

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).

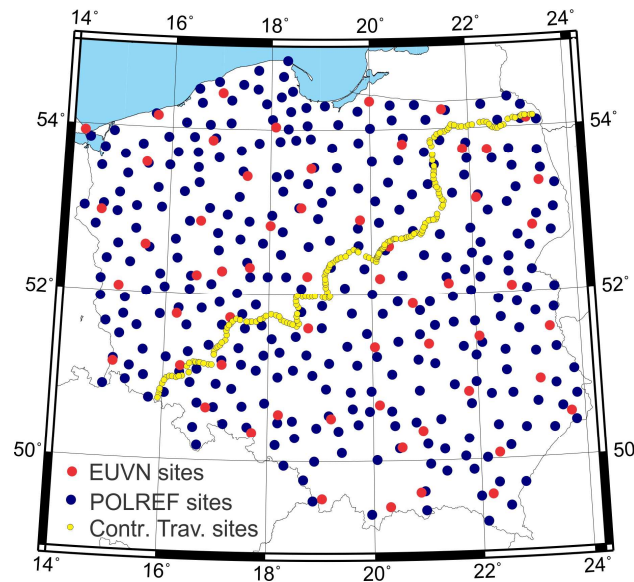


Figure 1: The location of the POLREF, EUVN and the GNSS/levelling control traverse sites.

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.

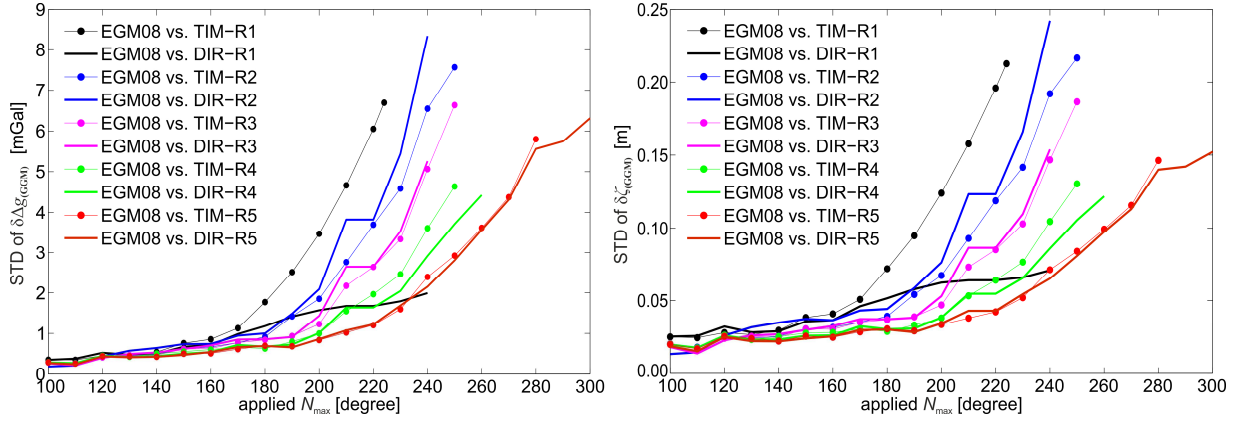


Figure 2: Standard deviations of differences between free-air gravity anomalies (left) and height anomalies (right) obtained from EGM08 and GOCE-based GGMs (the applied $N_{\max} = 100, 110, 120, \dots, 280/300$).

