Assessing the GOCE models accuracy in the Mediterranean area

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Abstract

The GOCE satellite mission has significantly improved the results obtained with the previous satellite missions CHAMP and GRACE. Using GOCE data satellite Global Geopotential Models were developed using three different approaches, namely the direct, the time-wise and the space-wise approaches. The last releases of these models are complete to degree and order 300 (direct approach) and 280 (time-wise and space-wise approaches). In this paper, the different releases of the three estimation methodologies are compared with observed gravity and GPS/levelling data in the Mediterranean area and in particular, the Italian and Greek databases are considered. Comparisons are also carried out with respect to EGM2008 in order to check for possible improvements in the medium frequencies. For the validation of GOCE and GOCE/GRACE models, the spectral enhancement approach has been used, during which the models are augmented with EGM2008, up to its full degree of expansion, and terrain effects. These enhanced GOCE/GRACE geoid heights and gravity anomalies are then compared with the local data and statistics of the residuals have been computed. These comparisons show that significant improvements are obtained when Greek data are considered while the same doesn’t occur with the Italian data.

Key words: GOCE Global Geopotential Models, gravity data, GPS/levelling undulations

1 Introduction

The Gravity field and Ocean Circulation Explorer (GOCE, ESA 1999) Earth Explorer mission of the European Space Agency (ESA) started on March 17th, 2009 when the GOCE satellite was launched from the Plesetsk cosmodrome in Russia. It was launched on a quasi-circular, quasi-polar orbit (having an inclination i = 96.7°) at an altitude of about 250 km. As it is well known, this mission was devoted to the estimation of the Earth’s gravity field based on the principle of gradiometric measurements (Floberghagen et al. 2011). The GOCE spacecraft carried an array of three pairs of tri-axial electrostatic accelerometers arranged along three orthogonal axes, constituting a gradiometer allowing the estimation of the second derivatives of the gravitational potential. The mission ended on November 11th, 2013 after more than four and a half years (much more than the official schedule which was planned on a two years lifetime).
The observations collected during the GOCE mission have been treated according to different data analysis strategies. Three methods were officially devised for handling the data and estimating satellite only global geopotential models: the direct approach (DIR; Bruinsma et al., 2013), the time-wise approach (TIM; Pail et al., 2011) and the space-wise approach

(SPW; Migliaccio et al., 2004). In addition to these official approaches, others have been proposed, e.g. those by Yi (2012) and Schall et al. (2014). In recent years, several releases of these GOCE models have been computed. The first GOCE-only model was computed in July 2010 (to degree and order 224; Pail et al. 2010) while the latest models (released in July 2014) extend up to harmonic degree and order 280 (TIM and SPW) and 300 (DIR). The mission objectives of GOCE were aiming at an accuracy of 1 cm and 1 mGal for spatial wavelengths of 100 km (Floberhagen et al. 2011). The latest, release 5 models, reach a cumulative geoid error of 1 cm at d/o 207 (DIR-R5) and d/o 145 (TIM-R5). It should be noted that these numbers refer to the formal internal accuracy of the models as derived from the error degree variances of their spherical harmonic coefficients. Improvements from the first to the last releases are mainly based on the increasing number of processed data and, in the case of the last releases, also on the lower orbits of the GOCE satellite. Up to now (beginning of 2015), five releases of the time-wise and direct approaches have been computed (Brockmann et al., 2014; Bruinsma et al., 2014). The estimated space-wise releases are three and the last one is described in Gatti et al. (2014).
In this paper, these GOCE based global geopotential models are compared with observed gravity data and GPS/levelling derived undulations, using the spectral enhancement method, as previously done by, e.g. Gruber et al. (2011), Šprlák et al. (2012), Tocho et al. (2014), Vergos et al. (2014) and Yi and Rummel (2014). In these studies, it was found that the main contribution from GOCE, as far as the Release 2 and Release 3 models are concerned, is up to d/o 180-190 and 195-220, respectively. Within the present study, data in the central Mediterranean area, covering Italy and the surrounding areas, and Greece are considered in these comparisons and checked against the EGM2008 global geopotential model (Pavlis et al., 2012).

2 The Italian and the Greek databases

2.1 The Italian gravity, GPS/leveling data and the DTM used for the validation

The Italian gravity data set is based on a collection of data coming from different sources. Data have been collected on a long time span (mostly between the fifties and the seventies) and have thus different precisions and accuracies that cannot be properly assessed due to lack of metadata (in a very loose way, it can be stated that the mean precision is around 0.5 mgal). They are also referred to different horizontal, vertical and gravimetric reference systems. In the framework of the Italian geoid computation, they have been homogenized for coordinate and gravimetric reference systems and checked for possible outliers (Barzaghi et al., 2007). This gravity database covers the area $5° \leq \lambda \leq 20°$, $35° \leq \varphi \leq 49°$ and contains 450,336 values which implies a mean spatial density between gravity points of 20”. The horizontal coordinates are referred to the ETRS89 reference system while orthometric heights are given in the Italian height system originating, for the peninsular part of Italy, at the Genova tide gauge (Sicily and Sardinia height networks are referred to Catania and Cagliari tide gauges, respectively). Gravity data are framed to the IGSN71/GRS80 system. The plot of the Italian gravity data is shown in Figure 1 while Mean, Standard Deviation (St. Dev.), Minimum and Maximum of the gravity anomalies are listed in Table 1. It must be also mentioned that the Italian gravity database has been included (to an unknown extent) in the database for EGM2008 computation.
GPS/levelling data have been surveyed by IGM (Istituto Geografico Militare) in the framework of the Italian GNSS reference network IGM95 (Surace, 1997). This network consists of more than 2000 points having a mean distance between points that was originally of about 20 km. In the past decade, the network has been densified to reach a mean distance

between points of about 7.5 km. The last adjustment of the network has been computed by IGM at the beginning of 2009 in the ETRF2000(2008.0) frame. The mean precision in each of the three coordinates is around 5 cm (1σ). In the peninsular part of Italy, 977 benchmarks of this network have been levelled with high precision spirit levelling thus allowing the estimation of geoid undulations. The distribution of these GPS/levelling points is plotted in Figure 2 and the statistics are shown in Table 1. These values will be considered in the comparisons. GPS/levelling points over Sicily and Sardinia will not be considered to avoid in-homogeneities among the data (as mentioned, they refer to different tide gauges).

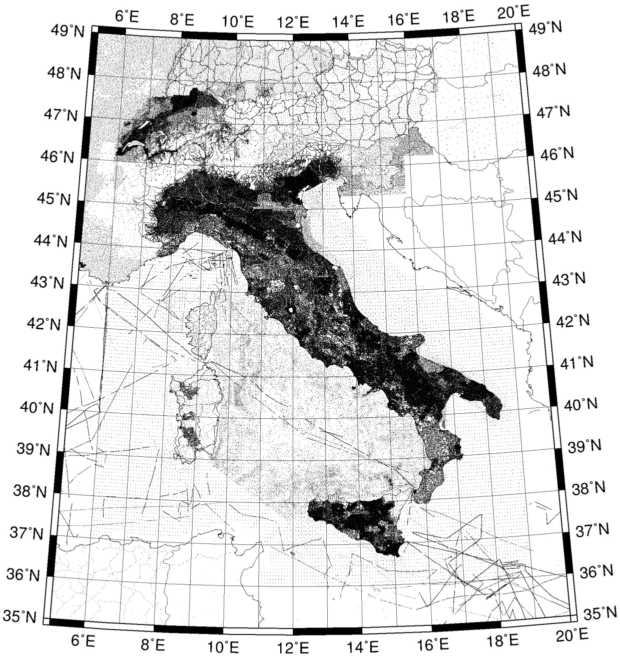

Figure 1: The Italian gravity database

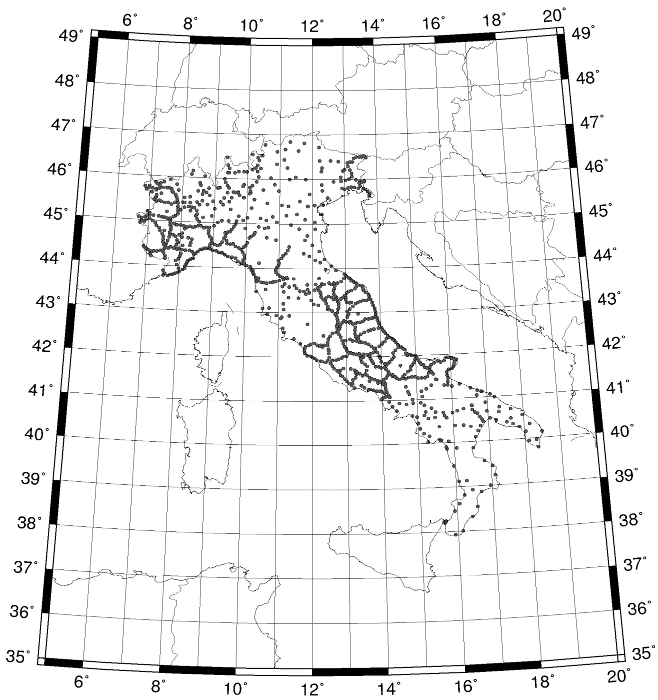

Figure 2: The GPS/leveling points over the Italian area (mainland)

Table 1: Statistics of the original free-air gravity anomalies and GPS/Levelling geoid heights in the Italian area

	Mean	St. Dev.	Min	Max
Δg_{obs}(mGal)	10.660	60.601	-163.200	269.710
$N^{GPS/Lev}$ (m)	46.635	3.431	36.378	54.805

The DTM compiled for estimating the last Italian geoid ITALGEO05 (Barzaghi et al., 2007) has been considered for the GOCE models validation. This DTM is mainly based on the SRTM3 (Shuttle Radar Topography Mission, http://dds.cr.usgs.gov/srtm/) at the spatial resolution of 3” × 3”. Other considered sources of information are:

- the Italian DTM (based on map digitalization) that has been used to fill the gaps in the Italian land region and for a strip of bathymetry near the coasts, where high resolution digitalised bathymetry is available;
- the 1’ × 1’ NOAA bathymetry (https://128.160.23.42/dbdbv/dbvquery.html) that has been used in deep seas areas;
- the GTOPO30 DTM (http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html) that has been considered for the remaining areas with no data.

