Evaluation of GOCE/GRACE GGMs over Attica and Thessaloniki, Greece, and Wo determination for height system unification

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Abstract

Within the frame of the *Elevation* project, recently acquired collocated GPS/Leveling observations over trigonometric benchmarks (BMs) have been used for the evaluation of the recent GOCE/GRACE Global Geopotential Models (GGMs) and the unification of the Greek Local Vertical Datum (LVD). To this extent all available satellite-only and combined GOCE/GRACE GGMs were evaluated to conclude on the possible improvement brought by GOCE in the determination of the geoid over Greece. At a second stage, the present work focuses on the determination of the zero-level geopotential value W_0^{LVD} for the Greek LVD. The estimation of W_0^{LVD} was carried out using a least squares adjustment of Helmert orthometric heights, surface gravity disturbances and geopotential values computed from EGM2008 and GOCE/GRACE GGMs over the available GPS/Levelling BMs. Moreover, given that the BMs used belong to two distinct areas, i.e., one over Attica and another in Thessaloniki, the W_0^{LVD} determination was carried out for each region separately, to conclude on the possible biases of the Hellenic LVD itself. From the evaluation of the GOCE/GRACE models it was concluded that the latest releases provide a significant, compared to EGM2008, improvement in the comparisons with the GPS/Levelling data, by as much as 3 cm, in terms of the standard deviation. Furthermore, the W_0^{LVD} determined for the Greek LVD indicates a bias of about -4.95 m^2/s^2 compared to the conventional value of 62636856.0 m^2/s^2.

Keywords

Global geopotential models, validation, GOCE, GPS/Levelling BMs, zero-level geopotential, LVD

1. Introduction

With the GOCE mission having reached its end in late 2013, the unprecedented contribution of the first mission to carry-on gradiometric observations in space was and is still being evaluated. GOCE contributed significantly not only in the field of geodesy, where its impact on gravity field and geoid modelling was long expected, but to oceanography, geophysics and even time-variable gravity field modelling. Its contribution to geodesy has been predominant, since GOCE provided improved representations of the Earth's gravity field especially in the long-to-medium and medium wavelengths of the spectrum. The improvements in the entire spectral band, and especially between degree and order (d/o) 210-240, contributed to improved geodetically-derived dynamic ocean topography (DOT) models (Albertella et al., 2012; Knudsen et al., 2011; Tziavos et al., 2013), new insights in the Earth's interior by modelling the Moho discontinuity (Reguzzoni et al., 2013) and even the identification of time-variable gravity changes due to seismic events (Fuchs et al., 2013). In the pure geodetic context, the contribution of GOCE is viewed in the improved representation of the Earth's gravity field functionals and especially gravity anomalies and geoid heights. These improvements are commonly viewed in terms of the differences with external validation datasets, such as terrestrial gravity anomalies and GPS/Levelling geoid heights (Gruber et al., 2011; Hirt et al., 2011; Šprlák et al., 2012; Tocho et al., 2014; Tziavos et al, in press; Vergos et al., 2014) on trigonometric benchmarks (BMs), compared to the best available combined Global Geopotential Model (GGM) from the pre-GOCE era, i.e., EGM2008 (Pavlis et al., 2012). The latter dataset is very useful for such GOCE GGM validation experiments since it offers an independent source of information that is not included in the development of GGMs. Moreover, GOCE data are now commonly used for the determination of the zero-level geopotential value towards the unification of Local Vertical Datums (LVD) to a global one (Grigoriadis et al., 2014; Gruber et al., 2012; Hayden et al., 2012; Sánchez et al., 2014; Tocho and Vergos, in press).

The focus of this work is twofold. The first part is devoted to the evaluation of almost all currently available GOCE, GOCE/GRACE and combined GGMs from the 1st release to the 5th release of the models. The second part is devoted to the determination of the zero-level geopotential value of the Greek LVD W_0^{LVD}. Both are carried out through a dedicated set of collocated GPS/Levelling geoid heights, which has been collected in the frame of the “Elevation” project (Anastasiou et al., 2013) for the regions of Thessaloniki and Attica (Athens region).

