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Validation of GOCE gravity field models over Poland using the EGM2008 and GPS/levelling data

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Abstract. Since the mid of 2010, global geopotential models based on GOCE mission data became available. The first two releases of GGMs contained four different solutions while in the third release only two solutions have been generated. In the presented study the available GOCE-derived gravity field models were evaluated in terms of height anomalies and gravity anomalies over Poland with the use of the respective functionals calculated from the EGM2008 geopotential model as well as height anomalies at 184 stations of high precision GPS/levelling control traverse.
The fit of GOCE gravity field models with the EGM2008 in terms of height anomalies and gravity anomalies measured with a standard deviation is below 10 cm, and 3 mGal, respectively. Their fit with GPS/levelling height anomalies at the stations of GPS/levelling control traverse is at the level of 10 cm. The results obtained indicate some improvement of the consecutive releases of GOCE gravity field models.

Keywords: geopotential model, GOCE, EGM2008, GPS/levelling, height anomaly, gravity anomaly

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1. Introduction

The latest gravity field modelling dedicated satellite mission is the Gravity Field and Steady-state Ocean Circulation Explorer (GOCE) which is a core satellite mission of the European Space Agency (ESA) Living Planet Program (ESA, 1999). The major observable is the gravity gradient provided by high precision gradiometer mounted on the satellite equipped with high and drag-free system. The GOCE satellite was launched on 17 March 2009. The objective of the mission was to provide a static geoid model with an accuracy of 1–2 cm and gravity field model of 1 mGal accuracy in a spatial resolution of about 100 km (a half-wavelength) (Drinkwater et al., 2003).

In order to fulfil the objectives of the GOCE satellite mission, three different approaches were applied to modelling the gravity field in GOCE High Level Processing Facility (HPF) (Rummel et al., 2004). They are denoted as a direct approach (DIR), a time-wise solution (TIM), and a space-wise solution (SPW). The main characteristics of those approaches can be described shortly as follows (Pail et al., 2011):

In direct approach, the a priori global geopotential model (GGM) EIGEN-5C (Förste et al., 2008) has been applied. The spherical harmonic coefficients and their derivatives were calculated by solving the inverse problem with the use of least squares method.

The time-wise approach is a pure solution, with no a priori gravity field information involved in the calculation. The spherical harmonic coefficients and their derivatives have been computed by solving normal equations with the use of least squares method.

In space-wise approach, the GOCE quick-look GGM – EGM_QLO_21 – has been used as prior gravity information. Other GGMs, in particular EGM2008, EIGEN-5C and ITG-GRACE2010 (Mayer-Gürr et al., 2010) were applied as reference gravity field models (for details see Migliaccio et al., 2010). The determination of the spherical harmonic coefficients and their derivatives was based on least squares collocation.

Beside the GOCE-only GGMs, combined geopotential models using GOCE and other satellite and terrestrial data have been generated under the Gravity Observation Combination (GOCO) project (Pail et al., 2010b).

The current GGMs based on GOCE solutions have been delivered in three releases. The major difference between the consecutive releases is the length of observation period determining data coverage, and the source of data used in the computations. The first release delivered in June 2010 was based on two months data (01 November 2009 to 31 December 2009). In March 2011, the second release was published. It was developed using already 8 months data: from November 2009 until June 2010. Subsequently, the third release published in November 2011, was based on 20 months data: from November 2009 to June 2011. More information on those releases can be found at http://earth.esa.int/GOCE/.

All geopotential models obtained from gravity field modelling dedicated space missions need validation in different parts of the Earth' globe. The results of validation of GGMs determined from CHAMP and then from GRACE mission data in different regions covering almost all continents were extensively described in literature. The GOCE GGMs of 1st release were evaluated, e.g. using truncated EGM2008 (up to degree and order 200) regional geoid and terrestrial gravity data over Norway. The obtained differences in height anomalies and gravity anomalies reached several decimetres with the standard deviation of 6–10 cm, and a few milligals, respectively (Šprlák et al., 2011). The 1st and 2nd releases of GOCE GGMs were similarly evaluated over the area of Slovakia. Standard deviations of the differences between height anomalies and gravity anomalies from GOCE models and truncated EGM2008 model were within the range of 6–21 cm, and 2–6 mGal, respectively (Janák and Pitoňák, 2011).

Area of Poland seems specifically suitable for validating GOCE-based GGMs due to its high precision quasigeoid (accuracy below 2 cm), high precision GPS/levelling traverse dedicated for validation of quasigeoid models (Krynski and Lyszkowicz, 2006, 2007; Krynski, 2007a). In addition, since high quality gravity data from Poland were provided for developing the EGM2008, the model fits very well gravity field over Poland (Krynski and Kloch, 2009).

The main purpose of this study is to validate gravity anomalies and height anomalies from the GGMs based on data from GOCE satellite mission with the use of gravity anomalies and height anomalies from the EGM2008 and high precision GPS/levelling sites over Poland as well as to assess the progress in GOCE mission products in terms of consecutive releases.