The area covered by this DTM/bathymetry model is $3° \leq \lambda \leq 22°$, $33° \leq \varphi \leq 50°$ and, on each side, is at least 1° larger than the area containing gravity data and GPS/levelling data. The resulting grid has a regular geographical mesh of 3” × 3” (Borghi et al., 2007).

2.2 The Greek gravity, GPS/leveling data and the DTM used for the validation

The local data used over the Greek territory, refer to gravity anomaly data and GPS/Levelling observations covering the entire part of continental Greece and the surrounding marine areas. As far as the gravity anomaly data are concerned, they come from a local gravity database that has been compiled in the frame of the determination of a new Greek geoid model (Tziavos et al., 2012; 2013). This set comprises a number of 294,777 irregular point free-air gravity anomalies (cf. Tziavos et al., 2010) covering the entire Hellenic territory (islands included) as well as parts of the neighbouring Balkan countries. Their accuracy (estimated through least-squares prediction) is at the ±2.25 mGal level, and they are framed to IGSN71/GRS80 with a mean density of ~2’’ . It should be noted that this is not the formal accuracy of the data, which is largely unknown, but the standard deviation of the differences after least-squares prediction. The formal accuracy of the Greek gravity data is unknown, since they have been collected over the past decades, from the early ‘50s to late ‘80s, with different instrumentation and measurement procedures and from different research groups. Therefore, their real accuracy cannot be accessed, given that in most cases no metadata are available. On the other hand, it should be within the 0.5 mGal level, given that the relative gravity surveys carried out were performed, in most cases, by forming loops, where the first and the last points of these loops belonged to the Greek gravity network. The available gravity data over Greece are presented in Figure 3.

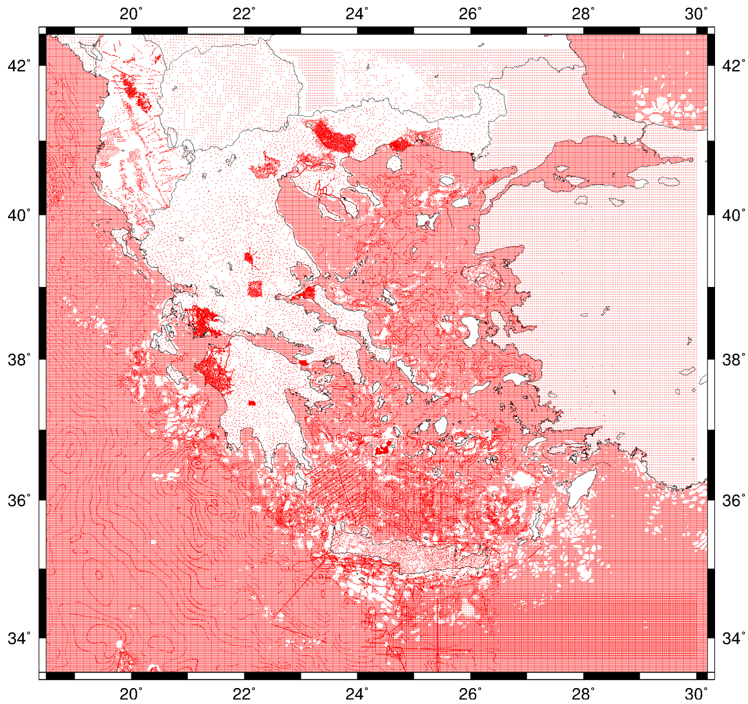

Figure 3: The Greek gravity database (294,777 irregular points)

The set of collocated GPS and Levelling data on Benchmarks (BMs) (1542 BMs) is based on historical orthometric heights from the HMGS (Hellenic Military Geographic Service) measured during the establishment of the Hellenic Vertical Datum (HVD) and ellipsoidal heights collected within the HEPOS (Hellenic Positioning System) project (Gianniou, 2008). The HVD in principle models the physical heights as Helmert orthometric heights, while their tie is to the tide-gauge station situated at Piraeus harbour, so that the HVD origin is relative to a MSL determined with sea level measurements for the period 1933-1978. Today, the true accuracy of the HVD is unknown, since a) it was not uniformly adjusted, b) it is not maintained by HMGS, and c) the formal errors provided by HMGS are ambiguous and over optimistic (Kotsakis and Katsampalos, 2010; Tziavos et al., 2012; Vergos et al., 2014). 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 1-4 cm (1σ) and 2-5 cm (1σ), respectively (Gianniou, 2008; Kotsakis and Katsampalos, 2010). The available GPS/Leveling BMs are evenly distributed within 22x28 km blocks over the entire country, so that in each block there are at least eight BMs (implying a mean distance of 8.8 km), where both orthometric heights are available and ellipsoidal heights have been measured. It should be noted that the orthometric heights refer to the mean-tide (MT) system, so their conversion to the TF system has been performed according to Ekman (1989). The distribution of the available GPS/Leveling data over Greece is shown in Figure 4. The statistics of these values are collected in Table 2.

Table 2: Statistics of the original free-air gravity anomalies and GPS/Leveling geoid heights over Greece.

	Mean	**St. Dev.**	**Min**	**Max**
Δg_{obs}(mGal)	-22.731	74.118	-236.099	269.927
$N^{GPS/Lev}$ (m)	35.605	5.762	19.485	43.883

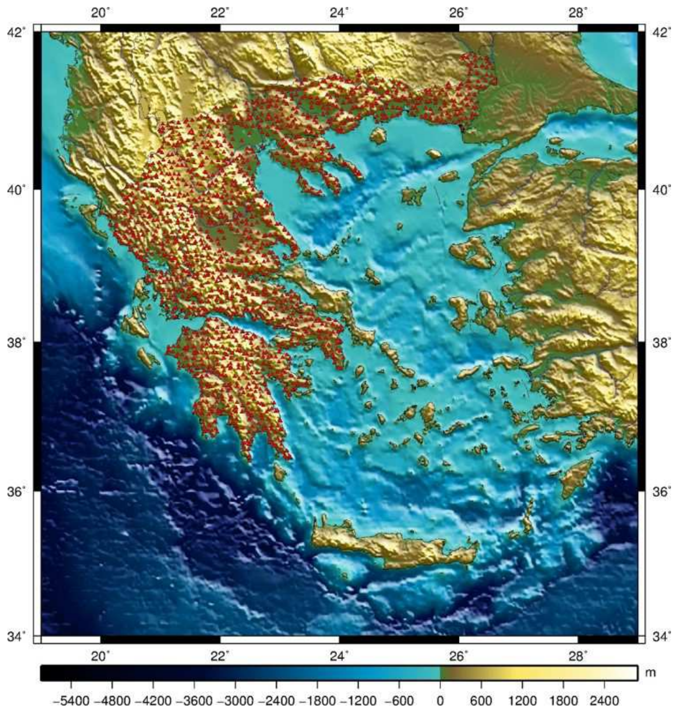

Figure 4: The GPS/leveling points in Greece (1542 BMs)

The topography and bathymetry model used for the GOCE models validation has been estimated for the entire Greek territory aiming at the determination of a new gravimetric geoid model for Greece (Tziavos et al., 2010). It has been based on the 3″×3″ SRTM data over continental Greece, while voids have been filled with data from available local DTMs from the HMGS. Over other countries, bicubic spline interpolation has been used due to the unavailability of local DTMs in order to fill-in voids in the original SRTM database. This resulted in the estimation of a new 3″ SRTM DTM model over all land areas in Greece (SRTMGr) within the region bounded between $30.5° \leq \varphi \leq 44.5°$ and $16.5° \leq \lambda \leq 33.0°$. In order to estimate terrain effects for marine areas as well, the SRTMGr model has been augmented with the latest bathymetry models by the Danish National Space Agency-DTU2010 (Andersen, 2010) and the Scripps Institute of Oceanography-SIOv11.1 (Smith and Sandwell 1997). Note that the DBMs (Digital Bathymetry Models) have a spatial resolution of 1′ only, so they have been re-gridded to agree with the 3″ spatial resolution of the SRTMGr model on land. A careful editing has been performed across the land-sea boundary in order to avoid double entries from the DTM and DBMs and using the coastline provided by the Generic Mapping Tools (Wessel and Smith 1998).

