

Comparison and testing of GOCE global gravity models in Central Europe

Research article

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Abstract:

Three different global gravity model solutions have been released by the European GOCE Gravity Consortium: a direct solution, a time-wise solution and a space-wise solution. To date, two releases of each solution have been issued. Each of these solutions has specific positives and weaknesses. This paper shows and analyzes the differences between each solution in Central Europe by means of comparison with respect to the EGM2008 and GOCO02S global gravity models. In order to make an independent comparison, the global GOCE models are tested by the SKTRF (Slovak Terrestrial Reference Frame) network in Slovakia.

Keywords:

Satellite gravity gradiometry • Gravitation tensor • Spherical harmonic coefficients • GOCE • earth gravity models

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1. Introduction

The first release of global gravity models based on GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) data has been available for users since July 2010. Three different approaches (solutions) have been prepared using 61 days of GOCE measurements which approximately correspond to first complete GOCE coverage. The three approaches are as follows: a direct solution (DIR) (Bruinsma et al., 2004; Bruinsma et al., 2010), a time-wise solution (TIM) (Pail et al., 2010) and a space-wise solution (SPW) (Migliaccio et al., 2010). An assessment of the three solution strategies was published by Pail and Plank (2002). Some mathematical background connected to the TIM solution was described by Pail and Plank (2004). Recently, in March 2011, the second release of solutions DIR and TIM became available and in June 2011 the second release of the SPW solution appeared. In Section 2 we describe the main features of the three approaches and the main differences between them. Section 3 is dedicated to the mutual comparison of gravity anomalies, height anomalies and deflections of the vertical

computed from each model in Central Europe. It is performed by means of comparison of the three GOCE solutions with the EGM2008 (Pavlis et al., 2008) and GOCO02S (Goiginger et al., 2011) global gravity models up to a corresponding degree and order. Comparison of the three solutions with the GNSS/levelling SKTRF network in region of Slovakia is shown in Section 4. Conclusions from various aspects are formulated in Section 5 based on the results obtained. An extensive global testing of the first release of global solutions was published recently by (Hirt et al., 2011) and (Gruber et al., 2011). Our experiments are focused on the area of central Europe and include an assessment of the second release of the GOCE solutions which has only very recently become available.

2. Main features of the GOCE global solutions

All three solutions are originally in a tide-free system. The basic parameters used for normalization of the coefficients are $R = 6378136.46$ m for DIR solution, $R = 6378136.3$ m for TIM and SPW solutions and $GM = 3986004.415 \cdot 10^{-8} \text{ m}^3 \cdot \text{s}^{-2}$ for all solutions. An important aspect of these solutions is their degree of independence from other missions or other data sources. The SPW solution is affected by the GOCE quick-look model (Mayrhofer et al., 2010) directly and by the EGM2008, EIGEN5C (Foerste et al., 2008)

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and ITG_GRACE2010 models indirectly, (for details see Migliaccio et al., 2010). For the DIR solution, the a-priori information from EIGEN5C and EIGEN-51C (Bruinsma et al., 2010) models has been used. The TIM is the GOCE-only solution in a strict sense, i.e. no a-priori gravity field information enters the solution, see (Pail et al., 2010). This independence is the main reason why the TIM solution is used to replace the less-precise components in the gravitation tensor before the transformation from the gradiometer reference frame (GRF) into the local north-oriented frame (LNOF).

Another evident difference between the three solutions is the maximum degree and order of the harmonic coefficients. This parameter varies from 210 to 250, see Table 1.

Table 1. Maximum degree and order of the three GOCE global solutions.

Solution	DIR	TIM	SPW
Release 1	240	224	210
Release 2	240	250	240

There are two different types of precise GOCE orbits: kinematic orbits and reduced dynamic orbits. While the solutions TIM and SPW employ the kinematic orbits which are rougher, the DIR solution uses the more accurate reduced dynamic orbits. However, the reduced dynamic orbits depend on a-priori gravity model EIGEN5C.

The major difference between Releases 1 and 2 for every solution is the GOCE data period taken into account. Release 1 is based on approximately 2 months of GOCE data only while Release 2 includes a much longer period of data, see Table 2. However, there are also other important differences. Below, we provide a short description of each solution and also try to stress the main differences between Releases 1 and 2. This information was collected mainly from the Model characteristics part of the data products themselves.

The direct solution, DIR, is based on the combination of normal equations coming from satellite to satellite tracking (SST) observations and normal equations coming from satellite gravity gradiometry (SGG) observations. Only diagonal components of the gravitation tensor are assumed in the DIR solution. SST normal equations are computed up to degree and order 120 for Release 1 and 150 for Release 2. These equations are filtered with a band-pass filter 10–125 mHz. The SGG normal equations are computed individually from diagonal components up to degree and order 240 and accumulated with the SST normal equations with the different weights shown in Table 3. The spherical cap stabilization (Metzler and Pail, 2005) is applied using the EIGEN-51C model (Bruinsma et al., 2010) for Release 1 and the ITG-GRACE2010S (Mayer-Gürr et al., 2010) for Release 2. The solution was obtained by a Cholesky's decomposition of the accumulated normal equations.

As it was stated above, the time-wise solution, TIM, is based solely on GOCE data. It is computed in co-operation between TU Graz, TU Munich, University of Bonn and Austrian Academy of Sciences, using so-called Sub-Processing Facility (SPF) 6000 software system, (see Pail et al., 2010). In this software system, the quick-look gravity field analysis is performed first producing the quick-look gravity field models Quick-Look-A and Quick-Look-B, see (Mayrhofer et al., 2010) and error estimates which serve as a basis of the TIM solution. The rest of the computation is performed in the so called Core Solver which consists of the Tuning Machine and the Final Solver, (see Pail et al., 2010). The main task of the Tuning Machine is detection of the outliers, derivation of optimum regularization and weighting parameters and filter coefficients for the Final Solver. The SST only solution is derived from kinematic orbits applying the energy integral approach in an inertial reference frame up to degree and order 100. The SGG normal equations are constructed from diagonal components of the gravitation tensor in the gradiometer reference frame up to degree and order 224 for Release 1 and 250 for Release 2. Optimum weighting of normal equations during the combination is based on variance component estimation. Kaula-regularization (Sneeuw and van Gelderen, 1997) is applied to zonal, near-zonal and higher order coefficients (above degree 170 for Release 1 and above degree 180 for Release 2).