2. Methodology, GGMs and local data

2.1 GOCE GGM validation methodology

In order to evaluate the geoid undulations derived from the GOCE GGMs (N^{GOCE}) an external dataset of “geometric” geoid heights from collocated GPS and spirit levelling observations on trigonometric BMs ($N^{GPS/Levelling}$) has been used. The residual geoid heights have been evaluated following a spectral enhancement approach as:

$$\Delta N = N^{GPS/Levelling} - N^{GOCE}\Big|_{2}^{n_1} - N^{EGM2008}\Big|_{n_{1+1}}^{2160} - N^{RTM} - N_0, \tag{1}$$

where, ΔN denotes the geoid heights differences between the GPS-derived and GGM-derived geoid heights. The latter are denoted as $N_{n_i}^{GOCE}$ and are determined after evaluating first heights anomalies from the GOCE and GOCE/GRACE GGMs and then converting them to geoid heights through the use of Bouguer anomalies and orthometric heights (Heiskanen and Moritz 1967, Eqs. 8.100-8.102). Based on the spectral enhancement approach (Gruber et al., 2011; Tocho et al., 2014; Vergos et al., 2014) the GOCE/GRACE GGMs contribute up to some maximum degree and order (d/o) of expansion n_1 ($N^{GOCE}\Big|_{2}^{n_1}$), and then EGM2008 is used as a fill-in information for the rest of the geoid signal from degree n_1+1 to degree 2160 ($N^{EGM2008}\Big|_{n_{1+1}}^{2160}$) along with Residual Terrain Model (RTM) effects on geoid heights (N^{RTM}) to represent the topographic signal above degree 2160. The estimation of the RTM effects on geoid heights comes from an SRTM-based 3 arcsec digital terrain model (Tziavos et al., 2010), so that the geoid spectrum represented is equivalent to d/o 216,000. Therefore the geoid omission error is very small (mm-level), so it can be neglected in the formed differences. It should be pointed out that the way the spectral enhancement of the low-degree GOCE-based GGMs is performed, is by computing the contribution from each GGM solely and then adding them together, i.e., no or minimal coefficient patching is performed. A more elaborate GGM combination around each degree n_1 (say for instance for ±5-10 d/o), would be to combine the coefficients of each model using as a weight their errors or error degree variances. Then, a spectrally consistent merging of the GGMs might yield better results and no discontinuities in the GGM merging degrees. In the present case, this would yield too much computational burden, given the amount of GGMs studied, with no statistically significant improvement in the final combined GGM-derived geoid heights. For the evaluation of the zero-degree geoid term (N_o) GRS80 was used as a reference ellipsoid and the computation was performed as in Heiskanen and Moritz (1967, Eq. 2.182). Finally, all computations have been performed in the Tide Free (TF) system with any conversions from the Zero Tide and the Mean Tide system to the TF being performed according to Ekman (1989). The evaluation scheme has been carried out for all d/o of each GGM up to their n_{max} with an increment step of 10 degrees. This increment step is sufficient in order to conclude on the spectral range that the GOCE GGMs perform better than EGM2008. For a more elaborate discussion of the followed methodology and conventions Gruber et al. (2011), Tocho et al. (2014), Tziavos et al. (in press) and Vergos et al. (2014) should be consulted.

