2013), Gravitational Gradients at Satellite Altitudes in Global Geophysical Studies, *Surveys in Geophysics* 34(5): 653-673, doi:10.1007/s10712-013-9243-1.
- Pail, R., H. Goiginger, R. Mayrhofer, W.D. Schuh, J.M. Brockmann et al (2010), GOCE gravity field model derived from orbit and gradiometry data applying the Time-Wise Method. In: Lacoste-Francis H (ed) Proceedings of the ESA living planet symposium, 28 June–2 July, Bergen, ESA, Publication SP-686.
- Pail, R., S. Bruinsma, F. Migliaccio, C. Förste, H. Goiginger, W.D. Schuh, E. Höck, M. Reguzzoni, J.M Brockmann, O. Abrikosov, M. Veicherts, T. Fecher, R. Mayrhofer, I. Krasbutter, F. Sanso and C.C. Tscherning (2011), First GOCE gravity field models derived by three different approaches, *Journal of Geodesy* 85(11):819–843, doi: 10.1007/s00190-011-0467-x.
- Pavlis, N.K., J.K. Factor, and S.A. Holmes (2007), Terrain-related gravimetric quantities computed for the next EGM. In: Proceed. of the 1st Intern. Symp. of the Intern. Gravity Field Service (IGFS), Istanbul, 318-323.
- Pavlis N., S.A. Holmes, S. Kenyon, and J. Factor (2012), The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). *Journal of Geophysical Research* 117, doi: 10.1029/2011JB008916.
- Reguzzoni, M., D. Sampietro and F. Sansò (2013), Global Moho from the combination of the CRUST2.0 model and GOCE data, *Geophysical Journal International*, 195(1), 222-237, doi: 10.1093/gji/ggt247.
- Rexer, M., C. Hirt, R. Pail, and S. Claessens (2013), Evaluation of the third- and fourth-generation GOCE Earth gravity field models with Australian terrestrial gravity data in spherical harmonics, *Journal of Geodesy* 88(4), 319-333, doi: 10.1007/s00190-013-0680-x.
- Rummel, R., Rapp, R.H., Sünkel, H., Tscherning, C.C. (1988), Comparisons of global topographic/isostatic models to the Earth's observed gravity field. Report No 388, Dep. Geodetic Sci. Surv., Ohio State University, Columbus, Ohio.
- Rummel, R., W. Yi, and C. Stummer (2011), GOCE gravitational gradiometry, *Journal of Geodesy* 85(11), 777-790, doi: 10.1007/s00190-011-0500-0.
- Schack, P., C. Stummer, M. Rexer, R. Pail and T. Gruber (2014), Assessment of GOCE gradiometer data during low orbit mission phase; European Geosciences Union General Assembly, Wien, 01.05.2014.
- Sprlák, M., C. Gerlach, O. Omang, B. Pettersen (2011), Comparison of GOCE derived satellite global gravity models with EGM2008, the OCTAS geoid and terrestrial gravity data: case study for Norway. In: Proceedings of the 4th International GOCE User Workshop, Munich, 31st March 2011, ESA SP-696, Noordwijk.
- Sprlák, M., C. Gerlach and B. Pettersen (2012), Validation of GOCE global gravity field models using terrestrial gravity data in Norway, *Journal of Geodetic Science* 2(2):134–143.
- Stummer, C., C. Siemes, R. Pail, B. Frommknecht, and R. Floberghagen (2012), Upgrade of the GOCE Level 1b gradiometer processor, *Advances in Space Research* 49(4):739–75, doi:10.1016/j.asr.2011.11.027.
- Szucz, E. (2012), Validation of GOCE time-wise gravity field models using GPS-levelling, gravity, vertical deflections and gravity gradients in Hungary. *Civil Engineering* 56(1):3 – 11.
- Tapley, B., and C. Reigber (2001), The GRACE mission: status and future plans. In: AGU Fall Meeting Abstr, Vol. 1.
- Tapley, B., B. Schutz, R. Eanes, J. Ries, and M. Watkins (1993), LAGEOS laser ranging contributions to geodynamics, geodesy, and orbital dynamics, *Geodynamics Series* 24:147–173.
- Tscherning, C.C. and D. Arabelos (2011), Gravity anomaly and gradient recovery from GOCE gradient data using LSC and comparisons with known ground data. In: Proceedings 4th International GOCE user workshop, Munich, ESA SP-696, Noordwijk.
- Tsoulis, D. and B. Stary (2005), An isostatic compensated gravity model using spherical layer distributions, *Journal of Geodesy* 78(7-8), 418-424, doi: 10.1007/s00190-004-0404-3.
- van der Meijde, M., R. Pail, R. Bingham and R. Floberghagen (2015), GOCE data, models, and applications: A review, *International Journal of Applied Earth Observation and Geoinformation*, Vol 35, Part A, March 2015, 4-15, doi: 10.1016/j.jag.2013.10.001.
- Voigt, C. and H. Denker (2011), Validation of GOCE gravity field models by astrogeodetic vertical deflections in Germany. In: Proceedings of the 4th International GOCE User Workshop, SP-696, ESA/ESTEC, The Netherlands, vol 4.
- Watts, A. B. (2011), Isostasy, In: Encyclopedia of Solid Earth Geophysics (Ed. Gupta, H. K.), 984 1, 647-662, Elsevier.
- Wieczorek, M.A. (2007), The gravity and topography of the terrestrial planets. In: Spohn, T., 988 Schubert, G. (Eds.), *Treatise on Geophysics*, vol. 10. Elsevier-Pergamon, Oxford, 165-989 206.