3 Validation of GOCE models

The accuracy of the GOCE global models has been evaluated considering the statistics of the residual data. In performing these comparisons, residual data have been computed according to the following scheme

$$\Delta g_{res} = \Delta g_{obs} - \Delta g^{GOCE}\Big|_{2}^{k} - \Delta g^{EGM\,2008}\Big|_{k+1}^{2159} - \Delta g_{RTE} \quad (1)$$

$$N_{res} = N_{obs} - N^{GOCE}\Big|_{2}^{k} - N^{EGM\,2008}\Big|_{k+1}^{2159} - N_{RTE} \quad (2)$$

The residuals Δg_{res} and N_{res} data are computed from the observed Δg_{obs} and N_{obs} by removing the medium wavelength components using GOCE models up to different degree *k* and the high frequencies using the EGM2008 global geopotential model from *k+1* to *2159* (where it is available at full degree and order). Furthermore, the very high frequency components, mainly related to the terrain effect, have been accounted for Residual Terrain Effect (RTE) computation (Forsberg, 1984). The adopted reduction scheme is set up in order to enhance the GOCE model contribution up to the selected degree *k.*
Also, the EGM2008 reduced data

$$\Delta g_{res} = \Delta g_{obs} - \Delta g^{EGM\,2008}\Big|_2^{2159} - \Delta g_{RTE} \tag{3}$$

$$N_{res} = N_{obs} - N^{EGM\,2008}\Big|_2^{2159} - N_{RTE} \tag{4}$$

have been calculated and used as reference values. In the Italian area, the RTE effect has been computed using the DTM described in section 2.1. The reference DTM used in RTE evaluation has been obtained by filtering the detailed DTM with a moving average window having a 3' radius (this window size has been defined based on a statistical analysis on the residuals for different smoothing versions of the detailed DTM). The RTE has been computed with the TC program of the GRAVSOFT package (Tscherning et al., 1994), with an integration radius of 80 km for gravity and 120 km for undulation[1], with the standard density value of 2.67 g/cm^3.

In the Greek area, the same computation for the RTE effects has been carried out. The RTE effects on geoid heights and gravity anomalies are estimated from a 3" resolution digital terrain and bathymetry model (Tziavos et al., 2010). The, smooth but varying, reference surface needed for the RTE effect is constructed by averaging the fine resolution topography grid (described in section 2.2) 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 statistics of the gravity anomaly and undulation residuals obtained using models at full resolutions are summarized in Table 3 and Table 4 for the Italian database. The statistics for the Greek database are presented in Table 5 and Table 6. The residuals have been computed for each considered model, i.e. for five DIRs, five TIMs and three SPWs releases.

[1]Different integration radii have been adopted based on some tests that have been done in the context of the Italian geoid estimation. These tests prove that, by increasing the integration radius, asymptotic RTE values for gravity and undulation are reached to r=80 km and r=120 km respectively.

Table 3: The statistics of the gravity anomaly residuals: the Italian database (450336 points)

MODEL	Max. degree	Mean(mgal)	St. Dev. (mgal)	Min(mgal)	Max(mgal)
DIR_r1	240	-0.730	8.162	-94.883	68.129
DIR_r2	240	-1.042	10.044	-93.916	74.628
DIR_r3	240	-0.800	9.809	-101.644	65.813
DIR_r4	260	-0.888	9.894	-102.047	67.320
DIR_r5	300	-0.508	12.909	-105.167	80.974
TIM_r1	224	-0.952	10.692	-102.385	66.108
TIM_r2	250	-0.912	11.505	-98.406	73.525
TIM_r3	250	-0.833	10.419	-102.638	66.069
TIM_r4	250	-0.927	9.354	-99.996	66.537
TIM_r5	280	-0.295	10.362	-105.448	66.532
SPW_r1	210	-0.935	9.752	-98.841	71.103
SPW_r2	240	-0.648	13.807	-100.069	68.723
SPW_r4	280	-0.390	13.125	-103.595	70.727
EGM2008	2159	-1.107	7.717	-95.462	69.501

Table 4: The statistics of the undulation residuals: the Italian database (977 points)

MODEL	Max. degree	Mean(m)	St. Dev. (m)	Min(m)	Max(m)
DIR_r1	240	-0.776	0.178	-1.294	-0.366
DIR_r2	240	-0.784	0.208	-1.396	-0.127
DIR_r3	240	-0.760	0.222	-1.343	-0.010
DIR_r4	260	-0.774	0.221	-1.396	-0.251
DIR_r5	300	-0.750	0.306	-1.637	0.205
TIM_r1	224	-0.763	0.274	-1.764	-0.090
TIM_r2	250	-0.756	0.271	-1.474	0.060
TIM_r3	250	-0.757	0.232	-1.360	-0.053
TIM_r4	250	-0.774	0.204	-1.355	-0.252
TIM_r5	280	-0.757	0.242	-1.467	-0.067
SPW_r1	210	-0.751	0.251	-1.664	-0.148
SPW_r2	240	-0.721	0.410	-1.974	0.421
SPW_r4	280	-0.749	0.323	-1.716	0.067
EGM2008	2159	-1.577	0.264	-2.200	-1.064

Table 5: The statistics of the gravity anomaly residuals: the Greek database (294777 points)

MODEL	Max. degree	Mean(mgal)	St. Dev. (mgal)	Min(mgal)	Max(mgal)
DIR_r1	240	0.713	5.372	-83.079	100.626
DIR_r2	240	0.823	7.857	-76.673	101.588
DIR_r3	240	0.621	7.529	-84.445	101.879
DIR_r4	260	0.525	8.046	-83.217	97.533
DIR_r5	300	0.326	9.326	-84.740	108.615
TIM_r1	224	0.307	8.671	-88.912	101.309
TIM_r2	250	0.473	8.520	-85.038	102.942
TIM_r3	250	0.525	8.175	-85.082	99.831
TIM_r4	250	0.617	6.878	-85.566	100.406
TIM_r5	280	0.417	7.751	-85.608	105.093
SPW_r1	210	0.413	8.143	-79.785	103.705
SPW_r2	240	0.203	10.511	-89.751	109.243
SPW_r4	280	0.498	8.777	-86.951	106.485
EGM2008	2159	0.568	5.316	-82.685	101.410

Table 6: The statistics of the undulation residuals: the Greek database (1542 points)

MODEL	Max. degree	Mean(m)	St. Dev. (m)	Min(m)	Max(m)
DIR_r1	240	-0.384	0.165	-0.973	0.206
DIR_r2	240	-0.397	0.195	-1.005	0.259
DIR_r3	240	-0.391	0.157	-0.882	0.144
DIR_r4	260	-0.386	0.218	-1.063	0.321
DIR_r5	300	-0.394	0.259	-1.291	0.532
TIM_r1	224	-0.406	0.276	-1.148	0.372
TIM_r2	250	-0.385	0.222	-1.189	0.396
TIM_r3	250	-0.385	0.204	-1.042	0.284
TIM_r4	250	-0.381	0.180	-0.977	0.167
TIM_r5	280	-0.395	0.226	-1.115	0.338
SPW_r1	210	-0.420	0.257	-1.165	0.338
SPW_r2	240	-0.384	0.243	-1.039	0.364
SPW_r4	280	-0.402	0.215	-1.146	0.211
EGM2008	2159	-0.416	0.139	-0.894	0.060

The plots of the gravity and undulation residuals from $k=100$ to models full resolution (in $\Delta k=5$ steps) are shown from Figure 5 to Figure 10 for the Italian databases and from Figure 11 to Figure 16 for the Greek databases.

