Validation of GOCE/GRACE satellite only and combined global geopotential models over Greece in the frame of the GOCESeaComb project

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Abstract

The GOCESeaComb project, funded by ESA in the frame of the PRODEX program, aims to utilize GOCE data within combination schemes in order to achieve high-quality and accuracy predictions related to Earth's gravity field, sea level and dynamic ocean topography. In this work the results from the detailed validation of the latest GOCE, GOCE/GRACE and combined global geopotential models are presented referring to the fourth release of the models and the various strategies (TIM, DIR, GOCO, EIGEN-S/c) employed for their determination. The validation is performed following two approaches. The first one refers to the evaluation of the GGMs signal and error in the form of the provided degree and error variances. The second refers to an external evaluation of the GGMs against local gravity, GPS/Leveling data and deflections of the vertical. In this validation step we follow a spectral enhancement approach of GOCE GGMs, where EGM08 is used to fill-in the medium and high-frequency content along with RTM effects for the high and ultra high part. From the evaluation with GPS/Levelling benchmarks, it is concluded that the GOCE/GRACE GGMs provide improved accuracies compared to EGM2008 by about 2 cm in the spectral range between d/o 120-230. Finally, GOCE/GRACE GGMs manage to provide the same, as EGM2008, level of reduction to the local gravity anomalies, with a standard deviation at the 6.1-6.2 mGal level and marginally better residuals, at the sub-arcsec level in the reduction of deflections of the vertical.

Keywords

Global geopotential models, validation, GOCE, GPS/Levelling BMs, gravity, deflections of the vertical

1. Introduction

With GOCE entering the Earth's atmosphere in November 11, 2013, the contribution and new insights that have been brought to many fields in the geosciences are significant. GOCE managed to provide improved representations in the medium wavelengths of the gravity field spectrum to degree and order 210-240, resulting in advances in gravity field determination, dynamic ocean topography (DOT) modelling, new outlooks in the Earth's interior, etc. There have been many studies during the recent years investigating the performance of GOCE Global Geopotential Models (GGMs). In terms of the GOCE GGM external validation with GPS/Levelling and gravity data as well as deflections of the vertical (DoVs) it was found that its main impact is up to d/o 180-190 and 195-220 for the Release 2 and Release 3 GGMs, respectively (Gruber et al., 2011; Hirt et al., 2011; Šprlák et al., 2012; Vergos et al., in press). GOCE contribution to height system unification has also gained increased importance since the results show that especially in areas of small geoid variability, GOCE omission error is at the 1-2 cm range, as far as the determination of the vertical datum level offsets are concerned (Gruber et al., 2012; Hayden et al., 2012). Finally, GOCE has contributed significantly to DOT modelling since it has brought new insights in the geodetic determination of ocean circulation (Albertella et al., 2012; Knudsen et al., 2011; Tziavos et al., 2013). The focus of this work refers to the evaluation over Greece of the available Release 4 GGMs from GOCE, GOCE/GRACE and combined ones. Special attention is paid to the improvements they aforementioned GGMs bring to gravity field and geoid modelling.

2. Methodology, GGMs and local data

2.1 GOCE GGM validation methodology

For the validation of GOCE/GRACE GGMs, two methodologies have been followed, one internal and an external one. On a first stage their spectra have been evaluated in terms of their signal and error degree variances (both by-degree and cumulatively), the signal-to-noise ratio (SNR) and gain relative to EGM2008 (Pavlis et al., 2012). The signal and error degree variances reveal the spectral content of the GGMs for the various d/o investigated as well as the cumulative signal spectrum and signal error. The SNR provides useful information for the relative signal strength given the signal error, while the gain, relative to EGM2008, provides an indicative measure of the improvement brought by the GOCE/GRACE GGMs w.r.t. the reference GGM used. The GGMs are provided as sets of dimensionless spherical harmonic coefficients $\delta\bar{C}^{*}_{nm}, \delta\bar{S}_{nm}$ with their errors $\varepsilon_{\delta\bar{C}^{*}_{nm}}, \varepsilon_{\delta\bar{S}_{nm}}$. The asterix implies that the spherical harmonic coefficients are fully normalized and the δ that the normal potential has been subtracted. Given that the coefficients and errors of various geopotential models need to be compared, and some of them use different values for the geocentric gravitational constant *GM* and equatorial radius *a*, it is necessary to scale their harmonic coefficients. In that way, the computed harmonic coefficients can be comparable (Sneeuw, 2000). Within the present validation and in the external one to follow, the Earth's geocentric gravitational constant *GM* and the gravity potential at the geoid *Wo* have been set to $GM=398600.4418\ 109\ m^3s^{-2}$ and $Wo=62636856.00\ m^2s^{-2}$. The mean Earth's radius R has been taken equal to 6378136.3 m and the normal gravity γ at the surface of the ellipsoid has been computed by the closed formula of Somigliana (Heiskanen and Moritz, 1967). Moreover, the GRS80 ellipsoid, along with its defining and derived quantities, has been used as reference. Given the availability of unified spherical harmonic coefficients and their errors, the by-degree and cumulative signal and errors can be evaluated (here we will focus on geoid signal and error for the investigated GGMs), which can be determined as outlined in Vergos et al. (2006; in press). As far as the SNR and gain are concerned, these can be evaluated either for each specific degree and order (2D case) or per-degree (1D case). In the latter, they are determined as (Sneeuw, 2000):

