Quality Control of Height Benchmarks in Attica, Greece, Combining GOCE/GRACE Satellite Data, Global Geopotential Models and Detailed Terrain Information

Vassilios D. Andritsanos, Orthodoxia Arabatzi, Vassilios Pagounis, and Maria Tsakiri

Abstract

The incorporation of the newly available satellite data of GOCE and GRACE missions into global geopotential model solutions provides valuable information on the low to medium frequency band of the gravity field spectrum, an important connection to height datum control and unification. The use of this enriched contribution to existing national height systems quality control will reveal the well known inconsistencies in previous vertical network establishment methods, as well as strengthen the connection solution between adjacent national networks.

The quality control of the vertical network in Attica region (Central Greece) is evaluated in the present study. Collocated GPS/levelling and gravity observation points are utilized with emphasis to trigonometric benchmarks and height reference sites. A spectral enhanced combination scheme is used for the network quality investigation based on the frequency content of pure satellite solutions (GOCE and GRACE) and combined satellite and ground global geopotential solutions of high degree of expansion. Detailed DTM (Digital Terrain Model) information is incorporated in order to estimate Residual Terrain Model (RTM) effects, leading to an expansion degree of 648,000 (1 arcsec). Finally, detailed information about the quality of the height network in Attica is presented in conjunction to proposals towards the establishment of a new height network.

Keywords

GOCE/CHAMP satellites • GPS/levelling • Height network control • Spectral enhanced method

1 Introduction

The first-order vertical control network of Greece was established and measured by the Hellenic Military Geographical Service from 1963 to 1986 (Milona-Kotroyianni 1989).

V.D. Andritsanos (✉) • V. Pagounis
Geospatial Technology Lab, Department of Civil Engineering and Surveying and Geoinformatics Engineering, Technological and Educational Institute of Athens, 12210 Athens, Greece
e-mail: vdandrit@teiath.gr

O. Arabatzi • M. Tsakiri
School of Rural and Surveying Engineering, National Technical University of Athens, 15780 Athens, Greece

Approximately 11,000 km of traverses and 11,000 vertical control benchmarks comprise the Greek vertical network. The tide gauge in Piraeus harbor is the fundamental control point of the network. The establishment of the Hellenic Vertical Network was based on sea level changes observations at the reference tide gauge and no W_o estimation was performed. On the other hand, the first order Hellenic triangulation network has some height information, due to a limited number of trigonometric leveling lines. This vertical information has not been validated since its creation. The validation of the vertical reference network before the establishment of the European interconnection is thus essential. A first thorough validation of the Hellenic triangulation network using EGM2008 (Pavlis et al. 2008) was performed by

International Association of Geodesy Symposia,
DOI 10.1007/1345_2017_7, © Springer International Publishing AG 2017

Kotsakis et al. (2010) using GPS data from Hellenic Positioning System (HEPOS; Gianniou 2008) and the leveling information of selected pillars. Recent regional studies were also performed by Vergos et al. (2014), Andritsanos et al. (2015), Vergos et al. (2015) using combination solutions of recent Global Geopotential Models (GGMs) from GOCE mission.

In the present study, the validation of recent (2014–2016) GOCE/GRACE/CHAMP geopotential models at newly measured GPS/Leveling benchmarks of Central Greece is performed. Within this validation, the confirmation of low frequency spectrum improvement through the assimilation of low degree harmonics of satellite missions is proven. Detailed terrain information using Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Shuttle Radar Topography Mission (STRM) mission data for the Residual Terrain Model (RTM) effect computation is take into account. The paper comprises three sections. Section 2 presents the methodology followed and the data availability and Sect. 3 describes the results of the study. The conclusions are given in Sect. 4.

2 Methodology and Data

2.1 Data Availability and Test Area

2.1.1 GPS/Levelling Information

Newly available campaigns in Attica were carried out during the last 2 years with 59 GPS/Levelling benchmarks used as test control points. Trigonometric pillars of the Greek Triangulation Network as well as height reference sites of the Hellenic Vertical Network were utilized in this study. The orthometric height of the abovementioned sites were computed using classical spirit leveling (height reference sites) as well as trigonometric leveling (pillars) and are part of the Hellenic Vertical Network, measured and evaluated from 1960 to 1989 (Milona-Kotroyianni 1989). The accuracy of the orthometric heights used is largely unknown since there is not any scientific publication on the adjustment procedure available. Based on its documentation, the orthometric heights of the Hellenic Vertical Network refer to a mean-tide system (IERS Conversions 2010). The geometric heights on these sites were measured using GPS observations during the last 2 years with an estimated accuracy at the level of 2–5 cm and 1–2 cm in the horizontal position. The estimated benchmarks coordinates from GNSS observations refer to the ITRF2008 reference system (epoch 2011.0). The locations of the test points of this study are presented in Fig. 1.