The space-wise solution, SPW, is produced in cooperation between the Politecnico di Milano and the University of Copenhagen. A computational procedure consists of the three main steps: the data pre-processing, the low frequency model estimation based on the SST data and the full model estimation based on the both SST and SGG data, see Migliaccio et al., (2004) and (2010). The aim of the data pre-processing is to remove outliers and to fill gaps. The gaps are filled with the values estimated by the collocation using an empirical covariance function. The SST model is derived by estimation of the gravitational potential along track by applying the energy conservation approach. Then the collocation is applied to produce the geographical grid of the potential values on a sphere at mean satellite altitude. The harmonic analysis is produced by numerical integration. The final SPW solution is computed iteratively. First, the long wavelength signal from SST model is removed from SGG data and a Wiener filter along the orbit is applied to reduce the coloured noise of the gradiometer. After filtering the gridding is performed on a sphere at mean satellite altitude applying the collocation to local patches of data. Then the spherical harmonic coefficients are derived using a numerical integration. The third main part of the procedure is iterated according to the scheme described in Migliaccio et al. (2010). More details can be found in Reguzzoni and Tselles (2009). The purpose of the iterations is to recover the signal removed by the filtering and to correct the small rotation of the data from the gradiometer reference frame to the local orbital reference frame. The error covariance matrix of the coefficients is estimated by a Monte Carlo method.

Table 2. Data periods included in particular solutions and releases.

Solution	From d/m/y	To d/m/y	Number of days	From d/m/y	To d/m/y	Number of days
	Release 1			Release 2		
DIR	01/11/2009	11/01/2010	72	01/11/2009	30/06/2010	242
TIM	01/11/2009	11/01/2010	72	01/11/2009	05/07/2010	247
SPW	30/10/2009	11/01/2010	74	31/10/2009	05/07/2010	248

Table 3. Weights used for different normal equation accumulation for DIR solutions.

Release	SST	SGG		
		V_{xx}	V_{yy}	V_{zz}
1	0.05	1.0	0.5	1.0
2	0.00001	1.0	1.0	1.0

3. Comparison in Central Europe

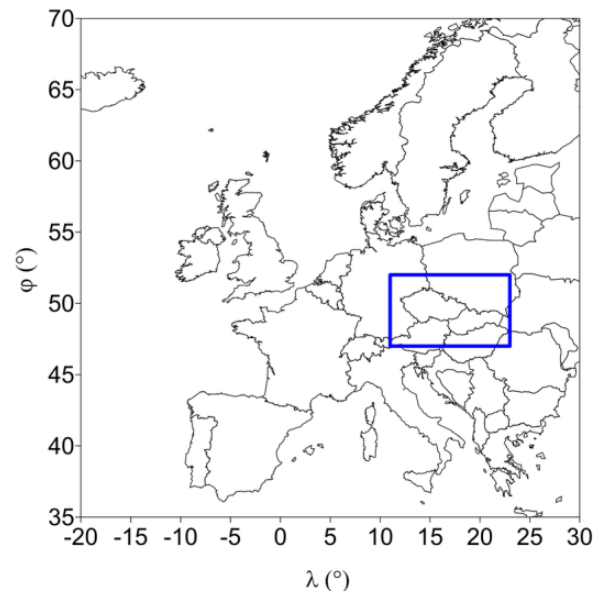
The comparison has been performed in the area bounded by parallels 47°N and 52°N and meridians 11°E and 24°E. The area in context of Europe is shown in Fig. 1. All models have been computed from spherical harmonic coefficients in a regular geographic grid $1' \times 1'$ using the GRAFIM software (Janák and Šprlák, 2006) developed in our department. A spherical harmonic synthesis for every model has been performed up to degree and order 210, which is the lowest maximum degree of all tested models, see Table 1, and also up to the maximum degree and order of each model. The summary of the maximum degrees used for the computation of each model is shown in Table 4. The following quantities have been compared: free-air gravity anomalies, height anomalies, meridian and prime-vertical components of deflection of the vertical.

Table 4. Maximum degrees and orders used for the models in our comparison.

Modelling	nmax			
	210	224	240	250
DIR (release 1)	x		x	
DIR (release 2)	x		x	
TIM (release 1)	x	x		
TIM (release 2)	x			x
SPW (release 1)	x			
SPW (release 2)	x		x	
EGM2008	x	x	x	x
GOCO025	x	x	x	x

The results of the comparison in terms of gravity anomalies are organised as follows. First the map of each quantity produced from TIM (release 1) solution is shown computed up to degree and

order 210 and 224. The other solutions are visually very similar so the other maps are omitted. Then the maps and histograms of differences between the particular solutions and EGM2008 or GOCO025, respectively, computed up to full degree and order of the particular GOCE solution are depicted. The EGM2008 or GOCO025 are always assumed to be in the identical spectral band as the particular GOCE solution. Finally a table with the statistical parameters of differences is shown for degree and order 210 as well as for the maximum degree and order for particular models, see Table 4. The results of the comparison in terms of height anomalies and components of the deflection of the vertical follow the same structure as for the gravity anomalies except that the maps of differences and the histograms are omitted. In order to simplify the notation of results, instead of appending the Release 1 or Release 2 after the name of a solution, we will append only the number 1 or 2, e.g. DIR1 will represent the direct solution (Release 1).

