Evaluation of GOCE/GRACE Global Geopotential Models over Greece with Collocated GPS/Levelling Observations and Local Gravity Data

G.S. Vergos, V.N. Grigoriadis, I.N. Tziavos, and C. Kotsakis

Abstract

The advent of the GOCE and GRACE missions during the last decade have brought new insights and promising results both in the static and time-variable representation of the Earth's gravity field. The focus of this work is directed to the evaluation of most available Global Geopotential Models (GGMs) from GOCE and GRACE, both satellite only as well as combined ones. The evaluation is carried out over an extensive network of collocated GPS/Levelling benchmarks (BMs) which covers the entire part of continental Greece and with respect to the reductions the GGMs provide in existing gravity data in order to assess their performance in a scenario that a remove-compute-restore procedure would be followed for geoid determination. From the evaluation with GPS/Levelling BMs, it was concluded that the GOCE/GRACE GGMs provide an absolute accuracy at the 12–15 cm level, up to degree and order (d/o) 250, when considering the geoid omission error. This is comparable and in some cases better than the performance of EGM2008 in Greece. Moreover, the latest (Release 3) versions of the GGMs provide considerably better results compared to the earlier version by 1–5 cm. In terms of relative errors, GOCE/GRACE GGMs reach the 1 cm level for baselines between 50 and 60 km, while for longer ones, 80–90 km, their performance is analogous to the local geoid model and the ultra-high degree combined GGMs. Finally, GOCE/GRACE GGMs manage to provide the same, as EGM2008, level of reduction to the local gravity anomalies, with a std at the 26.7–27.8 mGal level, when evaluated up to d/o 250.

Keywords

Global geopotential models • validation • GOCE • GPS/Levelling BMs • GRACE • Gravity reduction

1 Introduction

The advent of the Gravity field and Ocean Circulation Explorer (GOCE) and Gravity Recovery and Climate Experiment (GRACE) missions during the last decade has brought new insights, promising results and improved accuracies in the representation of the Earth's gravity field within the spectral band up to d/o 160–220 (∼90–130 km) as far as GOCE and GOCE/GRACE models are concerned. Recent results from the evaluation of GOCE/GRACE based GGMs with terrestrial gravity data and deflections of the vertical (Hirt et al. 2011) show that GOCE offers improved results between d/o 160 and 185, since for larger degrees of expansion signal loss is experienced. The same results have been acquired by Šprlák et al. (2012) over Norway, evaluating the GGMs with terrestrial gravity data. The R1 versions of the GGMs have a std up to 4.5 mGal up to d/o 160–170 which increases to 180 for GO-DIR-R1. The R2

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and R3 versions of the GGMs improve this performance, especially up to d/o 180–200 and 225–240 respectively. The only exception is the GO-DIR-R2 model which provides worse results compared to its R1 version. Gruber et al. (2011) evaluated the first release of GOCE/GRACE GGMs and concluded that the spectral band improved by GRACE data is up to d/o 170 (ITG-GRACE2010s model) while GOCE data (GO-TIM mainly) manage to boost this up to d/o 190. The best results in terms of the rms of the differences (mean of all models), after removing the bias, were achieved for the German dataset (3.5 cm), while the ones for Japan and Canada where at ∼10 cm. Likewise, the focus of this work refers to the evaluation over Greece of available GGMs from GOCE, GOCE/GRACE and combined ones, to conclude on the improvements they bring to gravity field and geoid modelling.

2 Validation Methodology, GGMs and Local Data Availability

2.1 Methodology for GGM Validation

For the evaluation of the GOCE/GRACE and combined models, first the GGM spectrum has been validated in terms of the by-degree and cumulative geoid signal and error. This was based on the formal GGM degree and error variances, the former indicating the geoid signal at various degrees and the latter the geoid error.

