

The Development of the European Gravimetric Geoid Model EGG07

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Abstract The European Gravity and Geoid Project (EGGP) is a project within IAG Commission 2, reporting to Sub-commission 2.4. The main goal of the project is to compute an improved European geoid and quasigeoid model based on new and improved data sets which have become available since the last computation in 1997 (EGG97). The improvements include better global geopotential models from the CHAMP

and GRACE missions, better digital elevation models (DEMs) in some regions (e.g., new national DEMs, SRTM3, GTOPO30), updated gravity data sets for selected areas, updated ship and altimetric gravity data, improved procedures for the merging of ship and altimetric data, the use of GPS/levelling data, as well as refined computation techniques.

This contribution describes the progress made during the 4-year term from 2003 to 2007, including the development of a new geoid and quasigeoid model EGG07 for entire Europe. First, the status of the gravity and terrain data sets as well as the development of the EGG07 model by the spectral combination approach is described. Then, the EGG07 and other models are evaluated by independent GPS and levelling data, showing that the use of GRACE geopotential models as well as upgraded gravity and terrain data leads to significant improvements compared to EGG97 (in total by 25 – 65%). The results indicate an accuracy potential of the EGG07 model in the order of 0.03 – 0.05 m at continental scales and 0.01 – 0.02 m over shorter distances up to a few 100 km, provided that high quality and resolution input data are available.

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1 Introduction

The last published high-resolution European geoid and quasigeoid model EGG97 dates back to 1997 and was computed at the Institut für Erdmessung (IfE), Leibniz Universität Hannover, as an IAG enterprise (cf. Denker

and Torge, 1998). EGG97 was based on the global geopotential model EGG96 (Lemoine et al., 1998) and high-resolution gravity and terrain data available at that time. The evaluation of EGG97 by GPS and levelling data revealed the existence of long wavelength errors at the level of 0.1 to 1 ppm, while the agreement over distances up to about 100 km was at the level of 0.01 – 0.02 m in many areas with a good quality and coverage of the input data (Denker and Torge, 1998; Denker, 1998).

However, since the development of EGG97, significant new or improved data sets have become available, including strongly improved global geopotential models from the CHAMP and GRACE missions, new national and global terrain data sets, new or updated gravity data sets, improved altimetric results, as well as new GPS and levelling results. Last but not least, also the gravity field modelling techniques improved. Considering all these advancements, a complete re-computation of the European geoid and quasigeoid was considered appropriate and promised significantly improved accuracies, especially at long wavelengths. Therefore, after the IUGG General Assembly in Sapporo in 2003, it was decided to support this task in the form of an IAG Commission 2 Project, named “CP2.1 – European Gravity and Geoid Project (EGGP)”. The EGGP is reporting to Sub-commission 2.4 and has strong connections to the International Gravity Field Service (IGFS), with its centres Bureau Gravimétrique International (BGI), International Geoid Service (IGeS), National Geospatial-Intelligence Agency (NGA), and Geo-ForschungsZentrum Potsdam (GFZ), as well as to several other IAG bodies, e.g., EUREF. The project is organised by a steering committee (H. Denker (Chair), J.-P. Barriot, R. Barzaghi, R. Forsberg, J. Ihde, A. Kenyeres, U. Marti, I.N. Tziavos) and has about 50 national delegates (project members) from most of the countries in Europe. Due to the confidentiality of many data sets, only one data and computation centre exists at the Institut für Erdmessung (IfE), complemented by a second confidential gravity data centre at Bureau Gravimétrique International (BGI). Further details on the project can be found in Denker et al. (2005), and the terms of reference are given in EGGP (2003).

Within the framework of the EGGP, interim results and status reports were provided roughly on an annual basis in Porto, 2004 (Denker et al., 2005), Austin, 2005 (Denker, 2005c) and Istanbul, 2006 (Denker

et al., 2007). The present contribution summarizes the progress made within the EGGP during the 4-year term from 2003 to 2007, including the development of a completely updated geoid and quasigeoid model EGG07. Moreover, the new model is evaluated by GPS and levelling data and the progress with regard to the previous EGG97 model is outlined.