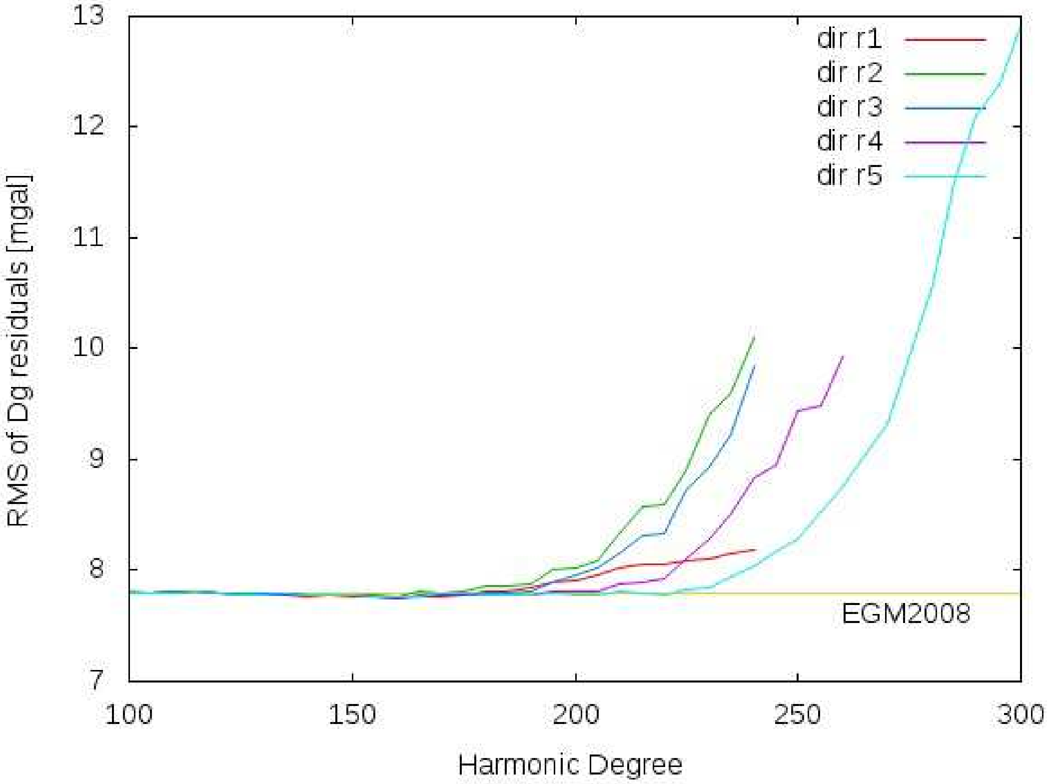

Figure 5: The r.m. s. of the residuals gravity data: the Italian database vs the DIR models

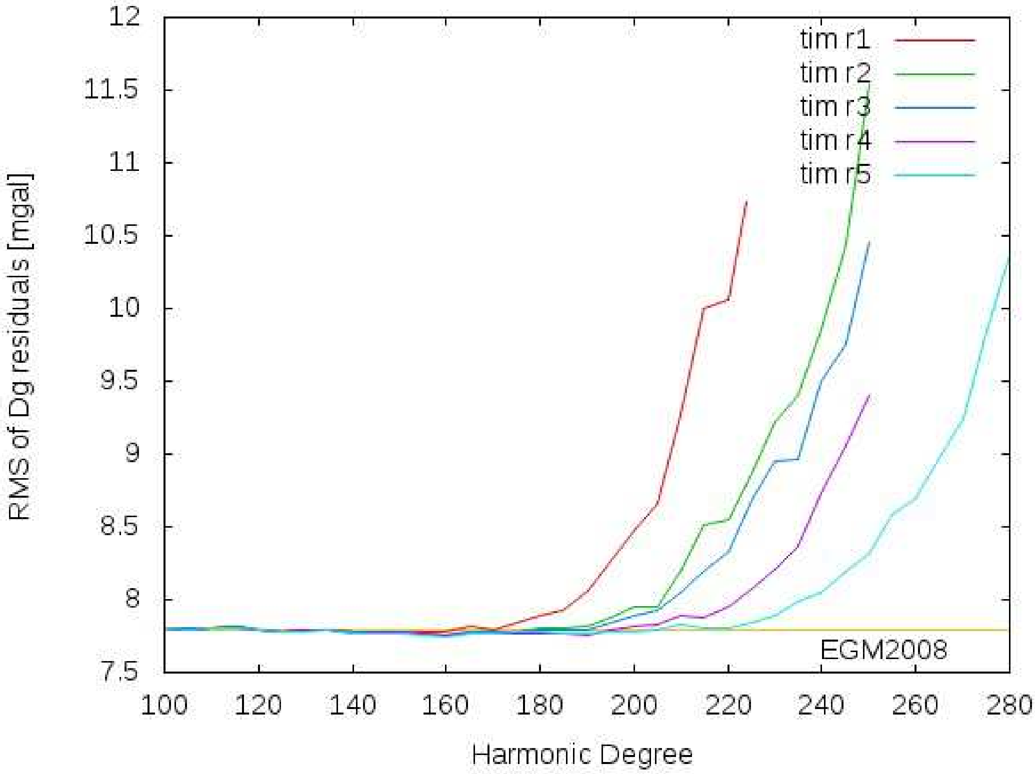

Figure 6: The r.m.s. of the residuals gravity data: the Italian database vs the TIM models

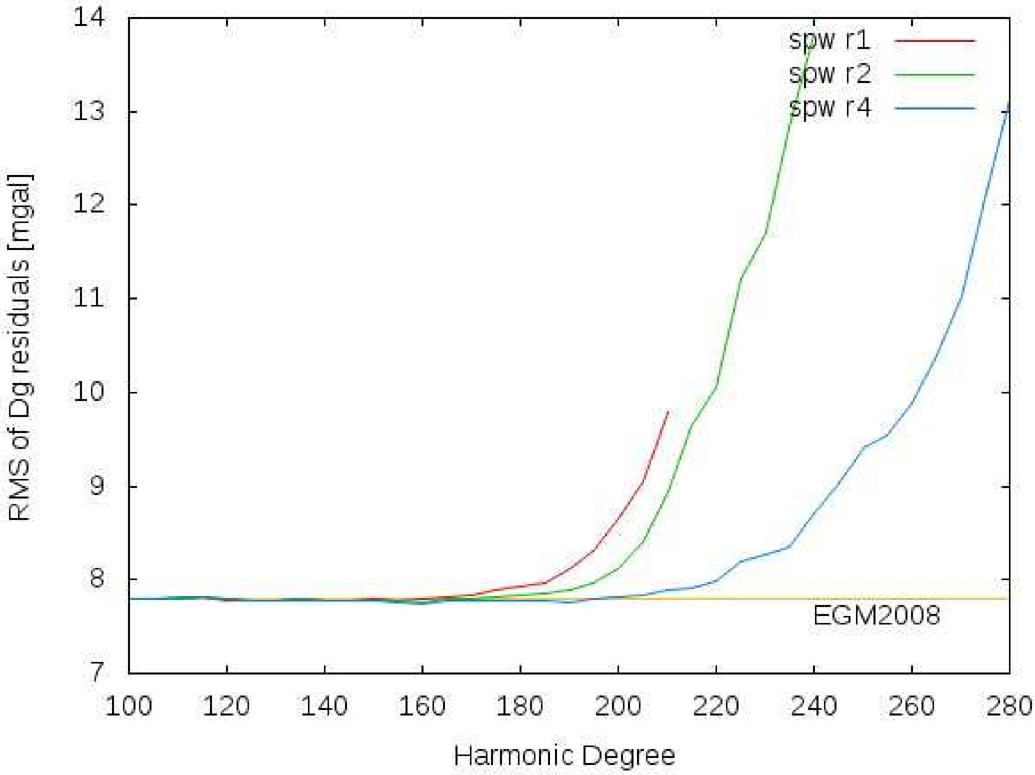

Figure 7: The r.m.s. of the residuals gravity data: the Italian database vs the SPW models

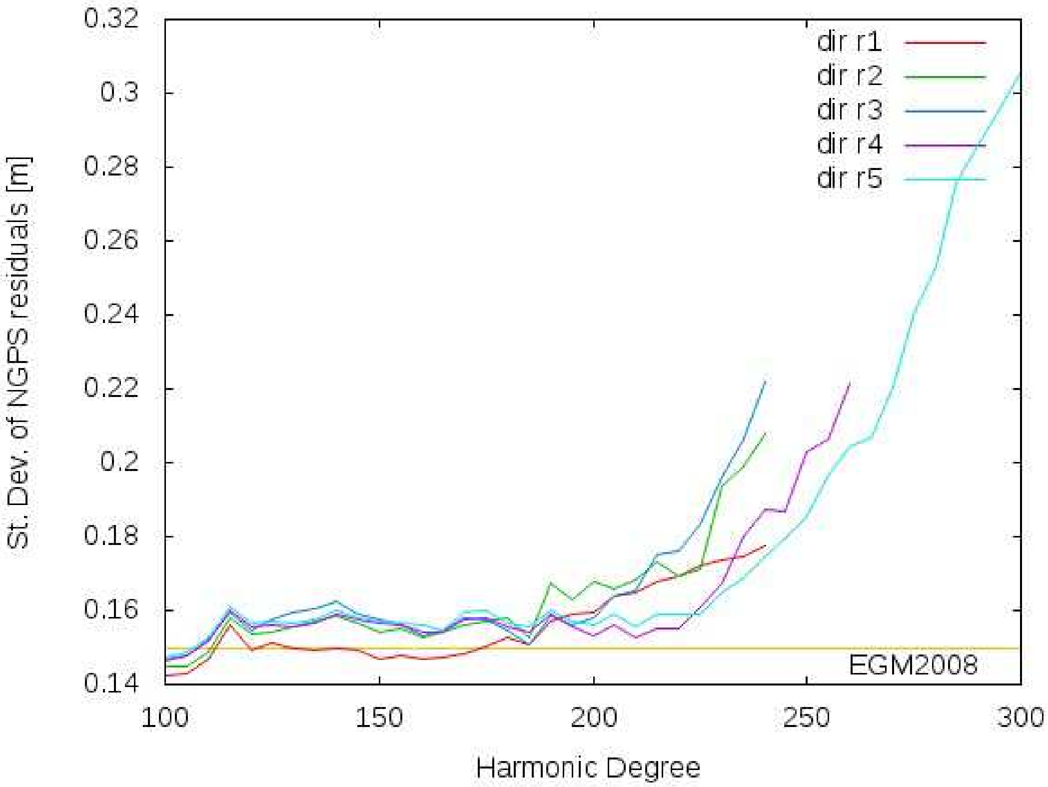

Figure 8: The St. Dev. of the residuals GPS/leveling data: the Italian database vs the DIR models