2. The global geopotential models investigated

Ten global geopotential models (Table 1) developed with the use of data from GOCE mission were evaluated. Eight of them, denoted by DIR1, DIR2, DIR3, TIM1, TIM2, TIM3, SPW1, and SPW2, are known in literature as GOCE-only models (see Migliaccio et al., 2011; Pail et al., 2011; Šprlák et al., 2011). The official names of GOCE GGMs at the International Centre for Global Earth Models (ICGEM) are given in Table 1. The last two GGMs: GOCO01 and GOCO02 are combined models. They are based on the combination of GOCE data with data from other missions. All those models are presently available at the web site http://icgem.gfz-potsdam.de/ICGEM/.

The EGM2008 global geopotential model was used as a reference model to validate the GOCE-based GGMs. This model was extensively evaluated over the area of Poland using four different GPS/levelling data sets and three quasigeoid models over Poland. The evaluation showed that, the fitting of EGM2008 height anomalies over Poland measured with a standard deviation is below 2 cm (Krynski and Kloch, 2009; Łyszkowicz, 2009).

3. Basic computation formulae

The global geopotential models given in Table 1 are expressed in terms of a set of fully normalized

Table 1. Global geopotential models investigate

GGM	Degree/order	Input data	GGM official name at ICGEM	Citation
DIR1	240	GOCE	GO_CONS_GCF_2_DIR_R1	Bruinsma et al., 2010
DIR2	240	GOCE	GO_CONS_GCF_2_DIR_R2	Bruinsma et al., 2010
DIR3	240	GOCE + GRACE + SLR	GO_CONS_GCF_2_DIR_R3	Bruinsma et al., 2010
TIM1	250	GOCE	GO_CONS_GCF_2_TIM_R1	Pail et al., 2010a
TIM2	224	GOCE	GO_CONS_GCF_2_TIM_R2	Pail et al., 2011
TIM3	250	GOCE	GO_CONS_GCF_2_TIM_R3	Pail et al., 2011
SPW1	210	GOCE	GO_CONS_GCF_2_SPW_R1	Migliaccio et al., 2010
SPW2	240	GOCE	GO_CONS_GCF_2_SPW_R2	Migliaccio et al., 2011
GOCO01	224	GOCE+GRACE	GOCO01	Pail et al., 2010b
GOCO02	250	GOCE+GRACE + CHAMP + SLR + satellite altimetry	GOCO02	Goiginger et al., 2011
EGM2008	2160	GRACE + terrestrial gravity + satellite altimetry + SLR	EGM2008	Pavlis et al., 2008

spherical harmonic coefficients $\overline{C}_{nm}$ and $\overline{S}_{nm}$ of n degree and m order. With the use of those coefficients gravity anomaly $\Delta g_{(r,\varphi,\lambda)}$ and height anomaly $\tilde{N}_{(r,\varphi,\lambda)}$ can be determined at arbitrary point (r, φ, λ) applying the following formulae (Torge, 1991):

$$\tilde{N}_{(r,\varphi,\lambda)} = \frac{GM}{a\gamma} \sum_{n=2}^{N_{\max}} \left(\frac{a}{r}\right)^{n+1} \sum_{m=0}^{n} (\bar{C}_{nm} \cos m\lambda + \bar{S}_{nm} \sin m\lambda) \bar{P}_{nm}(\sin\varphi) \tag{1}$$

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

where G is the Newtonian gravitational constant, M is the mass of the reference ellipsoid corresponding to the mass of the Earth, a is the semi-major axis of the reference ellipsoid, $\overline{P}_{nm}(\sin\varphi)$ are fully normalized associated Legendre functions, $N_{\max}$ is the maximum degree of gravity field model, and γ is the normal gravity on the reference ellipsoid at latitude φ.

4. Comparison of GOCE-based gravity field models with the EGM2008

Free-air gravity anomalies and height anomalies were calculated on 54′ × 54′ grid over the region of Poland from the GOCE-based GGMs specified in Table 1. The grid corresponds to the expected resolution of GOCE-derived GGMs. These anomalies have been compared with the respective ones computed similarly from the EGM2008. All GGMs used, including the EGM2008, were truncated to degree and order 200 ($N_{\max}$ = 200) which corresponds to the objective of GOCE mission in terms of its spatial resolution ~100 km, and makes the results of comparison more reliable. Figures 1–4 and 5–8 show the differences between GOCE-based GGMs and the EGM2008 in terms of free-air gravity anomalies and height anomalies, respectively.

