Reports on Geodesy and Geoinformatics, 2024, Vol. 117, pp. 38–44

DOI: 10.2478/rgg-2024-0005
Received: 7 January 2024 / Accepted: 19 February 2024
Published online: 6 March 2024

ORIGINAL ARTICLE

Accuracy assessment of high and ultra high-resolution combined GGMs, and recent satellite-only GGMs – Case studies of Poland and Ethiopia

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Abstract

The launch of dedicated satellite gravity missions (CHAMP, GRACE, GOCE, and GRACE–FO), as well as the availability of gravity data from satellite altimetry and terrestrial/airborne gravity measurements have led to a growing number of Global Geopotential Models (GGMs) developed. Thus, the evaluation of GGMs is necessary to ensure their accuracy in recovering the Earth's gravity field on local, regional, and global scales. The main objective of this research is to assess the accuracy of recent GGMs over Poland in Central Europe and Ethiopia in East Africa.

Combined GGMs of high (degree and order (d/o) 2190) and ultra high-resolution (d/o 5540) as well as five satellite-only GGMs were evaluated using gravity data from absolute gravity measurements and airborne gravity surveys over Poland and Ethiopia, respectively. Based on this evaluation, the estimated accuracy of the high-resolution combined GGM is at the level of 2 mGal. The estimated accuracy for the ultra-high-resolution combined GGM is ~2.5 times lower. The satellite-only GGMs investigated recover the gravity signal at an accuracy level of 10 mGal and 26 mGal, for the areas of Poland and Ethiopia, respectively. When compensating for the omitted gravity signal using a high-resolution combined GGM and the topography model, an accuracy of 2 mGal can be achieved.

Key words: Earth's gravity field, Global Geopotential Model, gravity anomaly, gravity disturbance, absolute and airborne gravity measurements

1 Introduction

The determination of the Earth's gravity field and its temporal variations with high accuracy and spatial resolution remains one of the fundamental tasks in geodesy and associated geoscience (geophysics, geology, geodynamics and etc.) disciplines. For example, it is essential for modelling the geoid (physical shape of the Earth) surface that is used as a reference surface for height measurements (Heiskanen and Moritz, 1967). It is also required for geophysical and geological research and applications such as understanding the Earth's interior, plate tectonics, near subsurface geological structures (e.g. Lambeck, 1988; Bennett, 2007). The time-varying of the Earth's gravity field clearly provides insight into the mass transport and thereby the geodynamic processes (Gruber et al., 2011).

Publisher: De Gruyter

Since the beginning of this century, dedicated gravity satellite missions (DGSMs), i.e. Challenging Minisatellite Payload (CHAMP; Reigber et al., 2002), Gravity Recovery and Climate Experiment (GRACE; Tapley et al., 2004), Gravity Field and Steady-State Ocean Circulation Explorer (GOCE; Drinkwater et al., 2003; Rummel et al., 2011) and GRACE Follow-On (GRACE-FO; Flechtner et al., 2015), have played a significant role in the modelling of the Earth's gravity field. Based on the data from these DGSMs, static satellite-only Global Geopotential Models (GGMs) up to degree and order (d/o) 330 have been developed. Moreover, temporal variations of long wavelength components (up to d/o 120) of the Earth's gravity field can be modelled using GGMs for dedicated time periods (e.g. daily, weekly, and monthly) developed using data from GRACE and GRACE-FO satellite missions (e.g. Ince et al., 2019). In addition to satellite-only GGMs, static combined GGMs of high (d/o 2190) or even ultra-high (d/o 5540) spatial resolutions have been developed by combining data from these DGSMs with other complementary gravity data (e.g. terrestrial, airborne, topographic and altimetry data). Currently, combined GGMs of high resolution, such as the Earth Gravitational Model 2008 (EGM2008; Pavlis et al., 2012), the European Improved Gravity model of the Earth by New techniques (EIGEN-6C4; Förste et al., 2014), and an ultra high-resolution GGM (e.g. XGM2019e; Zingerle et al., 2019, 2020) are publicly available. Moreover, satellite-only GGMs developed using data from dedicated gravity satellite missions are also provided to users. Validating those combined and satellite-only GGMs in global, regional and local scales using external data such as terrestrial/airborne gravity data and geoid/quasigeoid heights from GNSS/levelling (Global Navigation Satellite System/levelling) data have been considered as a subject of investigation for the International Centre for Global Earth Models (ICGEM; Ince et al., 2019) and many other scholars (e.g. Godah and Kryński, 2013; Godah et al., 2014; Godah and Krynski, 2015; Alothman et al., 2016; Odera and Fukuda, 2017; Godah et al., 2018a,b; Goyal et al., 2019; Odera, 2020; Wu et al., 2021; Yuan et al., 2022; Pham et al., 2023). Among these scholars, Yuan et al. (2022) and Pham et al. (2023) evaluated the Earth's gravity field up to spectral band of d/o 2190 from XGM2019e ultra high-resolution GGM. However, so far there has been no investigation conducted to evaluate the XGM2019e ultra high resolution GGM at its maximum d/o (i.e. d/o 5540). Moreover, the accuracy of recent satellite-only and combined GGMs remains unknown in many local/regional areas over the world.