2.1.2 Geopotential Model Availability

The geoid height information was obtained by the use of 12 newly available Global Geopotential Models (GGMs) published during the last 2 years (2014–2016). These models were used to their maximum degree and order (d/o). They incorporate satellite only or combined information (satellite and ground observations). The satellite models are divided to GOCE only models, GOCE, GRACE and CHAMP models and GRACE only or GRACE/GOCE models. EGM2008 (Pavlis et al. 2008) is used as reference model in the validation up to its maximum degree of expansion (2190). The detailed information of the 12 GGMs used in this study is presented in Table 1.

2.1.3 Detailed Terrain Information

The terrain effects on geoid height information were taken into account using satellite derived DTMs. Data from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) mission and Shuttle Radar Topography Mission (SRTM) were utilized in terrain representation. The 1 arcsec resolution of the terrain information led to an increased accuracy on the computation of the masses effect on the geoid. It is the first time that this high terrain resolution is used in the area under study. The differences between the heights of the two DTMs are presented in Table 2 where a mean difference of −3.6 m and a std. of ±8.2 m are noticed. These results are expected due to the different satellite measurement procedure of each mission. In addition, ASTER and SRTM mission internal accuracy reaches the level of ten of meters (namely, ±20 m and ±16 m).

2.2 Combination Scheme and Validation Procedure

2.2.1 Data Preprocessing and Datum Concept

The most important aspect in geodetic data combination techniques is the homogeneity of the reference systems used in the heterogeneous measurements. GPS observations for the horizontal positioning as well as for the ellipsoid height estimation, classical leveling techniques for the orthometric height estimation and GGM geoid heights must refer to a common system as accurately as possible. The horizontal positions refer to WGS84 global system. As far as the vertical position is concerned, the adopted tide system is also of great importance. WGS84/ITRF uses the tide-free system while geoid height from certain models refers to zero-tide system (ITU-GRACE16, ITU-GGC16, GOCO05C, GOCO05S, GGM05C and GGM05G). In this study, the "conventional tide-free system" (IERS Conventions 2010) is used. The zero-tide geoid heights were transformed to the tide-free system according to:

$$\delta C_{2,0}^{TF} = \delta C_{2,0}^{ZT} + 3.1108 \cdot 10^{-8} \frac{0.3}{\sqrt{0.5}} \qquad (1)$$

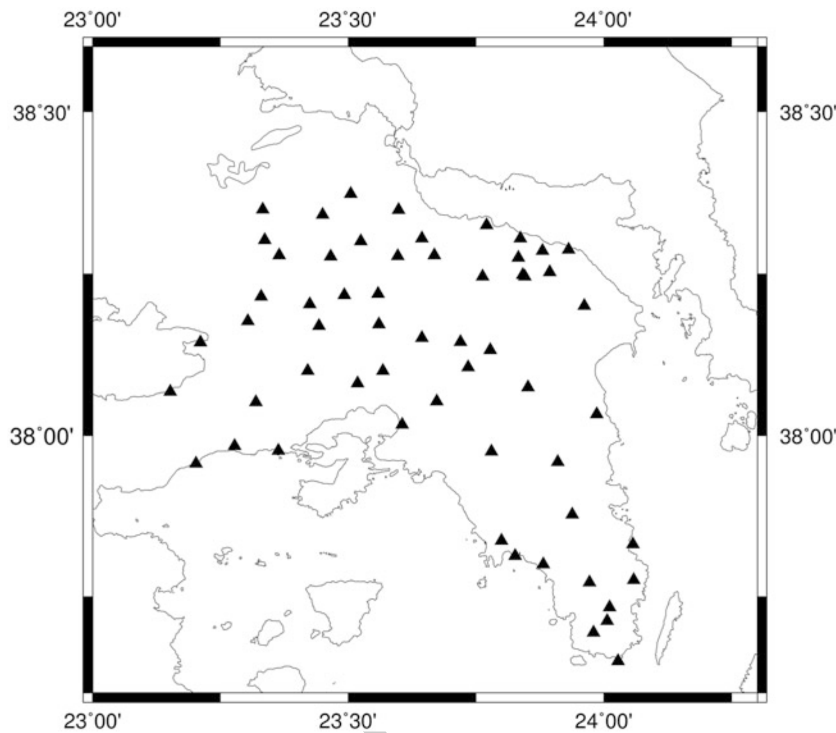

Fig. 1 The locations of the GPS/Levelling benchmarks in Attica

Table 1 The 12 GGMs used for the geoid height information

Satellite used	Model name	Max degree of expansion	Citation
GOCE only models	DIR ver. 4	260	Bruinsma et al. (2013)
	DIR ver. 5	300	Bruinsma et al. (2013)
	SPW ver. 4	280	Gatti et al. (2014)
	TIM ver. 4	250	~~Pail et al. (2016)~~
	TIM ver. 5	280	Brockmann et al. (2014)
GOCE, GRACE and CHAMP	EIGEN-6s4	300	~~Förste and Bruinsma~~ (2016)
	GOCO05c	720	Pail et al. (2016)
	GOCO05s	280	Mayer-Gürr et al. (2015)
GRACE and GRACE/GOCE	GGM05c	360	Ries et al. (2016)
	GGM05g	240	Bettadpur et al. (2015)
	ITU-GGC16	280	Akyilmaz et al. (2016a)
	ITU-GRACE16	180	Akyilmaz et al. (2016b)