The second step of the GGM evaluation refers to comparisons with collocated GPS/Levelling BMs, which cover the entire part of continental Greece. In all cases, band-limited versions of EGM2008 (Pavlis et al. 2012) to the GOCE/GRACE GGM d/o of expansion are used for the evaluation, while a local LSC-based gravimetric geoid model (N^{LSC}) is used as ground-truth (Tziavos et al. 2012, 2013), for the ultra-high degree models. Geoid heights were determined in the Tide-Free (TF) system from the various GGMs through their spherical harmonic coefficients (Pavlis et al. 2012), using GRS80 as the normal field (Heiskanen and Moritz 1967). All computations have been harmonized as to the ellipsoid used and the tide system, given that some GGMs were referenced to other ellipsoids and the Zero-Tide (ZT), rather than the TF, system (Ekman 1989). Note that the above approach guarantees the consistency of the compared GGMs, so that biases and/or errors due to differences in the reference ellipsoid, tide conventions and geoid reference are minimized.

When evaluating the absolute differences between collocated GPS, levelling and gravimetric geoid heights it has to be considered that the GPS/Levelling data represent the complete geoid spectrum whereas the GGMs are limited to their maximum degree of expansion and/or truncation. Therefore, the geoid omission error due to the GGMs truncation should be accounted for. Consequently, the geoid omission error was determined using Kaula's power law (Kaula 1966) and the Tscherning and Rapp (1974) degree variance model (see Table 1). Finally, the spectral range of the terrestrial data dictated by the area under study should be considered. The terrestrial data cover the entire part of continental Greece, an area roughly 6° × 7° in latitude and longitude respectively. The spatial extent of the area under study means that both long-wavelength signal and errors in the GGMs up to d/o ∼30–40 (half-wavelength) cannot be accounted for, so that they may appear as biases in the validation. Given that, the GGM evaluation is performed for d/o 60 and above. Moreover, the relative accuracy of the GGM and gravimetric geoid models was evaluated as a function of the baseline length (spherical distance S_{ij} in km). The final part of the GGM validation, refers to their evaluation with respect to the reduction they provide in existing gravity data, simulating a remove-compute-restore procedure for geoid determination (Tziavos et al. 2013).

Table 1 Geoid omission error rms values for various maximum degrees of GGM expansion. Maximum degree in the summation 500,000.Unit: [cm]

	180	210	220	224	240	250	359	1420	1949	2159
Kaula	35.6	30.5	29.1	28.6	26.7	25.6	17.8	4.5	3.3	2.9
Tsch. /Rapp	46.7	38.3	36.0	35.2	32.1	30.3	22.9	6.6	2.8	2.0

2.2 GGM and Terrestrial Data Sets

Within the present work, most available GGMs based on GOCE/GRACE data have been evaluated. Depending on the releases of GOCE gradients various solutions became available, a.k.a. GOCE Release 1, GOCE Release 2 and GOCE Release 3 models based on 2, 6 and 12 months of GOCE observations respectively. These will be denoted as GO-xxx-R1, GO-xxx-R2 and GO-xxx-R3 in the sequel. Depending on the processing strategy four classes of models can be distinguished as (a) the TIM models using the time-wise approach (Pail et al. 2011), (b) the DIR models using the direct approach (Bruinsma et al. 2010), (c) the SPW models using the space-wise approach (Migliaccio et al. 2010) and (d) combined models (GOCO0xx and DGM-1S) where both GOCE, GRACE and other satellite data are used (Goiginger et al. 2011; Hashemi et al. 2013; Mayer-Guerr et al. 2010; Pail et al. 2010). The GO-DIR models are not pure GOCE ones since (a) for the R1 version a-priori information from EIGEN-5c was used, (b) for R2 a-priori information from ITG-GRACE20120S was used, while (c) for R3 a-priori information from the GO-DIR-R2 was used along with SLR and GRACE data. Apart from the aforementioned GGMs, EGM2008 (Pavlis et al. 2012), EIGEN-51C (Bruinsma et al. 2010), the GRACE only model ITG-GRACE2010S (Mayer-Guerr et al. 2010) and the latest EIGEN-6S, EIGEN-6C (Förste et al. 2011) and EIGEN-6C2 (Förste et al. 2012) have been used as well, with the latest EIGEN combined models including GOCE Release 2 data.

The local data used, refer to GPS/Levelling observations (1,542 BMs) covering the entire part of continental Greece (cf. Kotsakis and Katsambalos 2010). This set of collocated GPS and Levelling data 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 harbor, so that the HVD origin is relative to a MSL determined with 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 Katsambalos 2010; Tziavos et al. 2012). As far as the ellipsoidal heights from the HEPOS project (www.hepos.gr) are concerned, they all refer to BMs belonging to the Hellenic trigonometric network (Gianniou 2008). All data were determined in ITRF00 (epoch t = 2,007.236) 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 Katsambalos 2010). 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). Finally, the GGM evaluation with gravity data is performed using 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 gravity observations (cf. Tziavos et al. 2010) covering the entire Hellenic territory (islands included) as well as parts of the neighbouring Balkan countries.