2 Gravity and Terrain Data

Since the start of the project, significant improvements of the gravity data base were made, including new or revised data sets for nearly all European countries. New gravity data sets were supplied for Austria, Belgium, Croatia, Cyprus, Denmark, Estonia, Finland, France, Germany, Greece, Italy, Latvia, Luxemburg, Netherlands, Norway, Portugal, Serbia, Slovenia, Spain, Sweden, Switzerland, and Turkey. Moreover, a few smaller updates are still pending and may be included in the near future.

Significant progress was also made in the collection and reprocessing of marine gravity data. All marine gravity data collected until 2003 were edited and crossover adjusted (cf. Denker and Roland, 2005), which lead to significant data improvements. The comparisons with independent altimetric gravity anomalies from, e.g., the KMS02 model (Andersen et al., 2005), showed a RMS difference of 18.0 mgal for the original data set, 10.2 mgal for the edited data set, and 7.8 mgal for the edited and crossover adjusted data set, respectively, which proves the effectiveness of the entire processing scheme (cf. Denker and Roland, 2005).

In addition, also after 2003, significant new marine gravity data sets became available, originating mainly from the authorities of the Scandinavian countries (coverage: Baltic Sea, North Sea, North Atlantic), France (coverage: western parts of the Mediterranean Sea, Atlantic) as well as the National Geospatial-Intelligence Agency (NGA), U.S.A. (coverage: central and eastern parts of the Mediterranean Sea). Moreover, also some airborne data sets were provided by the Scandinavian authorities, covering mainly the Baltic Sea and parts of the North Atlantic and Greenland coastal waters. The afore mentioned new gravity data sets were not crossover adjusted together with the other marine gravity data sources, mainly because all

of them are of high quality and also due to a lack of time.

In addition to this, the public domain data from the Arctic Gravity Project ArcGP (Forsberg and Kenyon, 2004) were integrated in the project data base. Finally, data from the EGG97 data base were utilized for some areas (e.g., Eastern Europe and Africa). All EGGP gravity data sets were carefully checked regarding the underlying reference systems, and if necessary, transformations were done to the target systems, being ETRS (European Terrestrial Reference System), EVRS (European Vertical Reference System) and absolute gravity. In the merging process of all data sources, emphasis was put on a careful check with respect to systematic and gross errors, which was one of the most time-consuming steps.

The progress in the collection of gravity data is documented for selected examples in Fig. 1. The left part of the figure shows the old status in 1997 (EGG97; Denker and Torge, 1998) and the right part shows the new status as of July 2007 (EGG07) for entire Europe (top), Scandinavia (middle) and the Mediterranean Sea (bottom, Morelli ship data excluded). In this context it should be noted that within the EGGP the Morelli ship gravity data for the Mediterranean Sea (e.g., Morelli et al., 1975) was completely excluded as comparisons with newer data sources revealed significant systematic discrepancies.

Comparable progress was made in the collection of high-resolution digital elevation models (DEMs). For the EGG97 computation, digital elevation models (DEMs) with a resolution of about 200 m were only available for Central and Western Europe, while coarser grids with a resolution of 0.5 km to 10 km had to be used for the remaining parts of Europe. As of 1997, only Germany released a very high resolution DEM with a grid size of $1'' \times 1''$ (approx. 30 m), but meanwhile also Switzerland and Austria provided $1'' \times 1''$ DEMs for the EGGP. At present, high-resolution national DEMs do not exist or are confidential for large parts of Eastern Europe. Hence, in all areas not covered by high-resolution national DEMs, fill-ins from public domain data sets had to be utilized. However, compared to EGG97, significantly improved fill-ins are available now, e.g., from the Shuttle Radar Topography Mission (SRTM) with a resolution of $3'' \times 3''$ (SRTM3; JPL, 2007) or the global public domain model GTOPO30 with a resolution of $30'' \times 30''$ (USGS, 2007). As the SRTM3 model

covers only the latitudes between 60°N and 54°S , the GTOPO30 model had to be used for the regions in the far North.