Evaluation of GOCE Gravity Models with SLR Orbit Tests

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Abstract

This report for the IAG Joint Working Group 2.3 is an assessment of various GOCE gravity field models. The GOCE models were evaluated by assessing the model performance for satellite orbit dynamics based on Satellite Laser Ranging (SLR) observations. Tests show all recent GOCE and GRACE-based gravity field models perform similarly in terms of the RMS fit of the SLR observations (for all models the RMS does not differ by more than 1 cm). GOCE_TIM models perform best for many of the satellites in this particular test. The estimate of C20 is likely to be a dominant source of long-wavelength gravity model error when SLR or GPS measurements are not used.

Orbit tests

Satellite orbit fits are a traditional measure of gravity model accuracy, testing primarily the long-wavelength components. This is a particularly demanding test for the GOCE and GRACE-based gravity models because Earth gravity models had previously depended on the tracking to various geodetic satellites to determine the low spherical harmonics degree part of the field, which led to these fields being noticeably tuned to their particular orbit inclinations. Satellite Laser Ranging (SLR) data from a global network of well-determined tracking stations can provide an unambiguous and precise measurement of the satellite orbit accuracy, especially for those compact spherical (cannonball) satellites such as Starlette, Stella, Ajisai, LAGEOS-1 and -2. These satellites, along with the BE-C satellite, Larets and LARES, are an important resource for measuring the long-term variations of the Earth's gravity field and geocenter variations [Cheng and Tapley, 2004, Cheng et al., 2013a and b], and testing the model performance of the newly developed GOCE gravity fields for satellite orbit dynamics. Those satellites were also widely used in geodesy and geodynamics study, such as observing the seasonal geocenter motion and providing a time series of the spherical harmonic degree 2 terms used for the ILRS (International Laser Ranging Service) contribution to the ITRF2013 reference frame. These tests also benefit for evaluating the orbit accuracy for those satellites due to the 'errors' in Earth's gravity field models.

Validation of GOCE models by orbit tests using SLR data has been reported by others, for example, by Gruber et al. [2011] (using only Lageos 1 and 2) and Baur et al. [2014] (using only Lageos 1 and Starlette) using different time periods and likely different models and parameterization. The results are not consistent. For example, a large RMS for Starlette orbit fits was reported by Baur et al. [2014].