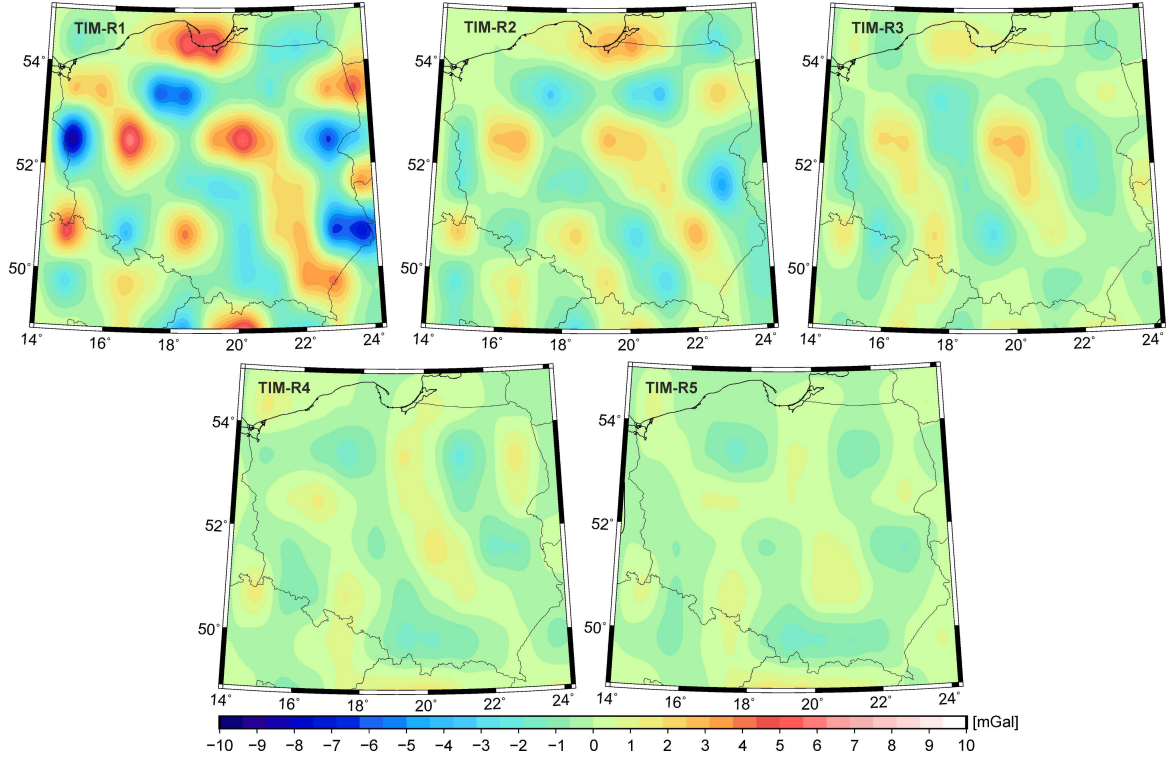


Figure 3: Differences between free-air gravity anomalies $\delta\Delta g_{(GGM)}$ obtained from EGM08 and TIM GOCE-based GGMs (the applied $N_{\max} = 200$).