Table 2 Difference between ASTER and SRTM-1 1 arcsec DTMs

(m)	max	min	mean	rms	sd
ASTER–SRTM1	167	−302	−3.628	7.379	8.223

Units in m

where $\delta C_{2,0}^{TF}$ is the 2nd degree harmonic coefficient of the disturbing potential in the tide-free system and $\delta C_{2,0}^{ZT}$ is the respective coefficient in the zero-tide system. The residual part of the equation is derived from the ellipsoid model constants and the position and mean gravity of the computation point (IERS Conventions 2010).

The mean-tide orthometric heights (H_{MT}) of the Hellenic Vertical Datum were also transformed to the tide-free system (H_{TF}) according to Ekman (1989):

$$H_{TF} = H_{MT} + (1 + k)\left(9.9 - 29.6\sin^2\varphi\right) \quad [cm] \qquad (2)$$

where k is the Love number and φ is the geodetic latitude of the point. The final complete contribution of the GGM to a specific degree was computed using:

$$N_{GGM} = \zeta + N_o + \frac{\Delta g_B}{\bar{\gamma}} H \qquad (3)$$

where $N_o = -0.4376m$ is the zero–degree harmonic on geoid heights w.r.t. WGS84, and the $\frac{\Delta g_B}{\gamma} H$ is the height anomaly to geoid height conversion term. The height anomaly ζ was computed from each model coefficients as:

$$\zeta(r, \vartheta, \lambda) = \frac{GM}{\gamma r} \sum_{n=2}^{n\,\max} \left(\frac{a}{r}\right)^n \sum_{m=0}^{n} \times \left(\delta \overline{C}_{nm} \cos m\lambda + \delta \overline{S}_{nm} \sin m\lambda\right) \overline{P}_{nm}(\cos\vartheta) \tag{4}$$

where r, ϑ, λ are the spherical coordinates of the point, γ is the normal gravity of the point and $\delta\overline{C}_{nm}$, $\delta\overline{S}_{nm}$, $\overline{P}_{nm}$ are the normalized spherical harmonic coefficients and Legendre functions of n degree and m order.

2.2.2 Combination Scheme and Heights Validation

The quality control of the GPS/Levelling benchmarks in Attica was achieved using a spectral enhancement approach (Vergos et al. 2014). In this method, EGM2008 is chosen as the reference GGM and the contribution of various GOCE/GRACE/CHAMP and surface gravity GGMs is taken into account in the low to medium frequency band. This enrichment of EGM2008 is calculated using an appropriate degree-step procedure. In this manner, the improvement of the newly available GGM can be considered w.r.t. the expansion degree of the tested model. In detail, the enhancement method can be divided into three steps:

Step a ➔ Geoid height of tested GGM i (N^i) is computed to a maximum degree of expansion n_1.

Step b ➔ Reference model EGM2008 ($N^{EGM2008}$) is used to fill-in medium and high frequency content (up to degree 2,190).

Step c ➔ Residual Terrain Modelling (N^{RTM}) effects complete the high and ultra high frequency information.

The residual geoid heights were computed using the following equation:

$$\Delta N = N^{GPS/Lev} - N^i\Big|_2^{n_1} - N^{EGM2008}\Big|_{n_1+1}^{2190} - N^{RTM} - N_o \tag{5}$$

A 10 degree step was used in the incorporation of the newly available test model information to the complete geoid spectrum. The signal of EGM2008 was substituted by the signal of the satellite-based model in successive different bands of the gravity spectrum from degree 2 to the maximum degree of the satellite model using the abovementioned degree step.

2.2.3 RTM Effects Consideration

The 1 arcsec detailed DTM information integrates the geoid signal to an expansion degree 648,000. The omission error in this combination procedure is below 1 mm based on the behavior of EGM2008 omission error model. The RTM effects computed from ASTER and SRTM1 DTMs are identical and the differences in the terrain effect to the geoid height are insignificant. The estimated RTM effects at the 59 GPS/Levelling benchmarks are presented in Fig. 2.

As seen from Fig. 2 the RTM effect to the geoid heights is below 3 mm, due to the small discrepancies of the terrain from the reference DTM used in the computations. This reference DTM is a mean surface used in RTM effects computations. A 5 arcmin resolution is chosen for this reference DTM according to the maximum degree of the geopotential model used.

3 Results and Discussion

The incorporation of the newly available models in EGM2008 signal resulted to improved statistics of the differences between GGM geoid heights and GPS/Levelling geoid heights at the tested benchmarks in Attica. Specifically, the assimilation of the frequency band 100–160 degree led to a significant improvement. The detailed model combination results are presented as follows.