Three-day orbit fits to the SLR tracking of 8 satellites during the year 2013 were used to evaluate the performance of several gravity fields in this test. The fields tested include EGM2008 [Pavlis et al., 2012], GGM05S [Tapley et al., 2013], EIGEN6C2 [Förste et al., 2012], EIGEN6C4 [Förste et al., 2014], GOCE03S [Mayer-Guerr et al., 2012], GO_CONS_GCF_2_DIR_R3 [Bruinsma et al., 2010], GO_CONS_GCF_2_DIR_R4 [Bruinsma et al., 2013], GO_CONS_GCF_2_DIR_R5 [Bruinsma et al., 2014], GO_CONS_GCF_2_TIM_R3 and GO_CONS_GCF_2_TIM_R4 [Pail et al., 2011], and GO_CONS_GCF_2_TIM_R5 [Brockmann et al., 2014] (the latter models hereafter denoted by GOCE_DIR and GOCE_TIM). GGM05S is the only solution that contains only GRACE information, while the GOCE_TIM models used exclusively GOCE data (GPS and gradiometer). The remaining fields contain some combination of GRACE, GOCE, CHAMP, SLR and terrestrial gravity information. The lower degree portion of EGM2008, GOCE03S, and the GOCE_DIR and EIGEN6C models included GRACE data. The gravity information from SLR tracking of LAGEOS was used in development of the

series of the EIGEN6C and GOCE_DIR models and GOCE03S included SLR tracking to LAGEOS 1 and 2.

Table 1 lists the orbit characterization [semi-major axis (a), eccentricity (e) and inclination (i)] at 1 January 2013, the number of arcs, the average number of observations per arc, and the average number of tracking stations for the satellites used in this analysis. The measurement and force models were consistent with that used for RL05 GRACE gravity solution [Bettadpur, 2007] based on the IERS2010 Conventions except for the gravity model. The SLRF2005/LPOD2005 coordinates were used for the SLR tracking stations [Ries, 2008]. In addition to the same GOT4.7 ocean tide and ocean pole tide models, the same Atmosphere-Ocean De-aliasing (AOD) time series used in the RL05 GRACE processing were used in the SLR orbit fits.

Table 1. Orbit characterization of satellites used in test

Satellite	a (m)	e	i (deg)	Arcs	Obs	Stations
LAGEOS 1	12266414	0.00396	109.86	119	668	19
LAGEOS 2	12165376	0.00141	52.65	116	573	17
Ajisai	7868998	0.00138	50.01	119	1301	18
Starlette	7332571	0.02007	49.84	119	736	16
Stella	7181361	0.00147	98.28	119	370	15
BEC	7492969	0.02577	41.16	119	773	13
Larets	7064115	0.00181	97.78	119	197	11
LARES	7820891	0.00151	69.55	119	716	16

The sensitivity of a satellite to the gravitational perturbation is altitude dependent. The maximum degree and order of the gravity field used here were 20x20 for LAGEOS-1 and -2, and 70x70 for BEC, Starlette, Stella, Ajisai, Larets and LARES. The choice of the size of gravity field is used in the standard SLR data processing with the mm accuracy for geodesy and geodynamic study being reported. The orbit fits were performed both with and without the adjustment, every 3-days, of a once-per-revolution (1-cpr) empirical acceleration for the transverse and cross-track components. When the empirical accelerations are not adjusted, most of the long-wavelength gravity model error signals are preserved in the SLR residuals. The drag coefficient, C_d , for Starlette, Stella, Ajisai, BEC, Larets and LARES and the empirical along-track acceleration, C_t , for LAGEOS-1 and -2, were adjusted every 0.5 to 1 day.

The RMS of the SLR residuals should reflect the relative performance of the various gravity field models at the longest wavelengths. Table 2 compares the results for the one-year average RMS for 3-day orbit fits without the adjustment of once-per-revolution empirical accelerations using the different gravity fields. Most of the models perform within 1 cm of each other, though there are some outliers. GOCO03S generally performs the worst, likely due to the value of C_{20} , which is significantly different from the other models (replacement of the SLR derived C_{20} in GOCO03S improves the orbit fit to a level comparable with the other models). The results for the LARES satellite are of particular interest, as the remarkable density of this satellite (made of solid tungsten) reduces the effect of the surface forces to nearly negligible levels.

It should be noted that the value of C_{20} has a particularly large influence in these tests. This can be seen in the case denoted by GGM05S*, where the natural GRACE-derived estimate of C_{20} was used rather than the adopted replacement value from SLR based on Cheng et al. [2013]. In all cases, the performance with the SLR-derived value of C_{20} adopted for GGM05S is better, though the GOCE-TIM models perform somewhat better.

