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High-frequency analysis of Earth gravity field models based on terrestrial gravity and GPS/levelling data: a case study in Greece

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Abstract: The present study aims at the validation of global gravity field models through numerical investigation in gravity field functionals based on spherical harmonic synthesis of the geopotential models and the analysis of terrestrial data. We examine gravity models produced according to the latest approaches for gravity field recovery based on the principles of the Gravity field and steady-state Ocean Circulation Explorer (GOCE) and Gravity Recovery And Climate Experiment (GRACE) satellite missions. Furthermore, we evaluate the overall spectrum of the ultra-high degree combined gravity models EGM2008 and EIGEN-6C3stat. The terrestrial data consist of gravity and collocated GPS/levelling data in the overall Hellenic region. The software presented here implements the algorithm of spherical harmonic synthesis in a degree-wise cumulative sense. This approach may quantify the band-limited performance of the individual models by monitoring the degree-wise computed functionals against the terrestrial data. The degree-wise analysis performed yields insight in the short-wavelengths of the Earth gravity field as these are expressed by the high degree harmonics.

Keywords: GOCE; Gravity models; Gravimetry; GPS/levelling; Spherical harmonic synthesis

1 Introduction

The role of global gravity field models is fundamental in various research objectives such as precise orbit determination of LEOs (Low Earth Orbiters), geoid modelling and geophysical research. In such cases, the accuracy of the gravity field functionals based on the global models e.g. gravity anomaly or geoid height, has a major effect in the overall analysis and the results.

During the last decade, gravity field mapping has been based on the innovative techniques that were introduced by the Gravity Recovery And Climate Experiment (GRACE) and Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite missions (Tapley et al. 2004, ESA 1999, Floberghagen et al. 2011). The new space-borne techniques of the two satellite gravity missions have generated extended numerical investigations as well as the evolution of theoretical approaches in gravity field modelling. Therefore, a series of gravity field models according to various methodologies has been demonstrated during the last few years. The GRACE mission in-orbit since 2002 is implementing the concept of low-low satellite-to-satellite tracking while the GOCE mission materialized the concept of space gravity gradiometry in the period 2009-2013. In addition, the concept of a future satellite gravity mission is being studied (Loomis et al. 2012, Sheard et al. 2012, Panet et al. 2013, Elsaka et al. 2014) by considering the achievements as well as the limitations of the measurement principles and the orbital design of the two aforementioned missions. Thus, the validation of the gravity field models determined by the current adopted approaches is a critical aspect in the satellite gravity missions' performance.

The assessment of global gravity models may be investigated by a variety of quality tests such as the analysis of satellite orbits and terrestrial data (Förste et al. 2008, Arabelos and Tscherning 2010, Tapley et al. 2005, Featherstone 2001, Lemoine et al. 1998, Perosanz et al. 1997), space-borne data analysis (Hashemi Farahani et al. 2013a, Papanikolaou and Tsoulis 2014) or even spectral assessment and error analysis of the harmonics coefficients (Tsoulis and Patlakis 2013, Baur et al. 2014).

The present study aims at the validation of current gravity models through the numerical comparison between the terrestrial data and the gravity field functionals computed through the procedure of spherical harmonic synthesis of the geopotential models. We focus in the eval-

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uation of global gravity models that have been produced according to the current methodologies adopted in the gravity field recovery based on the principles of GOCE and GRACE satellite gravity missions. The satellite gravity models, that are analyzed here, are referred to approaches such as the short-arc method (Mayer-Gürr 2006, Mayer-Gürr 2010), the celestial mechanics approach (Beutler et al. 2010), the acceleration approach (Ditmar et al. 2006, Hashemi Farahani et al. 2013b) and the three major methods adopted in the frame of the European Space Agency (ESA) project GOCE High-level Processing Facility (Pail et al. 2011) i.e. the direct (Bruinsma et al. 2013), time-wise (Pail et al. 2010) and space-wise (Migliaccio et al. 2011) solutions of the Earth's gravity field.

We examine the GOCE-based satellite gravity models that may be distinguished in the GOCE-only models and the models that have been extracted by optimum combination of GOCE and GRACE data processing. In addition, we have elaborated state-of-the-art models compiled exclusively by GRACE observations.

Furthermore, we focus on evaluating the ultra-high degree combined gravity models i.e. the EGM2008 (Pavlis et al. 2012) and EIGEN-6C3stat models (Förste et al. 2013). These two models are analyzed here in their whole spectral content which is expressed by the overall spherical harmonics range.

The terrestrial data consist of gravity and GPS/levelling measurements in the overall Hellenic region. These data have been obtained from the database of the Hellenic Military Geographical Service (HMGS). The data have been derived in the frame of national projects that are described as follows.

Studies for the validation of GOCE-based gravity models through terrestrial data over various geographical regions have been carried out by Gruber et al. (2011), Hirt et al. (2011), Šprlák et al. (2012), Voigt and Denker (2014), Rexer et al. (2014). An evaluation of global gravity models over Greece can be found in Kotsakis and Katsambalos (2010), Vergos et al. (2012), etc.

The spherical harmonic synthesis for gravity field functionals is implemented here in a degree-wise cumulative sense. The algorithm of harmonic synthesis is repeated for each individual degree and we monitor the residuals of the terrestrial data to the computed values considering the global gravity models. Therefore, the proposed analysis scheme may quantify the band-limited performance of the individual models.

The aforementioned degree-wise cumulative approach has been previously applied for global gravity models validation through a scheme of dynamic orbit analysis by Papanikolaou and Tsoulis (2014).