3.1 GOCE Only Models

Both DIR, TIM and SPW GOCE solutions contributed significantly to the improvement of the EGM2008 geoid signal. In particular, when replacing the frequency content of EGM2008 at the low and medium band (maximum degree between 100 and 160) the improvement reached 1–2 cm in terms of the std. (standard deviation) of the differences at the benchmarks. In Fig. 3, the results of the assimilation of TIM-based solutions (version 4 and version 5) to the EGM2008 signal is presented.

The incorporation of GOCE TIM-R4 signal to the EGM2008 up to the maximum degree of 100–160 band led to improved statistics in terms of sd of the differences. For the frequency band 160–220, the results showed no difference with pure EGM2008 solution. In addition, the same improvement is noticed when the maximum degree of GOCE TIM-R4 model reached the 220–240 band. The 5th release of the model, although it incorporates more coefficients (maximum degree 280), showed that the assimilation of TIM-R5 signal above degree 240 led to worst

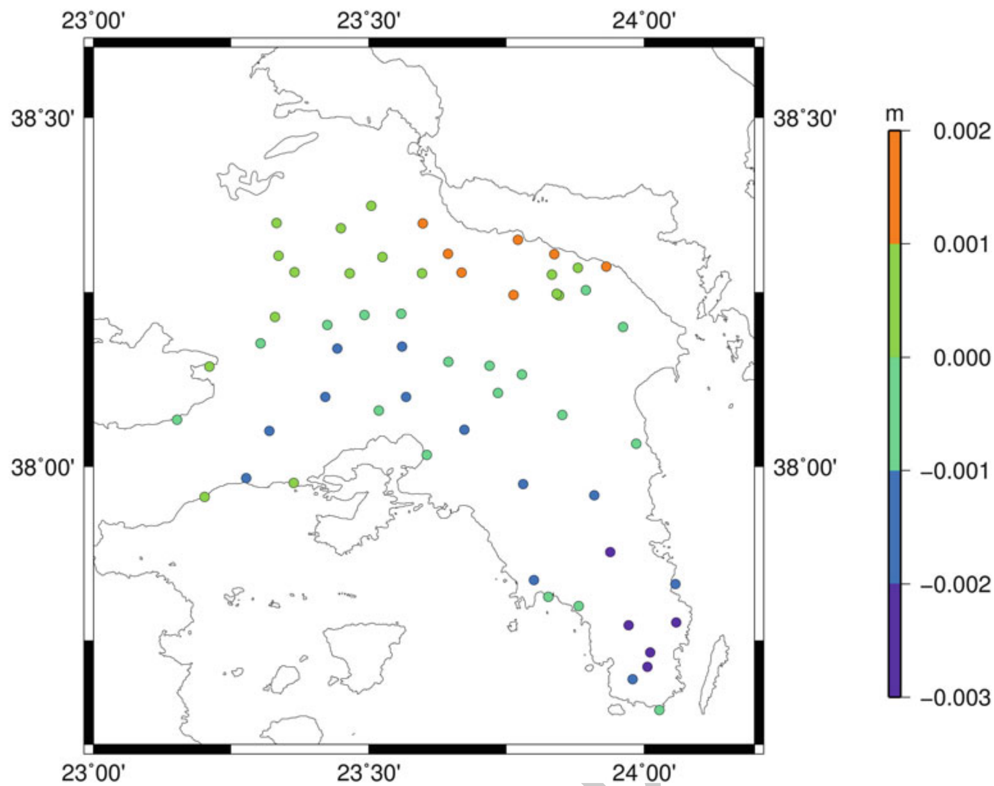

Fig. 2 The estimated RTM effects to the geoid height signal of the GPS/Levelling benchmarks using ASTER 1 arcsec DTM