All available DEMs were merged into a new European DEM with a common grid size of $3'' \times 3''$, covering the area $25^\circ\text{N} - 85^\circ\text{N}$ and $50^\circ\text{W} - 70^\circ\text{E}$. Furthermore, for the area of Germany, Austria and Switzerland, a corresponding $1'' \times 1''$ DEM was created. The $3'' \times 3''$ and $1'' \times 1''$ DEMs comprise about 6.6 and 1.7 billion elevations, respectively. In the merging process, the highest priority was given to the national DEMs, followed by the SRTM3 and GTOPO30 data. For testing purposes, a second $3'' \times 3''$ European DEM was created using only the public domain data sets SRTM3 and GTOPO30.

Within the merging process, the SRTM3 and GTOPO30 DEMs were also evaluated by comparisons with the high-resolution national DEMs. In Germany, the differences between the national and SRTM3 DEMs showed a standard deviation of 7.9 m and maximum values up to about 300 m. The largest differences were located in opencast mining areas and resulted from the different epochs of the data. Histograms of the differences showed a clear deviation from the normal distribution with a long tail towards too high SRTM3 elevations, which is expected due to the fact that SRTM is a "first return system", providing elevations of whatever the radar has bounced off from, and in many instances this is above the actual ground level (cf. Denker, 2005a).

The evaluation of the GTOPO30 model by national and SRTM3 DEMs demonstrated that in large parts of Europe the longitudes of GTOPO30 should be increased by $30''$ (one block). In Central Europe, the longitude shift reduced the standard deviation of the differences to the national and SRTM3 models by roughly 75% to about 10 m. Altogether, the national DEMs augmented by the SRTM3 and GTOPO30 data provide a significantly improved European DEM, as compared to EGG97.

3 Development of the EGG07 Model

Several updated geoid and quasigeoid computations were carried out up to now within the EGGP (e.g., Denker et al., 2005; Denker, 2005c). At first, the gravity and terrain data sets were taken from the EGG97 computation, but the global geopotential