2 Theoretical background

The basic tool for the synthetic evaluation of the Earth's gravity functionals is the expression of the gravitational potential V in terms of a spherical harmonic expansion (Heiskanen and Moritz 1967)

$$V = \frac{GM}{r} \times \sum_{n=0}^{\infty} \left(\frac{a_e}{r}\right)^n \sum_{m=0}^{n} \bar{P}_{nm}(\cos\theta)\left(\bar{C}_{nm}\cos(m\lambda) + \bar{S}_{nm}\sin(m\lambda)\right) \tag{1}$$

where GM is the product between the constant of gravitation G and the total Earth's mass M, a_e is the equatorial radius, (r, θ, λ) are the spherical coordinates of the computation point, $\bar{C}_{nm}$ and $\bar{S}_{nm}$ are the normalized spherical harmonic coefficients that are provided by the gravity model, and $\bar{P}_{nm}$ are the normalized associated Legendre functions with n and m denoting degree and order, respectively.

The Legendre functions are described in several textbooks e.g. Hobson (1931), Abramowitz and Stegun (1965), Heiskanen and Moritz (1967). The numerical stability and accuracy of the normalized associated Legendre functions presented in Eq. 1 is a critical computing problem (Bosch 2000, Claessens 2005, Montenbruck and Gill 2000), especially in the case of very high degree and order (Wittwer et al. 2008, Holmes and Featherstone 2002). The numerical stability is treated here by implementing appropriate recurrence relations into our source code that are recommended for this purpose (Montenbruck and Gill 2000).

The geoid undulation is given by the following equation (Heiskanen and Moritz 1967)

$$N(\varphi, \lambda) = \zeta_p(\varphi, \lambda, r) + \frac{\Delta g_B}{\bar{\gamma}} H \tag{2}$$

where Δg_B is the Bouger gravity anomaly, H is the orthometric height, p denotes the computation point with spherical coordinates (φ, λ, r) and $\bar{\gamma}$ is the average value of the normal gravity along the normal plumb line between telluroid and ellipsoid.

The height anomaly ζ_p, which expresses the distance between the computation point and the telluroid surface, is computed according to Bruns' formula

$$\zeta_p(\varphi, \lambda, r) = \frac{T_p - (W_0 - U_0)}{\gamma_p} \tag{3}$$

or equivalently

$$\zeta_p(\varphi, \lambda, r) = \frac{GM - GM_0}{r\gamma_p} - \frac{W_0 - U_0}{\gamma_p} + \frac{GM}{r\gamma_p} \times \sum_{n=2}^{\infty} \left(\frac{a_e}{r}\right)^n \sum_{m=0}^{n} \bar{P}_{nm}(\cos\theta)\left(d\bar{C}_{nm}\cos(m\lambda) + \bar{S}_{nm}\sin(m\lambda)\right) \tag{4}$$

where T_p is the disturbing potential, γ_p is the value of normal gravity at the point p and $d\bar{C}_{nm}$ are obtained from the differences between $\bar{C}_{nm}$ and $\bar{C}^e_{nm}(J_{2n}, m = 0)$ i.e. the coefficients of the zonal harmonics of the normal gravitational potential. In the present computations we consider the zonal harmonic coefficients for degree values equal to 2, 4, 6 and 8.

The W_0 and U_0 refer to the gravity potential of the actual and the normal gravity field respectively, while GM_0 is the geocentric gravitational constant of the normal gravity field. In the present study, we consider the values of GM_0 and U_0 with respect to the Geodetic Reference System 1980 (GRS80) which are given by Moritz (2000) and the W_0 value as it has been adopted by the International Earth Rotation and Reference Systems Service (IERS) Conventions (Petit and Luzum 2010). Moreover, our computations with respect to the WGS84 (World Geodetic System 1984) have shown small differences at sub-mm level in terms of geoid height.

The first term of Eq. 3)

$$N_0 = \frac{GM - GM_0}{r\gamma_p} - \frac{W_0 - U_0}{\gamma_p} \tag{5}$$

is known in the literature as the zero-degree term (Heiskanen and Moritz 1967).

The zero-degree term has been computed, within the study region, equal to −0.4422 meters with respect to GRS80.

Eq. 4 requires further analysis, prior to its implementation, in case where the ellipsoidal height of the computation point is not known as it is discussed in Rapp (1997). The steps for the additional reduction are well described by Rapp (1997) and Lemoine et al. (1998).

The Bouger gravity anomaly in Eq. 2 is obtained through the following reduction of the free-air gravity anomaly

$$\Delta g_B = \Delta g_{FA} - 0.1119H. \tag{6}$$

The free-air gravity anomaly Δg_{FA} is computed in terms of spherical harmonic expansion by the following equation

$$\Delta g_{FA} = \frac{GM}{r^2} \sum_{n=2}^{\infty} (n-1) \left(\frac{a_e}{r}\right)^n$$
$$\sum_{m=0}^{n} \bar{P}_{nm}(\cos\theta) \left(d\bar{C}_{nm}\cos(m\lambda) + \bar{S}_{nm}\sin(m\lambda)\right). \tag{7}$$

The equations presented in this section, which are expressed in spherical harmonic expansion series, are treated here in a degree-wise cumulative sense. We repeat the computational procedure for each degree and the expansion series are formed by using all previous harmonic coefficients up to that specific degree. This approach may reveal band-limited areas of the models' harmonics and represents the dynamic contribution of the coefficients belonging to an individual degree.

The gravity field models usually provide the series of the spherical harmonic coefficients $\bar{C}_{nm}$ and $\bar{S}_{nm}$ referring in the *tide free* system or "conventional tide free system" in a rigorous sense. This term assumes that the effects of all the constituents of the solid Earth and ocean tides have been removed. However, the gravity models may be referred in the "zero tide" system which contains the permanent part of the tides. In the current analysis, in order to be consistent with all models, the zero tide gravity models are converted in the tide free system. In this case, the permanent part of the tides is removed prior to the analysis according to the Earth tides modelling as it is extensively described in the IERS Conventions (Petit and Luzum 2010). For this purpose, we apply the required correction to the $\bar{C}_{20}$ coefficient that enters Eq. 1, 4 and 7

$$\bar{C}^{tf}_{20} = \bar{C}^{zt}_{20} - \Delta\bar{C}^{perm}_{20} \tag{8}$$

where $\Delta\bar{C}^{perm}_{20}$ is the correction, $\bar{C}^{zt}_{20}$ and $\bar{C}^{tf}_{20}$ are the zero-tide and tide-free coefficients correspondingly.