**Figure 1.** Area used for comparison (surrounded by rectangle) in context of Europe.

3.1. Comparison in terms of gravity anomalies

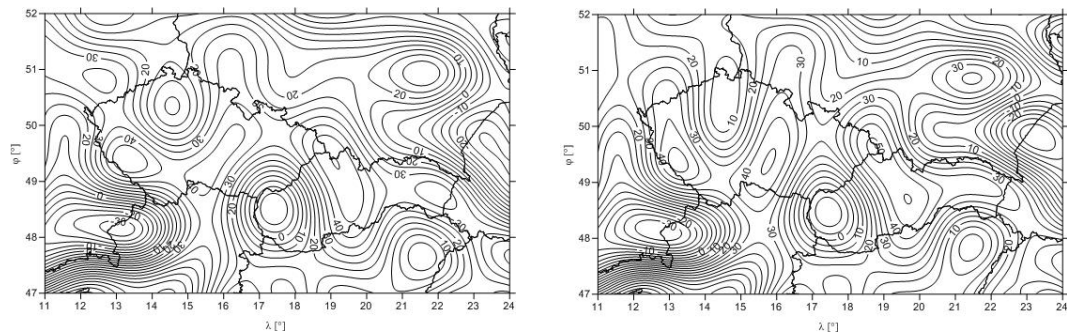


Figure 2. Free-air gravity anomalies: TIM1, $n_{\max} = 210$ (left), 224 (right), interval: 5 mGal.

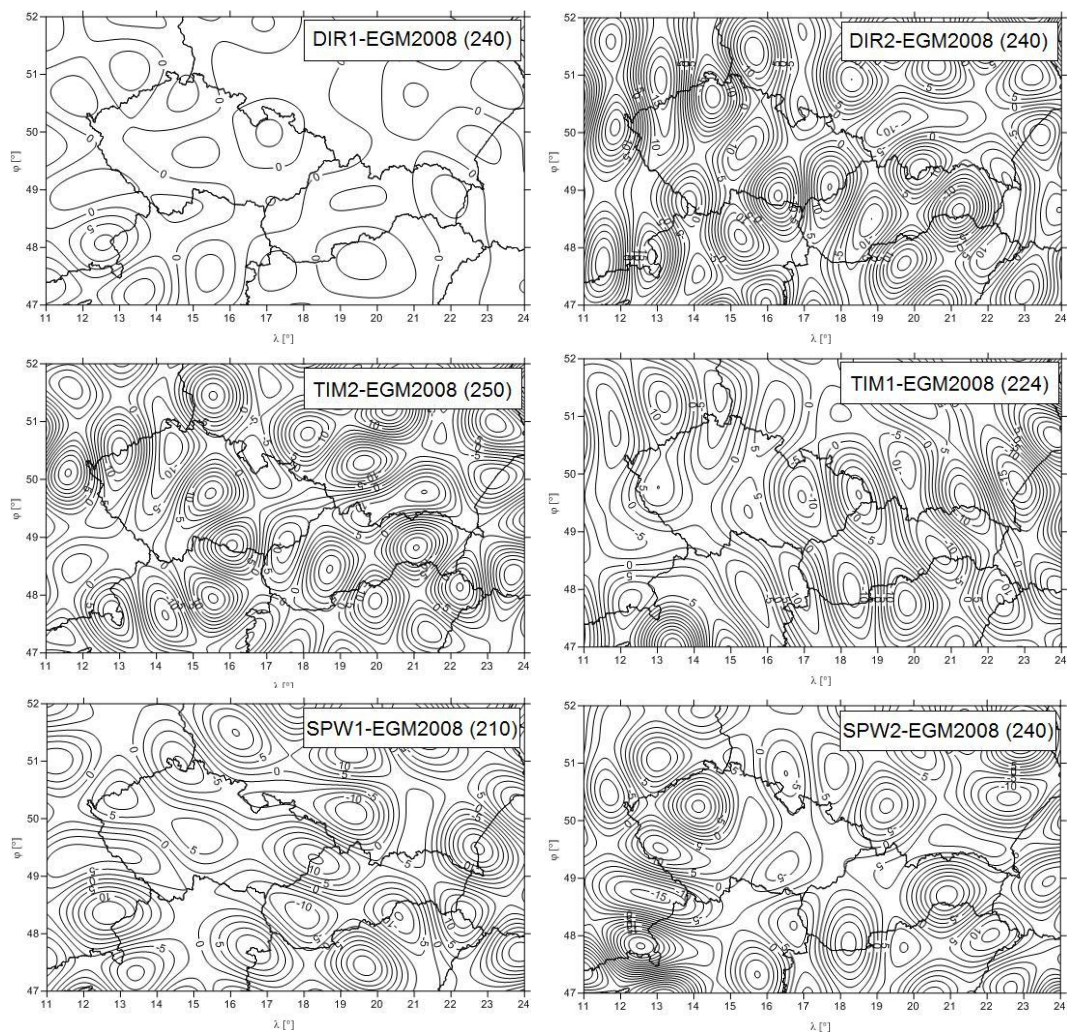


Figure 3. Differences between each GOCE solution (up to full degree and order) and EGM2008: Release 1 (left), Release 2 (right), interval: 2.5 mGal.