2.2 W_0^{LVD} estimation methodology over Greece

For the estimation of the zero-level geopotential value over Greece, we followed the methodology outlined in Grigoriadis et al. (2014) and Tocho and Vergos (in press). The methodology is based on a combination, through Least-Squares (LS), of available Helmert orthometric heights, surface gravity data and geopotential values on the trigonometric BMs, the latter two estimated from the available GGMs. This is one of the possible options for the unification of a LVD and its connection to a world height system, while the second one employs the formulation of a geodetic boundary value problem (GBVP) as the fixed gravimetric GBVP at sea and the scalar-free GBVP on land (Sánchez, 2009). For the marine areas knowledge of the mean dynamic ocean topography is needed, which can be obtained through a mean sea surface model and a GOCE-based GGM. For the continental part, the observations include the usual gravity anomalies, potential differences, deflections of the vertical (Sánchez, 2009; Tenzer et al., 2013).

In the present study, the observation equation is based on the definition of orthometric heights in Heiskanen and Moritz (1967) as:

$$H_i^{Helmert} = \frac{W_0^{LVD} - W_i}{\bar{g}_i^{Helmert}} , \tag{2}$$

where $H_i^{Helmert}$ is the known Helmert orthometric height at the BM w.r.t. the LVD, W_i is the actual gravity potential at the BM, and $\bar{g}_i^{Helmert}$ is the mean value of gravity. The generic estimation of W_0^{LVD} can then be carried out as:

$$\hat{W}_0^{LVD} = \frac{\sum_{i=1}^{m} p_i (\bar{g}_i^{Helmert} H_i^{Helmert} + W_i)}{\sum_{i=1}^{m} p_i} , \tag{3}$$

where the available observations are assigned positive weights p_i, so that the residuals after the adjustment are minimized. It is acknowledged that the estimation of W_0^{LVD} following the proposed approach is susceptible to the inherent uncertainties in the determination of Helmert orthometric heights and the accumulated errors in leveling data. In Eq. (3) the gravity potential W_i has been synthesized, according to the IERS conventions (2010), from the gravitational potential part V_i, obtained by the GGM spherical harmonic coefficients, and a centrifugal part Φ_i using the benchmark's known spatial position and the Earth's conventional rotational velocity. The mean gravity value $\bar{g}_i$ along the plumb line between the LVD's zero-height equipotential reference surface and the Earth's surface was estimated according to the Poincare-Prey reduction scheme (Heiskanen and Moritz 1967, Eq. 4-24). Further details can be found in

Grigoriadis et al. (2014). For the zero-level geopotential estimation, GRS80 has been used as the reference ellipsoid (Moritz, 1992), while the IERS conventions (2010) for the Earth's geocentric gravitational constant *GM* and the gravity potential at the geoid W_0 have been followed, so that GM=398600.4418 10^9 m^3s^{-2} and W_o=62636856.00 m^2s^{-2}.

2.3 GOCE/GRACE GGMs and external data for validation and W_0^{LVD} estimation

Twenty-one GGMs up to their maximum degree and order were used in this study for evaluation. Table 1 summarizes the GGMs evaluated with some of them being satellite-only ones and others being generated with combined information. In Table 1 we present the abbreviation of the GGM names that will be used in the present work, their official names as listed at the International Centre for Global Earth Models (ICGEM) service, their maximum d/o of expansion and a descriptive information on the data used for their development. EGM2008 (Pavlis et al., 2012) complete to d/o 2160 is used throughout as reference against which all GOCE/GRACE based ones are evaluated. For the GOCE and GOCE-GRACE models, their basic categorization is from the methodology used in their development (time-wise approach for TIM, direct approach for DIR, GOCE and GRACE combined for GOCO, etc.). Moreover, their designation as first, second, third, fourth and fifth release (R1, R2, R3, R4 and R5) refers to the effective volume of GOCE data used in their development, i.e., two, eight, twelve, 26.5 months of data and the entire mission (including the lower orbit data), respectively.