The main aim of this study is to assess the accuracy of the Earth's gravity field modelled using the recent ultra high-resolution, satellite-only and combined GGMs. The areas of Central Europe (Poland) and East Africa (Ethiopia) have been chosen as study areas that represent different regions of the world. They are also characterized with quite different gravity fields. The area of Poland has been chosen due to its unique coverage with a set of homogeneously distributed terrestrial data such as absolute gravity and GNSS/levelling data. Over this area, extended research (e.g. Krynski and Kloch, 2009; Godah and Kryński, 2013; Godah et al., 2014, 2015, 2018a), have been conducted to ensure the quality of satellite-only and combined GGMs for modelling the Earth's gravity field. In East Africa, the Earth's gravity field is not yet sufficiently determined, and thus, a proper evaluation of GGMs is required. The African Gravity and Geoid sub–commission of the Commission 2 "Gravity field" of the International Association of Geodesy (IAG) is currently aiming at specifying the most adequate gravity data required to develop a precise geoid model for Africa. In general, the investigation concerning the evaluation of the Earth's gravity field from GGMs over Africa has received little research attention. This is due to the heterogeneous terrestrial datasets (poor terrestrial/airborne gravity and GNSS/levelling data) in Africa. In the course of this study, the area of Ethiopia has been selected as high quality airborne gravity data are available (Bedada, 2010). Over this area, the Earth's gravity field can be recovered with an accuracy of ~2 mGal using EIGEN-6C4 combined GGM or satellite-only GGMs, in particular, release 5 GOCE-based GGMs, extended with EIGEN-6C4 combined GGM (Godah et al., 2018b). However, recent GGMs, i.e. those developed in the last five years including release 6 GOCE-based GGMs, SGG-UGM-2 (Liang et al., 2020) and XGM2019e, have not been evaluated over Poland and Ethiopia. Therefore, in this study, we will evaluate the recent satellite-only GGMs and high- and ultra-high resolution GGMs with the available gravity datasets to assess their accuracy. In the following, Section 2 describes the data used. In Section 3, the methods applied to evaluate the GGMs are specified. The results obtained and their analysis are given in Section 4. Finally, in Section 5, conclusions and recommendations concerning the accuracy of the Earth's gravity field on a regional/local scale obtained from GGMs investigated are drawn.