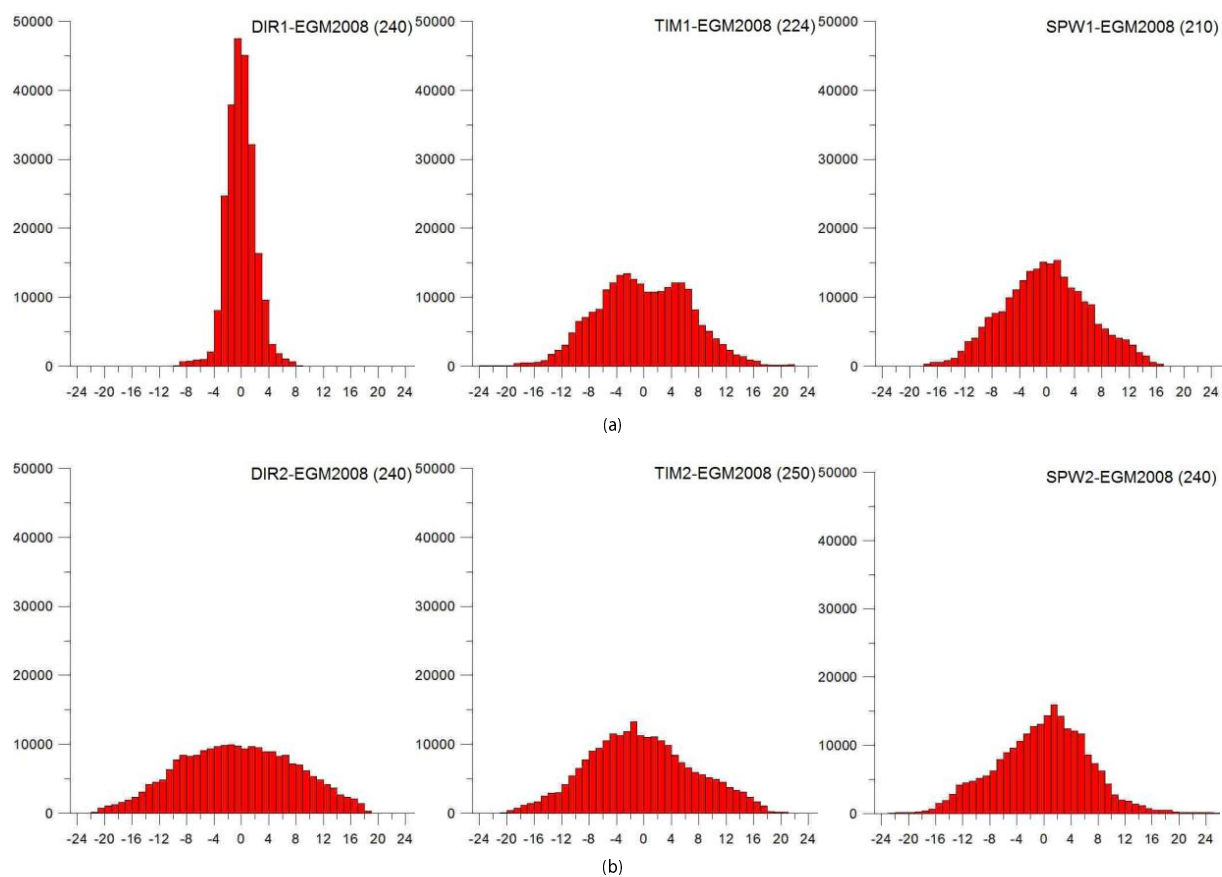


Figure 4. Histograms of differences between each solution (up to full degree and order) and EGM2008: Release 1 (a), Release 2 (b), interval: 1 mGal.