The respective correction is computed by taking in account the adopted formula by the IERS Conventions (Petit and Luzum 2010, Eq. 6.14)

$$\Delta\bar{C}^{perm}_{20} = \left(4.4228 \times 10^{-8}\right)(-0.31460)\,k_{20} \tag{9}$$

with k_{20} being a nominal Love number equal to 0.30190.

3 Data

The terrestrial data used in the present analysis have been provided by the Hellenic Military Geographical Service (HMGS) which established the national gravity, levelling and triangulation networks. Since the last decade, HMGS has maintained these networks by performing GPS and gravity surveys all over the Hellenic region. Here, we briefly describe the projects that have been performed and provided the gravity and GPS data used in the current analysis. Overall, the presented terrestrial data consist of 9658 gravity data points and 3293 co-located GPS/Levelling points.

3.1 GPS data

HMGS initialized the HEllenic GPS NETwork 2002 (HEGNET2002) project (Anagnostou 2007) in 2000. In the frame of this project, a national GPS network was established as it is illustrated in Fig. 1. The GPS measurements performed during 2000 and 2001 while the data was processed using Bernese GPS software (Dach et al. 2007). The measurements are referred to benchmarks of the national triangulation network. In particular, the HEGNET2002 network comprises the following data points that form the 1st order network.

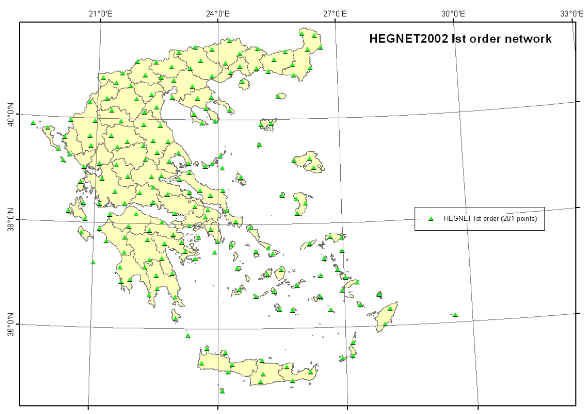

Figure 1: HEGNET2002 network referring in 1st order.

- the permanent GPS station DIONYSOS, defined as the network's reference station, which is considered in the International GNSS Service (IGS) network (Dow et al. 2009).
- 28 points at benchmarks of the national triangulation network that were adjusted as reference points.
- 201 points at benchmarks of the national triangulation network
- 9 points at tide gauges that have contributed in the SELF (Sea Level Fluctuations) project (Zerbini et al. 1996).
- 5 points at benchmarks where Satellite Laser Ranging (SLR) baselines have been measured in the frame of the WEGENER (Working group of European Geoscientists for the Establishment of Networks for Earth-science Research) project (Wilson 1996).

In 2004, HMGS initialized GPS and gravity surveys in order to cover the overall Hellenic region with spatial distribution of 8 points per 25 km × 25 km approximately. Since this project is still in progress, in the present analysis we use a part from these data that refers to the region of Central Greece and comprise 660 gravity and GPS data points that have been collected by field campaigns from 2004-2007.

In addition, we use here GPS data that have been collected in the frame of the Hellenic Positioning System (HEPOS) project (Gianniou 2010) which has been organized by the National Cadastre and Mapping Agency. These data consist of 2431 GPS points at benchmarks of the national triangulation network.

3.2 Levelling data

The Hellenic Vertical Datum was established by HMGS according to a Helmert-type orthometric height system. The orthometric heights of the national leveling network refer to one origin i.e. the tide gauge station placed at the Piraeus harbor. The measurements at this station during the period 1933-1978 were considered exclusively for the estimation of the local mean sea level (Takos 1989). The orthometric heights of the national triangulation network's benchmarks were estimated through spirit and trigonometric leveling ties with the national leveling network. Numerical investigations on the assessment of the Hellenic vertical datum have been carried out by Kotsakis et al. (2012), Grigoriadis et al. (2014) for the case of the Hellenic islands and Andritsanos et al. (2014), Tziavos et al. (2012) for selected regions in Central and Northen Greece.

Since the orthometric heights were estimated at the benchmarks of the triangulation network, the GPS observations performed at these points may yield geoid undulations with respect to the GPS/leveling technique

$$N^{GPS-lev} = h - H \tag{10}$$

where H denotes the orthometric height, h is the ellipsoidal height obtained by the GPS observations and $N^{GPS-lev}$ is the computed geoid undulation.

3.3 Gravity data

The national gravity network consists of 8 stations of zero order, 50 stations of 1^{st} order and 88 stations of 2^{nd} order, as shown in Fig. 2. The network is referred to the International Gravity Standardization Net 1971 (IGSN71) gravity datum (Morelli et al. 1974) through one reference station, i.e. the National Gravity Station located in Athens. The reference station has been connected through loops with gravity stations in Rome, Frankfurt and Addis Ababa which are part of the IGSN71 network.

In the frame of the aforementioned national field campaigns, gravity measurements were collected in parallel with the GPS survey as mentioned in Section 3.2. The measurements were observed by the relative gravimeters LaCoste & Romberg G730, G496, G63 and D107. Gravimetry observations were carried out by forming loops where the initial and final points have been selected as points of the gravity network. These data are provided as gravity values referred in the IGSN71 system.

Moreover, a set of 8998 gravity data points has been obtained from the database of the HMGS. These data were derived from past gravimetry surveys that were not performed at benchmarks of the triangulation/leveling network and the corresponding accuracy of the positioning and levelling is lower compared to the rest of the gravimetry field surveys. Therefore, this data set is applied in the present analysis separately in order to avoid systematic effects that may come from the reference system.