$$SNR_n = \frac{\sigma_n}{\varepsilon_{\sigma_n}}, \quad (1)$$

$$GAIN_n = \frac{\varepsilon_{\sigma_n^{EGM\,2008}}}{\varepsilon_{\sigma_n^{i}}}. \quad (2)$$

In Eq. (1) σ_n denotes the geoid degree variances of the model under study and ε_{σ_n} its error degree variances. In the case of the GGM 1D gain, this is evaluated as the ratio between the EGM2008 error degree variances, $\varepsilon_{\sigma_n^{EGM\,2008}}$, and those of the

GGM under study, $\varepsilon_{\sigma_n^i}$. The SNR represents the ratio between the GGM signal and its error spectrum per degree, i.e., indicating spectral bands that are solvable with power larger than the model error. The gain expresses the ratio between the errors of the “nominal” GGM, EGM2008 in our case, for a specific degree, and the GOCE-based ones. Both quantities are evaluated with their base 10 logarithm, so that the results that will be presented herein refer to the number significant digits either for the SNR or gain. Regarding the SNR we are looking for values larger than zero (0) since this is the threshold under which the GGM error is smaller than the signal. Accordingly, for the 1D gain, values larger than zero (0) indicate that the GOCE/GRACE GGM degree error is smaller than that of EGM2008.

For the external evaluation of the GOCE/GRACE GGMs, comparisons with collocated GPS/Levelling benchmarks (BMs), point free-air gravity anomalies and DoVs, which cover the entire part of continental Greece, are performed. As far as geoid heights are concerned, the differences between the GOCE/GRACE GGMs with the local data have been performed as:

$$\Delta N = N^{GPS/Lev} - N^i\Big|_2^{n_1} - N^{EGM2008}\Big|_{n_1+1}^{2160} - N^{RTM} - N_o, \quad (3)$$

where ΔN denotes the geoid heights differences at the GPS/Leveling BMs between the GPS-derived geoid heights ($N^{GPS/Lev}$) and those derived by the GGM ($N^i\big|_2^{n_1}$) under investigation. In Eq. (3) the evaluation is carried out with the GOCE/GRACE GGMs to some maximum degree of expansion (n_1), while the rest of the geoid signal is represented by EGM2008, from degree n_1+1 to degree 2160 along with RTM effects on geoid heights (N^{RTM}). The RTM effects on geoid heights are estimated on the BMs from a 3 arcsec resolution digital terrain and bathymetry model (Tziavos et al., 2010). The, smooth but varying, reference surface needed for the RTM effect is constructed by averaging the fine resolution topography grid and then low-pass filtering the average grid generated by taking moving averages of an appropriate number of adjacent blocks (Tziavos et al., 2010). The contribution of the zero-degree geoid term (N_o) is evaluated with respect to the GRS80 reference ellipsoid as in Heiskanen and Moritz (1967, Eq. 2.182). All computations were carried out in the Tide Free (TF) system, while any necessary transformations from the Zero-Tide (ZT) to the TF system were done following Ekman (1989). The aforementioned geoid height differences on BMs are first evaluated by the GOCE/GRACE GGM contribution, to their n_{max}, alone, i.e., without the fill-in information from EGM2008 and RTM effects, and then with all parameters outlined in Eq. (3). The latter is evaluated for every degree starting from $n_1=2$ up to the n_{max} of the GGM under investigation. Finally, it should be noted that the computed RTM effects correspond to a maximum harmonic degree of 216,000, so that the remaining omission error is negligible. In all geoid height evaluations a local LSC-based gravimetric geoid model (N^{LSC}) is used as ground-truth (Tziavos et al., 2013).