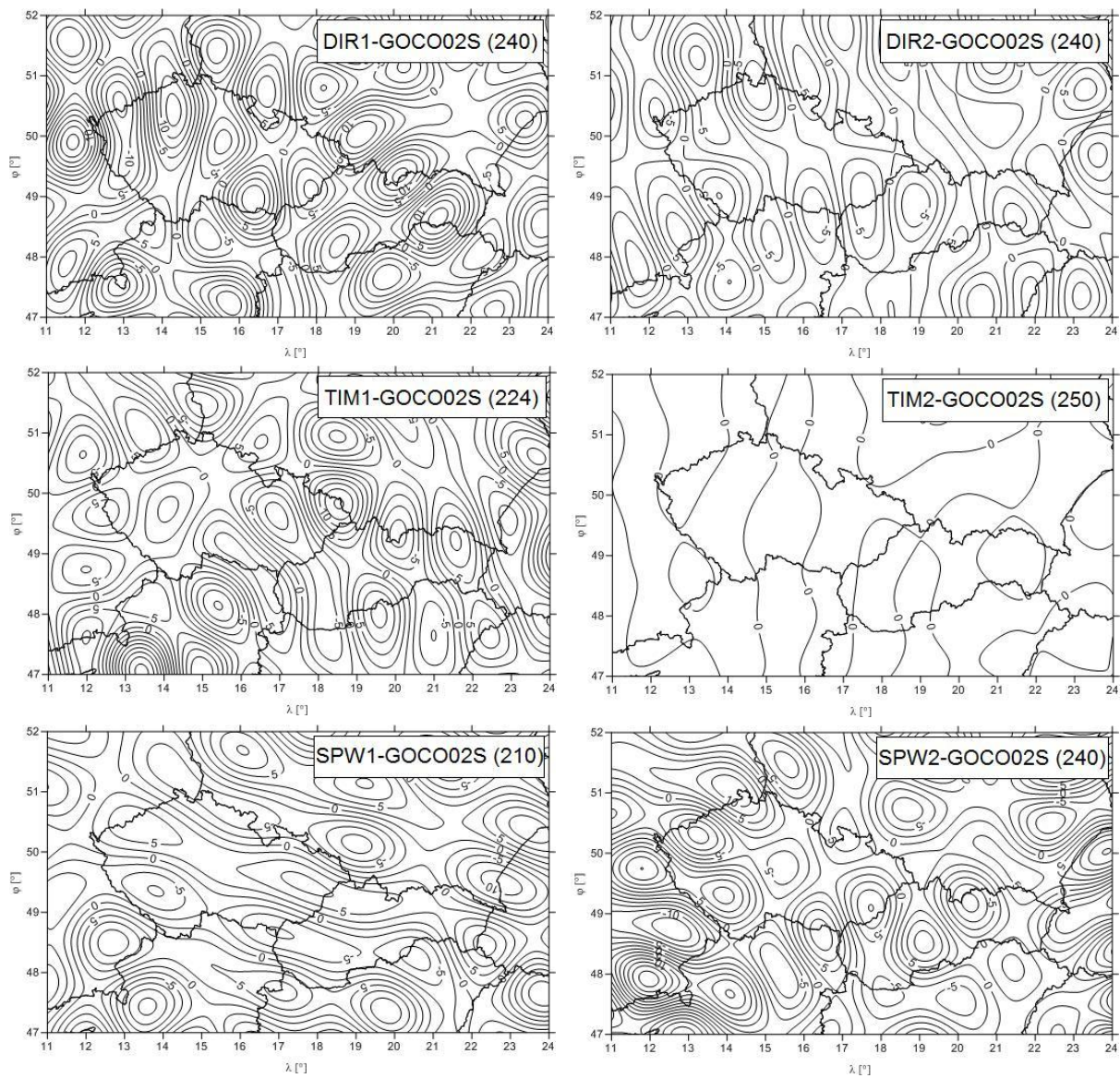


Figure 5. Differences between each solutions (up to full degree and order) and GOCO02S: Release 1 (left), Release 2 (right), interval: 2.5 mGal.

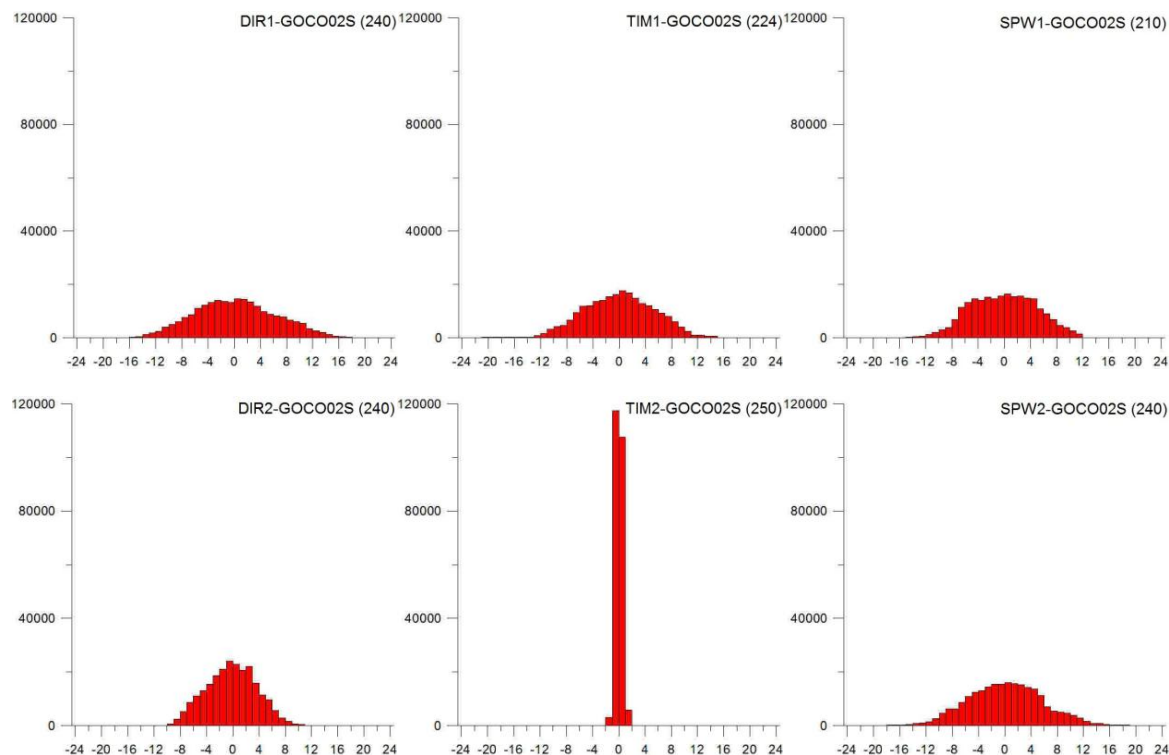


Figure 6. Histograms of differences between each solution (up to full degree and order) and GOCO02S: Release 1 (top), Release 2 (bottom), interval: 1 mGal.

Table 5. Basic statistics of free-air gravity anomaly differences. Total number of differences in each set: 233700.

Differences	Min	Max	Mean	Range	St. d.	$n_{\max}$
	(mGal)					
DIR1-EGM2008	-6.44	5.95	-0.04	12.39	1.59	210
	-9.09	8.09	-0.09	17.18	2.12	240
DIR2-EGM2008	-8.31	7.45	-0.03	15.76	3.02	210
	-21.73	18.73	-0.56	40.46	8.35	240
TIM1-EGM2008	-13.96	12.27	0.01	26.23	4.80	210
	-24.98	22.23	-0.04	47.20	6.85	224
TIM2-EGM2008	-7.31	7.84	0.06	15.15	2.90	210
	-20.30	21.18	-0.40	41.48	7.70	250
SPW1-EGM2008	-18.15	16.69	-0.05	34.84	6.31	210
SPW2-EGM2008	-11.31	13.30	0.03	24.61	4.20	210
	-24.97	25.35	-0.20	50.31	6.91	240
DIR1-GOCO02S	-7.22	6.30	-0.08	13.51	2.63	210
	-15.78	18.39	0.27	34.16	6.19	240
DIR2-GOCO02S	-3.99	4.17	-0.07	8.16	1.22	210
	-10.00	10.85	-0.20	20.85	3.79	240
TIM1-GOCO02S	-9.34	8.51	-0.03	17.86	3.12	210
	-21.11	15.33	-0.01	36.44	5.40	224
TIM2-GOCO02S	-0.71	0.81	0.03	1.52	0.27	210
	-1.34	1.57	0.01	2.91	0.46	250
SPW1-GOCO02S	-14.68	11.93	-0.09	26.60	5.02	210
SPW2-GOCO02S	-6.80	8.20	0.00	15.00	2.45	210
	-19.12	19.03	0.15	38.15	5.67	240