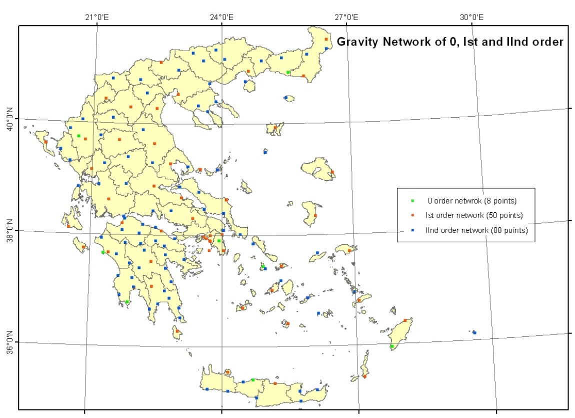

Figure 2: HMGS gravity network.

4 Computing and results

In the frame of the present computations, the *GRAVsynth* software for spherical harmonic synthesis has been developed by Papanikolaou (2013) with a part of the source code provided by Papanikolaou (2012). Our source code implements the harmonic synthesis for gravity field functionals i.e. the gravity anomaly, the height anomaly and the geoid undulation, according to the mathematical formulas described in Section 2. The computations run in a standard PC where the corresponding CPU time varies at about 4 hours for a data set of 9000 computation points based on harmonics series expansion with maximum degree up to 2000. Preliminary results of the current work have been reported in Papanikolaou and Papadopoulos (2013).

An accuracy assessment of our source code has been performed through comparison with the *HARMONIC_ SYNTH_ WGS84* software (Holmes and Pavlis 2008). The numerical comparison has led to differences in geoid heights that vary from 10^{-4} to 10^{-1} meters for the GPS/levelling data set of the 3293 computation points. It should be remarked that these discrepancies are partly affected by systematic differences in the adopted zero-degree term and the heights data sources.

Moreover, we have applied comparisons between GRAVsynth and the web-based calculation service (icgem.gfz-potsdam.de/ICGEM) of the International Centre of Global Earth Models (ICGEM). The numerical differences obtained for 65341 points in global scale, have yielded RMS values of 2 cm and 0.18 mgal in terms of geoid and free-air gravity anomalies, respectively.

The gravity field models that have been elaborated here are listed in Table 1 together with the type of data processed during the models' determination. The models are provided by the International Centre for Global Earth Models (ICGEM) according to the format of the ICGEM (Barthelmes and Förste 2011). We have analyzed the high-degree combined gravity models EGM2008 (Pavlis et al. 2012) and EIGEN-6C3stat (Förste et al. 2013), which is the latest available version of the European Improved Gravity model of the Earth by New techniques (EIGEN) series. In addition, we have considered satellite-only gravity models such as the latest releases of the GOCE models based on the direct (Bruinsma et al. 2013), time-wise (Pail et al. 2010) and space-wise (Migliaccio et al. 2011) approaches, the ITG-Goce02 (Schall et al. 2014) and JYY_GOCE04S (Yi et al. 2013) which are GOCE-only solutions, the DGM-1S (Hashemi Farahani et al. 2013b) and GOCO-03S (Mayer-Gürr et al. 2012) which are combined satellite-only models, the GGM05S (Tapley et al. 2013), AIUB-GRACE03S (Jäggi et al. 2012) and ITG-Grace2010s (Mayer-Gürr et al. 2010) which have been determined exclusively by GRACE observations analysis.

We have used the two latest ESA releases of the GOCE gravity models (Pail et al. 2011) i.e. the 4^{th} and 5^{th} releases, for the time-wise and direct approaches as well as the latest model of the space-wise approach that comes from the 2^{nd} release. In the following, we refer to these models by using the terms GOCE-DIR-Rx, GOCE-TIM-Rx and GOCE-SPW-Rx respectively for the three approaches and Rx denotes the particular release e.g. R5, R4, R2.

The latest GOCE release of time-wise and direct solutions i.e. the 5^{th} release (R5), has taken into account the entire data from the satellite mission's lifetime including the last low-orbit phase (GFCT 2014). During this last phase the orbital altitude has been decreased from the routine altitude of 260 km to 229 km. Therefore, the sensitivity of the GOCE observations analysis due to the Earth's gravitational perturbations has been increased. The strength of this sensitivity is pronounced in the present computations through the relative comparison of the results based on the R4 and R5 GOCE models.

Table 1: Satellite data and maximum degree of the used Earth gravity models.

Gravity Field Models	Degree	**Data type used** (x: yes / -: no)		
		Gravity	Altimetry	Satellite tracking
EGM2008	2190	x	x	GRACE
EIGEN-6C3stat	1949	x	x	GOCE, GRACE, LAGEOS
GO_ CONS_ GCF_ 2_ TIM_ R5	280	-	-	GOCE
GO_ CONS_ GCF_ 2_ DIR_ R5	300	-	-	GOCE, GRACE, LAGEOS
GO_ CONS_ GCF_ 2_ TIM_ R4	250	-	-	GOCE
GO_ CONS_ GCF_ 2_ DIR_ R4	260	-	-	GOCE, GRACE, LAGEOS
GO_ CONS_ GCF_ 2_ SPW_ R2	240	-	-	GOCE
ITG-Goce02	240	-	-	GOCE
JYY_ GOCE04S	230	-	-	GOCE
DGM-1S	250	-	-	GOCE, GRACE
GOCO-03S	250	-	-	GOCE, GRACE, CHAMP, SLR
GGM05S	160	-	-	GRACE
AIUB-GRACE03S	160	-	-	GRACE
ITG-Grace2010s	180	-	-	GRACE

The ITG-Goce02, GGM05S and ITG-Grace2010s models refer to the zero tide system and thus, we add the required correction in order to convert them to the tide free system according to the formula discussed in Section 2 (Eq. 9 and **??**).

According to the procedure of the spherical harmonic synthesis as presented in the previous sections, we have computed geoid undulations and free-air gravity anomalies at the data points presented in Section 3. The comparison between the values from the gravity models and the terrestrial gravity and GPS/leveling data, may be described by the following equations

$$\Delta N = N^{lev} - N^{GGM} = (h - H) - N^{GGM} \tag{11}$$

$$\Delta Dg = Dg^{fa}_{grav} - Dg^{fa}_{GGM} \tag{12}$$

where N_{GGM} is the geoid undulation computed by the global gravity model, H denotes the orthometric height, h refers to the ellipsoidal height obtained by the GPS observations and $N^{GPS-lev}$ denotes the geoid height by the GPS/levelling technique.