The same methodology has been followed for the evaluation of the reduction that the GOCE/GRACE GGMs provide to the available local point free-air gravity anomalies and DoVs, i.e., the contribution of the recent GGMs is filled-in by EGM2008 and RTM effects in order to derive the final residual fields. The evaluation in this case is performed from $n_1=2$ up to the n_{max} of the GGM under investigation, with an interval of 10 d/o, mainly due to the large number of gravity data. In any case the evaluation step does not alter the conclusions drawn.

2.2 GOCE/GRACE GGMs and local data

As far as the GOCE/GRACE GGMs are concerned, we will focus on the latest, Release 4, versions as well as to the latest combined models. Release 4 models are based on an effective data volume of 26.5 months of GOCE observations compared to 12 months for the Release 3 ones. Depending on the processing strategy three 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. 2013), and c) the GOCO combined models where both GOCE and GRACE data are used (Pail et al. 2010). For GOCO, we have included in the validation its Release 3 version (GOCO03s) given that a Release 4 version is not available. The GO-DIR-R4 model is a combined GRACE/GOCE/SLR model, while GO-DIR-R3 was used as an a-priori gravity field up to d/o 240. Apart from the aforementioned GGMs, EGM2008 (Pavlis et al. 2012) and the latest EIGEN-6S, EIGEN-6C and EIGEN-6C2 models (Förste et al 2012) have been used as well.

The local data used for the GGM external validation refer to GPS/Levelling observations (1542 BMs) covering the entire part of continental Greece (cf. Vergos et al., in press). This set of collocated GPS and Levelling data (see Figure 1) is based on historical orthometric heights from the HMGS (Hellenic Military Geographic Service) and ellipsoidal heights collected within the HEPOS (Hellenic Positioning System) project. The orthometric heights refer to the tide-gauge station located at the Piraeus harbor, where MSL measurements were performed over the period 1933-1978. The true accuracy though of the HVD's leveling network is largely unknown. The ellipsoidal heights were determined in ITRF00 (epoch t=2007.236) with their horizontal and vertical accuracy being estimated from the analysis of the original GPS observations to 1-4cm (1σ) and 2-5 cm (1σ), respectively. Moreover, point free-air gravity anomalies and DoVs have been used (see Figure 1) from the latest database that has been compiled in the frame of the determination of a new Greek geoid model (Tziavos et al., 2010; 2013). The gravity dataset comprise a number of 294777 irregular point gravity observations (cf. Tziavos et al., 2013) with an accuracy (estimated through least-squares prediction) at the ±2.25 mGal level. The DoV dataset (99 values) consists of two basic sub-sets, one (the main with 89 DoVs) collected from dedicated astrogeodetic observations (Tziavos, 1987) and a second (10 DoVs) collected during dedicated astrogeodetic observations with the ETH digital Zenith Camera DIADEM. The old DoV dataset was original determined in ED50 and properly transformed to GRS80 and a DoV accuracy varying between 0.1 to 0.3 arcsec (Tziavos, 1987). The DIADEM DoV dataset has a horizontal position accuracy of 10 cm and the deflections have an accuracy of ±0.15 arcsec (Somieski, 2008).

FIGURE 1

3. GGM spectral evaluation and external validation

3.1 GOCE GGM spectral evaluation

As already mentioned, the spectral evaluation of the GOCE GGMs is based on their signal and error degree variances, the SNR and the gain relative to

EGM2008. From this analysis, an improved representation of the geoid height error spectrum is evident as more GOCE data are included (TIM-R4 and DIR-R4 compared to GOCO03S), along with the improved error spectrum due to the use of GRACE data (DIR-R4 compared to TIM-R4). The DIR-R4 error spectrum is below that of EGM2008 up to d/o 214, while GOCO03s provides smaller errors up to degree 175. Among DIR-R4 and GOCO03s, the latter provides smaller errors up to d/o 98 due to the fact that in DIR-R4 GRACE and GOCE normal equations are blended for the entire spectrum, so that the influence of GOCE is visible in the low-degree harmonics. TIM-R4, which is based solely on GOCE observations gives smaller errors compared to EGM2008 from d/o 48 up to d/o 179, while it is better than GOCO03s from d/o 144 onwards. EIGEN6C and EIGEN6C2 have smaller errors compared to EGM2008 up to d/o 185 and then from d/o 319 onwards, signaling that in the intermediate band (d/o 185-318) EGM2008 was probably modeled in a more elaborate or enhanced way (given that this is the range that the satellite and terrestrial data are both used). In terms of the cumulative geoid errors, GOCO03s reaches the 1 cm geoid error to d/o 152, TIM-R4 to d/o 184 and DIR-R4 to d/o 192, while their total errors are at the 15.5 cm, 11.3 cm and 4.27 cm, respectively. The DIR-R4 errors are significantly better than those of TIM-R4, where the lack of GRACE observations in the latter is evident, especially in the low degree harmonics. Even though TIM-R4 uses only GOCE data, its error spectrum is better than that of GOCO03S after d/0 180, hence signaling the improvements brought by adding more GOCE observations. On the other hand, DIR-R4 provides the overall best error spectrum with the smallest cumulative geoid errors to all d/o of investigation, showing the benefits of combined satellite-only (GOCE and GRACE) GGMs. EIGEN6C and EIGEN6C2 reach the 1 cm error at d/o 153 and 162 (EGM2008 reaches the 1 cm error at d/o 71), while their cumulative error is at the 9.5 cm and 8.5 cm (EGM2008 has a cumulative geoid error of 8.2 cm), respectively. Especially for the cumulative and by-degree geoid errors it should be bear in mind that the GGM errors are formal/calibrated ones resulting from different weight schemes for each GGM. Hence, they may be biased since they can be optimistic.