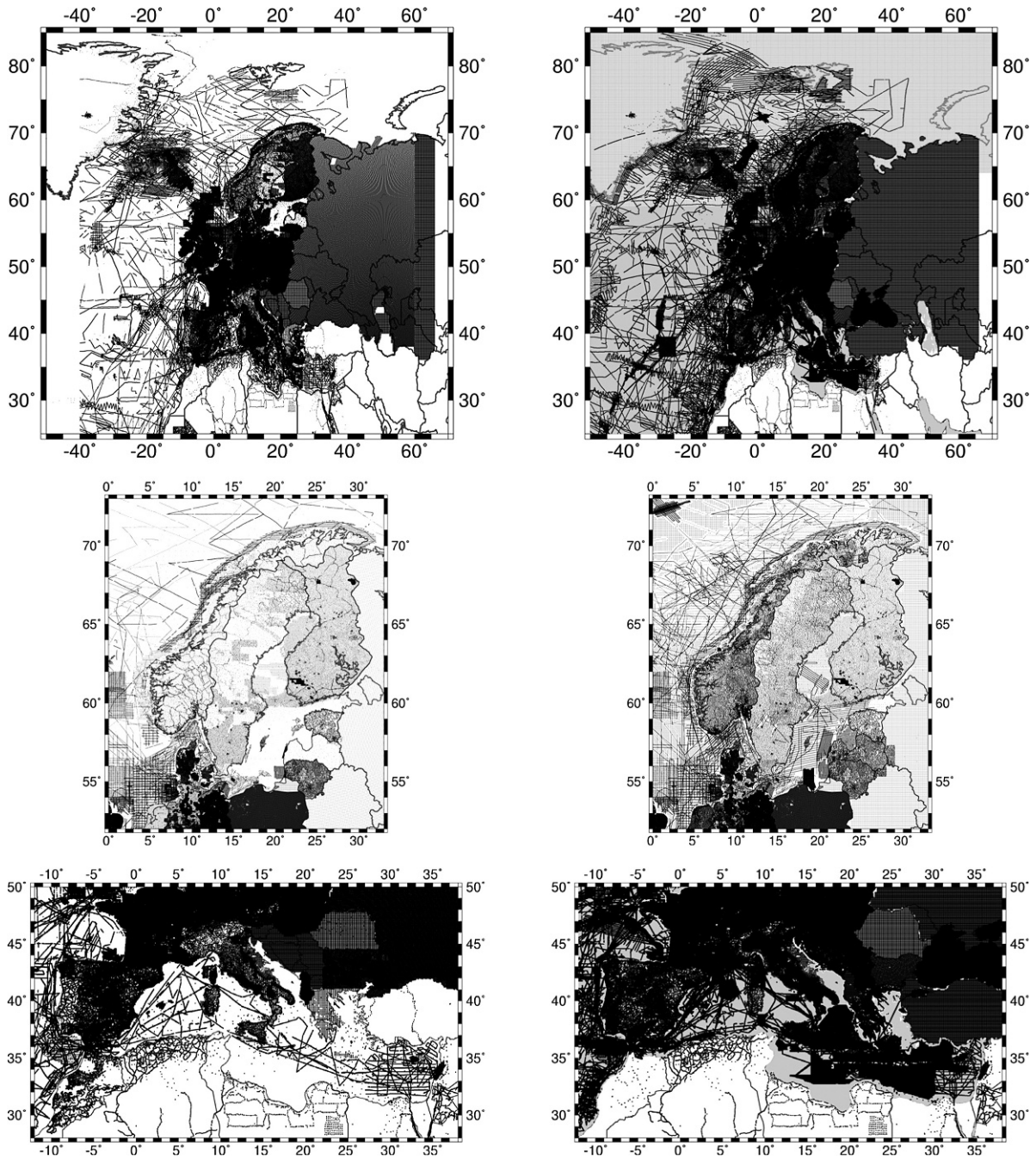


Fig. 1 Locations of terrestrial gravity data for entire Europe (*top*), Scandinavia (*middle*) and the Mediterranean Sea excluding the Morelli data (*bottom*). The left part shows the status in 1997 (EGG97) and the right part shows the status of July 2007 (EGG07). Grey shaded areas indicate ArcGP and KMS2002 data

model EGM96 was replaced by CHAMP and GRACE models. Secondly, all gravity and terrain data sets were completely updated and combined with the CHAMP and GRACE geopotential models. In contrast to the

previous interim results, the new EGG07 model is based on completely updated gravity and terrain data sets for entire Europe, as described in the previous section.

The computation strategy is outlined in Denker et al. (2005). The primary gravity field quantity to be computed is the height anomaly or the quasigeoid undulation, with the advantage that only gravity field observations at the Earth's surface and in its exterior enter into the calculations, avoiding assumptions about the Earth's interior gravity field. A geoid model can then be derived by introducing a density hypothesis, which should be identical to the one used for the computation of corresponding orthometric heights (e.g., Helmert heights).

The remove-restore technique is used, considering high-resolution terrestrial gravity and terrain data in combination with a state-of-the-art global geopotential model. Terrain reductions according to the residual terrain model (RTM) technique (Forsberg and Tscherning, 1981) are applied to smooth the data and to avoid aliasing effects. The gravity field modelling at IfE is based on the spectral combination technique (e.g., Wenzel, 1982) with integral formulas, which can be efficiently evaluated by ID FFT. In this method, the combination of terrestrial gravity data and a global geopotential model is done by means of spectral weights, which depend on the accuracy of the input data sets. Due to the high accuracy of the global models at long wavelengths, the terrestrial data mainly contribute the shorter wavelength components. So far, time has not allowed testing other modelling techniques, e.g., standard least-squares collocation, wavelets, or the fast collocation approach (e.g., Sansò and Tscherning, 2003), but this is envisaged for the future.

The final gravity data set used for the computation of the EGG07 model consisted of 5,354,653 observations from 709 sources. In addition, 195,840 gravity values from the ArcGP project (Forsberg and Kenyon, 2004) as well as 951,251 altimetric anomalies from the KMS2002 data set (Andersen et al., 2005) were utilized. Thus, in comparison with EGG97, the amount of gravity data approximately doubled (see also Fig. 1).

All gravity observations were RTM reduced, resulting in a significant data smoothing. The required reference topography was computed by a moving average filter over $30' \times 45'$ blocks. All terrain effect computations were done by exact prism formulas in combination with detailed and coarse grids for the outer zones; mainly to speed up the computations.