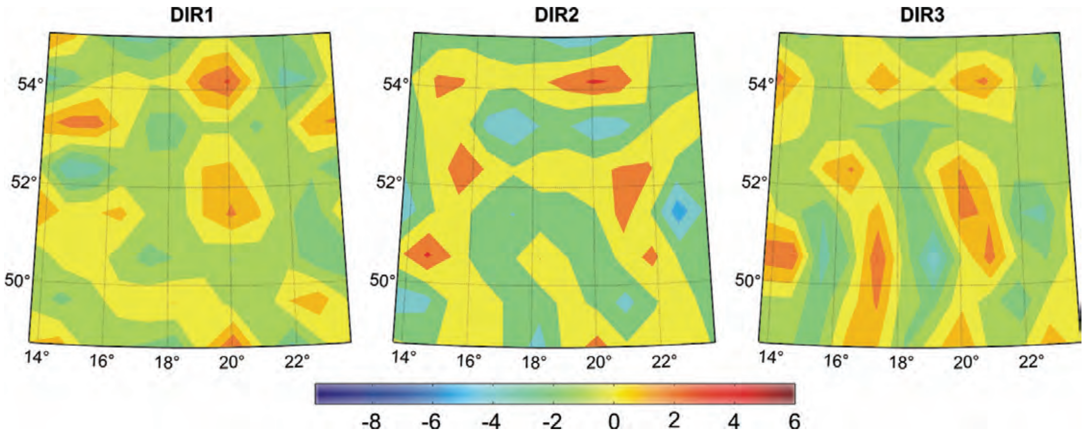

Fig. 1. Differences between free-air gravity anomalies obtained from EGM2008 and from GOCE direct solutions [mGal]

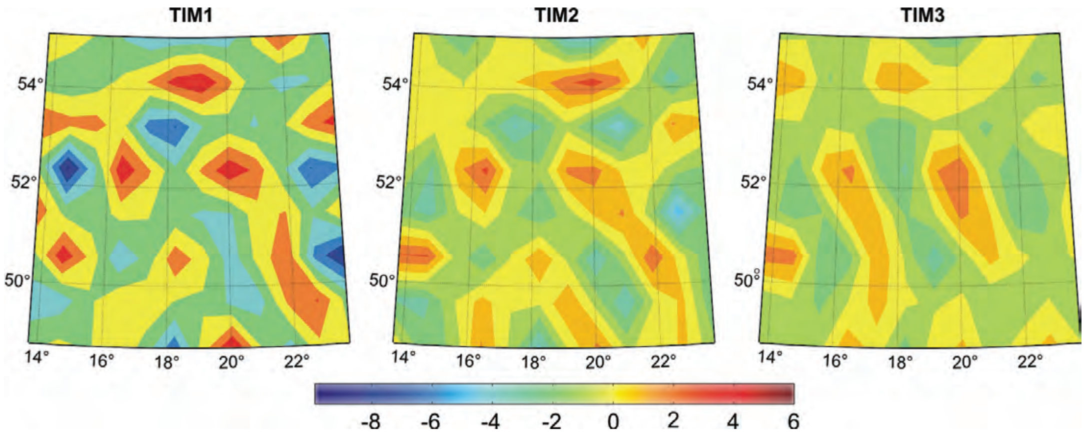

Fig. 2. Differences between free-air gravity anomalies obtained from EGM2008 and from GOCE time-wise solutions [mGal]

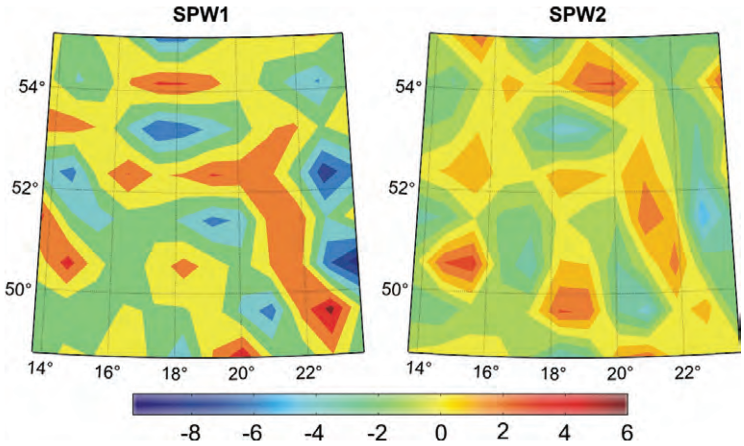

Fig. 3. Differences between free-air gravity anomalies obtained from EGM2008 and from GOCE space-wise solutions [mGal]

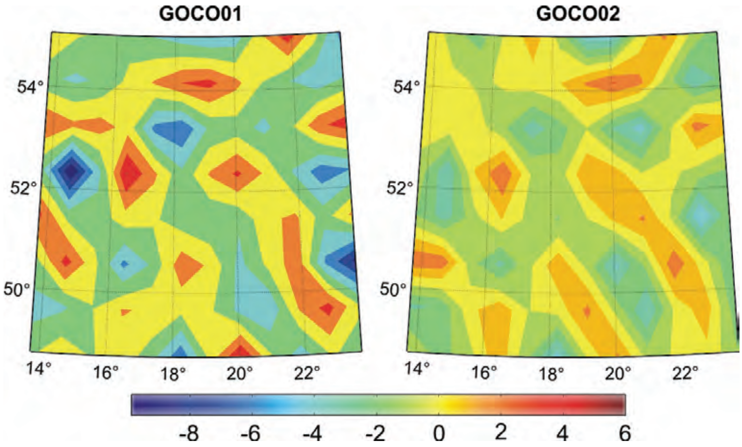

Fig. 4. Differences between free-air gravity anomalies obtained from EGM2008 and from GOCO models [mGal]