The GOCE_TIM models perform surprisingly well considering they rely only on GOCE information (GPS and gradiometer). They perform particularly well for Stella, Larets and LARES. It is well known that C_{20} has a significant long-term quadratic variation [Cheng et al., 2013], so that the epoch of the gravity field solution can influence the particular value of the C_{20} obtained. Since the testing period used

here is 2013.0-2014.0, it may be that the C20 estimate obtained by the GOCE_TIM models, which depended on only GOCE data from 2009-2013, may be closer to the appropriate 2013 value of C20 than models that used GRACE data spanning a longer time period and representing an earlier mean epoch. To evaluate the sensitivity to the epoch of C20, the GGM05S solution was tested again but with the SLR-derived estimate for C20 from Cheng et al. [2013] evaluated at epoch 2013.5, the middle of the test period. The results shown in Table 2 and denoted by GGM05S** indicate that the fit did indeed improve for every satellite.

Table 2. Average laser ranging residual RMS (cm) from 3-day orbit fits without adjusting the once-per-revolution (1-cpr) empirical accelerations.

Model	Lageos-1	Lageos-2	Ajisai	Starlette	Stella	BEC	Larets	LARES
EGM2008	2.02	1.45	7.82	5.81	5.54	9.08	7.61	7.01
GGM05S*	2.07	1.54	8.42	7.44	5.80	9.29	7.70	7.31
GGM05S	1.90	1.18	6.75	4.00	4.62	8.86	7.10	5.05
GGM05S**	1.88	1.14	6.62	3.67	4.47	8.86	7.03	4.75
EIGEN6C2	1.89	1.19	6.90	4.30	5.80	8.91	7.93	5.30
EIGEN6C4	1.92	1.22	6.94	4.50	4.89	8.88	7.11	5.62
GOCO03S	2.16	1.69	9.03	8.11	6.94	9.44	8.34	8.63
GOCE_DIR3	1.90	1.11	6.58	3.85	4.48	9.00	6.92	4.39
GOCE_DIR4	1.90	1.19	6.56	4.24	5.41	9.09	7.41	4.98
GOCE_DIR5	1.92	1.22	6.92	4.50	4.89	8.87	7.11	5.62
GOCE_TIM3	1.90	1.11	6.58	3.85	4.48	9.00	6.92	4.39
GOCE_TIM4	1.79	1.18	6.89	4.42	3.23	10.37	6.15	3.76
GOCE_TIM5	1.83	1.11	6.50	3.50	2.92	8.97	6.27	4.20

Notes: GGM05S* is the same as GGM05S except for retaining the GRACE-derived estimate of C20; GGM05S** denotes replacing C20 with the SLR-derived value evaluated at the middle of the test period.

Table 3. Average laser ranging residual RMS (cm) from 3-day orbit fits with adjusting the once-per-revolution (1-cpr) empirical accelerations

Model	Lageos-1	Lageos-2	Ajisai	Starlette	Stella	BEC	Larets	LARES
EGM2008	1.16	0.97	6.43	1.83	3.41	6.22	6.14	3.57
GGM05S	1.10	0.87	6.09	2.16	2.70	6.18	5.77	2.51
EIGEN6C2	1.11	0.89	6.12	1.95	3.28	6.18	5.95	3.07
EIGEN6C4	1.10	0.86	6.04	1.69	2.90	6.21	5.80	2.48
GOCO03S	1.15	0.94	6.32	1.95	3.48	6.27	6.26	3.39
GOCO_DIR3	1.09	0.84	5.99	1.68	2.68	6.24	7.11	2.09
GOCO_DIR4	1.11	0.89	5.39	1.79	2.90	6.43	5.53	2.74
GOCO_DIR5	1.10	0.86	6.02	1.68	2.90	6.18	5.80	2.48
GOCO_TIM3	1.08	0.84	5.99	1.68	2.68	6.24	5.63	2.09
GOCO_TIM4	1.10	0.93	6.41	2.37	2.56	6.30	5.48	2.48
GOCO_TIM5	1.08	0.86	6.13	1.79	2.14	6.26	5.47	2.02

Given the sensitivity of this test to the particular value of C20, one way to isolate its effect is to include the adjustment of the once-per-revolution empirical accelerations in the orbit fit. Adjustment of the 1-cpr parameters reduces the effect of errors in the zonal and resonance coefficients, as well as accommodates part of the errors in the nongravitational force models. The results for this case are shown in Table 3. The GOCE_TIM models still perform very well, but the performance for all models is generally within a few

mm of each other. There are only a few instances where a model performs somewhat worse than the others.