Table 1

For the evaluation of the GGMs, the local data used refer to 230 collocated GPS/Levelling observations on BMs over the regions of Thessaloniki and Attica (see Figure 1). This set is based on historical orthometric heights from the HMGS (Hellenic Military Geographic Service) and ellipsoidal heights collected by the research teams during the "Elevation" project (Anastasiou et al., 2013). The same set of BMs will be used for the estimation of the zero-level geopotential value of the Greek LVD. It should be noted that this is a completely independent set of GPS/Levelling observations than the usual one used during the latest GGM evaluation over Greece (see e.g., Tziavos et al., in press; Vergos et al., 2014) therefore the results acquired will provide a new independent look on the GOCE GGM performance. The main difference of this new dataset is that longer GPS observations (larger than two hours compared to one hour) have been carried out, while spirit levelling campaigns between the BMs, wherever possible due to the distance limitations, were performed to validate the available orthometric heights. The two areas under study have rather small extents (~$1^o \times 1^o$), so they will provide little insight in the validation of the longer wavelengths of the GGMs. For the specifications of the reference systems and tide conventions of the local data as well as the definition of the Greek LVD, Grigoriadis et al. (2014) and Vergos et al. (2014) should be consulted.

FIGURE 1

3. GGM external validation

Following the spectral enhancement approach for the GOCE GGMs, outlined previously, the geoid height differences for all models with the local GPS/Levelling data were evaluated with an incremental step of 10 degrees. Table 2 presents the statistics of the available GPS ellipsoidal heights, Helmert orthometric heights, the formed GPS/Levelling geometric “geoid” heights and the RTM effects on geoid heights for the network of the 230 BMs. Table 3 presents the statistics of the differences between the available local data and the synthesised GGM and RTM contribution. In Table 3, we report the statistics of the differences only for the GGM d/o n_1 (see Eq. 1) that provides the smallest standard deviation (std) of the differences with the GPS/Levelling data. The reference model, i.e., EGM2008 provides a std of 15.9 cm which is outperformed by the GOCE GGMs when the latter are used up to d/o 140. It should be pointed out, as outlined in Vergos et al. (2014), that Greece is a peculiar case for the validation of GOCE-based GGMs, since most of the country’s gravity data have been used in the development of EGM2008. Therefore, an improvement by GOCE compared to EGM2008, even if marginal, can be regarded as significant.

The combined EIGEN- models improve the std by 3 cm, for the latest 6C3stat version, while the improvement between the three versions. i.e., 6C, 6C2 and 6C3stat is at the mm level. The DIR models, based on both GOCE and GRACE data, show an improvement of 3.1 cm compared to EGM2008, while they reduce the range (difference between the minimum and maximum values of the differences) by 11.3-12.4 cm. The latter is of importance as well, since the largest and smallest difference are found at the BMs with the highest elevation, hence it can be concluded that the GOCE/GRACE GGMs manage to provide more uniform information for the geoid signal. One interesting point is that DIR-R1, which is based on the fewer GOCE data, performs equally well with the latest R5 model, but this is attributed to the fact that during its development, a-priori information from EIGEN-51C has been used. The TIM models show a similar performance with a reduction of the std and range between 2.8-3.1 cm and 11.4-12.7 cm. As expected, the GOCO GGMs being based on the first three releases of the GOCE data show inferior performance w.r.t. the R4 and R5 DIR and TIM models. Finally, GOGRA02s and JYY-GOCE02s have an astonishing performance, given that they are based on the second release of GOCE data. The std they offer is similar to that of the latest TIM GGM and they provide the same if larger amount of range reduction. ITG-GOCE02s provides the overall best std at the 12.7 cm and a range reduction of 12.1 cm, indicating promising prospects for the followed short-arc approach, when the R4 and R5 version of GOCE data are included.

Table 2

Table 3

The progressive evolution of the GOCE GGMs as more GOCE data are incorporated in their development is evidenced from Table 3 and Figure 2. A better insight in that respect can be gained from Figure 2 where the std of the differences per d/o for the DIR-R1, R2, R3, R4 and R5 models is presented. Ignoring DIR-R1 which is a combined model, the DIR GGMs are better than EGM2008 up to d/o 190, 180, 200 and 250 for the R2, R3, R4 and R5 models.