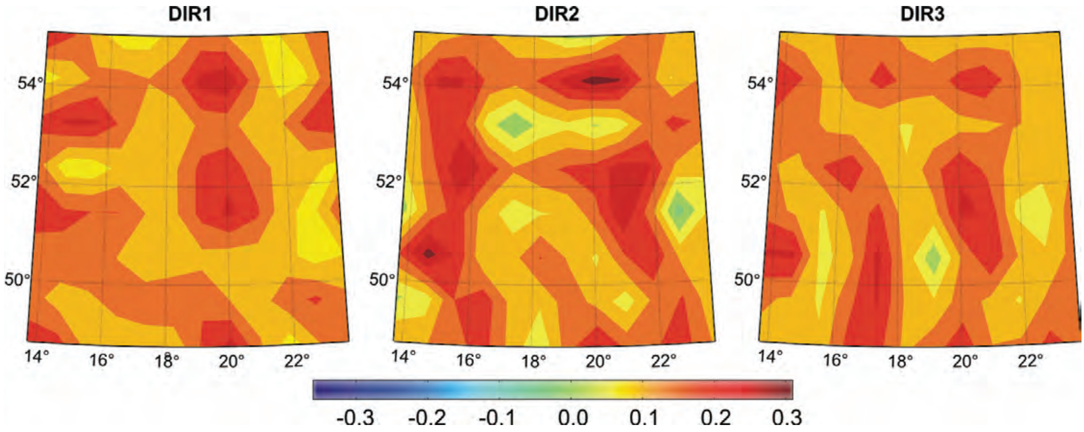

Fig. 5. Differences between height anomalies obtained from EGM2008 and from GOCE direct solutions [m]

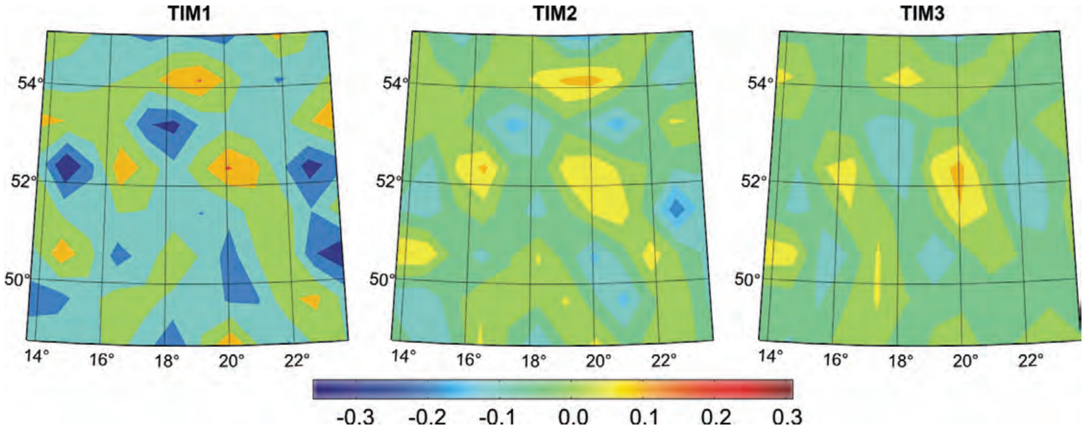

Fig. 6. Differences between height anomalies obtained from EGM2008 and from GOCE time-wise solutions [m]

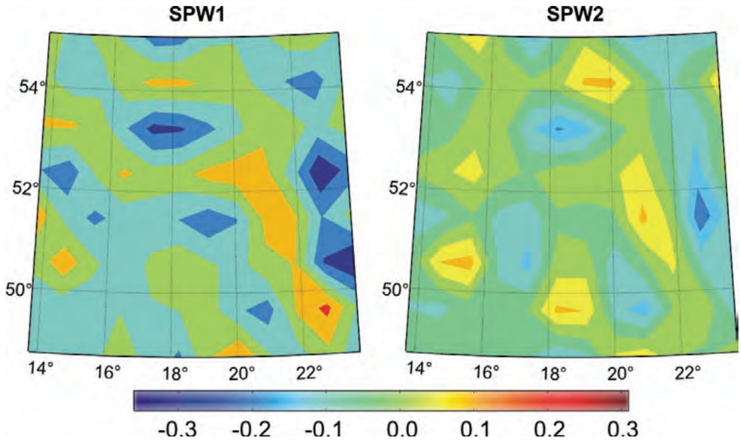

Fig. 7. Differences between height anomalies obtained from EGM2008 and from GOCE space-wise solutions [m]

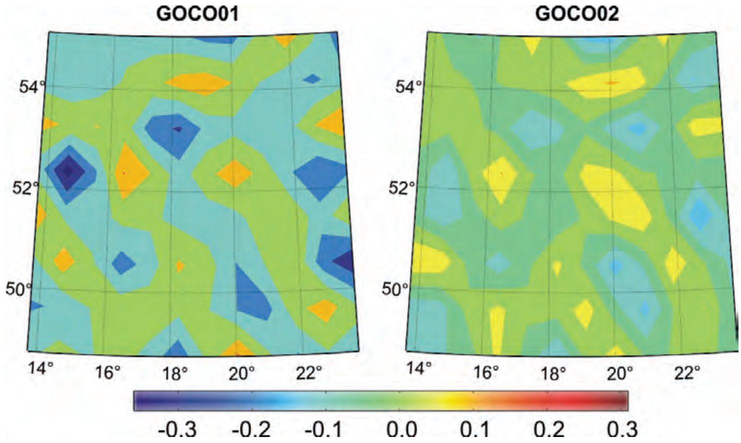

Fig. 8. Differences between height anomalies obtained from EGM2008 and from GOCO models [m]