2 Data used

2.1 Global Geopotential Models (GGMs)

In this study, five recent satellite-only GGMs, two high-resolution combined GGMs and one ultra high-resolution combined GGM were used. The satellite-only GGMs were mainly developed using data from GRACE and GOCE missions, whilst combined GGMs were developed using gravity data from dedicated gravity satellite missions in combination with complementary data such as altimetry and terrestrial gravity data. They are available for public use at the International Centre for Global Earth Models (ICGEMs) (http://icgem.gfzpotsdam.de/ICGEM/). The basic and most important information concerning those GGMs can be found on the header information of GGM files and in the associated files from the ICGEM. The main characteristics of those GGMs are summarized in Table 1. It should be noted that, currently, the EIGEN-6C4 combined GGM (Förste et al., 2014) performs as the best GGM for modelling the Earth gravity field over Poland and Ethiopia (see Godah et al., 2018a,b). Thus, this model has been utilized in this study to compensate for the gravity signal from maximum d/o of satellite-only GGMs investigated.

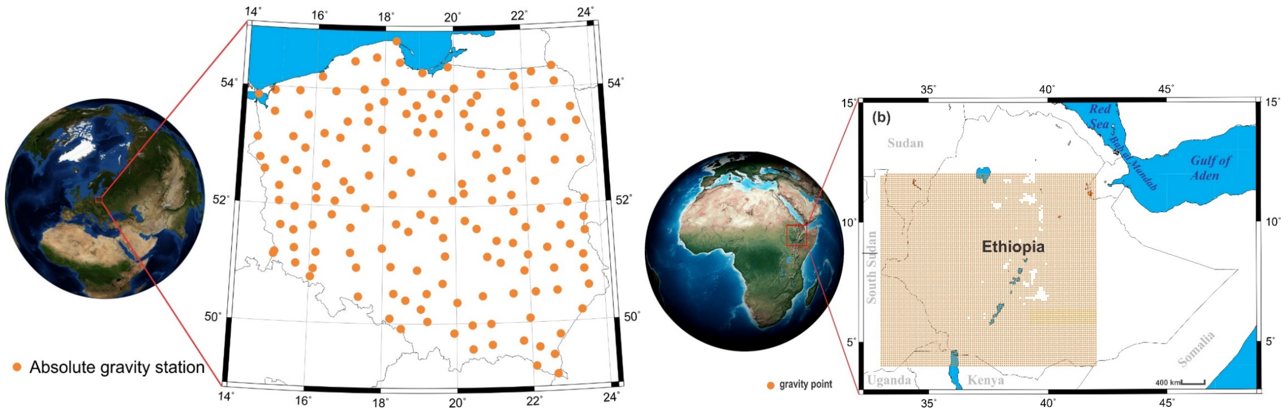
2.2 Terrestrial and airborne gravity data

For the area of Poland, absolute gravity data from 161 gravity stations of the modernized Polish gravity control network (Figure 1a), determined within the period 2012–2014 using the A10-020 absolute gravimeter by the team of the Institute of Geodesy and Cartography (IGiK), Warsaw, Poland, have been utilized in this investigation. At each of those stations a vertical gravity gradient was precisely determined using the LaCoste&Romberg (LCR) model G relative gravimeters. The uncertainty of the gravity value at the aforementioned gravity stations is estimated at ~7 μGal (Dykowski et al., 2015). In addition to these gravity data, very short wavelength (i.e. beyond the max. d/o of the combined GGM) gravity signals induced from topography were recovered over the area of Poland using the Shuttle Radar Topography Mission (SRTM) model with spatial resolution of $30'' \times 30''$ (SRTM30).

For the area of Ethiopia, gravity disturbances data, covering the area bounded by the parallels of 4°N and 12°N and the meridians of 33.1667°E and 42°E, have been used (Figure 1b). The spatial resolution of these data is $5' \times 5'$. The elevation of this area above the mean sea level is ranging from 99 to 2992 m with a mean elevation of 1225 m. Gravity disturbances were determined from airborne gravity survey acquired with along-track resolution (750–1125 m) and track spacing of 18 km during the period between 2006 and 2008 (Bedada, 2010). The estimated accuracy of these gravity disturbances is 2.6 mGal.