3.2. Comparison in terms of height anomalies

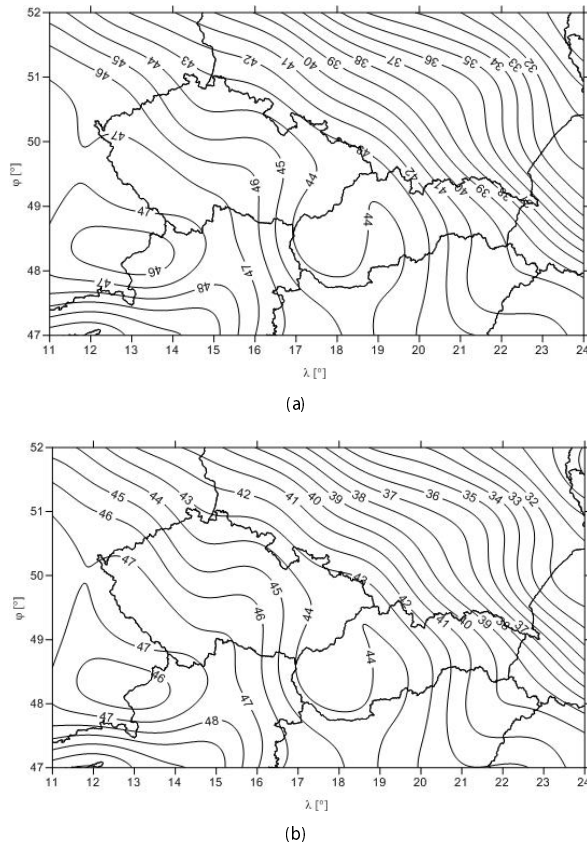
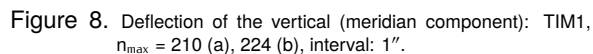


Figure 7. Height anomalies (quasigeoid undulation): TIM1, $n_{\max} = 210$ (a), 224 (b), interval: 1 m.

Table 6. Basic statistics of height anomaly differences. Total number of differences in each set: 233700.

Differences	Min	Max	Mean (m)	Range	St. d.	$n_{\max}$
DIR1-EGM2008	-0.25	0.18	0.00	0.43	0.06	210
	-0.33	0.23	-0.01	0.56	0.07	240
DIR2-EGM2008	-0.28	0.25	0.00	0.53	0.10	210
	-0.66	0.57	-0.02	1.22	0.24	240
TIM1-EGM2008	-0.44	0.43	0.02	0.87	0.16	210
	-0.77	0.70	0.02	1.47	0.21	224
TIM2-EGM2008	-0.23	0.27	0.01	0.50	0.10	210
	-0.57	0.58	0.00	1.16	0.22	250
SPW1-EGM2008	-0.60	0.54	0.00	1.14	0.21	210
SPW2-EGM2008	-0.36	0.43	0.01	0.79	0.14	210
	-0.75	0.75	0.00	1.50	0.21	240
DIR1-GOCO02S	-0.26	0.22	-0.01	0.48	0.09	210
	-0.47	0.53	0.01	1.00	0.18	240
DIR2-GOCO02S	-0.17	0.17	0.00	0.33	0.05	210
	-0.31	0.35	-0.01	0.66	0.11	240
TIM1-GOCO02S	-0.31	0.31	0.02	0.62	0.11	210
	-0.77	0.70	0.02	1.47	0.21	224
TIM2-GOCO02S	-0.02	0.04	0.01	0.06	0.01	210
	-0.04	0.06	0.01	0.10	0.02	250
SPW1-GOCO02S	-0.48	0.40	0.00	0.88	0.17	210
SPW2-GOCO02S	-0.22	0.27	0.01	0.49	0.08	210
	-0.57	0.55	0.01	1.12	0.17	240

Differences	Min	Max	Mean ($''$)	Range	St. d.	$n_{\max}$
DIR1-EGM2008	-0.88	0.84	-0.01	1.72	0.23	210
	-1.27	1.11	-0.01	2.38	0.32	240
DIR2-EGM2008	-1.08	1.44	0.00	2.52	0.41	210
	-2.40	2.65	-0.01	5.05	0.96	240
TIM1-EGM2008	-1.77	1.77	-0.01	3.53	0.63	210
	-2.68	3.43	-0.02	6.10	0.82	224
TIM2-EGM2008	-1.10	1.28	-0.01	2.38	0.41	210
	-3.21	3.13	0.00	6.34	1.13	250
SPW1-EGM2008	-2.64	2.83	-0.02	5.47	1.06	210
SPW2-EGM2008	-2.25	2.13	-0.03	4.38	0.65	210
	-4.53	3.88	-0.02	8.41	1.13	240
DIR1-GOCO02S	-0.90	0.85	0.00	1.75	0.34	210
	-2.17	2.25	0.01	4.42	0.85	240
DIR2-GOCO02S	-0.39	0.47	0.00	0.87	0.14	210
	-1.29	1.06	0.01	2.35	0.39	240
TIM1-GOCO02S	-1.15	1.16	-0.01	2.31	0.44	210
	-2.67	3.43	-0.02	6.10	0.82	224
TIM2-GOCO02S	-0.07	0.11	0.00	0.18	0.03	210
	-0.15	0.17	0.00	0.32	0.06	250
SPW1-GOCO02S	-2.06	2.20	-0.01	4.26	0.90	210
SPW2-GOCO02S	-1.39	1.26	-0.02	2.64	0.39	210
	-3.07	3.00	0.00	6.07	0.98	240