With regard to the global geopotential model used in combination with gravity and terrain data, previous studies have shown that the GRACE based models lead to substantial improvements as compared to EGM96 (e.g., Denker et al., 2005b). Different satellite-only and combined GRACE models were employed (e.g., from GeoForschungszentrum Potsdam – GFZ, Center of Space Research at the University of Texas – CSR, and Jet Propulsion Laboratory – JPL), and it turned out that it is advantageous to use a high-degree model with a maximum degree $l_{max} = 360$, as this leads to smaller residual quantities and reduced effects of approximation errors in the mathematical modelling. Hence, the pure GRACE satellite-only geopotential models were blended with the EGM96 coefficients from degree 90 onwards in corresponding test computations. The evaluation of all GRACE based quasigeoid models showed only small differences, where the newer models associated with longer observation periods gave slightly better results (cf. Denker, 2005b,c).

For the computation of EGG07, the latest high-degree geopotential model EIGEN-GL04C ($l_{max} = 360$) from GFZ Potsdam (Förste and Flechtner, 2007; see also Förste et al., 2005) was used, being a combination of CHAMP, GRACE and terrestrial data. It should be noted that the EGG07 model can also serve as a typical example for all other GRACE based solutions. The spectral weights used in connection with the EIGEN-GL04C model are shown in Fig. 2, together with corresponding values for a recent CHAMP model and the EGM96 model. A correlated noise model with an error

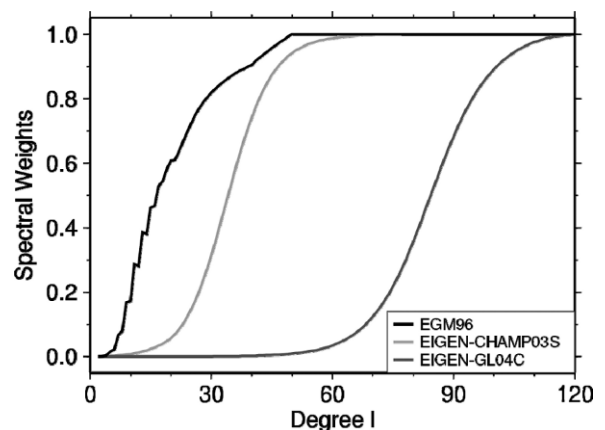


Fig. 2 Spectral weights in connection with the geopotential model EGM96, a recent CHAMP model, and the GRACE based model EIGEN-GL04C

standard deviation of 1 mgal was used for the terrestrial gravity data in the derivation of the spectral weights.

The computation area for the EGG07 model is $25^{\circ}\text{N} - 85^{\circ}\text{N}$ and $50^{\circ}\text{W} - 70^{\circ}\text{E}$. The grid spacing is $1' \times 1'$, yielding $3,600 \times 7,200 = 28,080,000$ grid points. The GRS80 constants, zero degree undulation terms, and the zero-tide system were used throughout all computations.

4 Evaluation of the EGG07 Model

The EGG07 quasigeoid model and all other test solutions were evaluated by independent national and European GPS and levelling data sets (all levelled heights were normal heights). In order to demonstrate the progress resulting from improved gravity and terrain data on the one hand as well as the GRACE based global geopotential models on the other hand, also the previous European quasigeoid model EGG97 (based on the geopotential model EGM96; denoted as EGG97/EGM96 below; Denker and Torge, 1998) and the solution EGG97/GRACE (EGG97 gravity and terrain data, EIGEN-GL04C geopotential model based on GRACE) are addressed.

Table 1 shows the statistics of the differences between the above mentioned quasigeoid models and GPS and levelling data from selected national and continental campaigns. In all cases, a constant bias was subtracted from the differences in order to account for different height system levels and very long wavelength errors in all data sets involved (GPS, levelling, quasigeoid). Results are provided for Germany (GPS/levelling data from Bundesamt für Kartographie und Geodäsie, BKG, Frankfurt; e.g., Liebsch et al., 2006), Netherlands, Austria, Switzerland, a French traverse from Marseille to Dunkerque (1,100 km long) with new levelling data (NIREF), Russia (Demianov and Majorov, 2004), and the EUVN_DA initiative (e.g., Kenyeres et al., 2007). The EUVN_DA project aimed at a densification of the previous EUVN campaign (Ihde et al., 2000) by collecting high quality GPS and levelling data from participating European countries. At present, about 1,300 points are available with interstation distances ranging from about 50 – 100 km. Within the EUVN_DA project, the normal heights were derived in part directly from geopotential numbers of UELN

(United European Levelling Network) stations and partially by simple transformations with up to three parameters.