DIR-R5 is the only model within the DIR family of GGMs that remains below EGM20008 for its entire spectrum up to d/o 250, showing the great value of the additional low-orbit GOCE data during the end of the mission. Comparing the different GOCE models (see Figure 2, right) TIM-R5 is better than EGM2008 to d/o 195, GOCO03S to d/o 190, and GOGRA02s to d/o 195. ITG-GOCE02s is surprisingly good again, being better than EGM2008 to d/o 195 and better than most of the other GOCE GGMs up to that d/o. At specific degrees, e.g., degree 170, it is better by ~1.5 cm compared to the other GGMs, even though ITG_GOCE02 is based on fewer GOCE observables. The overall best GGM is DIR-R5 since it manages to show a very good std and range with the GPS/Levelling data, but also the largest useful spectral band for the geoid spectrum spanning from d/o 40 to 250.

FIGURE 2

4. W_0^{LVD} estimation results for Greece

The estimation of the zero-level geopotential value of the Hellenic LVD is based on the same GPS/Levelling BMs employing Eqs. (2) and (3). In principle, physical heights in the Hellenic LVD were modeled as Helmert orthometric heights, while an unknown W_o value is associated with the LVD. The Helmert orthometric heights refer to the tide gauge (TG) station at the Piraeus port (Athens) where the local MSL was computed from sea level measurements over the period 1933-1978.

The true accuracy of the Hellenic LVD leveling network is largely unknown. First an un-weighted ($p_i=1$) Least squares (LS) estimation of the W_0^{LVD} has been performed (see Table 4), employing data from EGM2008, DIR-R4, DIR-R5, TIM-R4 and TIM-R5 all evaluated to their n_{max}. The EGM2008 estimated W_0^{LVD} is 62636860.77 m^2/s^2 and forms the initial reference for the GOCE GGMs. DIR-R4 and DIR-R5 provide different zero-level geopotential values by 8.7 cm and 7.6 cm, while TIM-R4 and TIM-R5 are close at the 2.7 cm and -1.5 cm. The latter is peculiar deviating significantly from the other GOCE models and can be probably attributed to the higher harmonics (higher than d/o 240) not being modelled properly in TIM-R5. This can be justified from Figure 2 as well, since above d/o

240, the differences of TIM-R5 with the local GPS/Leveling data increase by 4-8 cm. In any case, from this first estimate it can be concluded that the GOCE estimates do not seem robust among each other.

Table 4

One the other hand, when employing the enhanced GOCE GGMs, i.e., GOCE up to some d/o and then EGM2008, the results improve significantly. In this approach, the GOCE GGMs are used up to their degree that provides the best std (see also Table 3) and then EGM2008 is used as fill-in information. The new W_0^{LVD} are reported again in Table 4, where it can be seen that their differences are 3.8 cm, 3.5 cm, 3.4 cm and 3.8 cm for DIR-R4, DIR-R5, TIM-R4 and TIM-R5, respectively. Between them, the new GOCE estimates differ only by 0.1-0.4 cm, showing very good robustness. The std of the height residuals of the system observation equation (3) are, before the synthesis, 17.2 cm, 36.3 cm, 39.5 cm, 41.4 cm, and 40.4 cm for EGM2008, DIR-R4, DIR-R5, TIM-R4 and TIM-R5, respectively, while after the combination with EGM2008 they reduce to 13.7 cm for DIR-R4, 13.6 cm for DIR-R5, 13.9 cm for TIM-R4 and 13.7 for TIM-R5 models.