Given the availability of the GOCE/GRACE GGMs, first a spectral evaluation in terms of the formal/calibrated degree and error degree variances of their coefficients has been performed. From this evaluation it was concluded that GOCO03s provides the overall best results with smaller errors up to degree n ∼ 175, w.r.t. EGM2008, compared to n ∼ 153 and n ∼ 166 for GOCO01S and GOCO02S, respectively. The GOCE-DIR-R3 model has smaller formal errors compared to its earlier releases (R1 and R2), by 2–3 orders of magnitude and is better than EGM2008 to degree n ∼ 188. A general conclusion is that the R1 and R2 GOCE-only and GOCE/GRACE GGMs (TIM, DIR and SPW) are better than GRACE-based ones above n ∼ 140 due to the few GOCE observations used. Note that most models are based on a few months of GOCE data contrary to ∼7 years of GRACE observations. This situation changes completely with the R3 models which incorporate about 1 year of GOCE data. The DIR-R3 error spectrum is improved by ∼4 orders of magnitude compared to R1 and R2, while TIM-R3 by about 1–2 orders of magnitude. The improvement brought by including more GOCE data is evident when comparing the ITG-GRACE2010s model and GOCO02s, where GOCE data in the latter boost its error degree variances to be smaller than those of EGM2008 up to degree n = 175 contrary to n = 142 for the former. The Release 3 versions of GOCE-TIM, GOCE-DIR and GOCO are better than the first and second releases, since they have smaller errors to higher degrees. This is due to the use of more GOCE data (12 months) in the R3 releases and as far as the DIR models are concerned, the use of ITG-GRACE2010s as a reference for the R3 model contrary to EIGEN-51c for R1. In terms of the cumulative geoid errors, GOCO-01S, 02S, and 03S reach the 1 cm geoid error up to d/o 143, 159 and 190 respectively, while TIM-R1, TIM-R2 and TIM-R3 up to d/o 30, 36 and 56. The improvement brought by more GOCE data is evidenced in the DIR models as well, since the 1 cm error is reached up to d/o 48, 27 and 127 for the DIR-R1, DIR-R2 and DIR-R3 models. ITG-GRACE2010S reaches the 1 cm error up to d/o 138, hence the improved cumulative errors in the GOCO-03 s model compared to TIM-R3 and the significant improvement of the DIR-R3 to the earlier releases. It is clear that the inclusion of more GOCE data in the R3 models, offers a significant boost to the reduction of the formal geoid errors. As it will be presented below in the external evaluation with GPS/Levelling data, this improvement by 3 orders in the total cumulative geoid error of the GGMs to their maximum d/o of expansion, e.g., from 15.6 cm to 5.4 cm between GOCO01S and GOCO03S, is not depicted. The latter is due to their limited maximum degree of expansion, so that the GGM geoid omission error above d/o 250 counteracts any improvement in the cumulative geoid error, along with the limited and unknown accuracy of the levelling data.

3 Validation Results with GPS/Levelling and Gravity Data

In terms of the absolute differences between the GGMs and the GPS/Levelling geoid heights, the evaluation was performed for various degrees of expansion between d/o 60 and up to their n_{max}. The geoid omission error has been considered with Kaula's (1966) power law and the Tscherning and Rapp (1974) degree variance model, given that the former over- and underestimates the geoid power at low and high frequencies, respectively. Table 1 presents the so determined geoid omission errors for all available degrees that the GGMs were either truncated or reached their n_{max} and Table 2 summarizes the differences between the available GPS/Levelling and GGM geoid heights. As far as the national gravimetric geoid model is concerned, its std is at the 14 cm, so it will provide the basis for the evaluation of the ultra-high degree GGMs. One point that needs attention is the mean of the differences and the rms, being at −39.2 cm and ±41.6 cm. The development of this model was based on EGM2008 as a reference field and free-air gravity anomalies reduced to a global geopotential level tied to the nominal Wo value of 62,636,856.00 m^2/s^2. Therefore, this bias indicates the offset between the HVD and the W_o^{LVD} realized by the TG station at Piraeus harbor and a global geopotential level as used in the gravimetric geoid development. From the GPS/Levelling geoid height differences with the available GGMs, the improvement offered by the GOCE-based R3 models, w.r.t. the earlier releases is evident. For the GOCO models, the std of the differences drops by 3.7 cm between R1 and R3 (to d/o 220), 2.8 cm for the TIM models (to d/o 220) and 2.5 cm for the DIR ones (to d/o 240). The improvement for the DIR is marginal given that its R1 model provided an accuracy equal to that of the R2 for GOCO and TIM. This is due to the a-priori information from EIGEN-5C used in the development of GO-DIR-R1.