The estimate of drag coefficients is used to account for the error in the modeling of drag force on the satellite, including the errors in the atmosphere density model and modeling of the interaction of the satellite surface with the incident molecular flow. Better gravity models can improve the orbit fits, but should have little effect on the estimates of the drag coefficients. Table 4 shows the average of the daily estimates of Cd/Ct from different gravity models (Ct being an empirical ‘drag-like’ acceleration to account for a variety of forces that affect the orbit in the along-track direction for the LAGEOS satellites). The average daily estimate is consistent within two digits for most of satellites. It might be interesting to investigate why GOCE-TIM4 and 5 appear to favor LAGEOS-1 at the expense of LAGEOS-2 in this test.

Table 4. Average daily Cd/Ct estimates from 3-day orbit fits without adjusting once-per-revolution (1-cpr) empirical accelerations. The Cd estimates are dimensionless drag parameters; the Ct estimates are empirical along-track accelerations for the LAGEOS satellites in units of nanometer/s².

Model	Lageos-1	Lageos-2	Ajisai	Starlette	Stella	BEC	Larets	LARES
EGM2008	-2.11	1.53	3.33	2.93	3.10	2.51	2.64	2.64
GGM05S*	-2.10	1.44	3.33	2.94	3.03	2.50	2.64	2.64
GGM05S	-2.12	1.76	3.33	2.94	3.04	2.51	2.64	2.64
GGM05S**	-2.13	1.77	3.33	2.94	3.04	2.51	2.64	2.64
EIGEN6C2	-2.08	1.60	3.33	2.96	3.07	2.51	2.64	2.64
EIGEN6C4	-2.05	1.66	3.33	2.95	3.06	2.51	2.64	2.64
GOCO03S	-1.97	1.22	3.33	2.95	3.10	2.51	2.63	2.64
GOCE_DIR3	-2.10	1.77	3.33	2.97	3.02	2.51	2.63	2.60
GOCE_DIR4	-2.11	1.63	3.33	2.94	3.01	2.48	2.60	2.60
GOCE_DIR5	-2.05	1.70	3.33	2.95	3.05	2.51	2.64	2.60
GOCE_TIM3	-2.10	1.77	3.33	2.97	3.02	2.51	2.63	2.60
GOCE_TIM4	-1.75	2.47	3.33	2.97	3.07	2.52	2.64	2.60
GOCE_TIM5	-1.98	2.03	3.33	2.96	3.00	2.51	2.64	2.60

Adjustment of the 1-cpr empirical acceleration parameters is an effective way to accommodate the errors in the zonal and resonance coefficients as well as part of the errors in the nongravitational force models. Since many of them are strongly perturbed by drag (Starlette, Stella, Larets) or solar radiation pressure effects (Ajisai), we can look to LARES, which is the best probe for studying the gravity model errors. This satellite is sensitive to gravity model error, since it is much lower in altitude than the LAGEOS satellites, but its density is so high (the ratio of the mass/surface ratio normalized to LAGEOS-1 is 2.6:1) that the residual surface forces are very small (comparable or better than LAGEOS). It was also not used in any of the gravity models tested here.

Table 5 shows the estimate of the 1-cpr parameters for the transverse (along-track) and cross-track accelerations. The Cos-t and Sin-t, and Cos-c and Sin-c represent the cosine (C) and sine (S) terms for transverse (t) and cross-track (c), respectively, in units of nanometers/sec² (nm/s²). Table 5 shows that the mean S transverse and C cross-track are tiny and essentially the same for all fields. The mean C transverse terms are also tiny for models except for the models GOCE-DIR3/TIM3 and GOCE-TIM4. The S cross-track (Sin-c) terms are all significantly biased, suggesting that something else in the background model for LARES is causing an excessive nodal drift that the 1/revs are trying to accommodate. This bias is larger for EGM2008, GGM05S* and GOCO03S, reflecting the aforementioned effect of a biased value of C20, which requires larger Sin-c terms to offset.