Table 1. Main characteristics of GGMs used in this study

GGM Abbrev. Name	ICGEM Name	Max. d/o	GRACE data	GOCE data	Main terrestrial and altimetry data	Time of releasing	Reference
EIGEN-6C4	EIGEN-6C4	2190	~10.0 years	~4.5 years	DTU10 + DTU12 + EGM2008	2014	Förste et al. (2014)
XGM2019e	XGM2019e_2159	5540	~15 years	~5.0 years	The US National Geospatial-Intelligence Agency (NGA's) primary 15′ dataset	2019	Zingerle et al. (2019, 2020)
DIR_R06	GO_CONS_GCF_2_DIR_R6	300	~7.8 years	~5.0 years	–	2019	Bruinsma et al. (2014)
TIM_R06	GO_CONS_GCF_2_TIM_R6	300	–	~5.0 years	–	2019	Brockmann et al. (2021)
TIM_R06e	GO_CONS_GCF_2_TIM_R6e	300	–	~5.0 years	Polar region	2019	Zingerle et al. (2019)
SGG-UGM-2	SGG-UGM-2	2190	~10.0 years	~4.5 years	DTU10 + DTU12 + EGM2008	2020	Liang et al. (2020)
WHU	WHU-SWPU-GOGR2022S	300	~15.0 years	~5.0 years	–	2023	Zhao et al. (2023)
GOSG02S	GOSG02S	300	–	~5.0 years	–	2023	Xu et al. (2023)



(a) (b)

Figure 1. Locations of absolute gravity data in: (a) Poland, (b) Ethiopia

3 Method

Terrestrial gravity anomalies Δg_{Terr} from absoulte gravity data over Poland were determined as follows:

$$\Delta g_{\text{Terr}} = g_{\text{abs}} - \gamma \tag{1}$$

where g_{abs} is absolute gravity value at the stations of the modernized Polish gravity control network (Figure 1a), and γ is the normal gravity (Moritz, 2000) computed on the Earth's surface.

Gravity disturbance $\delta g_{\text{Airborne}}$ over Ethiopia were obtained via the downward continuation of airborne gravity data using Fourier Transformation (FT) as follows (Forsberg and Olesen, 2010):

$$\delta g_{\text{Airborne}} = \delta g(x, y, 0) = F^{-1}\left[e^{\kappa z} F\left\{\delta g(x, y, z)\right\}\right] \tag{2a}$$

with

$$\kappa = \sqrt{k_x + k_y} \tag{2b}$$

where x, y, z denote the Cartesian coordinates of the gravity point, $\delta g(x, y, z)$ is the gravity disturbance at the flight altitude, $\delta g(x, y, 0)$ is the gravity disturbance on the geoid surface, the F is the planar Fourier operator, k_x and k_y are wavenumbers (spatial circular frequencies) corresponding to x and y spatial coordinates, respectively, and e is the exponential function. The detailed procedure for obtaining $\delta g_{\text{Airborne}}$ over Ethiopia were given in (Bedada, 2010).

With the use of GRAVSOFT (Tscherning, 1992) and GrafLab (GRAvity Field LABoratory; Bucha and Janák, 2014) software packages, gravity anomaly Δg and gravity disturbance δg were determined from GGMs as follows (Barthelmes, 2009):

$$\Delta g(r, \lambda, \varphi) = \frac{GM}{r^2} \sum_{n=0}^{N_{\max}} \left(\frac{R}{r}\right)^n (n-1) \sum_{m=0}^{n} \bar{P}_{nm}(\sin\varphi) \cdot \left(\bar{C}_{nm} \cos m\lambda + \bar{S}_{nm} \sin m\lambda\right) \tag{3}$$