Regarding the GOCE/GRACE models, their performance is equivalent to that of EGM2008, when truncated to d/o 250, being inferior by just 1–2 cm for the latest, R3, releases. This shows the great improvement offered by the inclusion of more GOCE data, especially in view of the fact that EGM2008 contains detailed local gravity data over Greece even at that d/o. The mean offset between the GPS/Levelling data and all used GGMs is consistent and at the ∼35 cm level, signaling an offset between the Greek local vertical datum and a global vertical datum. This is monitored by all GOCE models, even the ones where no a-priori information and/or GRACE data are used, and it is very close to the mean offset with EGM2008 up to d/o 2159 (37 cm). This is a valuable conclusion for GOCE-only models towards the unification of the local/national vertical datums (LVD) to a global one. It provides good evidence that even a medium wavelength gravity field representation by GOCE to say d/o 250 can indeed determine 95 % of the mean offsets of LVD so that their link to a global one can be rigorously modeled. Comparing the performance of GRACE- and GOCE-based models, ITG-GRACE2010s provides better results up to d/o 160 compared to all GGMs where GOCE data have been used, either solely or in combination with GRACE. The former is 2–3 cm better than the GOCE and GOCE/GRACE GGMs, while the turning point is d/o 170–180 where the improvement by GOCE inclusion is at the 2–6 cm level. GOCE and GOCE/GRACE GGMs retain their signal strength up to d/o 220–230 since for higher degrees the improvement offered is marginal (few mm) and hence statistically insignificant.

In terms of absolute errors, the GGMs seem to provide expected results when taking into account the geoid omission error. GOCO03s has a std of 49.6 cm up to d/o 250, so considering the geoid omission error of 30.3 cm and the GOCO03s cumulative geoid error of 15.5 cm an un-modeled error of ∼36 cm remains. This may stem from the quality of, mainly, the orthometric heights within the HVD, which are known to be of low, yet unknown, accuracy. These can be as many as 10 cm or more (Tziavos et al. 2012), so the rest can be attributed to errors in GOCO03s not depicted in its formal error degree variances. The same results are derived for the other combined GGMs, such as GO-DIR-R3 which has a std with the GPS/Levelling geoid heights at 48.2 cm (d/o 240), with a geoid omission error of 32.1 cm and a formal cumulative geoid error of only 5.6 cm. The latter may signals that the formal error degree variances are optimistic, so that proper error modeling would require external information for validation. On the other hand, when the same models are evaluated over reliable Levelling networks, e.g., in Germany (Gruber et al. 2011) the std of the differences is at the 3.5 cm level, i.e., within the formal cumulative geoid error of the GGMs. Thus, the remaining un-modelled error can be largely attributed the (bad) quality of the HVD, so that a spectral enhancement approach should be followed in the future for the evaluation of GOCE GGMs over Greece. As far as GO-TIM-R3 and GO-SPW-R2 are concerned, the former is superior by ∼2.8 cm, while the Release3 version of the GO-TIM model provides the same level of accuracy as the GOCO03 and GO-DIR-R3 models, which is quite significant as to the value of GOCE data given that GO-TIM is a pure GOCE model, whereas the latter two incorporate GRACE data as well. Some useful conclusions can be drawn from the ultra-high degree models EIGEN6C and EIGEN6C2 as well, where gravity data are included. Especially the latter, being a revised version of EIGEN6C, provides better agreement with the GPS/Levelling data in Greece (13.7 cm) for lower n_{max} compared to EGM2008 (14.1 cm). This is a marginal improvement, but it signals that the satellite mission data can indeed boost the achievable accuracy by GGM representations of the Earth's gravity field. These levels of accuracy are practically the same as that achieved by the gravimetric geoid model, therefore the local data seem not to provide more information, which is expected since the Hellenic database has been included in the EGM2008 development.