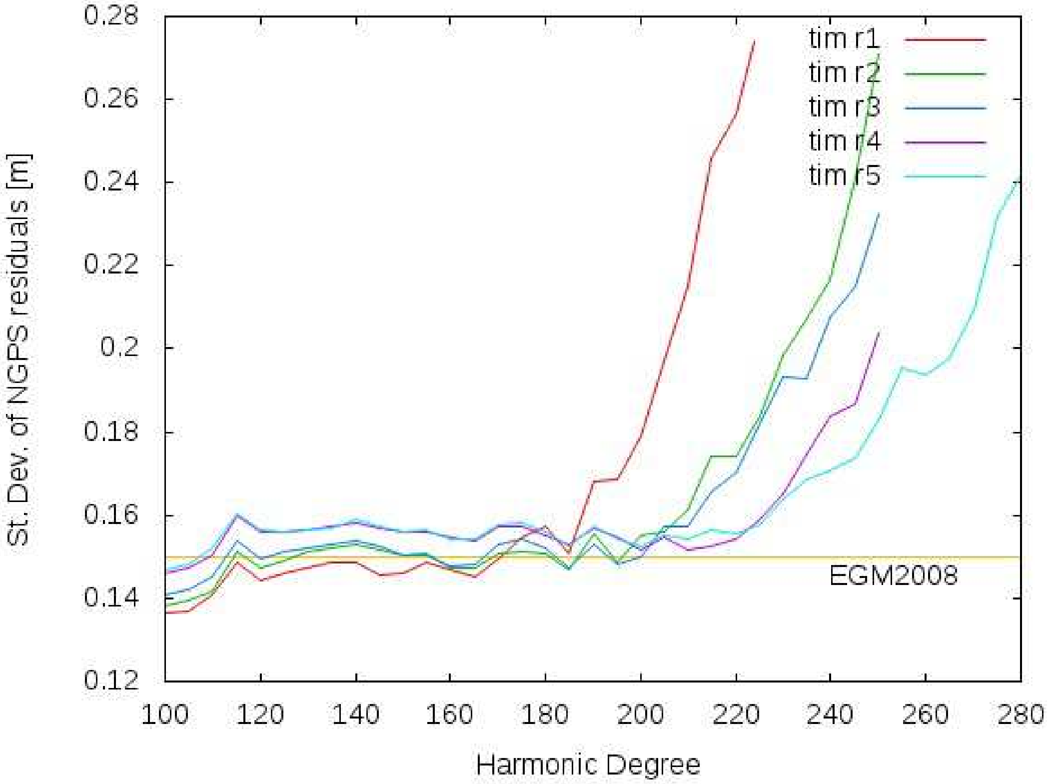

Figure 9: The St. Dev. of the residuals GPS/leveling data: the Italian database vs the TIM models

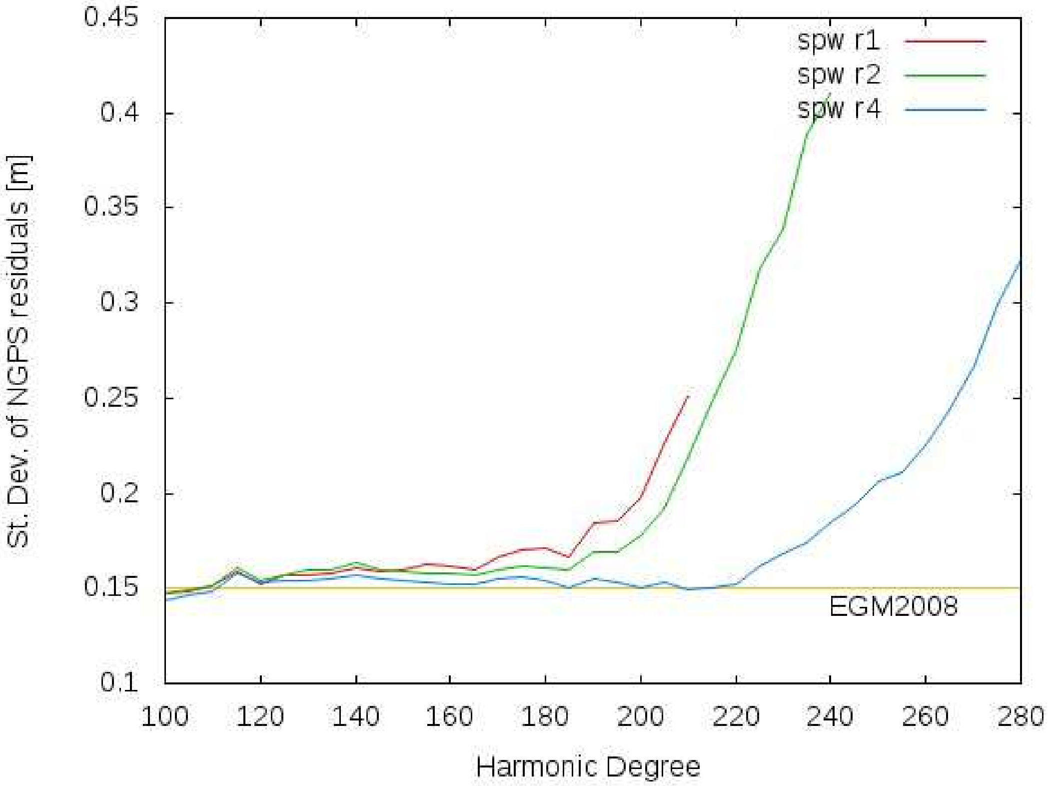

Figure 10: The St. Dev. of the residuals GPS/leveling data: the Italian database vs the SPW models

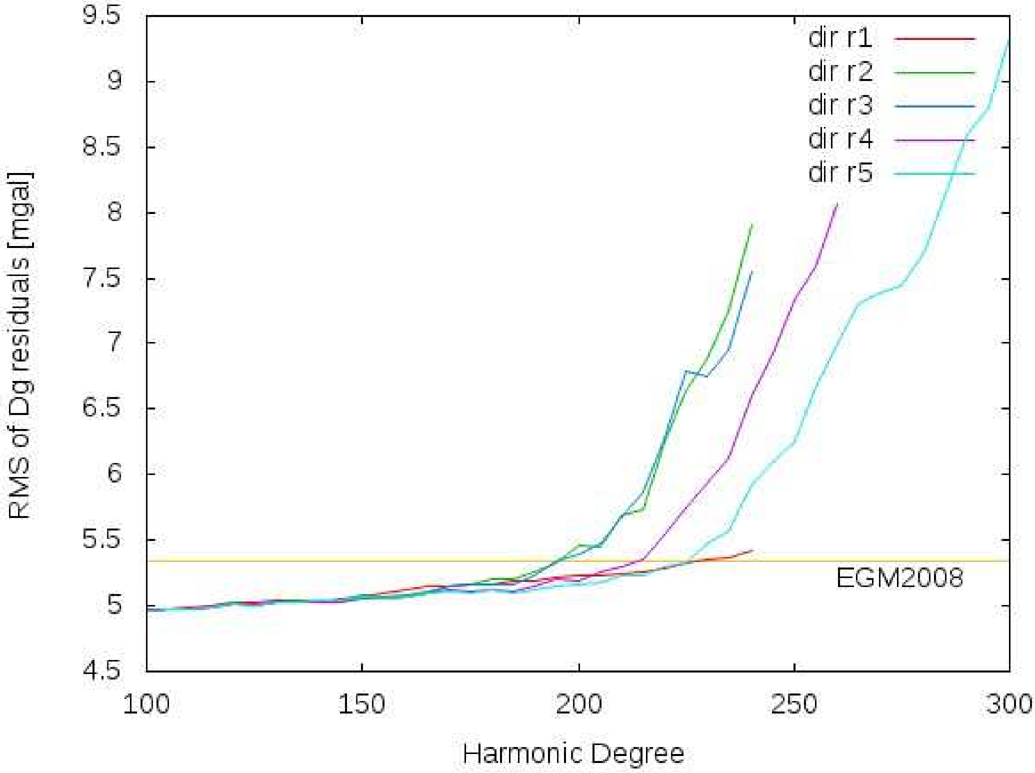

Figure 11: The r.m.s. of the residuals gravity data: the Greek database vs the DIR models