From the analysis of these residuals it was found that a height correlation exists, so that the zero-level geopotential determined from each BM had a decreasing values with increasing height. This meant that the highest BM were providing a value close to 62636856 m^2/s^2 while the lowest ones a value as high as 62636865 m^2/s^2. To overcome this problem, a revised model of Eqs. (2) and (3) was tested, where a height-dependent parameter λ was estimated along-side the W_0^{LVD} for the combined with EGM2008 GOCE GGMs (see Table 4), as:

$$H_i^{Helmert} = \frac{W_0^{LVD} - W_i}{\bar{g}_i^{Helmert}} + \lambda H_i^{Helmert} \quad . \tag{4}$$

The estimated height-dependent parameters λ were for all GOCE GGMs of the order of $(2.559 \pm 0.008) \times 10^{-4}$ m^2/s^2, while for EGM2008 it was two orders of magnitude smaller and was deemed insignificant. The new GOCE-based W_0^{LVD}

shows even more robustness, since they differ to each other by $\delta\hat{W}_0^{LVD} = 0.3 - 0.4$ cm only. This is a very good proof not only of the appropriateness of the proposed methodology (with its inherent uncertainties due to the use of orthometric heights), but of the capability of GOCE GGMs to be used for height system control, and vertical reference system unification, since they manage to “pick-up” the height dependency of the high-elevation BMs, something that could not be done by EGM2008. The latter is due to the fact that EGM2008 is based on local gravity data to model the medium part of the gravity field spectrum, which are very sparse over mountain ranges. The std of the height residuals reduces further to 12.6 cm for DIR-R4, 12.5 cm for DIR-R5, 12.8 cm for TIM-R4 and 12.7 cm for TIM-R5.

Finally, two weighted LS adjustment schemes were investigated, the first one using the inverse of the BM orthometric height as the observation weight and the second one using the inverse of the spherical distance L_i of the BM from the tide-gauge at the Piraeus harbor, which serves as the origin of the Greek LVD. These two new scenarios were carried out for DIR-R5 only, since it was the GGM with the overall smallest std against the GPS/Levelling BMs and the one with the smallest height residuals during the W_0^{LVD} determination. When using a weight of $p_i = 1/H_i^{helm}$ the estimated W_0^{LVD} is 62636860.94±0.002 m^2/s^2 and with a weight of $p_i = 1/L_i$ the estimated W_0^{LVD} is 62636860.92±0.002 m^2/s^2. Therefore, it becomes apparent that the extra weights are redundant and their significance is little, if any.

The finally proposed $\hat{W}_0^{LVD}$ for the Greek territory, based on the available data, is that of the combined DIR-R5 model with the estimation of the height-dependent parameter, i.e., $\hat{W}_0^{LVD}$=$62636860.95 \pm 0.008 m^2/s^2$. A final estimation is worthy, i.e., that of estimating the $\hat{W}_0^{LVD}$ for the areas of Attica and Thessaloniki separately. If this is done with the selected DIR-R5+EGM2008 combination, then the resulting values are $\hat{W}_0^{Attica}$=$62636860.31 \pm 0.021 m^2/s^2$ and $\hat{W}_0^{Thessaloniki}$=$62636860.79 \pm 0.021 m^2/s^2$. Their difference is 4.8 cm, showing that there is indeed a bias between the various stations of the Greek LVD. The difference between the tide-gauge records situated at the Piraeus harbor (Attica) and the harbor of Thessaloniki is 2.5 cm, indicating that their LVD bias cannot be attributed solely to the properties of the sea, but probably also to the geoid commission error in both DIR-R5 and EGM2008 (mostly the latter) and inconsistencies in the Greek LVD. The latter being a point that needs attention when existing orthometric heights are to be implemented for $\hat{W}_0^{LVD}$ determination.

5. Conclusions

In this work a detailed evaluation of the latest complete set of GOCE, GOCE/GRACE and combined GGMs has been presented employing a local set of collocated GPS/Levelling observations. From the results acquired it can be concluded that as the GOCE models progress from the 1st to the 5th release the useful spectrum is getting larger. Being limited up to d/o 180-200 for the first releases it reaches d/o 245 for DIR-R5, with significant improvement in the spectral range between d/o 185-230. The latest releases of the GOCE/GRACE GGMs are better as much as 3.2 cm in terms of the std and 12.6 cm in terms of the range, compared to EGM2008.