A strong annual variation with an amplitude of 0.25 nm/s² is dominant in the C transverse (Cos-t), which could be due to hydrological excitation while the atmosphere and ocean mass variations were modeled through the Atmosphere-Ocean De-aliasing (AOD) model. It is also interesting that the S

transverse (Sin-t) for all models are essentially identical. Spectral analysis reveals a strong signal with an amplitude of 0.34 nm/s^2 and a period of ~ 134 days in Sin-t, and a strong signal with an amplitude of 0.53 nm/s^2 and a period of 11.9 days appears in C cross-track (Cos-c) for all models. A signal with an amplitude of 0.58 nm/s^2 and a period of ~ 197 days is dominant in S cross-track (Sin-c) for all models. The 134-day signal is near the period of the node with respect to the Sun or, equivalently, the S1 tide perturbation period for LARES. The 11.9-day is near the perturbation period of the M2 tide band. The sources of these excitations in the LARES orbit are an interesting topic for further research. The significant reduction in the fits to LARES when adjusting the 1-cpr accelerations indicates that the time variable part of the gravity field is an important component limiting the fits indicated in Table 2.

Table 5. Average of the once-per-revolution (1-cpr) empirical accelerations estimate from 3-day orbit fits of LARES satellite (in units of nm/s^2).

Model	Cos-t	Sin-t	Cos-c	Sin-c
EGM2008	-0.062	-0.029	-0.019	-4.151
GGM05S*	-0.002	-0.028	-0.020	-4.859
GGM05S	-0.002	-0.028	-0.022	-2.788
GGM05S**	-0.002	-0.028	-0.021	-2.477
EIGEN6C2	-0.016	-0.029	-0.018	-2.708
EIGEN6C4	0.020	-0.028	-0.018	-3.373
GOCO03S	-0.019	-0.028	-0.015	-5.699
GOCE_DIR3	0.212	-0.026	-0.015	-2.139
GOCE_DIR4	-0.045	-0.029	-0.021	-2.142
GOCE_DIR5	0.020	-0.028	-0.018	-3.373
GOCE_TIM3	0.212	-0.026	-0.015	-2.139
GOCE_TIM4	-0.132	-0.028	-0.012	-1.058
GOCE_TIM5	-0.045	-0.028	-0.021	-2.152

Summary

The orbit fit tests show all recent GOCE and GRACE-based models perform similarly in cm level. The GOCE_TIM models did not include SLR or GRACE data, yet they perform here as well or better as models that did. After removing the effect of possible biases in C20, the results indicate that there is little to distinguish between the available mean gravity field models, suggesting that the temporal variations in C20 is likely to be a dominant source of long-wavelength gravity model error. It is well known that the value of C20 has a significant long-term trend, and the SLR data is essential in monitoring this trend for the most precise applications.

References

- Bettadpur, S., UTCSR Level-2 Processing Standards Document for Level-2 Product Release 0004, GRACE 327-742, (<ftp://podaac.jpl.nasa.gov/pub/grace/doc/>), February 27, 2007.
- Brockmann, J. M., N. Zehentner, E. Höck, R. Pail, I. Loth, T. Mayer-Gürr, and W.-D. Schuh, EGM_TIM_RL05: An independent geoid with centimeter accuracy purely based on the GOCE mission. *Geophys. Res. Lett.*, 41, doi:10.1002/2014GL061904, 2014.
- Bruinsma S. L., J. C. Marty, G. Balmino, R. Biancale, C. Förste, O. Abrikosov, and H. Neumayer, GOCE gravity field recovery by means of the direct numerical method, presented at the ESA Living Planet Symposium, 27th June - 2nd July 2010, Bergen, Norway, 2010, ESA Publication SP 686.
- Bruinsma, S., Förste, C., Abrikosov, O., Marty, J.-C., Rio, M.-H., Mulet, S., Bonvalot, S. (2013): The new ESA satellite-only gravity field model via the direct approach, *Geophysical Research Letters*, 40, 14, p. 3607-3612. doi.org/10.1002/grl.50716, 2013.