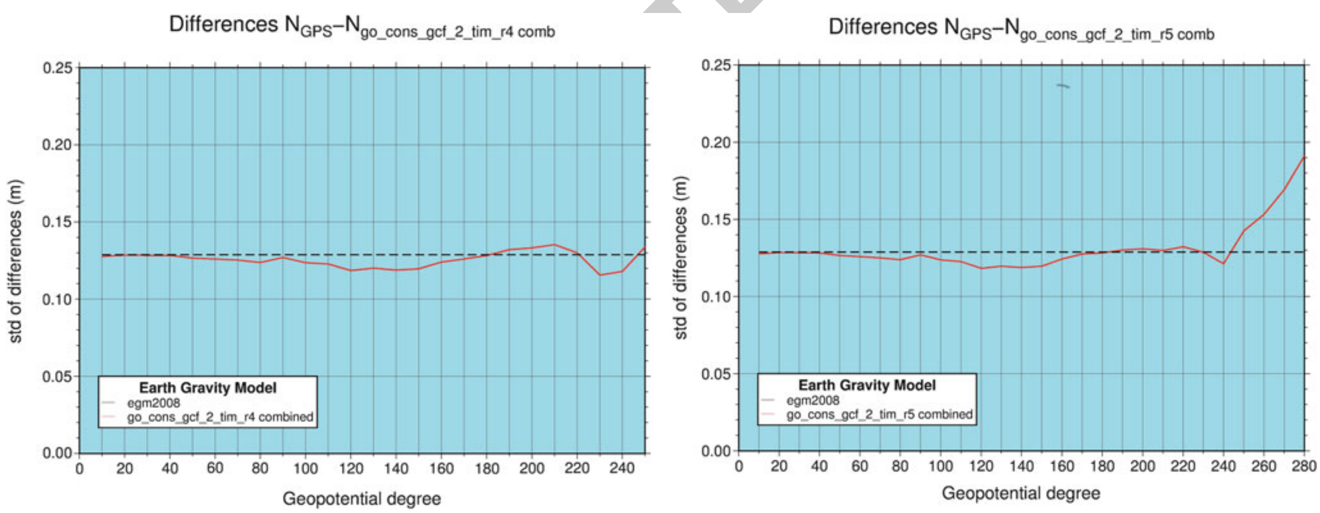

Fig. 3 The sd of the differences from the assimilation of GOCE TIM-R4 model (*left*) and GOCE TIM-R5 model (*right*) to the EGM2008 signal AQ5

results (see Fig. 3—right part). Similar results were noticed in all GOCE- only models. The incorporation of higher harmonics of the test models to the combination solution led to worst statistics. The differences at the 59 GPS/Leveling points are presented in Fig. 4. The maximum degree of the test model is 140 and 300, respectively (GOCE DIR ver. 5 model).

3.2 GOCE, GRACE and CHAMP Satellite and Combined Models

In this type of model, a constant improvement in the statistics of the differences at the GPS/Levelling benchmarks is noticed. The major improvement can be seen at the assimilation band of 100–160 degree. It is worth emphasiz-

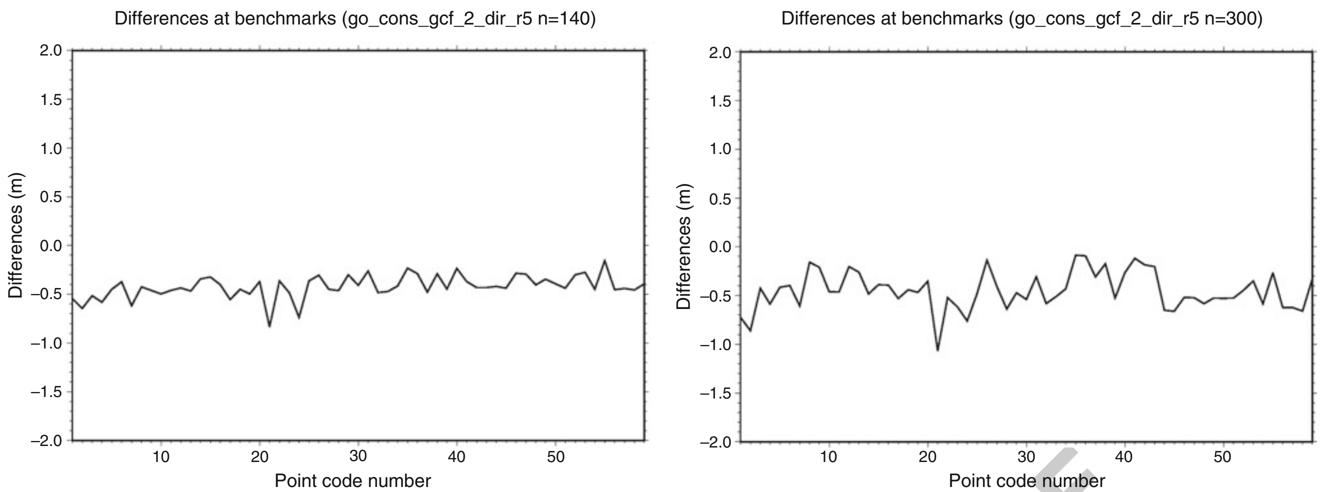

Fig. 4 Differences at the benchmarks using nmax = 140 (*left part*) and nmax = 300 (*right part*) in the assimilation of GOCE DIR-R5 model to EGM2008 signal