Moreover, an estimation of the zero-level geopotential value of the Greek LVD was carried out, based on a LS adjustment scheme. From that analysis it was concluded that the combined GOCE GGM and EGM2008 W_0^{LVD} is very robust showing differences of the order of 0.1-0.4 cm. When including in the adjustment a parameter to absorb the dependency with height, then height residuals of about 12.5 cm are determined for DIR-R4 compared to 17.2 cm for EGM2008. The use of observation weights, either the inverse of the height of the BM or the inverse of the distance from the tide-gauge that serves as the origin of the Greek LVD, did not alter the results and was deemed insignificant. When evaluating the W_0^{LVD} for the two regions separately, a bias between the local vertical datums of Thessaloniki and Attica of the order of 4.8 cm was found. Part of it, about 2.5 cm, can be attributed to the dynamic ocean topography difference between the two regions, as realized by the difference in the mean sea level records, while the rest is due to the GGM commission error and the inherent inconsistences of the Greek LVD.

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Table 1: GOCE/GRACE GGMs used for evaluation.

Models	n_{max}	Data	ICGEM name	References
EIGEN-51C	360	S(GRACE, LAGEOS),G,A	EIGEN-51C	Förste et al., 2008
EIGEN-6C	1420	S(GOCE, GRACE, LAGEOS),G,A	EIGEN-6C	Förste et al., 2011
EIGEN-6C2	1949	S(GOCE, GRACE, LAGEOS),G,A	EIGEN-6C2	Förste et al., 2012
EIGEN-6C3stat	1949	S(GOCE, GRACE, LAGEOS),G,A	EIGEN-6C3stat	Förste et al., 2012
DIR-R1	240	S(GOCE)	GO_CONS_GCF_2_DIR_R1	Bruinsma et al., 2010
DIR-R2	240	S(GOCE)	GO_CONS_GCF_2_DIR_R2	Bruinsma et al., 2010
DIR-R3	240	S(GOCE, GRACE, LAGEOS)	GO_CONS_GCF_2_DIR_R3	Bruinsma et al., 2010
DIR-R4	260	S(GOCE, GRACE, LAGEOS)	GO_CONS_GCF_2_DIR_R4	Bruinsma et al., 2013
DIR-R5	300	S(GOCE, GRACE, LAGEOS)	GO_CONS_GCF_2_DIR_R5	Bruinsma et al., 2013
TIM-R1	224	S(GOCE)	GO_CONS_GCF_2_TIM_R1	Pail et al., 2010
TIM-R2	250	S(GOCE)	GO_CONS_GCF_2_TIM_R2	Pail et al., 2011
TIM-R3	250	S(GOCE)	GO_CONS_GCF_2_TIM_R3	Pail et al., 2011
TIM-R4	250	S(GOCE)	GO_CONS_GCF_2_TIM_R4	Pail et al., 2011
TIM-R5	280	S(GOCE)	GO_CONS_GCF_2_TIM_R5	Pail et al., 2011
GOCO01S	224	S(GOCE, GRACE)	GOCO01S	Pail et al., 2011
GOCO02S	250	S(GOCE, GRACE)	GOCO02S	Goinginger et al., 2011
GOCO03S	250	S (GOCE, GRACE)	GOCO03S	Mayer-Gürr et al., 2012
ITG-GOCE02	240	S (GOCE)	ITG-GOCE02	Schall et al. 2014
GOGRA02S	230	S(GOCE, GRACE)	GOGRA02S	Yi et al., 2013
JYY-GOCE02S	230	S (GOCE)	JYY-GOCE02S	Yi et al., 2013
EGM2008	2160	S(GRACE),G,A	EGM2008	Pavlis et al., 2012