3.4. Comparison in terms of the prime vertical component of the deflection of the vertical

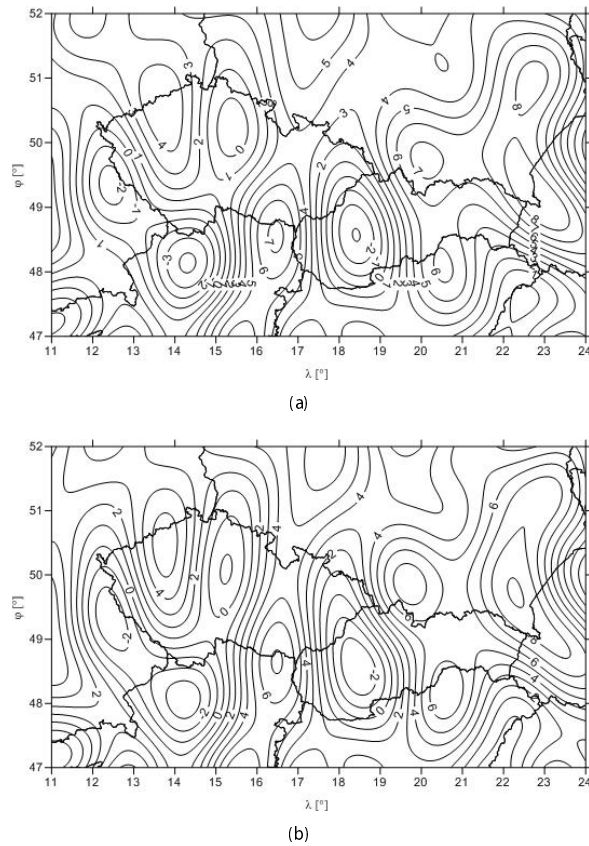


Figure 9. Deflection of the vertical (prime vertical component): TIM1, $n_{\max} = 210$ (a), 224 (b), interval: $1''$.

During the course of this experiment, more maps and histograms were produced. However, in order to keep the paper to a reasonable length, we have tried to make a representative sample enabling us to see the most important features of particular global GOCE solutions.

Before we start to analyze the results, we should remember that in our comparison there is no absolute reference. The EGM2008 and GOCO02S are used as a certain master reference but not in an absolute sense. Thus if some GOCE solution is very close to EGM or GOCO, it does not necessarily mean that the solution is better than the others. A slightly different situation in our second testing is described in Section 4.

Let us start by analyzing Fig. 3 and Fig. 4. The most evident information is that solution DIR1 is very similar to EGM2008. Although EGM2008 is not listed as a direct data source for the DIR1 solution, the EIGEN-51C model incorporates the DNSC08GRA global dataset of gravity anomaly (Andersen et al., 2010) which is based on EGM2008 model over the continents, see (Hirt et al., 2011). The high correlation of DIR1 with the EGM2008, or listed a-priori

Table 8. Basic statistics of differences of the prime vertical component of deflection of the vertical. Total number of differences in each set: 233700.

Differences	Min	Max	Mean	Range	St. d.	$n_{\max}$
	(″)					
DIR1-EGM2008	-0.93	0.74	0.01	1.67	0.24	210
	-1.24	0.87	0.01	2.11	0.31	240
DIR2-EGM2008	-1.32	1.30	-0.01	2.62	0.49	210
	-3.59	3.91	0.02	7.50	0.96	240
TIM1-EGM2008	-2.24	2.08	-0.02	4.31	0.81	210
	-3.60	3.13	-0.03	6.73	1.22	224
TIM2-EGM2008	-1.21	1.31	-0.01	2.52	0.45	210
	-3.15	3.05	0.01	6.20	1.19	250
SPW1-EGM2008	-2.25	2.10	-0.03	4.35	0.83	210
SPW2-EGM2008	-1.51	1.68	-0.01	3.19	0.59	210
	-3.01	2.65	-0.02	5.66	0.95	240
DIR1-GOCO02S	-1.25	1.08	0.02	2.33	0.44	210
	-2.65	2.83	0.00	5.48	0.99	240
DIR2-GOCO02S	-0.65	0.80	-0.01	1.45	0.21	210
	-1.57	1.92	0.01	3.49	0.70	240
TIM1-GOCO02S	-1.62	1.51	-0.01	3.13	0.50	210
	-3.60	3.13	-0.03	6.73	1.22	224
TIM2-GOCO02S	-0.13	0.12	0.00	0.25	0.05	210
	-0.28	0.28	0.00	0.55	0.08	250
SPW1-GOCO02S	-1.58	1.74	-0.02	3.32	0.58	210
SPW2-GOCO02S	-0.85	0.83	0.00	1.68	0.34	210
	-2.29	1.83	-0.03	4.11	0.73	240

model EIGEN-51C, is not necessarily a positive feature, because it means that DIR1 most probably also absorbs weaknesses of those models, mainly the inhomogeneous accuracy. However, this cannot be seen from our results as EGM2008 performs very well in central Europe.

Next, we can see that Release 1 and Release 2 for every solution differ significantly. On one hand, from Fig. 3 we see that the differences of Release 2 are larger than the differences of Release 1 for the DIR solution and they have approximately the same magnitude but a different pattern for the TIM and SPW solutions. This could seemingly indicate that the Release 2 is not better. On the other hand, we have to keep in mind that Release 2 for the TIM and SPW solutions has a higher resolution, so when we make a comparison of Release 1 and 2 with the same resolution (up to degree and order 210, see Tab. 5) we see that the Release 2 performs significantly better than the Release 1 for both the TIM and SPW solutions. Increasing the resolution from degree 210 up to the maximum degree and order causes higher differences against the EGM2008 for all solutions.