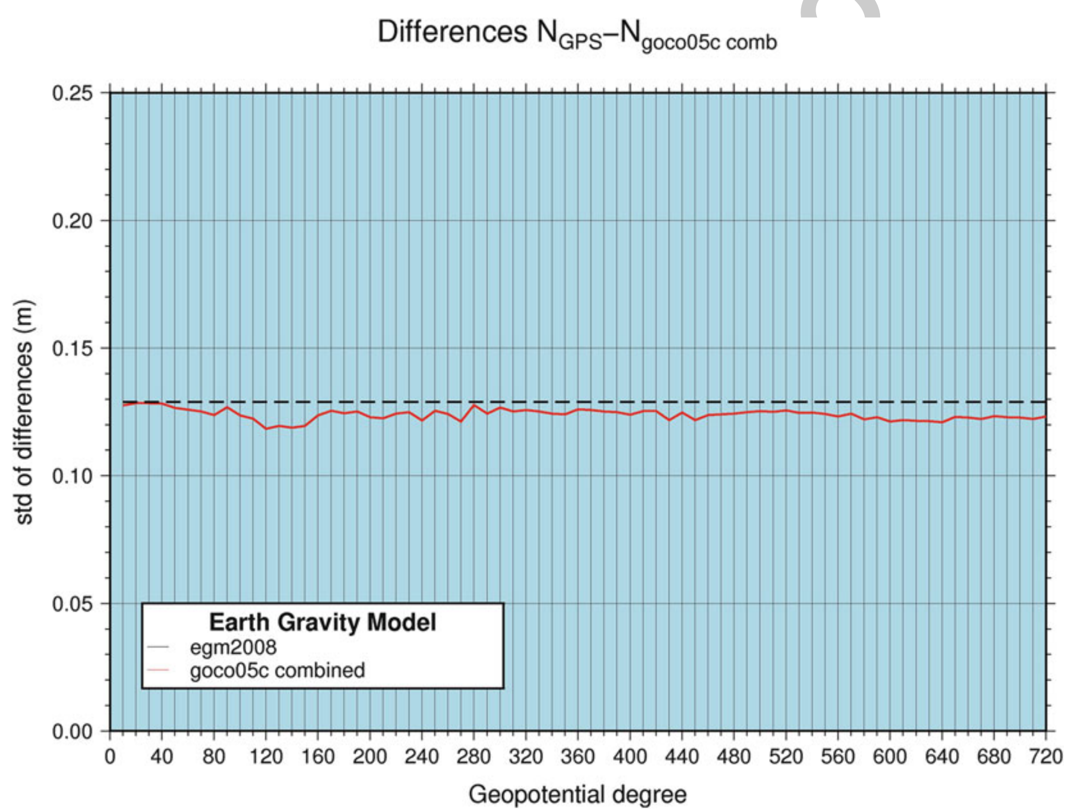

Fig. 5 The sd of the differences from the assimilation of GOCO05C model to the EGM2008 signal

ing the case of the GOCO05C model whereby the surface gravity data enriched the geoid signal in a manner that the assimilation of GOCO05C signal to EGM2008 heights led to statistical improvement regardless the maximum degree of expansion of the tested model. Figure 5 demonstrates the abovementioned statement.

3.3 GRACE: Only and GRACE/GOCE Combined Models

The same improvement in the assimilation band of degrees 100–160 is noticed in the results of GGM05C, GGM05G, ITU-GGC16 and ITU-GRACE16 models. The major differ-

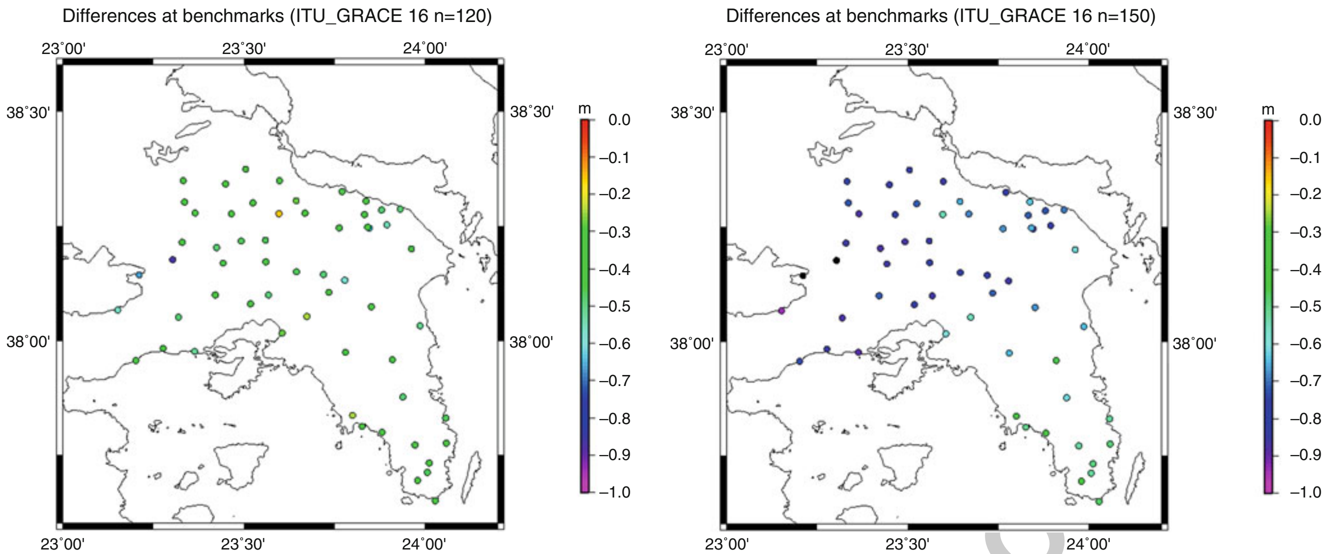

Fig. 6 The differences at the GPS/Levelling benchmarks when the assimilation degree of ITU-GRACE16 model reaches the maximum 120 (*left part*) and 150 (*right part*)