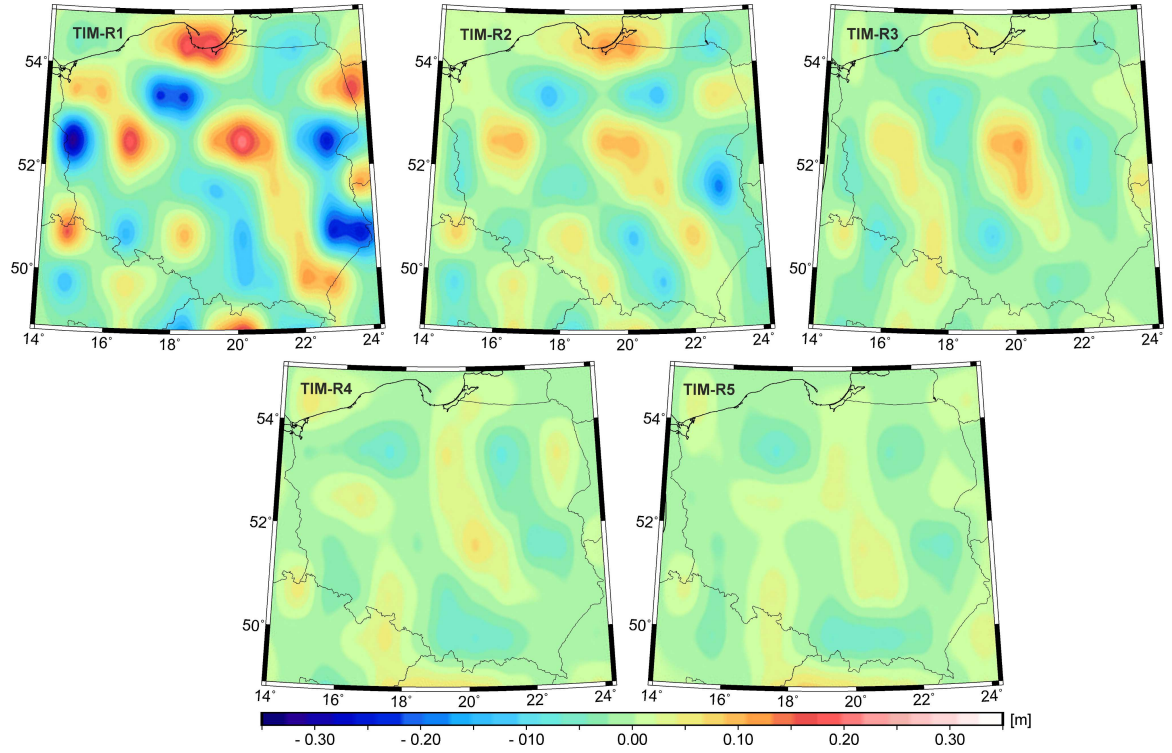


Figure 4: Differences between height anomalies $\delta\zeta_{(\text{GGM})}$ obtained from EGM08 and TIM GOCE-based GGMs (the applied $N_{\text{max}} = 200$).

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.

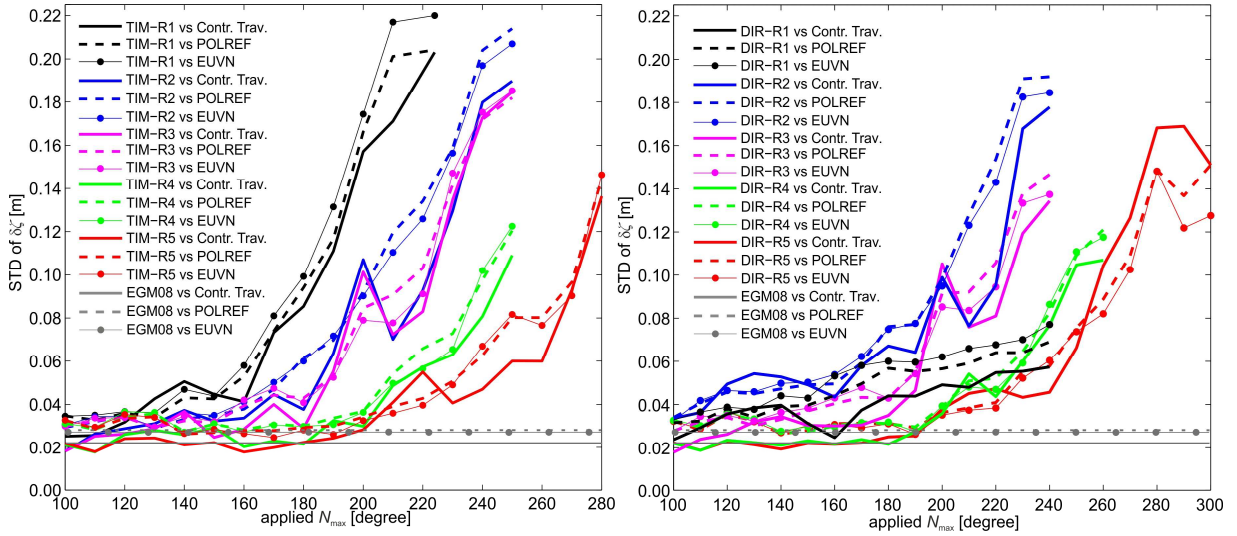


Figure 5: Standard deviations of differences between height anomalies obtained from GNSS/levelling data and from TIM (left) and DIR (right) GOCE-based GGMs (the applied $N_{\max} = 100, 110, 120, \dots, 280/300$).

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.
- Ilhe 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.