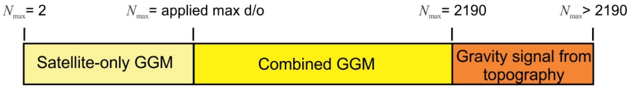


Figure 2. The SEM method

$$\delta g(r,\lambda,\varphi) = \frac{GM}{r^2}\sum_{n=0}^{N_{\max}}\left(\frac{R}{r}\right)^n (n+1)\sum_{m=0}^{n}\bar{P}_{nm}(\sin\varphi) \cdot \left(\bar{C}_{nm}\cos m\lambda + \bar{S}_{nm}\sin m\lambda\right) \quad (4)$$

where r is radius of the computation point (P), φ is latitude of P, λ is longitude of P, $\bar{C}_{nm}$ and $\bar{S}_{nm}$ are fully normalized spherical harmonic coefficients of degree n and order m of the GGM used, GM is geocentric gravitational constant, R is the reference radius of the Earth, $\bar{P}_{nm}$ is fully normalized associated Legendre function of degree n and order m, and $N_{\max}$ is applied maximum degree of the GGM. It should be noted that for ultra-high degrees and orders (e.g. 5540), $\bar{P}_{nm}$ were computed using the extended-range arithmetic algorithm (cf. Fukushima, 2012).

For combined GGMs, the differences between gravity field obtained from GGMs and terrestrial/airborne gravity data ($d\Delta g_{\text{res}}$ and $d\delta g_{\text{res}}$) were determined as follows:

$$d\Delta g_{\text{res}} = \Delta g_{\text{Terr}} - \Delta g - \Delta g_{\text{Topo}} \quad (5)$$

$$d\delta g_{\text{res}} = \delta g_{\text{Airborne}} - \delta g - \delta g_{\text{Topo}} \quad (6)$$

where Δg_{Terr} presents terrestrial gravity anomaly, Δg_{Topo} is gravity correction induced from the topography beyond $N_{\max}$ determined using SRTM30 and the residual terrain modelling (RTM) technique (Forsberg, 1984), $\delta g_{\text{Airborne}}$ denotes the gravity disturbance determined from the airborne gravity measurements and δg_{Topo} is the very short wavelength gravity disturbance signal induced from the topography beyond $N_{\max}$. It should be mentioned that gravity signals induced from topography (i.e. Δg_{Topo} and δg_{Topo}) and determined with the use of global topography model are required to avoid the spectral inconsistency between terrestrial/airborne gravity data and GGMs. However, within the course of this study, the term δg_{Topo} is neglected as the spatial resolution (i.e. $5' \times 5'$) of airborne gravity data for the area of Ethiopia is compatible with the corresponding one (i.e. d/o 2190) of combined GGMs investigated.

For the satellite-only GGMs, the spectral enhancing method (SEM; Hirt et al., 2011) has been implemented. In this method, gravity signal beyond the applied maximum d/o of the satellite-only GGM is compensated by a gravity signal from an appropriate combined GGM and topography model (see Figure 2). Thus, the differences $d\Delta g_{\text{Sat-only}}$, $d\delta g_{\text{Sat-only}}$, $d\Delta g_{\text{SEM}}$ and $d\delta g_{\text{SEM}}$ can be determined as follows:

$$d\Delta g_{\text{Sat-only}} = \Delta g_{\text{Terr}} - \Delta g\big|_0^{N_{\max}} \quad (7)$$

$$d\delta g_{\text{Sat-only}} = \delta g_{\text{Terr}} - \delta g\big|_0^{N_{\max}} \quad (8)$$

$$d\Delta g_{\text{SEM}} = d\Delta g_{\text{Sat-only}} - \Delta g_{\text{EIGEN-6C4}}\big|_{N_{\max}+1}^{2190} - \Delta g_{\text{Top}} \quad (9)$$

$$d\delta g_{\text{SEM}} = d\delta g_{\text{Sat-only}} - \delta g_{\text{EIGEN-6C4}}\big|_{N_{\max}+1}^{2190} - \delta g_{\text{Top}} \quad (10)$$

4 Results

Table 2 provides the statistics of the differences $d\Delta g_{\text{res}}$ for the area of Poland. Figures 3 and 4 show standard deviations (STDs) of $d\Delta g_{\text{Sat-only}}$ and $d\Delta g_{\text{SEM}}$ obtained with the use of satellite-only GGMs truncated at applied maximum d/o ranging from d/o 100 to 300 with 10 d/o step, respectively. The statistics of $d\Delta g_{\text{Sat-only}}$ and $d\Delta g_{\text{SEM}}$ at d/o 200 which corresponds to a spatial resolution of 100 km half-wavelength at the equator, i.e. the objective of the GOCE mission in terms of spatial resolution, are given in Table 3.