Figure 2 depicts the SNR and gain for the evaluated GOCE/GRACE GGMs. As it can be seen DIR-R4 retains better, compared to EGM2008, SNR for the entire spectrum up to d/o 211, while GOCO03S up to d/o 169. The SNR of TIM-R4 is worse than that of EGM2008 up to d/o 47 and better from d/o 48 to 181. EIGEN6S, incorporating all available GRACE and GOCE data, retains an SNR better than EGM2008 up to d/o 166, while for the two latest EIGEN combined models, their SNR is better than that of EGM2008 in the spectral bands between d/o 2-189 and 320-1420 for EIGEN6C and in the spectral bands between d/o 2-187 and 322-1949 for EIGEN6C2. As for the gain (see Figure 2) the useful spectral band offered by the latest GOCE/GRACE models becomes apparent in terms of significant digits of the model gain w.r.t. EGM2008. This band is between d/o 47 to 180 for TIM-R4, and for the entire spectrum up to d/o 169 for GOCO03s and 214 for DIR-R4.

FIGURE 2

3.2 GOCE GGM evaluation with GPS/Levelling data

As far as the evaluation with the GPS/Levelling data is concerned, Table 1 summarizes the differences between the available GPS/Levelling and GGM geoid heights. Both the national gravimetric geoid model and EGM2008 provide a standard deviation (std) at the 14 cm, so they will provide the basis for the evaluation of the GOCE/GRACE and combined GGMs. When satellite only models are evaluated to their n_{max} without any spectral enhancement from EGM2008 and RTM effects, then, as expected, their differences are quite large (47 cm to 51 cm) due to the omission error. On the other hand, when fill-in information from EGM2008 along with the computed RTM effects are taken into account, then their performance is comparable and better than that of both EGM2008 and the local model. Figure 3 depicts the variation of the std of the geoid height differences between the enhanced GOCE/GRACE GGMs and GPS/Levelling.

TABLE 1

The useful spectral range, i.e., with errors smaller than EGM2008 is up to d/o 215 for DIR-R4, while the smallest std at 12.3 cm is achieved at d/o 165. For TIM-R4 this spectral band is extended to d/o 225, while in the band between d/o 215 and

225 it provides better std compared to DIR-R4. The overall smallest std for TIM-R4 is reached at d/o 166 being at the 12.3 cm level. GOCO03S, given that it contains only 12 months of GOCE data, manages to provide better std than EGM2008 up to d/o 185, while in the range between d/o 110 to 125 it provides std's close to EGM2008. The overall best std is reached at d/o 163 being at the 12.4 cm level. It is interesting to notice that for both DIR-R4 and TIM-R4, the std are oscillating close to that of EGM2008 in the band between d/o 110 and 130. This consistent behavior is a matter of further research and can be probably attributed to EGM2008 and its development strategy. EIGEN6S has a similar behavior with the other satellite only models, while regarding EIGEN6c and EIGEN6c2 it was noticing that the latter provides smaller std for the entire spectrum compared to EGM2008, with the exception of d/o 108-111 where its std is 0.2-0.4 cm worse than that of EGM2008. This signals the fact that EIGEN6C2 is indeed a more robust GGM compared to EGM2008, due to the use of GOCE observations in its development.