- Bruinsma, S. L., C. Förste, O. Abrikosov, J.-M. Lemoine, J.-C. Marty, S. Mulet, M.-H. Rio, and S. Bonvalot, ESA's satellite-only gravity field model via the direct approach based on all GOCE data. *Geophys. Res. Lett.*, 41, 7508–7514, doi:10.1002/2014GL062045, 2014.
- Baur O., H. Bock, E. Höck, A. Jaggi, S. Krauss, T. Mayer-Coürr, T. Resubelt, C. Siemes and N. Zehenter, Comparison of GOCE-GPS gravity fields derived by different approaches, *J Geod*, 88:959-973, doi: 10.1007/s00190-014-0736-6, 2014.
- Cheng M. K. and B. D. Tapley, Variations in the Earth's oblateness during the past 28 years, *J. Geophys. Res.*, 109, B09402, doi:10.1029/2004JB003028, 2004.
- Cheng M. K., B. D. Tapley and J. C. Ries, Deceleration in the Earth's Oblateness, *JGR*, Vol. 118, 740-747, doi:10.1002/jgrb.50058, 2013a.
- Cheng M. K., J. C. Ries and B. D. Tapley, Geocenter variations from analysis of SLR data. In Altamimi, Collilieux X (eds) *Reference Frames for Applications in Geosciences*, IAG Symposia, Vol 138, 19-25, Springer-Verlag. Doi 10.1007/978-3-642-32998-2_4, 2013b.
- Förste, C., S. L. Bruinsma, F. Flechtner, J.-C. Marty, J.-M. Lemoine, C. Dahle, O. Abrikosov, H. Neumayer, R. Biancale, F. Barthelmes, and G. Balmino, A preliminary update of the Direct approach GOCE Processing and a new release of EIGEN-6C, *Eos Trans., Fall Meet. Suppl.*, Abstract G31B-0923, 2012.
- Förste, Ch., S.L. Bruinsma, O. Abrikosov, J.-M. Lemoine, T. Schaller, H.-J. Götze, J. Ebbing, J.C., Marty, F. Flechtner¹, G. Balmino, and R. Biancale, EIGEN-6C4-The latest combined global gravity field model including GOCE data up to degree and order 2190 of GFZ Potsdam and GRGS Toulouse. Presented at 5th GOCE User Workshop, Paris, 25. – 28.11.2014
- Gruber, Th., P.N.A.M. Visser, Ch. Ackermann and M. Hosse, Validation of GOCE gravity field models by means of orbit residuals and geoid comparisons, *J Geod*, 85/11: 845-860, doi: 10.1007/s00190-011-0486-7, 2011.
- Mayer-Guerr T., D. Rieser, E. Höck, J. M. Brockmann, W.-D. Schuh, I. Krasbutter, J. Kusche, A. Maier, S. Krauss, W. Hausleitner, O. Baur, A. Jäggi, U. Meyer, L. Prange, R. Pail, T. Fecher, and T. Gruber, The new combined satellite only model GOCO03s, Presented at the International Symposium on Gravity, Geoid and Height Systems, Venice, Italy, 2012.
- Pail R, Bruinsma S, Migliaccio F., Förste C., Goiginger H., Schuh W.-D, Höck E, Reguzzoni M., Brockmann J. M, Abrikosov O., Veicherts M., Fecher T., Mayrhofer R., Krasbutter I., Sansó, F., Tscherning, C.C., First GOCE gravity field models derived by three different approaches. *J Geod*, 85/11: 819-843, doi: 10.1007/s00190-011-0467-x, 2011.
- Pavlis, N. K., S. A. Holmes, S. C. Kenyon, and J. K. Factor, The development and evaluation of the Earth Gravitational Model 2008 (EGM2008), *J. Geophys. Res.* V117, B4, DOI: 10.1029/2011JB008916, 2012.
- Tapley, B. D., F. Flechtner, S. V. Bettadpur, and M. M. Watkins, The status and future prospect for GRACE after the first decade, *Eos Trans., Fall Meet. Suppl.*, Abstract G32A-01, 2013.