Table 2. Statistics of $d\Delta g_{\text{res}}$ between gravity anomalies from absolute gravity data and combined GGMs over Poland (mGal)

GGMs	Max. d/o (degree)	Min.	Max.	Mean	STD
EIGEN-6C4	2019	−6.11	3.72	−1.03	1.70
SGG-UGM-2	2190	−6.18	3.20	−1.00	1.79
XGM2019e	2190 5540	−20.50 −14.78	15.40 22.09	-0.77 0.19	7.19 4.40

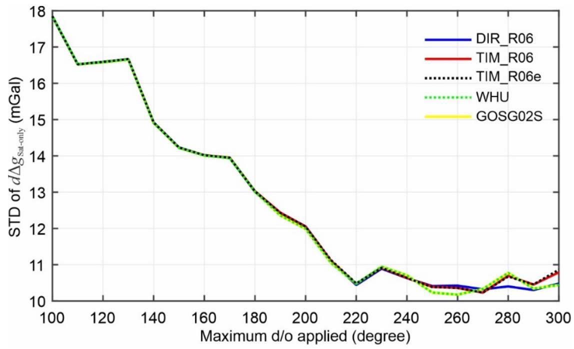


Figure 3. Standard deviation of the differences $d\Delta g_{\text{Sat-only}}$ over Poland

For the area of Ethiopia, the statistics of $d\delta g_{\text{res}}$ are given in Table 4. The STDs of $d\delta g_{\text{Sat-only}}$ and $d\delta g_{\text{SEM}}$ determined using satellite-only GGMs at d/o from 100 to 300 with 10 d/o step are shown in Figure 5 and 6, respectively. The statistics of these differences ($d\delta g_{\text{Sat-only}}$ and $d\delta g_{\text{SEM}}$) at d/o 200 are provided in Table 5.

The statistics provided in Table 2 and Table 4 indicate that gravity anomalies over Poland and gravity disturbance over Ethiopia can be recovered using the SGG-UGM-2 combined GGM with an accuracy, in terms of standard deviations of $d\Delta g_{\text{res}}$ and $d\delta g_{\text{res}}$, at the level of ~2 mGal. It is worth noting that this accuracy agrees well with the one of the EIGEN-6C4 combined GGM published in Godah et al. (2018a,b). For the XGM2019e combined GGM, the STDs of $d\Delta g_{\text{res}}$ evaluated at d/o 5540 and $d\delta g_{\text{res}}$ evaluated at d/o 2190 is ~2.5 times larger than corresponding ones obtained when evaluating SGG-UGM-2 and EIGEN-6C4 combined GGMs. This can be ascribed to the fact that XGM2019e was developed using lower quality gravity data, in particular, in the spectral range above d/o 719 (cf. Zingerle et al., 2019, 2020) compared to the quality of gravity data incorporated in SGG-UGM-2 and EIGEN-6C4 combined GGMs.