The statistics of differences between GOCE-based GGMs and the EGM2008 in terms of height anomalies and gravity anomalies are given in Table 2. The results presented in Figures 1–4 and 5–8 together with those in Table 2 show clear improvement in terms of both height anomalies and gravity anomalies with growing data set in consecutive releases of GOCE solutions investigated. The improvement from 1st to 2nd release (except DIR1) is about 4 cm/1.3 mGal and from 2nd to 3rd release – about 2 cm/0.6 mGal. For TIM1, SPW1 and GOCO01 solutions the standard deviations are almost twice bigger than those for DIR1. This might be due to the DIR1 model was relied strongly on the a priori information from the EIGEN-5C geopotential model in the determination of the GOCE-based GGM. TIM3 has shown the best fit with the EGM2008 in both standard deviation and dispersion.

5. Comparison of GOCE-based gravity field models with GPS/levelling height anomalies

Height anomalies of 184 stations of high precision GPS/levelling control traverse across Poland (Fig. 9), of which 44 stations were considered as 1st order benchmarks and the remaining stations – as 2nd order benchmarks (difference in the length of GPS observing sessions and applied strategy of data processing) (Krynski, 2007b), were used to evaluate the GOCE--based GGMs.

Table 2. The statistics of differences between GOCE-based GGMs and the EGM2008 in terms of height anomalies and gravity anomalies ($N_{\max}$ = 200)

GGM	Height anomalies [m]				Gravity anomalies [mGal]			
	Min	Max	Mean	STD	Min	Max	Mean	STD
DIR1	0.065	0.293	0.159	0.055	–2.986	3.195	–0.075	1.391
DIR2	–0.029	0.329	0.159	0.073	–5.343	4.420	–0.136	1.974
DIR3	0.011	0.268	0.159	0.050	–3.917	3.099	–0.053	1.329
TIM1	–0.312	0.213	–0.020	0.110	–8.679	6.280	–0.175	3.115
TIM2	–0.189	0.128	–0.011	0.064	–4.749	3.565	–0.149	1.774
TIM3	–0.111	0.122	–0.007	0.045	–2.814	3.029	–0.040	1.197
SPW1	–0.315	0.233	–0.009	0.107	–9.009	6.734	–0.159	3.020
SPW2	–0.193	0.122	–0.015	0.067	–4.845	3.719	–0.178	1.829
GOCO01	–0.352	0.216	–0.008	0.108	–9.875	6.194	–0.181	3.092
GOCO02	–0.156	0.110	–0.006	0.060	–4.130	3.109	–0.143	1.696

To provide a reliable comparison, data sets being compared should possibly represent the same spectral characteristics. Height anomalies of the GPS/levelling control traverse $N_{GPS/levelling}$, as obtained with the use of high resolution terrestrial gravity data, contain medium- and short-wavelength components. They were thus reduced to the spectral resolution of the GOCE model ($N_{\max}GOCE$ = 200) by removing the medium-wavelength component

$$N_{EGM2008}{}^{N_{\max}=2160}_{N_{\max}=N_{\max}GOCE+1} \tag{3}$$

using the EGM2008 as a reference model (Gruber, 2009). The deference δ can be expressed as follows:

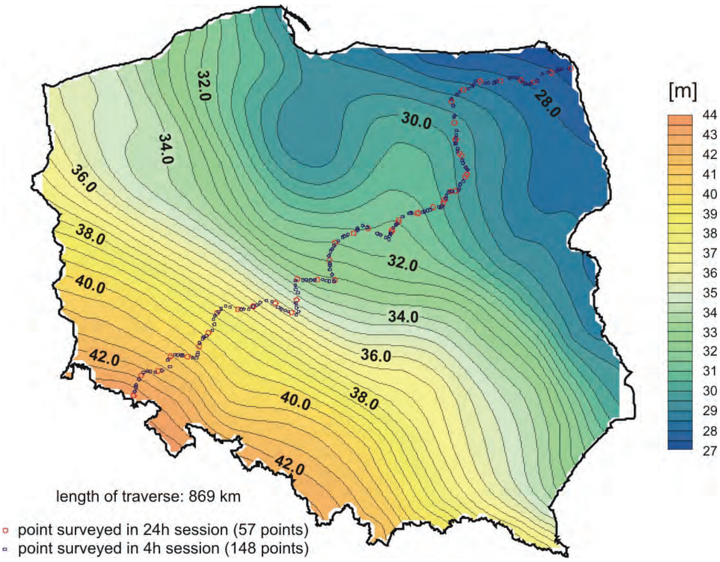

Fig. 9. GPS/levelling control traverse stations (Krynski, 2007b)