FIGURE 3

3.3 GOCE GGM evaluation with gravity and DoV data

The same analysis has been performed for the reduction of the available point gravity anomalies and DoVs, with the results being summarized in Table 2 and Table 3, respectively. From the evaluation of the gravity anomaly data set it was concluded that the residual fields of the GOCE/GRACE models provide the same level of reduction, in terms of the std, as EGM2008. It should be noted that as in the evaluation with the GPS/Levelling data, the contribution of GOCE/GRACE GGMs is filled with EGM2008 and RTM in order to reduce the omission error. TIM-R4 provides the same std for the residuals as EGM2008 up to d/o 120 (6.19 mGal), while after that it starts to increase and reaches 7.86 mGal at d/o 250 (filled with EGM2008 and RTM effects above that d/o). DIR-R4 reaches d/o 125 with a std similar to that of EGM2008 and at d/o 260 it increases to 8.91 mGal. Finally, GOCO03S reaches d/o 121 with a std similar to that of EGM2008 and at d/o 250 it increases to 9.19 mGal. The same behaviour is found for the combined models as well, with EIGEN6c2 providing a std of 6.52 mGal to its n_{max} of 1949, while it retains the same level of reduction as EGM2008 up to d/o ~220. From

Table 2 it can be concluded that the improvement offered by GOCE/GRACE GGMs, if any, can be found in the reduction of the mean value to the 0 mGal level. But this is marginal, since EGM2008 provides a mean value for the residual field of only 0.2 mGal. It should be noted though that most of the gravity anomalies that were used in the comparisons have also been used in the development of EGM08. Therefore, the comparisons with EGM08 are indicative, although an improvement at least in terms of the mean value would be expected.

TABLE 2

A slightly better performance is found for the evaluation with the DoV dataset, where the GOCE/GRACE GGMs improve not only the mean value but the std as well. Again the contribution of GOCE/GRACE GGMs is filled with EGM2008 and RTM in order to reduce the omission error. For ξ (see Table3), EIGEN6c and EIGEN6C2 reach a std of 2.07 and 2.11 arcsec at d/o 840 and 910, respectively, which are slightly better that the std of 2.18 arcsec for EGM2008. It is noticing that EIGEN6S manages to provide a std at the 2 arcsec level, the overall best, at d/o 225, along with the smallest mean at -0.23 arcsec. GOCO03S, TIM-R4 and DIR-R4 all reach at d/o 220 a std of 2.05, 2.10 and 2.09 arcsec, respectively with mean values below that of EGM2008. For DIR-R4, it is interesting to notice that its Release 3 version provides a std of 2.03 arcsec. The η component of the DoV presents slightly worst statistics, probably due to its higher variability over Greece (see Table 3). The combined GGMs are similar to EGM2008 with a std at the 2.3 arcsec level, while only TIM-T4 provides a std at the 2.19 arcsec. Finally, the mean value is smaller for the GOCE/GRACE GGMs by 0.05 arcsec the most, compared to EGM2008. It can be concluded therefore that for the DoVs, which are mapped in the high and ultra-high frequencies of the gravity field spectrum, GGMs, even combined ones, do not manage to depict their entire content, so that local data, with high spatial sampling are needed as well along with information about density variations.

TABLE 3

4. Conclusions

An evaluation of the latest GOCE, GOCE/GRACE and combined GGMs has been presented, focusing on their spectral comparison and validation with local data. From the results acquired it becomes clear that the useful spectral band is between d/o 47 to 180 for TIM-R4, while it spans the entire spectrum up to d/o 169 for GOCO03s and 214 for DIR-R4. These spectral bands are confirmed from the evaluation with the GPS/Leveling data over Greece, since in terms of the std of the geoid height differences DIR-R4, TIM-R4 and GOCO provide smaller values up to d/o 215, 225 and 185, respectively. Moreover, d/o 163-165 seem to be the ones that the GOCE/GRACE models perform the best, since they improve the std, compared to EGM2008, by 2 cm. Finally, for the free-air gravity anomalies the evaluated GGMs perform similar to EGM2008, without any significant improvement, while the same is concluded for the DoV dataset as well, where the improvement is marginal.

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References

Albertella A, Savcenko R, Janjić T, Rummel R, Bosch W, Schröter J (2012) High resolution dynamic ocean topography in the Southern Ocean from GOCE. Geophys J Inter 190: 922–930.

Bruinsma SL, Förste C, Abrikosov O, Marty J-C, Rio M-H, Mulet S, Bonvalot S (2013) The new ESA satellite-only gravity field model via the direct approach. Geophys Res Lett 40*:* 3607–3612, doi:10.1002/grl.50716.