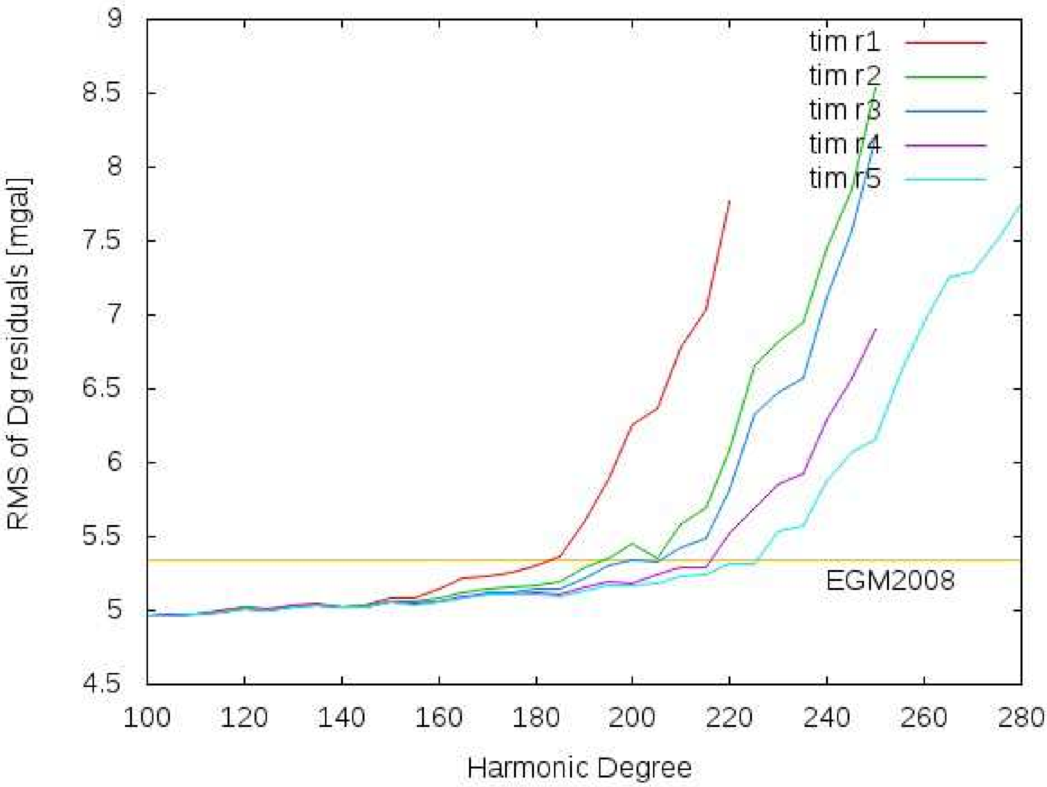

Figure 12: The r.m.s. of the residuals gravity data: the Greek database vs the TIM models

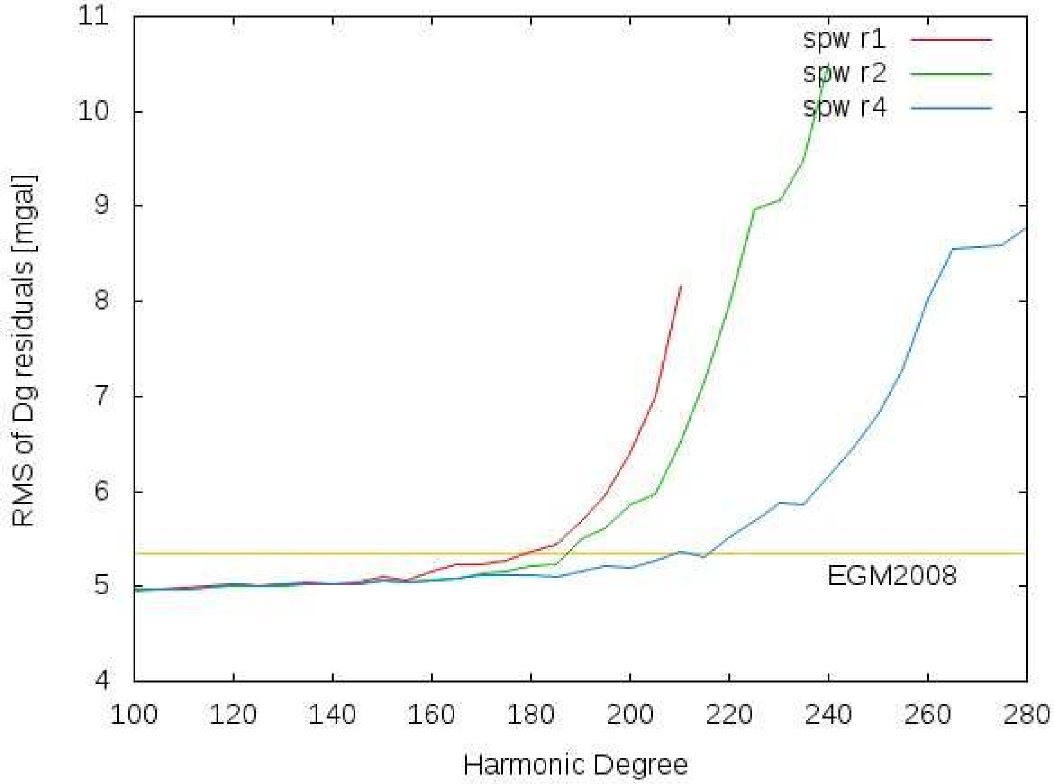

Figure 13: The r.m.s. of the residuals gravity data: the Greek database vs the SPW models

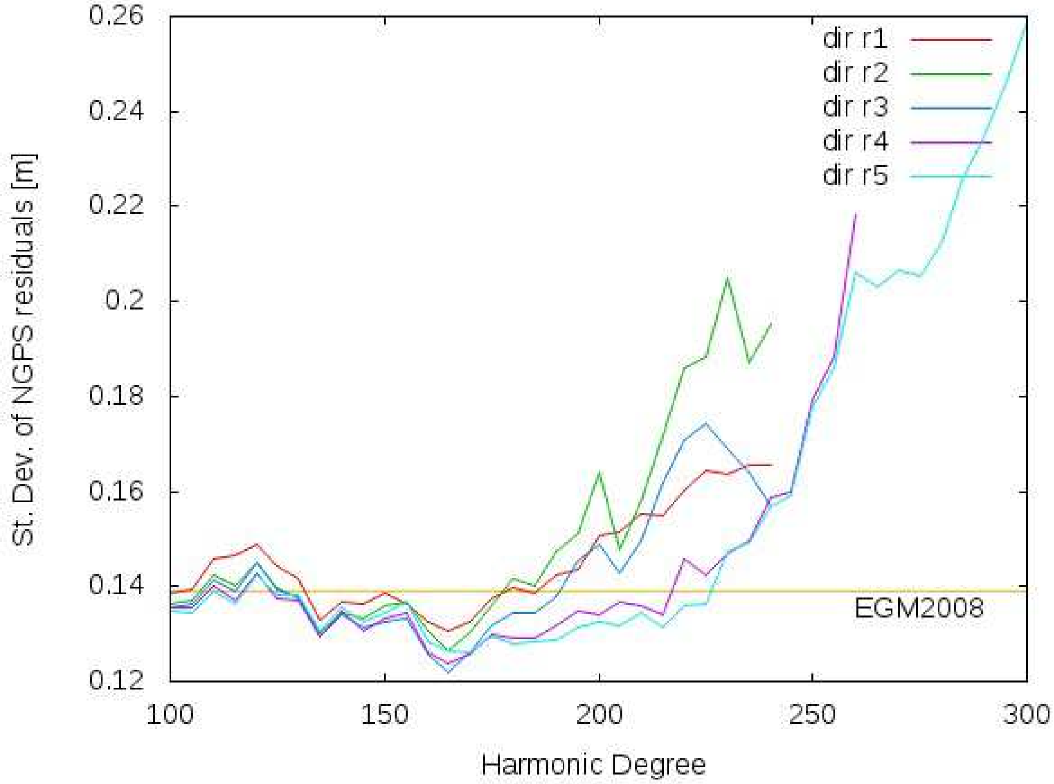

Figure 14: The St. Dev. of the residuals GPS/leveling data: the Greek database vs the DIR models