For the EUVN_DA and the Russian GPS and levelling data set, the differences with respect to EGG97 and EGG07 are also depicted in Fig. 3.

The results in Fig. 3 and Table 1 clearly show that the new EGG07 model performs significantly better than EGG97. The improvements result from the updated gravity and terrain data as well as from the utilization of a GRACE based global geopotential model. Table 1 shows that solely through the introduction of a GRACE based global geopotential model, the RMS differences reduce by 27% (Switzerland) to 64% (Germany), when going from the EGG97/EGM96 to the EGG97/GRACE solution. However, also the update and re-processing of the gravity and terrain data leads to substantial improvements in the GPS and levelling comparisons in most cases. The additional improvements from the upgraded terrestrial data range from 0% (Germany) to 23% (Netherlands); the improvements are in particular high in those areas where the data basis was significantly extended, e.g., in Belgium, Netherlands, and Austria. The overall improvement of EGG07 over EGG97 ranges from about 25 – 65% (see Table 1). Also long wavelength discrepancies are significantly reduced from 0.1 to 1.0 ppm for the EGG97 model to typically below 0.1 ppm for all GRACE based solutions (cf. also Denker et al., 2005; Denker, 2005b,c).

Of special interest are the results from the comparisons with the EUVN_DA GPS and levelling data set. Figure 3 (top) shows that the EGG07 model performs quite well over most parts of Europe, the two exceptions being Great Britain and Italy. Regarding Great Britain, the levelling heights are suspected to contain systematic errors (e.g., Hipkin et al., 2004); this is also confirmed by removing a north-south and east-west trend in the comparisons, which reduces the RMS difference from about 0.15 m (bias case) to 0.05 m (bias and tilt case). On the other hand, the situation for Italy is less transparent, as the differences exhibit wavy structures and not a clear trend. Furthermore, the older EGG97 model appears to fit better to the Italian GPS and levelling data than EGG07, but nevertheless it is not believed that EGG97 is more accurate in Italy than EGG07. In fact, the differences between EGG07 and EGG97 in Italy are mainly a result of replacing the EGM96 geopotential model by a GRACE based

Table 1 Comparisons of GPS and levelling data with EGG97 (named EGG97/EGM96), EGG97/GRACE (EGG97 gravity and terrain data, GRACE geopotential model), and EGG07 (named EGG07/GRACE). A constant bias is subtracted. Units are m

GPS/Levelling	Quasigeoid	#	RMS [m]	Min [m]	Max [m]	Improvement versus EGG97
Germany	EGG97/EGM96	907	0.099	-0.192	+0.338	-
	EGG97/GRACE	907	0.036	-0.092	+0.120	64%
	EGG07/GRACE	907	0.036	-0.152	+0.075	64%
Netherlands	EGG97/EGM96	84	0.035	-0.062	+0.120	-
	EGG97/GRACE	84	0.023	-0.046	+0.058	34%
	EGG07/GRACE	84	0.015	-0.044	+0.047	57%
Austria	EGG97/EGM96	106	0.108	-0.181	+0.247	-
	EGG97/GRACE	106	0.072	-0.130	+0.188	33%
Switzerland	EGG07/GRACE	106	0.054	-0.145	+0.096	50%
	EGG97/EGM96	188	0.081	-0.129	+0.258	-
	EGG97/GRACE	188	0.059	-0.200	+0.294	27%
France (Traverse with new levelling)	EGG07/GRACE	188	0.061	-0.204	+0.152	25%
	EGG97/EGM96	16	0.086	-0.175	+0.128	-
	EGG97/GRACE	16	0.034	-0.063	+0.070	60%
Russia	EGG07/GRACE	16	0.039	-0.067	+0.086	55%
	EGG97/EGM96	48	0.253	-0.760	+0.693	-
	EGG97/GRACE	48	0.127	-0.245	+0.295	50%
EUVN_DA (all)	EGG07/GRACE	48	0.089	-0.139	+0.192	65%
	EGG97/EGM96	1,285	0.257	-0.928	+0.716	-
	EGG97/GRACE	1,285	0.217	-0.737	+0.0602	16%
EUVN_DA (excl. Great Britain and Italy)	EGG07/GRACE	1,285	0.207	-0.693	+0.587	19%
	EGG97/EGM96	908	0.158	-0.669	+0.641	-
	EGG97/GRACE	908	0.097	-0.392	+0.521	39%
	EGG07/GRACE	908	0.079	-0.518	+0.549	50%