The results presented in Figures 3 and 5 reveal that satellite-only GGMs can recover the gravity field over the area of Poland and

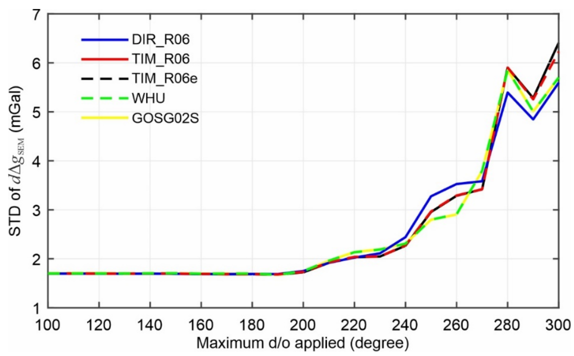


Figure 4. Standard deviation of the differences $d\Delta g_{\text{SEM}}$ over Poland

Table 3. Statistics of $d\Delta g_{\text{Sat-only}}$ and $d\Delta g_{\text{SEM}}$ at d/o 200 over Poland (mGal)

GGM	$d\Delta g_{\text{Sat-only}}$ Min	Max	Mean	STD	$d\Delta g_{\text{SEM}}$ Min	Max	Mean	STD
DIR_R06	−40.01	36.37	−1.66	12.06	−6.19	3.55	−1.07	1.75
TIM_R06	−39.99	36.64	−1.64	12.04	−5.99	3.55	−1.05	1.73
TIM_R06e	−39.87	36.57	−1.63	12.05	−5.86	3.41	−1.04	1.72
WHU	−39.89	36.16	−1.66	11.99	−5.79	3.31	−1.07	1.75
GOSG02S	−39.90	36.15	−1.66	11.98	−5.78	3.31	−1.07	1.74

Table 4. Statistics of $d\delta g_{\text{res}}$ over Ethiopia (mGal)

GGMs	Max. d/o (degree)	Min.	Max.	Mean	STD
EIGEN-6C4	2019	−12.33	12.06	0.29	2.30
SGG-UGM-2	2190	−19.63	20.76	0.24	2.25
XGM2019e	2190	−27.34	49.63	0.28	5.56

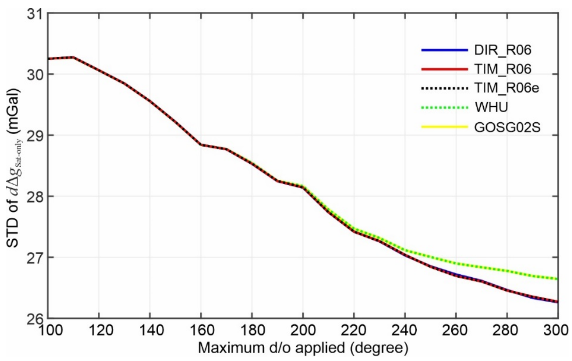


Figure 5. Standard deviation of the differences $d\delta g_{\text{Sat-only}}$ over Ethiopia

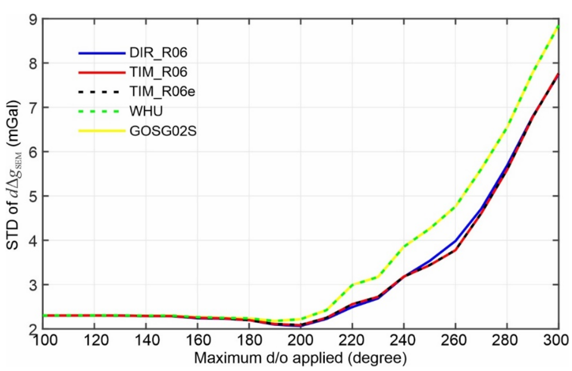


Figure 6. Standard deviation of the differences $d\delta g_{\text{SEM}}$ over Ethiopia

Ethiopia with an accuracy level of 10 mGal and 26 mGal, respectively. When compensating for the gravity signal beyond the applied $N_{\max}$ using EIGEN-6C4 combined GGM and the SRTM model, the STDs of $d\Delta g_{\text{SEM}}$ at d/o from 100 to 200 are at the level of 2 mGal (Figs. 4 and 6). For instance, at d/o 200, the STDs of $d\Delta g_{\text{SEM}}$ and $d\delta g_{\text{SEM}}$ are ~1.7 mGal and ~2.2 mGal, for Poland and Ethiopia, respectively. As seen from Figures 4 and 6, the STDs of $d\Delta g_{\text{SEM}}$ gradually increase from d/o 200 and onward and reach the level of 6 mGal and 8 mGal, for Poland and Ethiopia, respectively, at d/o 300. This might be ascribed to the fact that the Earth's gravity field up to spectral wavelength that corresponds to d/o 200 can be recovered with a high accuracy (i.e. 1 mGal) using GOCE data, while from d/o 200 and onward GOCE data are dominated by noise that prevents recovering the Earth's gravity field with such high accuracy (e.g. Godah et al., 2015).