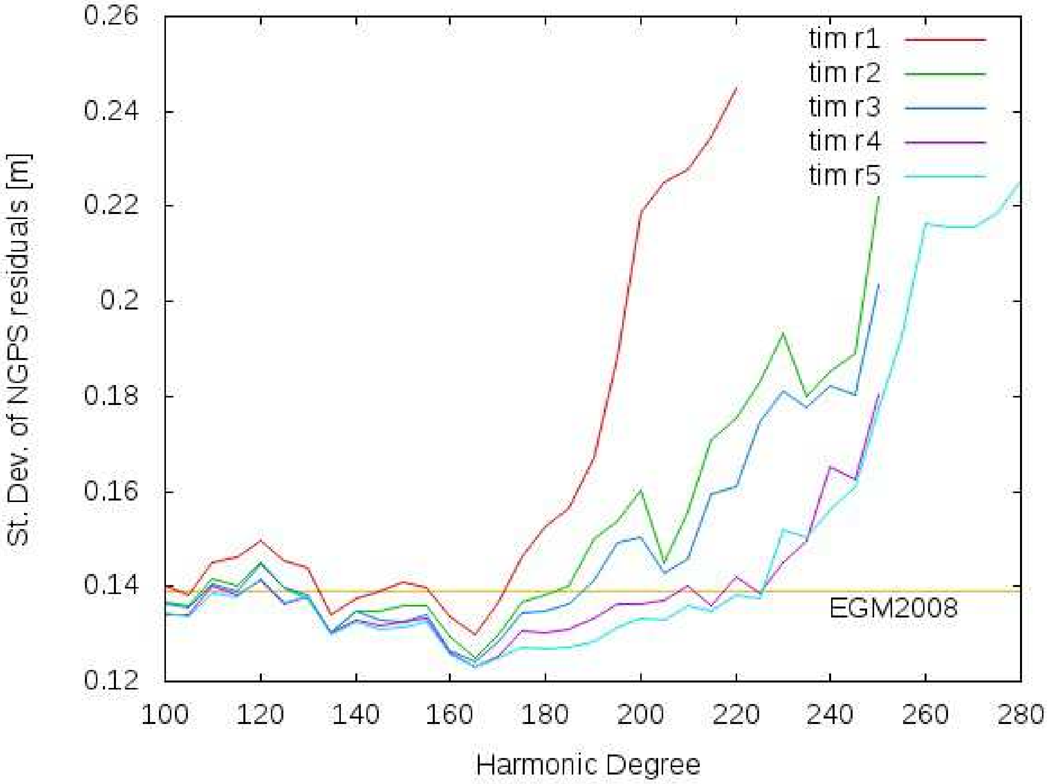

Figure 15: The St. Dev. of the residuals GPS/leveling data: the Greek database vs the TIM models

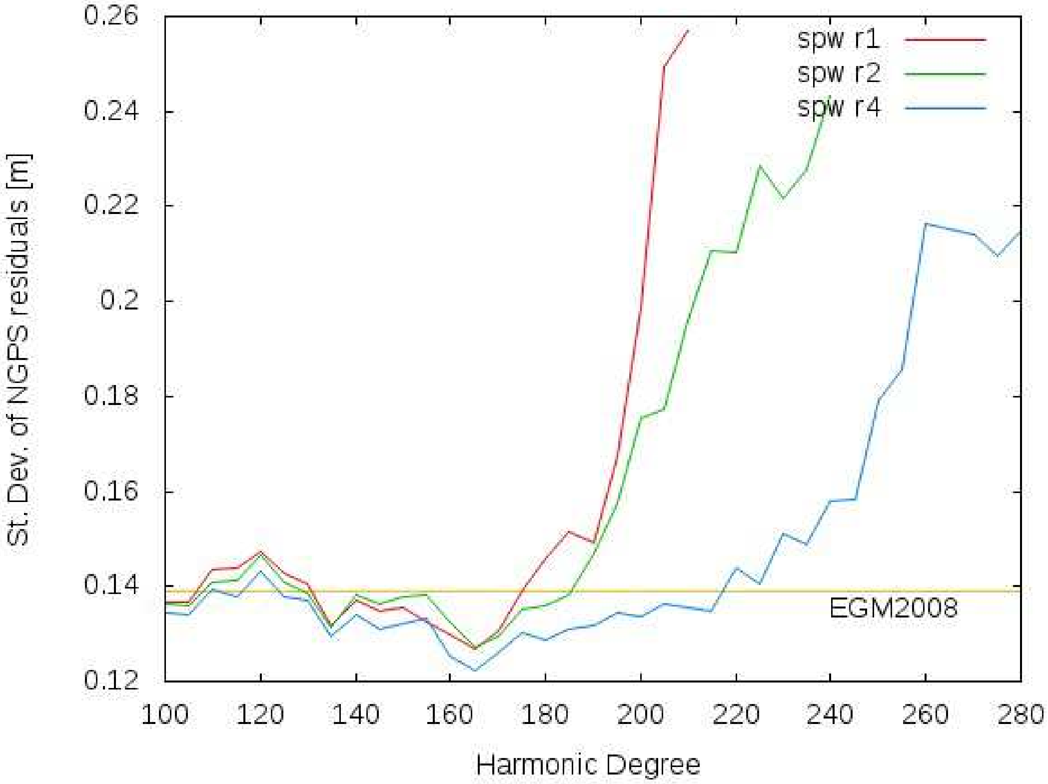

Figure 16: The St. Dev. of the residuals GPS/leveling data: the Greek database vs the SPW models

4 Comments and discussion

Over Italy, and as far as the evaluation of gravity data is concerned, no significant improvements are clearly visible in the medium frequency band, up to degree 200-220 (see Figures 5-7). As for the case of the Greek gravity database (see the discussion in the next paragraphs), there is an improvement in the GOCE models while moving from the first to the last release. This is basically due to the data included in the solutions. However, in all the tested models/releases, the r.m.s. are equivalent (or worse) to those obtained using EGM2008. Particularly, this holds also for the last releases of the models, up to degree 200 for the SPW-R4 solutions and 220 for the TIM-R5 and DIR-R5 solutions (see Figure 17-left panel). The only remarkable improvement is in the mean (see Table 3). The mean of the residuals for the last releases are remarkably smaller than the one obtained with EGM2008. Particularly, the TIM-R5 residuals have a mean value of -0,39 mGal that is nearly one fourth of the EGM2008 value. This proves that low frequency biases are accounted for in the GOCE GGMs. In comparing the different GOCE models, TIM-R5 is the one having the lower residuals St. Dev. as compared e.g. to those of the last releases DIR-R5 and SPW-R4. Also, as expected, the SPW-R4 model gives poorer results because it doesn't include the lower orbit data.

From the evaluation of the gravity anomaly data set over Greece it was concluded that the residual fields of the GOCE/GRACE models provide slightly better results than EGM2008, in terms of the St. Dev., and the improvement is at the 0.5 mGal level. 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 RTE in order to reduce the omission error. TIM-R5 is better than EGM2008 up to d/o 230 (see Figure 12) while the overall best results are achieved at d/o 212, where TIM-R5 provides both the smallest St. Dev. and range compared to EGM008 by 0.5 and 5 mGal, respectively. The mean reduction is also seen and it drops from 0.57 to 0.45 mGal. This reduction might seem insignificant, but the fact that the already small mean w.r.t. EGM2008 reduces further, is a positive sign as to the reduction of long and medium wavelength errors due to GOCE. With the inclusion of more GOCE data, the useful spectral range increases from d/o 185 to 190, 195, 218 and 230 for TIM-R1, TIM-R2, TIM-R3, TIM-R4 and TIM-R5, respectively. DIR-R5 provides better results compared to EGM2008 up to d/o 232 (see Figure 11), while the overall best results in terms of both the St. Dev. and range of the differences are found at d/o 214, being the same as those of TIM-R5. Between the various versions, DIR-R1 and DIR-R2 show similar performance up to d/o ~180, while DIR-R4 brings significant improvement boosting the useful spectral range from d/o 195 to d/o 210. The inclusion of the lower orbit GOCE data boosts even further the useful envelop up d/o 232 for DIR-R5. SPW-R4 provides worse results (see Figure 13), as expected due to the fact that it does not include the lower orbit GOCE data, and is better than EGM2008 up to d/o 218. Such a behaviour is expected since the main contribution of the lower orbit GOCE data is expected in the higher degrees of the GOCE GGMs. This becomes more evident in Figure 17, where the results for TIM-R5, DIR-R5 and SPW-R4 are depicted. It is clear that these GGMs have similar performance up to d/o 187, while above that the contribution of the lower orbit GOCE SGG data becomes evident in DIR-R5 and TIM-R5, since they remain lower than EGM2008 up to higher harmonic degrees. Nevertheless, even though SPW-R1 and SPW-R2 show a more or less similar performance, better than EGM2008 up to d/o 178 and 183, respectively, SPW-R4 improves considerably the rms of the residuals and reaches a useful spectral range up to d/o 218. The cross-comparison of the Greek gravity data with the ones over Italy seems to indicate that the precision of the latter is lower. The St. Dev. of the residuals in the Italian area are always larger (~7.8 mGal in the best case) than those obtained with the Greek data (~5.1 mGal). This can explain the behaviour at medium frequencies: Italian data could be too noisy to reveal the medium frequency improvements (below degree 200-220) w.r.t. EGM2008.