The terms Dg^{fa}_{grav} and Dg^{fa}_{GGM} denote the free-air gravity anomaly derived by the gravity data and the computed values based on the gravity models respectively.

The computations have been carried out for the three data sets described in Section 3 i.e. the 3293 GPS/leveling and 8998 gravity data points in the overall Hellenic region as well as the 660 gravity data points in the Central Greece. The two gravity data sets are applied individually in the computations since the corresponding campaign surveys were not performed according to common standards and thus, systematic differences may occur.

The numerical comparison between the gravity models and the terrestrial data has also been considered as a valuable tool in order to detect outliers. We have removed part of the data i.e. 45 points, by setting limits in maximum difference as outliers' limits i.e. 300 mgal and 5 meters for the differences in gravity anomalies and geoid heights respectively.

The numerical comparison is expressed by representative statistical quantities such as the root mean square (RMS), standard deviation, mean, maximum and minimum values. The respective results are shown in Tables 2 and 3.

In general, the gravity models derived from the combination of the GOCE and GRACE data has yielded a better fit according to the residuals of the gravity and the GPS/levelling data. The comparison among the GOCE R5 and R4 released models reveal the contribution of the additional GOCE data during the last phase of low-orbit (GFCT 2014). The lower orbital altitude provided sensitivity to the estimation of additional spherical harmonic coefficients at higher degree. Therefore, the R5 models are given at higher degree. This overall improvement has been captured in the present computations at the level cm- and 0.5 mgal level based on the GPS/levelling and gravity data residuals, respectively (Tables 2 and 3).

The space-wise model (GOCE-SPW-R2) presents higher residuals than the other GOCE-based models but leads to better results than the GRACE-only models. Nevertheless, the space-wise model has yielded low performance in the

Table 2: Statistics of the comparison between GPS/levelling data and geoid heights based on global gravity models after the estimation of a constant bias. Data refer to a set of 3293 data points over the Hellenic region. Maximum degree of its model is considered. Unit is meters.

Gravity Field Models	*RMS*	*bias*	*Min*	*Max*
EGM2008	0.278	0.692	−4.233	3.843
EIGEN-6C3stat	0.273	0.690	−4.301	3.930
GOCE-DIR-R5	0.552	0.818	−4.439	3.916
GOCE-DIR-R4	0.568	0.823	−4.455	3.831
GOCE-TIM-R5	0.567	0.813	−4.465	3.871
GOCE-TIM-R4	0.574	0.826	−4.591	3.876
GOCE-SPW-R2	0.643	0.862	−4.601	3.962
ITG-Goce02	0.612	0.8431	−4.4938	3.7642
JYY_ GOCE04S	0.609	0.8507	−4.5231	3.9242
DGM-1S	0.622	0.841	−4.634	3.936
GOCO-03S	0.604	0.841	−4.482	3.883
GGM05S	0.900	0.9124	−5.5884	3.9872
AIUB-GRACE03S	0.759	0.8904	−4.4836	2.7196
ITG-Grace2010s	0.759	0.911	−5.115	3.446

Table 3: Statistics of the comparison between gravity anomalies based on global gravity models and a data set of 8998 free-air gravity anomalies over Greece. Maximum degree of its model is considered. Unit is mgal.

Gravity Field Models	*RMS*	σ	*Mean*	*Min*	*Max*
EGM2008	21.96	20.56	7.70	−192.26	288.43
EIGEN-6C3stat	22.39	21.08	7.55	−186.16	285.37
GOCE-DIR-R5	44.94	40.81	18.82	−206.84	270.10
GOCE-DIR-R4	45.76	41.44	19.39	−204.12	260.35
GOCE-TIM-R5	45.16	41.09	18.75	−204.51	265.62
GOCE-TIM-R4	45.50	41.12	19.49	−199.61	263.43
GOCE-SPW-R2	48.69	43.46	21.96	−189.31	255.92
ITG-Goce02	47.16	42.54	20.37	−192.73	259.25
JYY_ GOCE04S	46.72	42.06	20.33	−193.19	257.16
DGM-1S	47.17	42.72	20.01	−192.15	260.56
GOCO-03S	46.70	42.13	20.16	−190.19	253.36
GGM05S	53.41	47.89	23.65	−186.82	254.50
AIUB-GRACE03S	51.87	46.27	23.45	−171.75	257.57
ITG-Grace2010s	51.89	46.15	23.71	−178.93	248.88

analysis of the GRACE satellites orbit and inter-satellite K-band ranging (KBR) observations (Papanikolaou and Tsoulis 2014).

The analysis of the GPS/levelling data reveals systematic errors that can be absorbed through the estimation of a constant bias (Table 2). The bias is estimated based on the least-squares method according to the equations of observations as follows:

$$N^{lev} = N^{GGM} + bias + v. \tag{13}$$

where v denotes the random errors.

The estimated bias varies from 70 to 90 cm for various geopotential models shown in Table 2. The bias' order of magnitude may imply the presence of systematic differences in the level surface of the vertical reference frame. As mentioned in Section 3.2, the present orthometric heights refer to the Hellenic Vertical Datum. The datum was established according to the local mean level estimated by the tide gauge station at the Piraeus harbor. Therefore, the bias may be interpreted as a level difference between the local mean sea level and the geoid approximated through a global gravity model. According to the present computations, the level of the heights has been found to be about

69 cm lower than the global geoid with respect to the high-degree gravity models.

However, further analysis is required for modelling the residuals between these two level surfaces which may include additional parameters for treating tilts and other systematic errors in heights systems. By estimating additional parameters the fitting of the global gravity models may improved in terms of geoid residuals. On the other hand, such parametric models may absorb part of the errors of the global gravity models. Since the scope of this study is the evaluation of the gravity models, we estimate only one constant bias parameter.