ence from all previous models is the case of GRACE – only model (ITU-GRACE16). This model performed well until the maximum degree of assimilation 120 but after the degree 150 it rapidly diverges. Figure 6 presents the differences at the GPS/Levelling benchmarks when the maximum degree of expansion of ITU-GRACE16 is 120 and 150.

3.4 Discussion on the Hellenic Vertical Network Quality

The enrichment of EGM2008 signal with the newly GGMs from GOCE, GRACE and CHAMP missions led to an improvement of 1–2 cm in terms of the sd of the differences at the benchmarks of the Hellenic Vertical Network. The estimated accuracy in the area of Attica from ±13 cm dropped to ±11 cm with the assimilation of the 100–160 frequency band of the new models (see also Andritsanos et al. 2014). The quality of this network can be validated accurately taking into account the estimated accuracy of GPS observations (various GPS solution strategies, e.g. Andritsanos et al. 2016a) and the computed geoid error through error propagation (Andritsanos et al. 2016b). The main drawback in this statistical procedure is the fact that the estimated accuracy of the orthometric heights of the Hellenic Vertical Network through an integrated adjustment is largely unknown and not scientifically documented. In this manner, only some assumptions can be made on the accuracy of the orthometric heights at the benchmarks (see, e.g., Vergos et al. 2014; Andritsanos et al. 2016b). A thorough study on the possible trends of the network (Andritsanos et al. 2016b) will reveal problematic areas and possible correlations with gravity based corrections. The W_o estimation for the Hellenic Vertical Network and its connection to the adopted value from IERS Conventions (2010) (Vergos et al. 2015) using recent satellite gravity dedicated missions is the contemporary alternative of tide gauge based network establishment. The local W_o estimation will provide an ideal solution to the numerous arbitrary height systems on the Greek islands.

4 Conclusions

The combination of newly available GOCE/GRACE global geopotential models with the reference model EGM2008 and adequate terrain information from RTM effects improved the statistics of geoid differences at GPS/Leveling benchmarks. The lower degree information from these models outperformed the satellite contribution of EGM2008. This improvement presented in the area of Attica can lead to the quality control of the Hellenic Vertical Datum. The sd of the differences at 59 newly measured GPS/Levelling benchmarks reaches ±11 cm after the enrichment of EGM2008 signal with GOCE, GRACE and CHAMP low to medium frequency information. The assimilation of the full signal of the tested models to the EGM2008 geoid heights led to worst results noticing that the absence of surface gravity data cannot be completely recovered by the attenuated satellite gravity signal. The case of GOCO05C, which incorporates surface data in its solution, corroborates the abovementioned statement.

References

Advanced Spaceborne Thermal Emission and Reflection Radiometer – ASTER Mission. Internet resources: https://asterweb.jpl.nasa.gov/index.asp

Andritsanos VD, Vergos GS, Grigoriadis VN, Pagounis V, Tziavos IN Spectral characteristics of the Hellenic vertical network – validation over Central and Northern Greece using GOCE/GRACE global geopotential models. Presented at the European Geosciences Union – General Assembly 2014, Vienna – Austria – April, 27th to May, 2nd 2014

Andritsanos VD, Grigoriadis VN, Vergos GS, Pagounis V, Tziavos IN (2015) GOCE/GRACE GGM evaluation over Attica and Thessaloniki, Greece and local geoid modelling in support of height unification. South-Eastern Eur J Earth Obs Geomatics 4

Andritsanos VD, Arabatzi O, Gianniou M, Pagounis V, Tziavos IN, Vergos GS, Zacharis E(2016a) Comparisons of various GPS processing solutions towards an efficient validation of the Hellenic vertical network: the ELEVATION project. J Surv Eng 142(1). http://dx.doi.org/10.1061/(ASCE)SU.1943-5428.0000164

Andritsanos VD, Grigoriadis VN, Natsiopoulos DA, Vergos GS, Gruber T, Fecher T (2016b) GOCE variance and covariance contribution to height unification. Presented at the GGHS 2016 Symposium, Thessaloniki 19–23 September

Akyilmaz O, Ustun A, Aydin C, Arslan N, Doganalp S, Guney C, Mercan H, Uygur SO, Uz M, Yagci O (2016a) ITU_GGC16 The combined global gravity field model including GRACE & GOCE data up to degree and order 280. http://doi.org/10.5880/icgem.2016.005