$$\delta = \left\{N_{GPS/levelling} - N_{EGM2008}{}^{N_{\max}=2160}_{N_{\max}=N_{\max}GOCE+1}\right\} - \{N_{GOCE} + N_0\} \tag{4}$$

with N_{GOCE} – the height anomaly determined using GOCE GGMs, and the additive constant N_0 – a bias determined as follows (Heiskanen and Moritz, 1967):

$$N_0 = \frac{GM - GM_0}{R\bar{\gamma}} - \frac{W_0 - U_0}{\bar{\gamma}} \tag{5}$$

where M_0 is the mass of the reference ellipsoid corresponding to the mass of the Earth, U_0 is the gravity potential of the ellipsoid, R is the mean radius of the ellipsoid, $\bar{\gamma}$ is the mean normal gravity at the surface of the reference ellipsoid. The parameters M_0, U_0, $\bar{\gamma}$, and R are related to the Geodetic Reference System 1980 (Moritz, 1980). On the other hand, M is the mass of the Earth and W_0 is the gravity potential of the Earths' according to general definitions and numerical standards of the International Earth Rotation and Reference Systems Service Conventions (McCarthy and Petit, 2004).

The remove of the medium-wavelength component from the GPS/levelling height anomalies results in a significant reduction of the amplitude of the height anomalies differences. It improves the quality of the fit of the investigated DIR models.

Figure 10 shows the differences δ' between height anomalies from GOCE direct solutions and the respective ones of the GPS/levelling at the control traverse sites (unfiltered data)

$$\delta' = \quad N_{GPS/levelling} - \{N_{GOCE} \quad + N_0\} \quad (6)$$

as well as the differences δ with removed medium-wavelength component from the GPS/levelling data using Eq (4) (filtered data).

The statistics of the differences δ between height anomalies obtained from GOCE-based GGMs and the respective ones from GPS/levelling control traverse are given in Table 3.

The results presented in Table 3 show that the standard deviations using 1st or 1st & 2nd order sites do not significantly differ. They correspond to those obtained when evaluating the EGM2008 over Poland (Krynski and Kloch, 2009). As in the case of the comparison with the EGM2008, the GOCE-based GGMs compared with high precision GPS/levelling height anomalies exhibit the improvement with growing data set becoming available from 1st to 2nd release. Standard deviation of height anomalies becomes reduced by about 4.2 cm in case of all GGMs investigated except DIR1. From 2nd to 3rd release the improvement is not clear.

The accuracy of the ground truth, i.e. reference height anomalies at the GPS/levelling control traverse stations is at the level of 1–2 cm (Krynski and Kloch, 2009). Relatively large standard deviations and dispersions result from the quality of GOCE signal at some GPS/levelling sites which is reflected in the statistics of the differences in height anomalies from GOCE-based GGMs and GPS/levelling at the sites of control traverse.

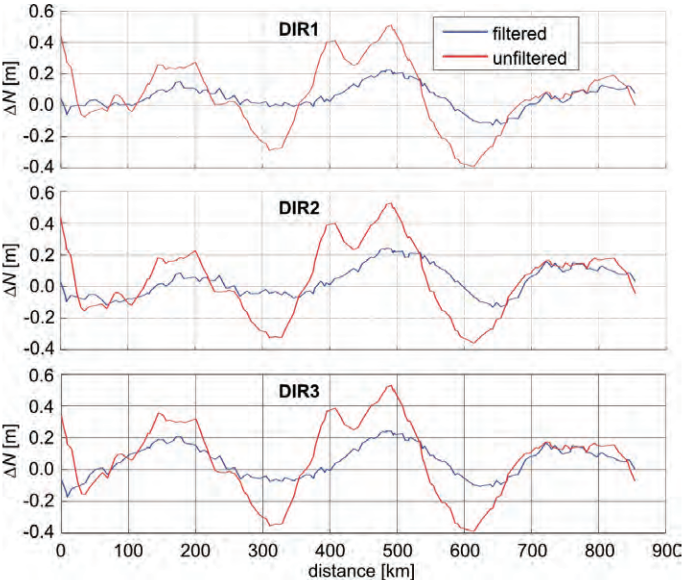

Fig. 10. Differences between height anomalies from GOCE direct solutions and GPS/levelling control traverse sites: unfiltered δ' (red) when using the GPS/levelling height anomalies without remove of medium-wavelength component; filtered δ (blue), i.e. after removing the medium-wavelength component from the GPS/levelling data

Table 3. Statistics of the differences δ between height anomalies obtained from GOCE-based GGMs and the respective ones from GPS/levelling along the control traverse [m]

GGM ($N_{\max}$ = 200)	44 stations of 1st order				184 stations of 1st&2nd order			
	Min	Max	Mean	STD	Min	Max	Mean	STD
DIR1	–0.099	0.231	0.064	0.087	–0.127	0.231	0.056	0.084
DIR2	–0.111	0.245	0.055	0.104	–0.132	0.245	0.043	0.103
DIR3	–0.103	0.248	0.066	0.107	–0.175	0.248	0.058	0.105
TIM1	–0.155	0.393	0.062	0.157	–0.175	0.393	0.049	0.157
TIM2	–0.159	0.261	0.037	0.109	–0.190	0.261	0.029	0.107
TIM3	–0.126	0.269	0.060	0.112	–0.164	0.269	0.055	0.108
SPW1	–0.125	0.360	0.079	0.135	–0.166	0.360	0.058	0.136
SPW2	–0.132	0.236	0.057	0.094	–0.143	0.236	0.046	0.092
GOCO01	–0.161	0.326	0.049	0.140	–0.190	0.326	0.041	0.139
GOCO02	–0.148	0.224	0.035	0.102	–0.184	0.224	0.030	0.099