In particular, the bias is estimated to be 75 cm approximately for considering only the GPS/leveling data in Central Greece while in the overall Hellenic region the bias estimation is equal to 69 cm (Table 1). These values are valid for EGM2008 and EIGEN-6Cstat models up to their maximum degree. This small discrepancy in bias estimation is justified due to systematic differences in the Hellenic vertical datum among the mainland and islands (Kotsakis et al. 2012, Grigoriadis et al. 2014). Our bias estimation is in close agreement with Tziavos et al. (2012) who obtained a mean value of 75 cm for EGM2008 based on GPS/levelling data in the region of Thessaloniki in Northern Greece. Nevertheless, there are significant differences in comparison with the bias estimated by Kotsakis and Katsmbalos (2010) and Vergos et al. (2014).

The degree-wise cumulative analysis, as it has been discussed in Section 2, has been implemented for selected satellite-only gravity models as well as the EGM2008 and EIGEN-6C3stat combined gravity models. The degree interval between the sequential iterations of the harmonics synthesis algorithm has been set as 1. The data used refer to 660 gravity and GPS/levelling computation points in Central Greece. The corresponding results are illustrated in Fig. 3 to 8. The corresponding satellite-only models have been distinguished in the following selected groups for the application of the degree-wise cumulative analysis i.e. the models based on the time-wise, space-wise and direct approaches (Pail et al. 2011), the GOCE-only models, the GRACE-only models and the satellite gravity models based on the combination of GOCE and GRACE data analysis.

The two high-degree combined gravity models have been analyzed according to the degree-wise cumulative approach over the full degree range (Fig. 3 and 4). This analysis has captured the small RMS variations as a function of the truncated degree and may yield insights into the different spectral ranges of the ultra-high degree gravity models. The numerical comparison detects discrepancies over the degree 1000 that vary at the level of a few mm and 10^{-1} mgal in terms of RMS differences for the geoid height and gravity anomaly respectively. Moreover, the differences of the corresponding RMS values present wide variations in the degree bandwidth from 70 to 250 that may reach the level of a few cm and 0.3 mgal for geoid height and gravity anomaly respectively. Beyond degree 250, the RMS differences are getting smoother and reduced. This behavior implies the impact of incorporating the GOCE data incorporation in the EIGEN-6C3stat model. In particular, this reflects the major effect of the space-borne gravity gradiometry data that have been analyzed for gravity field modelling in the degree range from 0 to 235 (Förste et al. 2013). Furthermore, the threshold at degree 70 is affected by the combination algorithm for the various data included in the gravity field solutions of the EIGEN series (Förste et al. 2008). We should also mention that the satellite observations underlying the two combined models refer to the LAGEOS, GRACE and GOCE data analysis in the case of the EIGEN-6C3stat (Förste et al. 2013) while the ITG-GRACE03s model (Mayer-Gürr 2007), which is a GRACE-only model, has been incorporated in the case of EGM2008 (Pavlis et al. 2012).

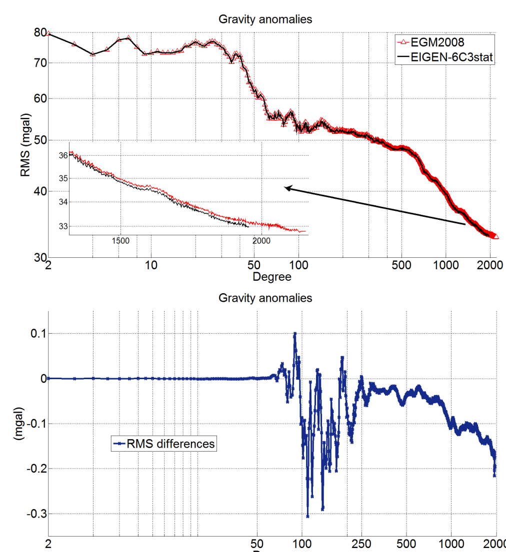

Figure 3: RMS variations in free-air gravity anomaly that have been obtained from comparison between terrestrial gravity data and computed values based on the EIGEN-6C3 and EGM2008 models. RMS differences (EIGEN-6C3 minus EGM2008) at the level of 10^{-1} mgal are monitored over the degree 1000 while wide discrepancies are occurred in the degree bandwidth 70 to 250.

In the case of the satellite-only gravity models, the degree-wise cumulative analysis has been oriented in the degree range from 100 up to the maximum degree of its individual model (Fig. 5 to 8). The differences in the monitored residuals, by means of the RMS differences, among

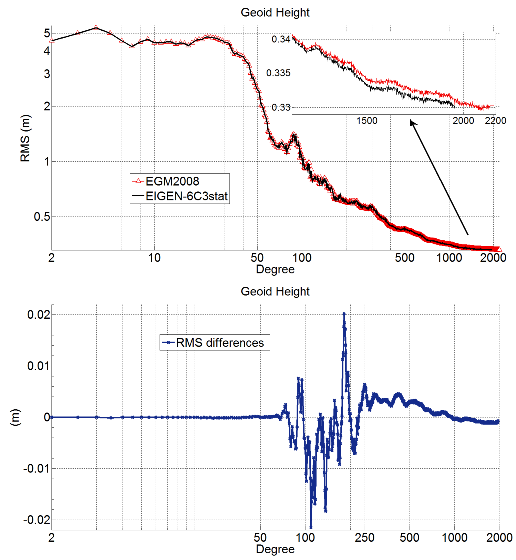

Figure 4: RMS variations in geoid undulation that have been obtained from comparison between terrestrial GPS/levelling data and computed values based on the EIGEN-6C3 and EGM2008 models. RMS differences (EIGEN-6C3 minus EGM2008) at the level of few mm are captured over the degree 1000 while wide discrepancies are occurred in the degree bandwidth 70 to 250.