Table 3 depicts the relative accuracies for the local gravimetric geoid model, EGM2008, EIGEN6C, EIGEN6C2, EIGEN6S and the Release3 versions of the TIM, DIR, and GOCO GGMs. For short baselines, up to 10 km, the contribution of local gravity data to the LSC-based geoid is clear, since it is better by 2 ppm compared to EGM2008, EIGEN6C and EIGEN6C2. This is due to the fact that even

Table 2 Statistics (mean and std) of the differences between GPS/levelling and geoid heights from the GGMs for various degrees. Unit: [m]

Model		60	80	140	160	180	220	240	250	360	1420	1949	2159
EGM2008	Mean	0.349	0.036	−0.297	−0.284	−0.288	−0.318	−0.332	−0.343	−0.331	−0.375	−0.374	−0.374
	Std	1.733	1.387	0.724	0.724	0.642	0.529	0.497	0.472	0.369	0.152	0.142	0.141
EIGEN-51C(n_{max}=359)	Mean	0.351	0.045	−0.292	−0.273	−0.275	−0.308			0.309			
	Std	1.734	1.388	0.709	0.724	0.644	0.537			0.403			
EIGEN-6C	Mean	0.350	0.042	−0.304	−0.298	−0.303	−0.337		−0.361	−0.349	−0.394		
	Std	1.733	1.386	0.714	0.727	0.651	0.524		0.478	0.379	0.161		
EIGEN-6C2	Mean	0.350	0.041	−0.303	−0.296	−0.302	−0.356		−0.356	−0.344	−0.389	−0.388	
	Std	1.733	1.386	0.715	0.727	0.651	0.525		0.475	0.374	0.149	0.137	
EIGEN-6S	Mean	0.350	0.042	−0.302	−0.300	−0.307	−0.344	−0.358					
	Std	1.733	1.386	0.716	0.722	0.646	0.508	0.512					
ITG-GRACE2010S	Mean	0.349	0.041	−0.304	−0.308	−0.299							
	Std	1.734	1.386	0.716	0.692	0.690							
DGM-1S	Mean	0.349	0.041	−0.304	−0.298	−0.303	−0.341	−0.363					
	Std	1.734	1.386	0.716	0.720	0.647	0.527	0.515					
GOCO01S(n_{max}=224)	Mean	0.349	0.041	−0.303	−0.301	−0.305	−0.341						
	Std	1.734	1.386	0.716	0.714	0.661	0.547						
GOCO02S	Mean	0.349	0.041	−0.305	−0.300	−0.305	−0.341		−0.358				
	std	1.734	1.386	0.716	0.718	0.643	0.522		0.501				
GOCO03S	Mean	0.349	0.041	−0.304	−0.299	−0.303	−0.335		−0.353				
	Std	1.733	1.386	0.717	0.717	0.645	0.510		0.496				
GO-DIR-R1	Mean	0.347	0.042	−0.297	−0.292	−0.298	−0.330	−0.344					
	Std	1.733	1.385	0.714	0.725	0.656	0.535	0.507					
GO-DIR-R2	Mean	0.351	0.043	−0.302	−0.298	−0.306	−0.347	−0.357					
	Std	1.734	1.386	0.713	0.719	0.644	0.505	0.510					
GO-DIR-R3	Mean	0.350	0.042	−0.302	−0.295	−0.301	−0.341	−0.352					
	Std	1.734	1.386	0.716	0.722	0.645	0.496	0.482					
GO-TIM-R1(n_{max}=224)	Mean	0.343	0.037	−0.307	−0.305	−0.310	0.348						
	Std	1.734	1.383	0.716	0.720	0.663	0.544						
GO-TIM-R2	Mean	0.345	0.038	−0.305	−0.301	−0.306	−0.345		−0.360				
	Std	1.733	1.384	0.716	0.720	0.644	0.525		0.502				
GO-TIM-R3	Mean	0.347	0.010	−0.304	−0.298	−0.303	−0.337		−0.356				
	Std	1.734	1.386	0.718	0.720	0.647	0.516		0.494				
GO-SPW-R1(n_{max}=210)	Mean	0.345	0.042	−0.300	−0.297	−0.303	−0.371						
	Std	1.735	1.388	0.714	0.725	0.675	0.586						
GO-SPW-R2	Mean	0.338	0.029	−0.312	−0.309	−0.315	−0.347	−0.345					
	Std	1.732	1.384	0.716	0.719	0.642	0.539	0.537					
N^{LSC}	Max		Min			Mean			Rms			Std	
	0.119		−1.033			−0.392			±0.416			0.140	