Ekman M (1989) Impacts of Geodynamic Phenomena on Systems for Height and Gravity. Bull Geod 63(3): 281–296.

Förste Ch et al. (2012) A preliminary update of the Direct approach GOCE Processing and a new release of EIGEN-6C. Presented at the AGU Fall Meeting 3 - 7 Dec 2012 San Francisco, Abstract No. G31B-0923.

Gruber Th, Visser PNAM, Ackermann Ch, Hosse M (2011) Validation of GOCE gravity field models by means of orbit residuals and geoid comparisons. J Geod 85(11): 845-860.

Gruber T, Gerlach C, Haagmans R (2012) Intercontinental height datum connection with GOCE and GPS-levelling data. J Geod Scien 2(4): 270-280, doi: 10.2478/v10156-012-0001-y.

Heiskanen WA and Moritz H (1967) Physical Geodesy, W.H. Freeman and Company, San 895 Francisco.

Hayden T, Amjadiparvar B, Rangelova E, Sideris MG (2012) Evaluation of W0 in Canada using tide gauges and GOCE gravity field models. J Geod Scien 2(4): 257–269, doi: 10.2478/v10156-012-0008-4.

Hirt C, Gruber T and Featherstone WE (2011) Evaluation of the first GOCE static gravity field models using terrestrial gravity, vertical deflections and EGM2008 quasigeoid heights. J Geod 85(10): 723-740.

Knudsen P, Bingham R, Andersen OB, Rio M-H (2011) A global mean dynamic topography and ocean circulation estimation using a preliminary GOCE gravity model. J Geod 85(11): 861-879.

Pail R, et al. (2010) Combined satellite gravity field model GOCO01S derived from GOCE and GRACE. Geophys Res Lett 37(L20314), doi:10.1029/2010GL044906.

Pail R, et al. (2011) First GOCE gravity field models derived by three different approaches. J Geod 85(11): 819-843.

Pavlis NK, Holmes SA, Kenyon SC, Factor JK (2012) The Development and Evaluation of the Earth Gravitational Model 2008 (EGM2008). J Geophys Res 117(B04406), doi:10.1029/2011JB008916.

Sneeuw N (2000) A semi-analytical approach to gravity field analysis from satellite observations. Deutsche Geodätische Kommission Reihe C (Heft 527). Verlag der Bayerischen Akademie der Wissenschaften, München, p 117 ISBN (Print) 3-7696-9566-6, ISSN 0065-5325.

Somieski A-E (2008) Astrogeodetic geoid and isostatic consideration in the North Aegean Sea, Greece. Dissertation for the Degree of Doctor of Philosophy, ETHZ, Dissert ETH No 17790, http://dx.doi.org/10.3929/ethz-a-005710420.

Šprlák M, Gerlach C, and Pettersen PR (2012) Validation of GOCE global gravity field models using terrestrial gravity data in Norway. J Geod Science 2(2): 134-143.

Tziavos IN (1987) Determination of geoidal heights and deflections of the vertical for the Hellenic area using heterogeneous data. Bul Géod 61: 177 - 197.

Tziavos IN, Vergos GS, Grigoriadis VN (2010) Investigation of topographic reductions and aliasing effects to gravity and the geoid over Greece based on various digital terrain models. Surv Geophys 31(3):23-67. doi: 10.1007/s10712-009-9085-z.

Tziavos IN, Vergos GS, Mertikas SP, Daskalakis A, Grigoriadis VN, Tripolitsiotis A (2013) The contribution of local gravimetric geoid models to the calibration of satellite altimetry data and an outlook of the latest GOCE GGM performance in GAVDOS. Adv Space Res 51(8): 1502-1522, doi: 10.1016/j.asr.2012.06.013.

Vergos GS, Grigoriadis VN, Tziavos IN, Kotsakis C (in press) Evaluation of GOCE/GRACE Global Geopotential Models over Greece with collocated GPS/Levelling observations and local gravity data. International Symposium on Gravity, Geoid and Height Systems (GGHS 2012), IAG Symp, 141, in press.

Vergos GS, Tziavos IN, Sideris MG (2006) On the validation of CHAMP- and GRACE-type EGMs and the construction of a combined model. Geodesy and Cartography 55(3): 115-131.