(Data: S = Satellite Tracking Data, G = Gravity Data, A = Altimetry-derived Gravity Data
GRACE (**G**ravity **R**ecovery **A**nd **C**limate **E**xperiment)
CHAMP (**CHA**llenging **M**ini-satellite **P**ayload)
GOCE (**G**ravity field and steady state **O**cean **C**irculation **E**xplorer)
LAGEOS (**La**ser G**EO**dynamics **S**atellite)
SLR (**S**atellite **L**aser **R**anking)

Table 2: Statistics of the ellipsoidal (h), orthometric (H), GPS/Levelling ($N^{GPS/Lev}$) geoid heights and RTM effects (N^{RTM}) on the BMs (total of 230 BMs). Units: [m]

	max	**min**	**mean**	**std**
h	1231.429	38.021	248.724	±209.418
H	1189.398	0.681	208.782	±209.360
$N^{GPS/Lev}$	42.763	34.752	39.942	±1.848
N^{RTM}	0.077	-0.019	0.018	±0.019

Table 3: Statistics of the differences between GPS/levelling and geoid heights from the GGMs. n_1 denotes the maximum d/o that the GOCE GGMs are used, whilst above that they are complemented with EGM2008 and RTM. Units: [m]

	n1	**range**	**mean**	**std**
EGM2008	2160	0.849	-0.505	±0.159
EIGEN-51C	90	0.823	-0.471	±0.152
EIGEN-6C	140	0.727	-0.467	±0.131
EIGEN-6C2	140	0.727	-0.467	±0.130
EIGEN-6C3stat	140	0.731	-0.464	±0.129
DIR-R1	120	0.725	-0.460	±0.128
DIR-R2	140	0.732	-0.469	±0.129
DIR-R3	140	0.729	-0.475	±0.131
DIR-R4	140	0.733	-0.467	±0.129
DIR-R5	140	0.736	-0.469	±0.128
TIM-R1	120	0.722	-0.491	±0.129
TIM-R2	140	0.731	-0.477	±0.128
TIM-R3	140	0.728	-0.478	±0.130
TIM-R4	140	0.729	-0.471	±0.131
TIM-R5	140	0.735	-0.465	±0.131
GOCO01s	120	0.726	-0.476	±0.133
GOCO02s	140	0.734	-0.473	±0.132
GOCO03s	140	0.734	-0.473	±0.131
ITG-GOCE02s	140	0.728	-0.469	±0.127
GOGRA02s	140	0.733	-0.473	±0.133
JYY-GOCE02s	140	0.723	-0.464	±0.130

Table 4: Estimates of the zero-height geopotential value for Greece.

	$\hat{W}_o^{\mathbf{LVD}}$ **[m^{2}s^{-2}]**	
	un-weighted	*with λ estimation*
EGM2008 (2160)	62636860.77±0.04	
EGM2008 (260)	62636859.43±0.04	
DIR-R4 (250)	62636859.90±0.04	62636860.92±0.008
DIR-R4 (140)+EGM2008	62636860.39±0.04	
DIR-R5 (300)	62636860.01±0.04	
DIR-R5 (140)+EGM2008	62636860.42±0.04	62636860.95±0.008
TIM-R4 (250)	62636860.50±0.04	62636860.96±0.008
TIM-R4 (140)+EGM2008	62636860.43±0.04	
TIM-R5 (280)	62636860.92±0.04	
TIM-R5 (140)+EGM2008	62636860.39±0.04	62636860.93±0.008

Figure 1: Distribution of local GPS/Levelling data in Athens (left) and Thessaloniki (right) for GOCE GGM validation.

Figure 2: Standard deviation of the differences between the five releases of the DIR GGMs (left; R1 normal line, R2 dashed line, R3 dash-dot line, R4 dotted line and R5 line with x-marker) and the latest GGMs (right; TIM-R5 normal line, DIR-R5 dashed line, ITG-GOCE02 dash-dot line, GOGRA02s dotted line, GOCO03s line with x-marker, and EIGEN6c3stat line with circle) with the GPS/Levelling geoid heights for various degrees of expansion.