It should be noted that the distribution of both differences δ' and δ along the control traverse exhibit a distinct periodicity. Similar behaviour to the one of DIR solution in Figure 10 has been observed for all other GOCE-based GGMs, i.e. TIM, SPW, and GOCO. Also the comparison of GOCE-derived height anomalies at the traverse sites with the corresponding ones obtained from the EGM2008 exhibits similar periodic pattern. Figure 11 shows the distribution (along the traverse's chord) of the differences between height anomalies obtained from DIR1 solution and the respective ones from the EGM2008, truncated EGM2008 ($N_{\max}$ = 200), unfiltered, and filtered GPS/levelling height anomalies.

Consistency of spectral features of EGM2008 with GPS/levelling data as well as truncated EGM2008 with filtered GPS/levelling data is clearly seen in Figure 11.

The wavelengths of the observed variations of height anomaly differences have been estimated with the use of the least squares method by approximating them with the sine function

$$f(x) = A \cdot \sin(\omega \cdot x + \varphi) + D \qquad (7)$$

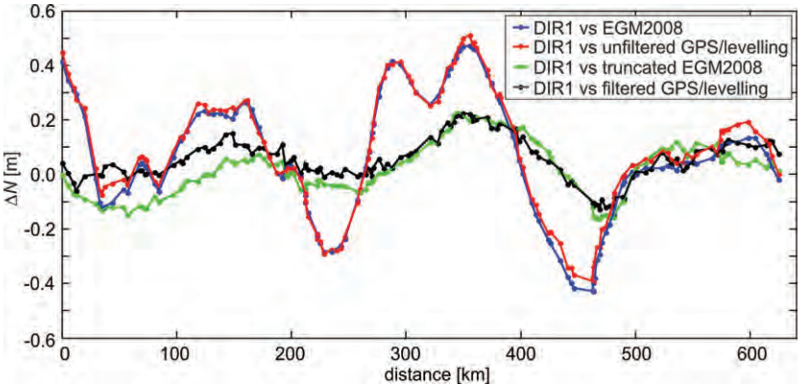

Fig. 11. Differences between height anomalies from DIR1 solution and the respective ones from the EGM2008 (blue), truncated EGM2008 (green), unfiltered GPS/levelling height anomalies (red), and filtered GPS/levelling height anomalies (black)

where A – the amplitude, ω – the frequency, φ – the phase, and D – bias, are the parameters to be determined.

The approximation was performed along the traverse's chord and along the parallel, after applying appropriate projection to the actual distance along the traverse. The projection was used to determine the wavelength referred to geographic grid. The values of the determined wavelengths are given in Table 4. Figure 12 shows this pattern along the traverse's chord for the case of direct solutions.

The wavelengths shown in Table 4 reflect actual spatial resolution of the GOCE-based GGMs over Poland. Both, Figure 12 and Table 4 show that the wavelengths distinctly decrease from 1st to 2nd release for all four GOCE-based solutions investigated. It corresponds to the growth of spatial resolution of GGMs of consecutive releases which could be expected due to substantial extension of the length of observation period. No such progress is observed from 2nd to 3rd release. On the other hand, the amplitudes and phases of the periodic pattern in Figure 12 are similar in all four GOCE-based GGMs solutions. It indicates the consistency of those solutions with respect to high quality of GPS/levelling data at the control traverse. In addition, the fitting of the sine function to the height anomalies differences has shown that their periodic pattern became very clear with the increase of the time span of GOCE observations, such as in the 3rd release solutions.

6. Conclusions

Height anomalies and gravity anomalies obtained from the current ten GOCE-based GGMs were compared with the corresponding functionals obtained from the EGM2008 and with high precision GPS/levelling height anomalies over Poland.

The results of comparison of GOCE-based GGMs with EGM2008 have shown good agreement. Except the DIR1, all approaches provided quite similar results within the same release. The DIR1 solution has presented the best performance among all approaches of the first release. It should not be a surprise since the EIGEN-5C geopotential model has been used for the a priori information when generating the solution. The TIM3 solution exhibits the best fit with the EGM2008 in terms standard deviations of both, height anomalies and gravity anomalies. The comparison shows also substantial improvements with increasing of the period of GOCE observation used for the solutions.