Table 1: Statistics of the differences between GPS/levelling and geoid heights from the GGMs to their n_{max}, before (normal font) and after combination with EGM2008 and RTM effects (italics). The first column (n_1) represents the maximum d/o after which EGM2008 is used. Unit: [m]

	n_1	**max**	**min**	**mean**	**std**
EGM2008	----	0.168	-0.810	-0.374	0.141
EIGEN6S	----	1.400	-1.837	-0.358	0.512
EIGEN6S	*165*	*0.049*	*-0.885*	*-0.394*	*0.124*
EIGEN6c	----	0.357	-0.867	-0.394	0.161
EIGEN6c	*165*	*0.072*	*-0.884*	*-0.392*	*0.129*
EIGEN6c2	----	0.193	-0.929	-0.388	0.137
EIGEN6c2	*165*	*0.061*	*-0.860*	*-0.389*	*0.123*
GOCO03S	----	1.415	-1.795	-0.353	0.496
GOCO03S	*163*	*0.076*	*-0.866*	*-0.393*	*0.123*
DIR-R4	----	1.379	-1.607	-0.361	0.476
DIR-R4	*165*	*0.054*	*-0.856*	*-0.391*	*0.123*
TIM-R4	----	1.260	-1.628	-0.352	0.484
TIM-R4	*166*	*0.060*	*-0.849*	*-0.395*	*0.123*
N^{LSC}	----	0.119	-1.033	-0.392	0.140

Table 2: Statistics of the original free-air gravity anomalies over Greece, reduced (normal lettering) and residual fields (italics) from the various GGMs. The first column (n_1) represents the maximum d/o after which EGM2008 is used. Unit: [mGal]

	n_1	max	min	mean	std
Δg_f (original)	----	269.93	-236.10	-22.73	74.11
Δg_{res} (EGM2008)	----	*101.01*	*-96.45*	*-0.16*	*6.15*
Δg_{red} (EIGEN6S)	----	219.29	*-134.89*	*-4.07*	*27.97*
Δg_{res} (EIGEN6S)	*120*	*101.31*	*-96.08*	*-0.05*	*6.19*
Δg_{red} (EIGEN6c)	----	118.96	*-137.87*	*-0.57*	*9.34*
Δg_{res} (EIGEN6c)	*124*	*101.33*	*-96.06*	*-0.05*	*6.19*
Δg_{red} (EIGEN6c2)	----	94.97	*-149.20*	*-0.22*	*6.73*
Δg_{res} (EIGEN6c2)	*125*	*101.33*	*-96.13*	*-0.06*	*6.19*
Δg_{red} (GOCO03S)	----	*224.65*	*-132.06*	*-4.42*	*27.43*
Δg_{res} (GOCO03S)	*121*	*101.74*	*-96.56*	*-0.05*	*6.19*
Δg_{red} (GO-DIR-R4)	----	*223.69*	*-129.92*	*-4.34*	*27.76*
Δg_{res} (GO-DIR-R4)	*125*	*101.59*	*-95.86*	*-0.05*	*6.19*
Δg_{red} (GO-TIM-R4)	----	*223.57*	*-133.43*	*-4.35*	*27.34*
Δg_{res} (GO-TIM-R4)	*120*	*101.71*	*-95.67*	*-0.04*	*6.19*

Table 3: Statistics of the original north-south (ξ) and west-east (η) deflections of the vertical over Greece and residual fields from the GGMs. The first column (n_1) represents the maximum d/o after which EGM2008 is used. Unit: [arcsec]

	n_1	max	min	mean	std
ξ/η (original)	----	10.88/14.77	-27.77/-25.84	-6.89/-2.56	7.36/7.65
ξ_{res}/η_{res} (EGM2008)	----	5.44/5.96	-5.21/-4.41	-0.34/0.58	2.18/2.28
ξ_{res}/η_{res} (EIGEN6S)	225	4.70/5.93	-5.01/-4.01	-0.23/0.61	2.03/2.28
ξ_{res}/η_{res} (EIGEN6c)	840	5.19/5.97	-5.22/-4.53	-0.29/0.59	2.07/2.29
ξ_{res}/η_{res} (EIGEN6c2)	910	5.45/5.97	-5.34/-4.54	-0.30/0.59	2.10/2.29
ξ_{res}/η_{res} (GOCO03S)	220	4.97/4.85	-5.35/-5.07	-0.23/0.52	2.05/2.24
ξ_{res}/η_{res} (GO-DIR-R4)	220	5.41/5.61	-5.48/-4.97	-0.23/0.52	2.09/2.26
ξ_{res}/η_{res} (GO-TIM-R4)	220	5.24/5.29	-4.92/-5.59	-0.27/0.55	2.10/2.19