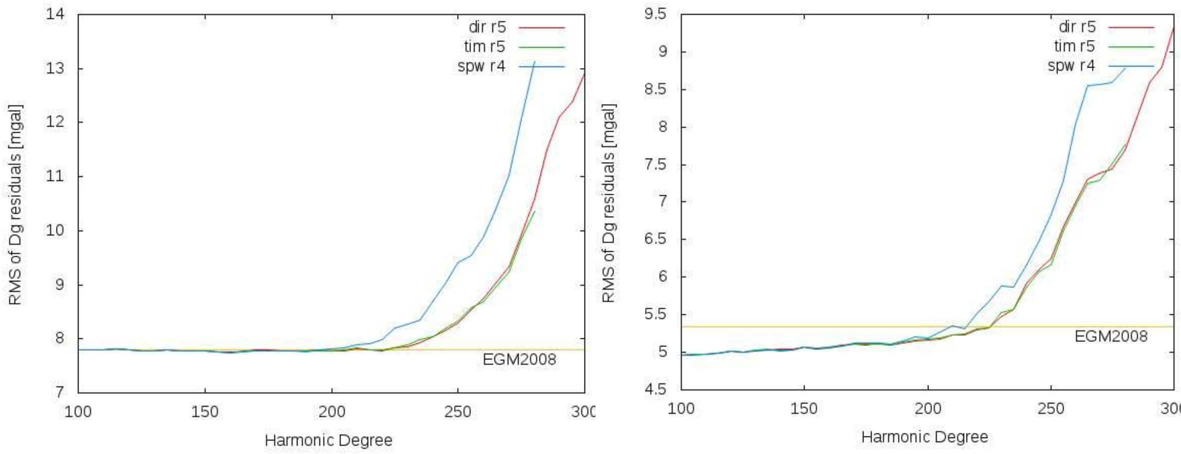

Figure 17: The r.m.s. of gravity residuals vs last released models
(Italy – left panel; Greece – right panel)

When Italian GPS/levelling observations are considered, the same remarks given for the gravity data hold. Also in this case, there are no significant improvements with respect to EGM2008 (see Figures 8-10 and Table 4). The only remarkable improvement is in the mean values of the residuals that are half the value that is obtained using EGM2008. As it is for the gravity data, the best model over Italy, at full resolution, is TIM-R5, particularly if St.Dev. is considered (the corresponding value is also slightly better than the one referring to EGM2008). This can be clearly seen in Figure 18 (left panel) in which the green line corresponding to this solution is below the other two curves at degree 280. On the other hand, The SPW-R4 is better than the DIR-R5 and TIM-R5 up to degree 220.

With respect to the evaluation of the GPS/Levelling data over Greece, when satellite only models are evaluated to their maximum degrees without any spectral enhancement from EGM2008 and RTE effects, then, as expected, their differences are quite large (38.1 cm to 42.0 cm) due to the omission error (Vergos et al., 2014). When they are evaluated to their maximum degrees and then spectrally enhanced from EGM2008 and RTE effects then their differences reach the 15-27 cm level (see Table 6). On the other hand, when fill-in information from EGM2008 along with the computed RTE effects are taken into account for the intermediate degrees of expansion, then their performances are comparable and better than that of EGM2008. This is evidenced from Figures 14-16, which depict the variation of the St. Dev. of the geoid height differences between the enhanced GOCE/GRACE GGMs and GPS/Levelling. The useful spectral range, i.e., with errors smaller than EGM2008 is up to d/o 225 for DIR-R5, while the smallest St. Dev. at 12.3 cm is achieved at d/o 169. For TIM-R5 this spectral band is similar to d/o 224, while in the band between d/o 190 to 225 it provides slightly worse St. Dev. compared to DIR-R5. The overall smallest St. Dev. for TIM-R5 is reached at d/o 166 being at the 12.1 cm level. For the SPW-R4 model the useful spectral range is up to d/o 216, given that it contains only 26 months of GOCE data, while the R5 version of DIR and TIM contain the lower orbit GOCE SSG data. This is evidenced in the spectral band between d/o 190-225, that SPW-R4 deviates from DIR-R5 and TIM-R5 (see

Figure 18). It is interesting to notice that the St. Dev. of DIR-R4/R5, TIM-R4/R5 and SPW-R4 is smaller and larger than that of EGM2008 in the band between d/o 110 and 130 (see Figure 18). This consistent behaviour is a matter of further research and can be seen, to a smaller extent, in the comparison with the Italian GPS/Leveling data (notice the peak around 110-120 in Figure 18). In comparing GPS/Leveling data, similar results with the gravity data can be drawn as far as the progress with the addition of more GOCE data is concerned. The increased amount of data in the latest releases manage to boost the useful spectral range by 50 degrees for the DIR models, 60 degrees for the TIM GGMs and 45 degrees for the SPW ones, showing the improved representation of the shorter scales of the Earth's gravity field with the addition of more GOCE and of the late-stage lower orbit observations.

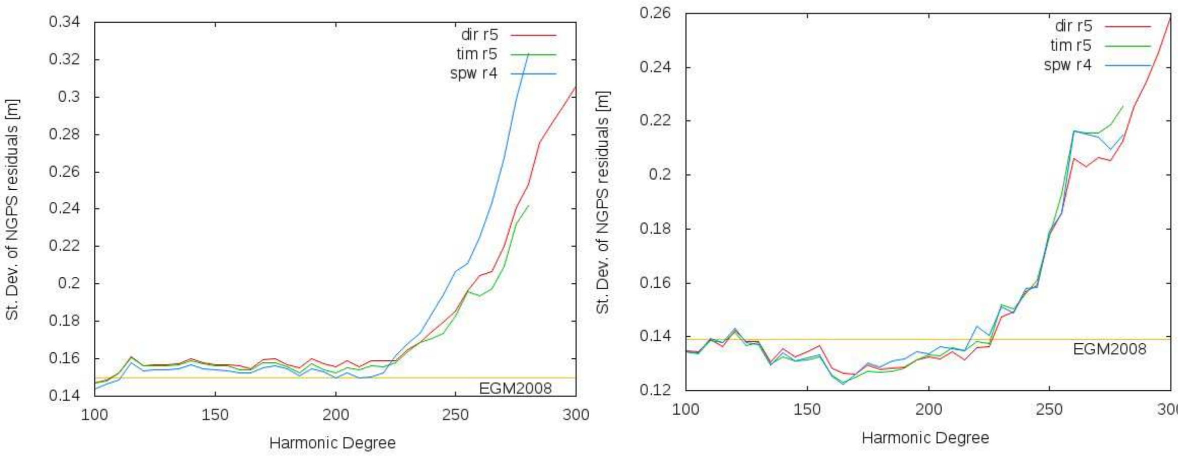

Figure 18: The St. Dev. of undulation residuals vs last released models
(Italy – left panel; Greece – right panel)

5 Conclusions

The GOCE models, in their different releases, have been compared in the Mediterranean area with the Italian and the Greek gravity and GPS/levelling data. The two test areas include the Central Mediterranean (the Italian database) and the area of the Aegean Sea (the Greek database). Both areas are characterized by strong variations of the gravity field related to topography and/or geodynamical signals. Thus, due to the roughness of the gravity field in the two test areas, this can be considered as a valuable test for the evaluation of GOCE models. EGM2008 has been considered as well, as a benchmark solution. In estimating the residuals, EGM2008 has been used to account for the high frequency components for both gravity and geoid undulation to degree and order 2159. Furthermore, RTE has been computed to smooth the high frequencies related to the topography. The final residuals have been compared to those obtained using EGM2008. RTE effect has been computed also in this case. When Greek data are considered, the results show improvements w.r.t. EGM2008 up to d/o 230. This is a standard result that is frequently obtained when using GOCE models. Furthermore, clear improvements are visible while moving from the first to the last model release: this is (again) an expected result. In this respect, the best solution over the Greek area is the DIR-R5 model. However, the TIM-R5 is very close to this best fit model in terms of statistics. The SPW-R4 is worse than these two models but it must be mentioned that it doesn't include the last GOCE data collected at lower altitudes.

The comparisons in the Central Mediterranean area based on the Italian gravity and GPS/levelling data cannot be interpreted so clearly. The GOCE models/releases residuals have statistics that are always equivalent (or worse) to those obtained using EGM2008, either considering gravity and GPS/levelling. So, nearly no improvements are obtained up to d/o 230 as it is for the Greek database. The DIR-R5 and the TIM-R5 models are practically equivalent if gravity data are considered. SPW-R4 is, also in this case, the poorest solution, especially at full resolution. Same conclusions can be stated in case of GPS/levelling Italian data (but for the slightly better performance of SPW-R4 w.r.t. DIR-R5 and TIM-R4 around degree 210). The only remarkable reduction is in the mean of the geoid undulation and gravity residuals w.r.t. EGM2008 (e.g. in GPS/levelling data, the GOCE model residuals have mean values that are roughly half the EGM2008 value.) These critical results are possibly due to the quite poor quality of the Italian data (particularly of gravity data that have been measured over a large time span and are quite old). However, in the whole, these comparisons show how valuable the GOCE models are and how effective they are in properly reducing the ground based data by providing a reliable estimate of the low frequency component of the gravity field of the Earth.

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