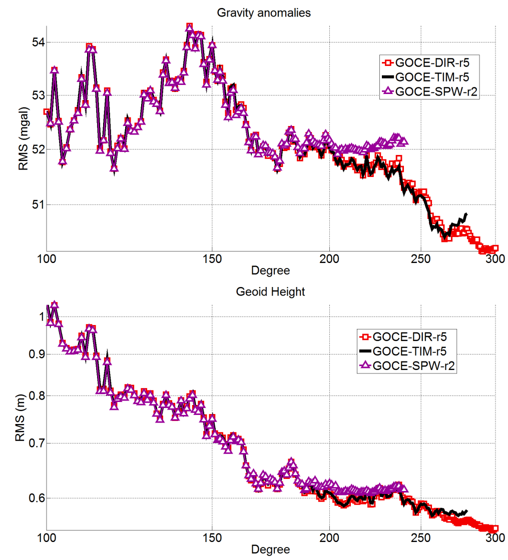

Figure 5: RMS variations in gravity anomaly and geoid height that have been obtained from comparison between terrestrial data and computed values based on the GOCE gravity models by the ESA latest releases. RMS differences at the level of 10^{-1} mgal and cm are monitored for the space-wise model over the degree 200.

the GOCE-based models are identified beyond degree 200 that may approach the level of a $3{\times}10^{-1}$ mgal and a few mm for the gravity and GPS/levelling data respectively (Fig. 5 to 7).

In the case of the GRACE-only gravity models (Fig. 8) the RMS discrepancies are captured beyond degree 150 while significant deterioration of the residuals are revealed over a threshold at degree 167 for ITG-GRACE2010s and GGM05S models.

In general, the latest GOCE-based models i.e. GOCE-DIR-R5 and GOCE-TIM-R5, have yielded the lowest residuals compared to the other satellite-only gravity models. This performance draws clearly the quality of the additional GOCE observations during the last low-orbit phase under the decreased orbital altitude (GFCT 2014).

The geographical distribution of the results based on the EGM2008 model is displayed in Fig. 9 to 11 along with the embedded frequency distribution. It should be pointed out that the residuals of the geoid heights have been computed prior to the bias estimation according to Eq. 13.

The current study focuses on the degree-wise analysis of the various global gravity models based on different approaches in gravity field modelling. The assessment of the gravity models is performed through a degree-by-degree comparison among the models in their overall degree range. Therefore, such analysis aims at investigating particular degree bandwidths of the gravity models.

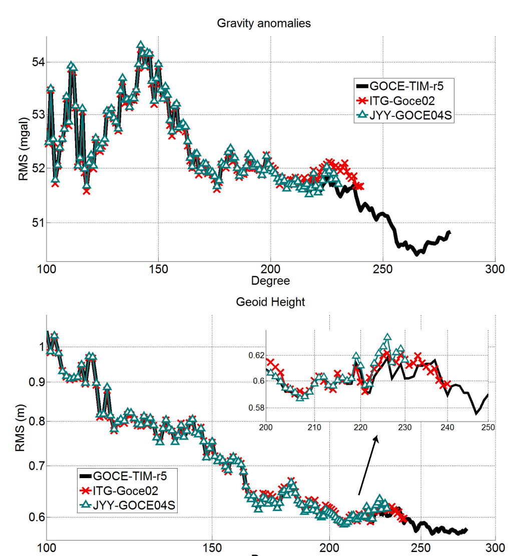

Figure 6: RMS variations in gravity anomaly and geoid height that have been obtained from comparison between terrestrial data and computed values based on GOCE-only extracted gravity models. RMS differences are captured over the degree 220.

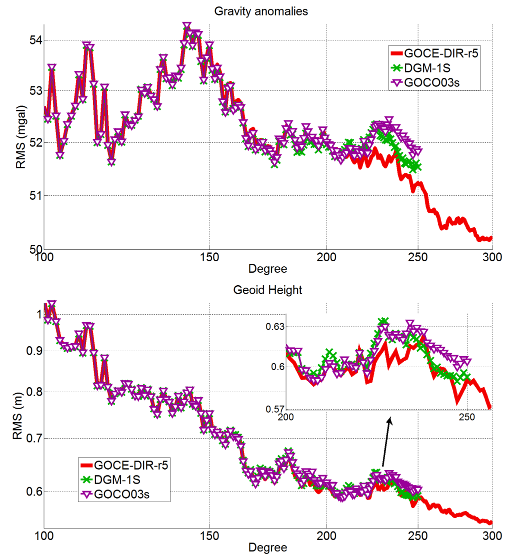

Figure 7: RMS variations in gravity anomaly and geoid height that have been obtained from comparison between terrestrial data and computed values based on gravity models derived from optimum combination of GRACE and GOCE data. RMS differences are captured over the degree 200.

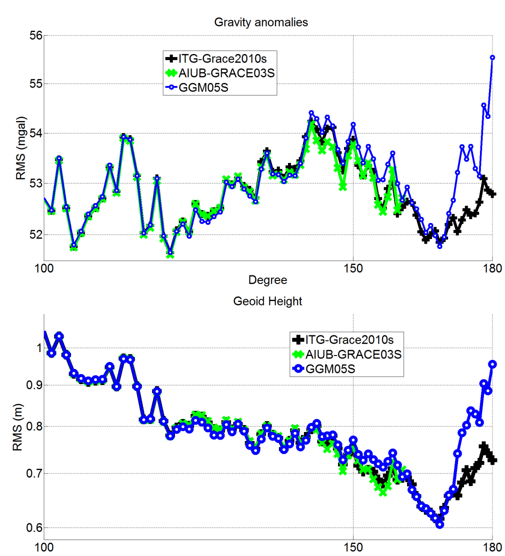

Figure 8: RMS variations in gravity anomaly and geoid height that have been obtained from comparison between terrestrial data and computed values based on GRACE-only extracted gravity models. RMS differences are captured over the degree 150 while significant deterioration of the residuals are revealed over a threshold at degree 167.

In the frame of the current investigation, we do not treat the omission error (Gruber et al. 2011, Sprlak et al. 2012). The order of magnitude of the omission error (Vergos et al. 2014) is lower than the actual gravity signal captured by the gravity models and thus, it does not affect in a major sense the conclusions of the present analysis.