Table 3 Relative accuracies for the local geoid model and GOCE/GRACE GGMs. Unit: [ppm]

Baselines (km)	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100	>100
N^{LSC}	10.4	6.5	4.4	3.3	2.7	2.2	1.9	1.7	1.5	1.4	0.6
EGM2008 (2159)	12.2	7.2	4.8	3.7	3.1	2.6	2.2	2.0	1.8	1.6	0.7
EGM2008 (250)	23.8	20.7	16.6	14.0	12.1	10.6	9.4	8.3	7.4	6.6	2.6
EIGEN6S (240)	23.9	20.9	16.9	14.3	12.3	10.8	9.6	8.6	7.6	6.7	2.6
EIGEN6C (250)	23.7	20.6	16.4	13.8	11.7	10.1	8.8	7.8	6.9	6.1	2.4
EIGEN6C (1420)	13.9	8.6	5.3	4.2	3.4	2.9	2.5	2.3	2.0	1.9	0.8
EIGEN6C2 (250)	23.7	20.6	16.4	13.8	11.7	10.1	8.8	7.8	6.9	6.0	2.4
EIGEN6C2 (1949)	12.4	7.3	4.8	3.7	3.0	2.5	2.2	1.9	1.7	1.6	0.6
GOCO03S (250)	23.7	20.6	16.5	13.9	11.9	10.5	9.2	8.1	7.2	6.4	2.5
GO-DIR-R3 (240)	23.7	20.6	16.5	13.8	11.8	10.2	8.9	7.9	6.9	6.2	2.4
GO-TIM-R3 (250)	23.6	20.6	16.5	13.9	11.9	10.4	9.2	8.1	7.2	6.4	2.5

Table 4 Statistics of the original free-air gravity anomalies over Greece, contribution of the various GGMs (normal lettering) and reduced fields (italics). Unit: [mGal]

	Max	Min	Mean	Rms	Std
Δgf (original)	269.93	−236.10	−22.73	±77.52	74.11
EGM2008 (2159)	213.98	−236.87	−22.45	±77.58	74.26
Δg red EGM2008	*92.08*	*−147.41*	*−0.28*	*±5.87*	*5.86*
EGM2008 (250)	117.06	−192.91	−18.46	±73.35	70.99
Δg red EGM2008	*210.26*	*−138.39*	*−4.27*	*±27.07*	*26.74*
EIGEN6s (240)	113.71	−189.64	−18.64	±73.56	71.15
Δg red EIGEN6s	219.29	*−134.89*	*−4.07*	*±28.27*	*27.97*
EIEGN6c (250)	116.69	−194.28	−18.58	±73.46	71.07
Δg red EIGEN6C	211.25	*−137.17*	*−4.15*	*±27.07*	*26.75*
EIGEN6c (1420)	190.35	−242.27	−22.17	±77.64	74.40
Δg red EIGEN6c	118.96	*−137.87*	*−0.57*	*±9.36*	*9.34*
EIEGN6c2 (250)	115.19	−193.78	−18.59	±73.43	71.04
Δg red EIGEN6C2	210.37	*−135.02*	*−4.14*	*±27.07*	*26.76*
EIGEN6c2 (1949)	209.43	−238.29	−22.52	±77.68	74.35
Δg red EIGEN6c2	94.97	*−149.20*	*−0.22*	*±6.73*	*6.73*
GOCO03S (250)	107.50	−191.92	−18.31	±73.03	70.69
Δg red GOCO03s	*224.65*	*−132.06*	*−4.42*	*±27.78*	*27.43*
GO-DIR-R3 (240)	106.05	−190.98	−18.39	±73.14	70.80
Δg red GO-DIR-R3	*223.69*	*−129.92*	*−4.34*	*±28.10*	*27.76*
GO-TIM-R3 (250)	109.49	−192.80	−18.39	±73.16	70.81
Δg red GO-TIM-R3	*223.57*	*−133.43*	*−4.35*	*±27.68*	*27nn34*