5 Summary and Conclusions

In this study, the accuracy of recent Global Geopotential Models (GGMs), including five satellite-only GGMs, one combined high-resolution GGM and one combined ultra high-resolution GGM have been assessed over two geographical regions, Central Europe (Poland) and East Africa (Ethiopia). High-quality terrestrial gravity anomalies obtained from absolute gravity measurements from the area of Poland and gravity disturbances obtained from airborne gravity survey for Ethiopia have been used as ground truth data. Gravity anomalies and gravity disturbances from those GGMs have been determined using GRAVSOFT and GrafLab software packages. For the ultra high-resolution GGM, the extended-range arithmetic algorithm has been utilized to compute the fully normalized associated Legendre functions. The main findings reveal that:

- Gravity anomalies in Poland and gravity disturbances in Ethiopia can be ascertained using the SGG-UGM-2 high-resolution combined GGM with an accuracy of approximately 2 mGal.
- The accuracy of the XGM2019e ultra high-resolution combined GGM is at the level of 5±0.6 mGal, notably 2-3 times lower than that of the SGG-UGM-2 or EIGEN-6C4 combined GGMs. This reduced accuracy is likely due to the utilization of lower-quality terrestrial/airborne gravity and altimetry data during the development of XGM2019e.
- Satellite-only GGMs can recover the gravity field with the accuracy of 10 mGal and 26 mGal in terms of gravity anomalies for Poland and gravity disturbances for Ethiopia, respectively. When compensating for the omitted gravity signal using the EIGEN-6C4 combined GGM and the SRTM topography model, gravity anomalies and gravity disturbances can be obtained from satellite-only GGMs at the accuracy level of 2 mGal. However, the use of the spherical coefficients from d/o 200 and onward up to d/o 300 reduces the accuracy of the satellite-only GGMs investigated to 6 mGal for Poland and 8 mGal for Ethiopia. This can be attributed to the higher noise level in d/o 200–300 spherical coefficients in the GOCE data.

Overall, the SGG-UGM-2 combined GGM and satellite-only GGMs (DIR_R06, TIM_R06, TIM_R06e, WHU, GOSG02S) after compensating for gravity signal from EIGEN-6C4, are characterized

Table 5. Statistics of $d\delta g_{\text{Sat-only}}$ and $d\delta g_{\text{SEM}}$ at d/o 200 over Ethiopia

GGM	$d\delta g_{\text{Sat-only}}$				$d\delta g_{\text{SEM}}$			
	Min	Max	Mean	STD	Min	Max	Mean	STD
DIR_R06	−110.09	159.47	−2.05	28.14	−9.94	11.06	0.29	2.07
TIM_R06	−110.24	159.42	−2.07	28.14	−9.98	11.21	0.27	2.09
TIM_R06e	−110.20	159.45	−2.07	28.14	−9.95	11.20	0.27	2.09
WHU	−111.18	159.91	−2.07	28.17	−9.49	12.03	0.26	2.22
GOSG02S	−111.18	159.93	−2.06	28.17	−9.47	12.04	0.28	2.22

with a similar high accuracy, i.e. the accuracy level of 2 mGal. It is not the case with the XGM2019e ultra high-resolution combined GGM, whose accuracy is ~5 mGal.

Acknowledgments

This work was supported by the Polish National Science Centre (NCN) within the research Grant No.2021/42/E/ST10/00218 and the statutory project of Institute of Geodesy and Cartography, Warsaw, Poland.

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