The deviation of the GOCE-based GGMs height anomalies from the corresponding ones at GPS/le-

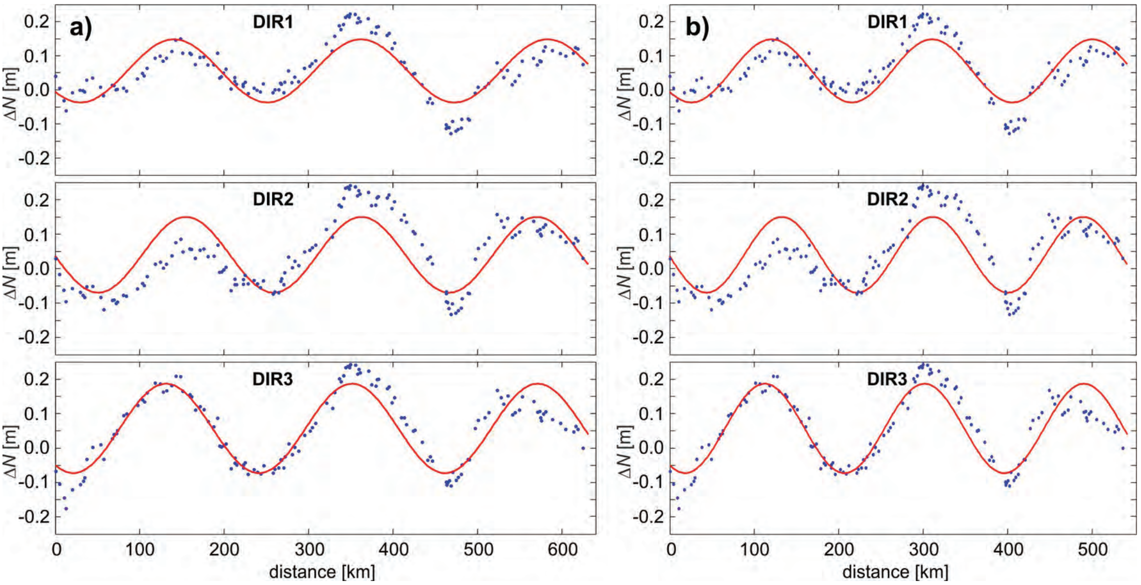

Fig. 12. Periodic pattern of the distribution of differences between the height anomalies from direct solutions GOCE GGMs and corresponding sites of GPS/levelling control traverse a) along the traverse's chord and b) along the parallel

Table 4. Estimated wavelengths of the differences between height anomalies from GOCE GGMs and corresponding sites of GPS/levelling control traverse along the traverse's chord and along the parallel [km]

Model	Along the traverse's chord			Along the parallel		
	1st Release	2nd Release	3rd Release	1st Release	2nd Release	3rd Release
DIR	221	208	220	184	173	183
TIM	225	221	227	187	183	188
SPW	250	203	–	207	169	–
GOCO	218	213	–	181	177	–

velling control traverse sites is at the level of 10 cm. The investigation demonstrates that the differences of height anomalies along the control traverse exhibit a periodic pattern. The wavelengths of this pattern are within the range of 250–203 km along the traverse's chord and 207–169 km after the projection into a parallel. An explicit improvement in terms of standard deviation with increasing of the time span of GOCE observations was detected from 1st to 2nd release. Also the wavelengths indicating spatial resolution of the model have decreased, as it could be expected. On the other hand, this improvement was not clear from 2nd to 3rd release. The results of the comparison of GOCE solutions with GPS/levelling data might be affected by residual medium- and short-wavelength components, still remained in the GPS/levelling data after filtering.

The results obtained indicate that the objectives of GOCE mission concerning the accuracy of 1–2 cm and 1 mGal with resolution ~100 km have not been reached yet. Further improvement should be expected with upcoming releases of GOCE-based GGMs.

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Ocena jakości na obszarze Polski modeli pola siły ciężkości opracowanych na podstawie danych z misji GOCE przy użyciu modelu EGM2008 i danych satelitarno-niwelacyjnych

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Streszczenie. Od połowy 2010 roku są udostępnione globalne modele geopotencjału opracowane na podstawie danych z misji GOCE. Pierwsze dwie generacje modeli geopotencjału z misji GOCE zawierały cztery różne rozwiązania podczas gdy trzecia – składała się zaledwie z dwóch rozwiązań. Jakość dostępnych modeli pola siły ciężkości z misji GOCE została w niniejszym opracowaniu oceniona w wyniku porównania obliczonych z nich anomalii wysokości i anomalii grawimetrycznych z odpowiednimi funkcjonałami obliczonymi z modelu geopotencjału EGM2008 oraz z anomaliami wysokości 184 stacji precyzyjnego satelitarno-niwelacyjnego trawersu kontrolnego.
Odchylenia standardowe różnic anomalii wysokości i anomalii grawimetrycznych pomiędzy uzyskanymi z opracowanych na podstawie danych z misji GOCE modeli geopotencjału i z modelu EGM2008 wynoszą odpowiednio 10 cm i 3 mGal. Dopasowanie modeli geopotencjału z misji GOCE do anomalii wysokości satelitarno-niwelacyjnego trawersu kontrolnego kształtuje się również na poziomie 10 cm. Uzyskane wyniki wskazują na poprawę w kolejnych generacjach modeli geopotencjału z misji GOCE.

Słowa kluczowe: model geopotencjału, GOCE, EGM2008, dane satelitarno-niwelacyjne, anomalia wysokości, anomalia grawimetryczna