model, which leads to long wavelength changes over Italy and the Central and Western Mediterranean Sea. At present, the situation is further analysed with the help of Italian colleagues.

For the EUVN_DA data set, the RMS difference reduces from 0.16 m (EGG97) to 0.08 m (EGG07) when excluding Great Britain and Italy (see Table 1). The differences show small long wavelength structures (see Fig. 3 top right) and include error components from all data sets involved, i.e. GPS, levelling and quasigeoid. On the whole, the EUVN_DA results are considered as quite satisfactory, as the data set is covering a very large area from the Iberian Peninsula to Northern Scandinavia, the Baltic States, Poland and Bulgaria.

Significant improvements were also obtained over Russia (see Table 1 and Fig. 3). The RMS difference reduced from 0.25 m for EGG97 to 0.09 m for EGG07 (65% improvement), which is remarkable as this is just the result of reprocessing the supplied mean Bouguer anomalies with new terrain models from the SRTM mission.

For the French traverse from Marseille to Dunkerque (1,100 km long), the RMS difference

is 0.039 m for EGG07, which is a 55% reduction versus EGG97. It is also interesting to note that the RMS difference with the IGN69 (old) levelling heights is only 0.075 m for EGG07, which clearly proves that the new levelling is better than the old one.

Regarding the other national GPS and levelling data sets, the RMS differences for EGG07 range from about 0.01 to 0.06 m, the higher values being associated with Austria and Switzerland (high mountain areas). In smaller regions with extensions up to a few 100 km, the agreement is even better and in the order of 0.01 – 0.02 m. In this context, it should be noted again that the differences include error contributions from all data sets involved, i.e. GPS, levelling, and gravimetric quasigeoid. Furthermore, the RMS differences between the gravimetric quasigeoid and GPS and levelling data are also in a reasonable agreement with the internal error estimates of about 0.02 – 0.03 m for the GRACE based solutions. The accuracies achieved for large parts of Europe are about the optimum one can expect at present with up-to-date gravity, terrain, and GRACE data; further improvements are mainly anticipated from the GOCE mission, as the terrestrial