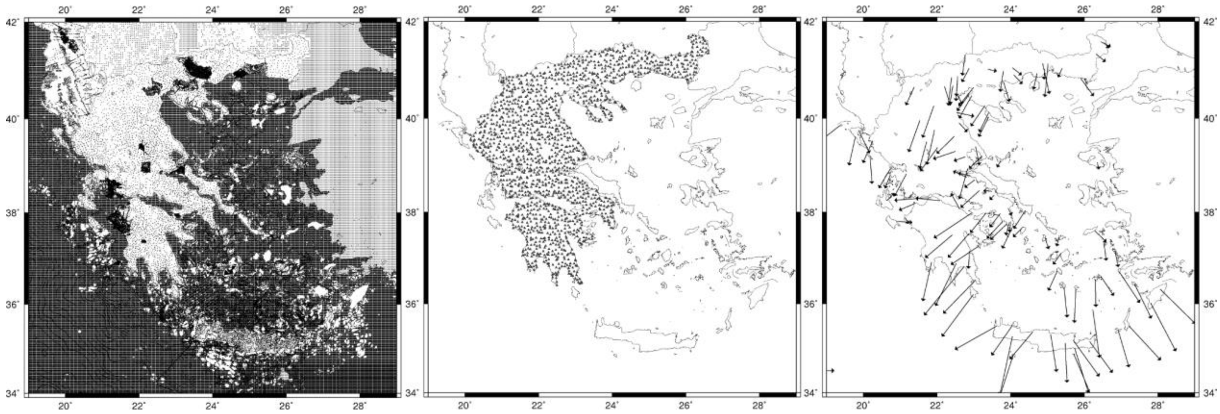

Figure 1: Distribution of local gravity (left), GPS/Levelling (centre) and deflections of the vertical (right) data in Greece for GOCE GGM validation.

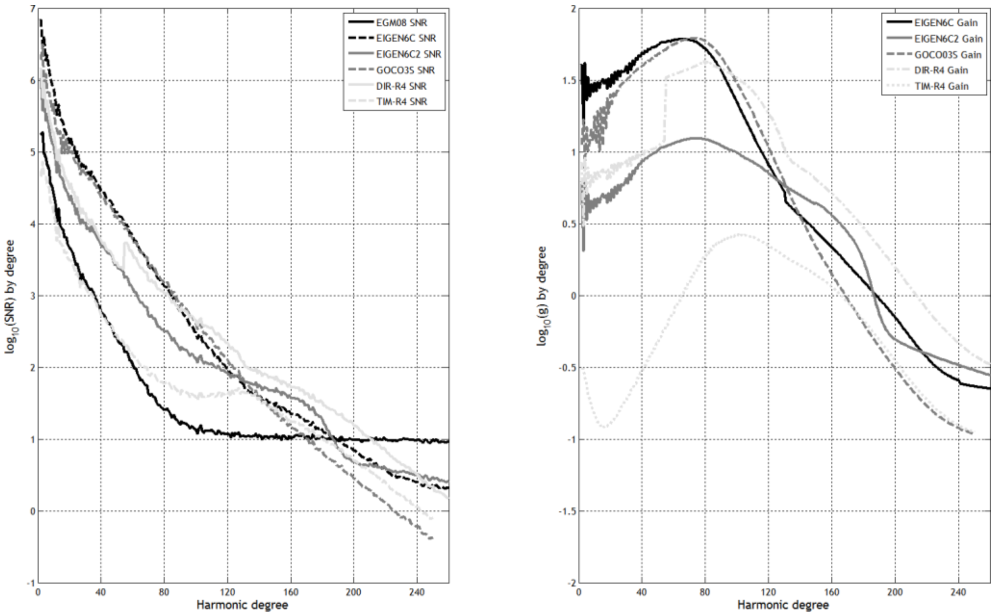

Figure 2: GOCE GGM SNR and gain relative to EGM2008.

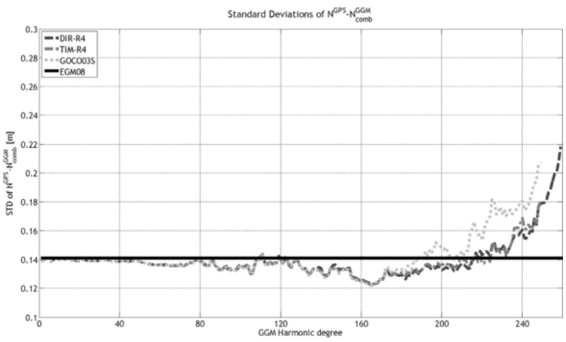

Figure 3: Standard deviation of the differences between DIR-R4, TIM-R4 and GOCO03S with the GPS/Levelling geoid heights for various degrees of expansion.