Akyilmaz O, Ustun A, Aydin C, Arslan N, Doganalp S, Guney C, Mercan H, Uygur SO, Uz M, Yagci O (2016b) ITU_GRACE16 The global gravity field model including GRACE data up to degree and order 180 of ITU and other collaborating institutions. http://doi.org/10.5880/icgem.2016.006

Bettadpur S, Ries J, Eanes R, Nagel P, Pie N, Poole S, Richter T, Save H (2015) Evaluation of the GGM05 Mean Earth Gravity models. In: Geophysical Research Abstracts, vol 17. EGU2015-4153

Brockmann JM, Zehentner N, Höck E, Pail R, Loth I, Mayer-Gürr T, Schuh W-D (2014) EGM_TIM_RL05: an independent geoid with centimeter accuracy purely based on the GOCE mission. Geophys Res Lett 41(22):8089–8099. doi:10.1002/2014GL061904

Bruinsma SL, Foerste C, Abrikosov O, Marty JC, Rio MH, 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

~~Förste C, Bruinsma SL (2016) EIGEN-6S4: a time-variable satellite-only gravity field model to d/o 300 based on LAGEOS, GRACE and GOCE data from the collaboration of GFZ Potsdam and GRGS Toulouse. http://doi.org/10.5880/icgem.2016.004~~

Ekman M (1989) Impacts of geodynamic phenomena on systems for height and gravity. Bull Geod 63(3):281–296

Gatti A, Reguzzoni M, Migliaccio F, Sanso F Space-wise grids of gravity gradients from GOCE data at nominal satellite altitude. Presented at the 5th GOCE User Workshop, Paris, 25–28 November 2014

Gianniou M (2008) "HEPOS: designing and implementing an RTK-Network", geoinformatics magazine for surveying, mapping & GIS professionals, Jan./Feb. 2008 vol 11, pp 10–13

Kotsakis C, Katsambalos K, Ampatzidis D, Gianniou M (2010) Evaluation of EGM08 using GPS and leveling heights in Greece; IAG Symposia vol 135, "Gravity, Geoid and Earth Observation", pp 481–488, Springer eds., doi: 10.1007/978-3-642-10634-7_64

Mayer-Gürr T, et al The combined satellite gravity field model GOCO05s. Presented at EGU General Assembly, Vienna, April, 2015

Milona-Kotroyianni E (1989) The 1st order leveling network in the Hellenic territory. Hellenic Army Geographic Service Internal Report

Pail R, Goiginger H, Mayrhofer R, Schuh W, Brockmann JM, Krasbutter I, Hoeck E, Fecher T (2010) GOCE gravity field model derived from orbit and gradiometry data applying the time-wise method. Presented at the ESA Living Planet Symposium 2010, Bergen, June 27–July 2, Bergen, Norway AQ6

Pail R, Gruber T, Fecher T, GOCO Project Team (2016) The Combined Gravity Model GOCO05c. http://doi.org/10.5880/icgem.2016.003

Pavlis NK, Holmes SA, Kenyon SC, Factor JK (2008) An Earth gravitational model to degree 2160: EGM2008. Presented at the 2008 General Assembly of the European Geosciences Union, Vienna, Austria, April 13–18

Ries J, Bettadpur S, Eanes R, Kang Z, Ko U, McCullough C, Nagel P, Pie N, Poole S, Richter T, Save H, Tapley B (2016) The combined gravity model GGM05C. http://dx.doi.org/10.5880/icgem.2016.002

Shuttle Radar Topography Mission Internet resources: http://www2.jpl.nasa.gov/srtm

Vergos GS, Grigoriadis VN, Tziavos IN, Kotsakis C (2014) Evaluation of GOCE/GRACE global geopotential models over Greece with collocated GPS/levelling observations and local gravity data. In: IAG Symposia, vol 141, pp 85–92. doi: 10.1007/978-3-319-10837-7_11

Vergos, GS, Andritsanos VD, Grigoriadis VN, Pagounis V, Tziavos IN (2015) Evaluation of GOCE/GRACE GGMs Over Attica and Thessaloniki, Greece, and Wo Determination for Height System Unification; IAG Symposia Series, Springer eds., doi: 10.1007/1345_2015_53

AUTHOR QUERIES

AQ1. Ref. “Milona-Kotroyanni 1989” has been changed to “Milona-Kotroyianni 1989”. Please check, and correct if necessary.
AQ2. Ref. “IERS Conversions 2010” is cited in the text but not provided in the reference list. Please provide it in the reference list or delete the citation from the text.
AQ3. Ref. “Förste et al. 2016” has been changed to “Förste and Bruinsma 2016”. Please check, and correct if necessary.
AQ4. Ref. “Akyilmaz et al. 2015a” has been changed to “Akyilmaz et al. 2016a, 2016b”. Please check, and correct if necessary.
AQ5. Please provide revised artwork of Fig. 3, as Text are small and we could not able to improve text size.
AQ6. Ref. “Pail et al.” is not cited in the text. Please provide the citation or delete it from the list.