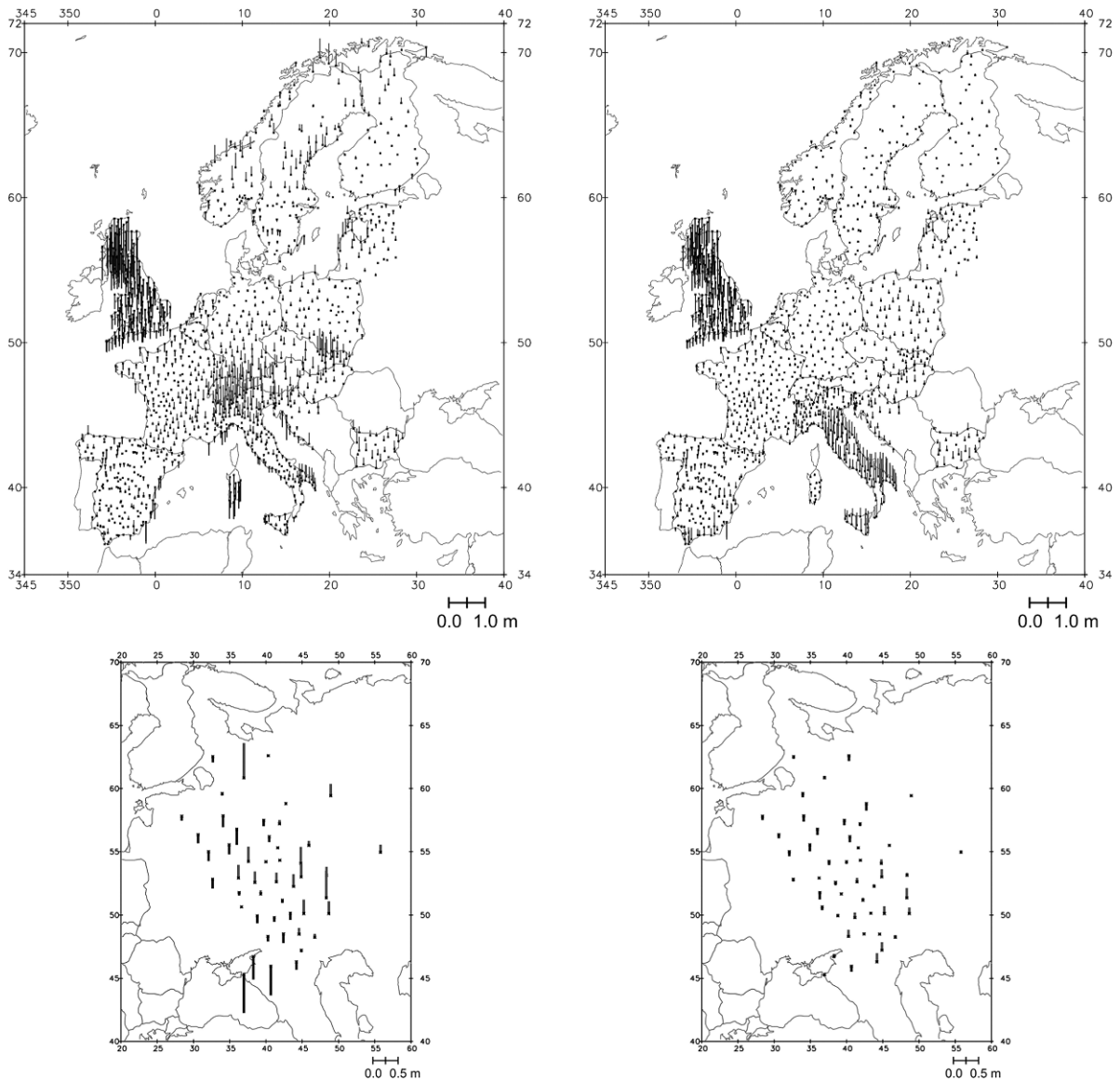


Fig. 3 Comparison of GPS and levelling data from the EUVN_DA initiative (*top*) and Russia (*bottom*) with the quasigeoid solutions EGG97 (*left part*) and EGG07 (*right part*). A constant bias is subtracted

data sets can hardly be improved in many regions of Europe.

5 Conclusions

Significant progress was made within the framework of the European Gravity and Geoid Project EGGP regarding the collection and homogenization of high-resolution gravity and terrain data. A completely updated quasigeoid model EGG07 was derived for

entire Europe. The evaluation of this model by independent GPS and levelling data showed that the use of GRACE geopotential models as well as upgraded gravity and terrain data leads to significant improvements compared to EGG97 (in total by 25 – 65%). In addition, the long wavelength errors, existing in EGG97, were substantially reduced to typically below 0.1 ppm. The results indicate an accuracy potential of the gravimetric quasigeoid models in the order of 0.03 – 0.05 m at continental scales and 0.01 – 0.02 m over shorter distances up to a few 100 km, provided

that high quality and resolution input data are available in the area of interest.

The data base may still be improved in coastal zones and sea areas as well as over large parts of Eastern Europe. Furthermore, modelling problems may exist in the high mountains which have to be studied further. Nevertheless, the present accuracy potential allows a number of interesting applications, including accurate estimates of the potential W_0 (reference geopotential of the vertical datum) and vertical datum unifications. Finally, it is a pleasure to thank all persons and agencies that supported the EGGP with data and expert know-how.

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