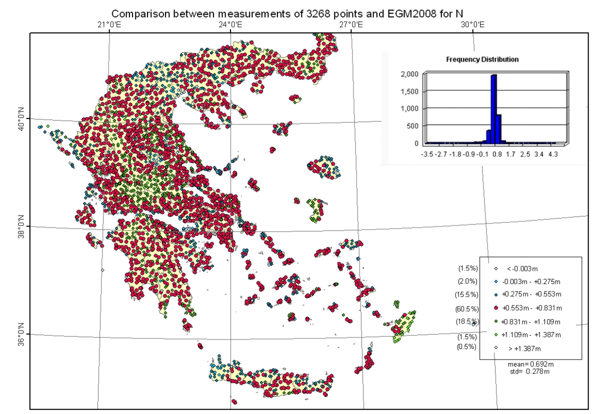

Figure 9: Geographical distribution of the geoid heights' residuals based on EGM2008 computed values and GPS/levelling data. Data refer to 3268 data points over the Hellenic region.

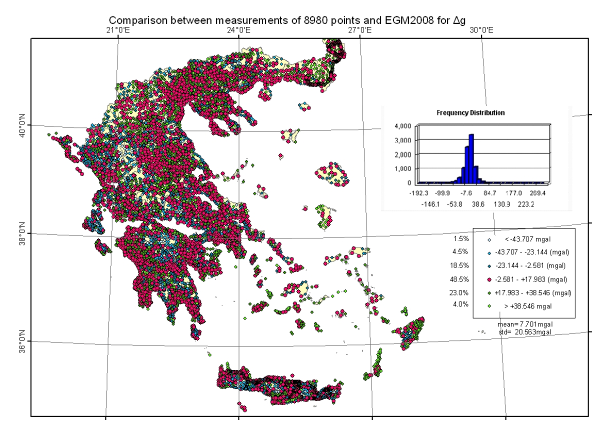

Figure 10: Geographical distribution of residuals in free-air gravity anomalies based on EGM2008 and terrestrial gravity data. Data refer to 8980 data points over the Hellenic region.

5 Summary and conclusions

The present study provides a validation of current global gravity models and a relative comparison among them in order to evaluate the different approaches in gravity field modelling. In particular, the present investigation focuses

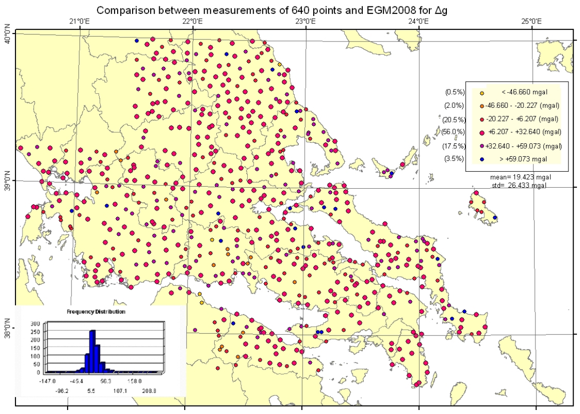

Figure 11: Geographical distribution of residuals between free-air gravity anomalies based on EGM2008 and terrestrial gravity data over 660 points in the Central Greece.

on the assessment of the GOCE-based gravity models for capturing the contribution of the latest satellite gravity mission in Earth's gravity field recovery.

We have implemented a computing procedure for spherical harmonic synthesis in a degree-wise cumulative sense. Based on such approach, we aim at quantifying the band-limited performance of the individual gravity models and detecting degree bandwidths and thresholds that reveal particular characteristics of the Earth gravity field solutions. We have been monitoring the residuals of the degree-wise computed gravity field functionals against the terrestrial data and record the variations of the RMS as a function of the harmonics degree.

We applied the degree-wise approach to the latest GOCE-based satellite gravity models as well as to the ultra-high degree combined models. The proposed analysis reveals specific degrees within the models where significant discrepancies are occurring. This approach has been demonstrated as a valuable tool in the assessment of the gravity models over the harmonics range even to high degrees beyond 2000.

In general, the combination of GRACE and GOCE data analysis led to significant improvement in the Earth's gravity field modelling. This is quite pronounced in the comparison of the GOCE-GRACE satellite gravity models against the state-of-the-art GRACE-only models.

The current analysis is oriented to the high frequencies of the Earth's gravity field as these are expressed by the higher degrees of the geopotential models. The comparison among the ultra-high degree gravity models EGM2008 and EIGEN-6C3stat, demonstrates that the second model which has included GOCE observations leads to slightly better results in terms of the data residuals within the study region. This low improvement is better outlined in harmonics degrees higher than 1000. Moreover, a threshold in degrees around 200 has shown detectable differences in the different approaches of the GOCE-based gravity models while a degree threshold equal to 167 has revealed significant deterioration of the GRACE-only models' performance.

The validation procedure is carried out through the numerical comparison between computed gravity field functionals and terrestrial data i.e. gravity and GPS/levelling data over the Hellenic region. Therefore the current analysis exhibit the fitting level of the current gravity models in Greece based on the latest data sets that have been collected in national gravity and GPS surveys during the last decade.

Furthermore, the terrestrial gravity data have been found to be sensitive as an evaluation test even to the higher degree harmonics. This is justified due to the effect of the Earth gravity field frequencies in the measured gravity signal by the gravimeters. Vice versa, the high-degree combined gravity models e.g. EGM2008 and EIGEN-6C3stat, may define a valuable tool for the detection of significant errors in the terrestrial data and thus, remove them as outliers. Even further, the high-degree models yield geoid undulation residuals of the GPS/levelling data that may reveal systematic errors of the local height system and the adopted mean sea level. In particular, it has been found according to the current analysis that the level of the used orhtometric heights, based on the mean sea level of the study region, has been estimated to be lower by about 69 cm than the geoid approximated by the EGM2008 or EIGEN-6C3stat gravity field models.

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