though local gravity data are used in the development of ultra-high degree GGMs, their contribution is attenuated given the use of satellite data, neighbouring gravity data, lower spatial resolution of the final model and a global, rather than local, error modelling. As expected the GOCE and GOCE/GRACE GGMs have inferior performance for small baselines by as much as 13–15 ppm. This is resolved for longer baselines, e.g., >40–50 km, where the satellite only GGMs provide an error close to the 1 cm level, in the relative sense. After the 80–90 km benchmark, corresponding to the satellite GGM resolution, their performance can be regarded as approximately the same with the local model and high-degree GGMs. Compared to EGM2008 when truncated up to d/o 250, the GOCE and GOCE/GRACE GGMs are superior, even at the sub-ppm level for baselines larger than 50 km, This is clearly due to the use of GOCE data, while the largest improvement (0.5 ppm) is found for baselines between 80 and 90 km. This is clearly marginal, but it indicates the maximum spectral band (80 km correspond up to d/o ∼230) that the Release3 GGMs manage to improve.

The final set of tests for the evaluation of the GOCE/GRACE GGMs is related to the reduction they provide over a database of irregularly distributed free-air gravity anomalies covering Greece nationwide. Within this test, the original field of Δg_f has been reduced using all available GGMs and the resulting fields have been investigated as to the mean and std reduction that each GGM offers. This simulates the first remove step within the well-known remove-compute-restore procedure for geoid determination. Table 4 summarizes the statistics of the original free-air gravity anomalies, the GGM contribution and the reduced fields, only for EGM2008, the latest EIGEN6 models and the Release3 versions of the GOCE/GRACE GGMs. As expected the overall best reduction is achieved with EGM2008 when used up to d/o 2,159, with the std of the reduced field at the ±5.8 mGal level and the mean close to zero, something expected due to the inclusion of terrestrial gravity data in that model. EIGEN6C and EIGEN6C2 are quite close, with the latter being less than 0.5 mGal, in terms of the std, better than EGM2008. In order to validate the performance of the GOCE/GRACE GGMs, it is worth comparing them with the reduced field when using EGM2008 up to d/o 250. For the latter case the performance of all GGMs is comparable, with EGM2008 offering a, statistically insignificant, improvement at the sub-mGal level. The reduction that the GOCE/GRACE GGMs offer is approximately the same, with the std reduced at the ±26.6 to ±27.8 mGal and the mean to −4.3 mGal. It should be mentioned again that the GOCE/GRACE GGMs use only satellite data and achieve the same performance as EGM2008 (up to d/o 250), while the latter employs gravity and altimetry data well, hence its performance is subject to correlations with the local terrestrial gravity data.

Conclusions

A detailed evaluation has been carried out for all available releases of the GOCE and GOCE/GRACE GGMs (R1, R2, and R3) each of them employing an increasing number of GOCE observations. From the results acquired, the improvement of incorporating more GOCE data in the GGMs is evident, ranging from 2.5 to 3.7 cm in terms of geoid height differences w.r.t. the GPS/Levelling data and the few mGal level when compared with the free-air gravity anomaly field. The latest (Release3) versions of the GOCE/GRACE GGMs manage to provide a 1 cm relative accuracy for baselines larger than 40–50 km, which is quite encouraging for their use in medium-wavelength geoid related studies. Comparing the performance of GRACE- and GOCE-based models, the former provides better results up to d/o 160–170 while the improvement by GOCE is found from d/o 170–180 up to d/o 220–230 for the Release3 models. The latest combined GGMs EIGEN6C and especially EIGEN6C2 provide slightly better results compared to EGM2008 even for lower maximum degrees of expansion. Therefore, combined GGMs, employing all available GOCE, GRACE, gravity and altimetry observations can now be determined with increased accuracy. This is the direction of our future work for GOCE GGM evaluation, where a spectral enhancement approach will be followed while national /regional high-resolution geoid solution based on GOCE GGMs will be sought.

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