A closer look at the statistics in Tab. 5 reveals that the solutions of DIR2, TIM2 and SPW2 using up to full resolution have a lower mean value than EGM2008. This feature is not observed for Release 1, or for Release 2 using up to degree and order 210. It is not even visible in Tables 6–8. Most likely it is due to insufficient accuracy in the higher degree and order coefficients (above degree and

order 224). The DIR1 solution is not affected because of its high dependence on the EGM2008.

The DIR2, TIM2 and SPW2 solutions are approximately in similar agreement with EGM2008 although there are slight differences. The SPW2 shows the worst range of differences but, curiously, the best standard deviations in terms of the free-air gravity anomalies and the height anomalies, Tab. 5 and 6. However, the statistical significance of this feature has not been tested.

When analyzing the comparison with the GOCO02S global model, we should keep in mind that the GOCO model was also compiled by the GOCE Gravity Consortium from CHAMP (Challenging Minisatellite Payload), GRACE (Gravity Recovery and Climate Experiment) GOCE and SLR (Satellite Laser Ranging) data. Therefore GOCO02S is dependent on GOCE data and especially on the TIM2 solution as we immediately see in Fig. 5 and 6 and also in Tables 5–8. From Goiginger et al. (2011) we learn that GOCO02S is a global model complete up to degree and order 250, while for degrees 0–120 the GRACE coefficients dominate (sectoral coefficients are also significantly influenced by the CHAMP and GOCE SST solutions), for degrees 120–140 there is comparable influence of the GRACE and GOCE SGG solutions, for degrees 140–225 the GOCE SGG coefficients dominate and for 225–250 the Kaula regularization prevails.

While the GOCE Release 1 solutions are approximately at the same level of conformity to GOCO02S, the Release 2 solutions are strictly graded. The TIM2 solution is in almost perfect agreement, the DIR2 solution performs worse but is still in much better agreement with GOCO02S than with EGM2008 and the SPW2 solution performs the worst.

4. Regional testing in Slovakia

The Slovak Terrestrial Reference Frame (SKTRF) has been built since 1993 by Geodetic and Cartographic Institute (GCI) in cooperation with other institutions using Global Navigation Satellite Systems (GNSS). Nowadays it consists of about 60 GNSS points. Among them there are approximately 20 permanent stations and 40 epoch-wise GNSS points. We performed our testing using 31 points of the SKTRF network at which a reliable sea-level height obtained from precise levelling method was available, see Fig. 10.

The ellipsoidal coordinates (φ, λ, h) were provided by GCI in ETRS89 system (Boucher and Altamini, 1992), epoch 2008.5. Consequently, we transformed these coordinates to ITRF05 (Altamini et al., 2007), epoch 2010.0 to become consistent with the GOCE global solutions. The sea-level heights were provided by GCI in the Baltic (Kronstadt) vertical datum with the national denotation Bpv. These sea-level heights are defined as normal heights of Molodensky's type. Combining these heights with the ellipsoidal heights the height anomalies on test points were computed. The gravity values were provided by GCI in national gravity system GR-95 (Klobušiak and Pecár, 2004), which is based on free-fall absolute gravity measurements. Consequently, the free-air gravity

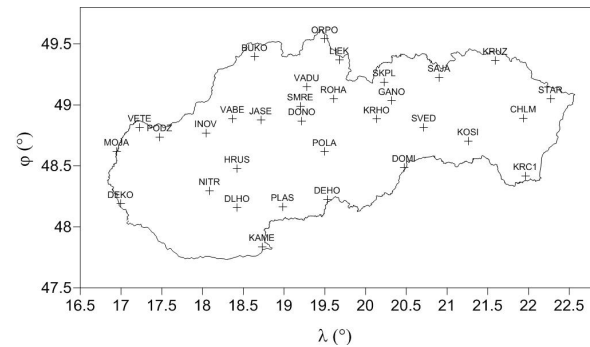


Figure 10. Distribution of the SKTRF stations.

Table 9. Basic statistics of differences of free-air gravity anomalies. Total number of differences in each set: 31

Differences	Min	Max	Mean (mGal)	Range	St. d.	n _{max}
DIR1-measured	-63.4	25.8	-7.3	89.2	18.4	240
DIR2-measured	-56.1	17.1	-7.3	73.2	17.1	240
TIM1-measured	-71.0	28.6	-7.7	99.6	20.0	224
TIM2-measured	-62.9	15.7	-7.4	78.6	17.3	250
SPW1-measured	-63.0	24.0	-7.1	87.0	18.3	210
SPW2-measured	-65.4	18.7	-7.2	84.0	17.2	240
EGM2008-measured	-60.9	27.1	-7.1	88.0	17.8	2160
GOCO02S-measured	-63.2	16.1	-7.4	79.2	17.3	250

anomalies consistent with the GRS80 normal gravity field were computed.

The free-air gravity anomalies and height anomalies from each global GOCE solution up to full degree and order were again computed using the GRAFIM software (Janák and Šprlák, 2006). In order to minimize any omission error, the influence of spherical harmonics higher than the full degree of GOCE models was computed from EGM2008 up to degree and order 2160 using the GRAFIM software. This higher degree contribution was subtracted from the free-air gravity anomalies and height anomalies computed from measured values on the SKTRF stations. Any influence of spherical harmonics above degree and order 2160 in the omission error was neglected. Subsequently, a comparison in terms of free-air gravity anomalies and height anomalies was performed.

First, the histograms of differences between the values computed from particular GOCE solutions and the measured values at the SKTRF points for free-air gravity anomalies and for height anomalies are shown, Figs. 11 and 12, and then the tables with basic statistics are presented, Tables 9 and 10. A comparison of the measured values with EGM2008 and GOCO02S is also present.

If we want to interpret the results obtained at the SKTRF points, we should remember that the free-air gravity anomalies coming from terrestrial gravity measurements and the height anomalies computed from GNSS measurements and spirit levelling mea-

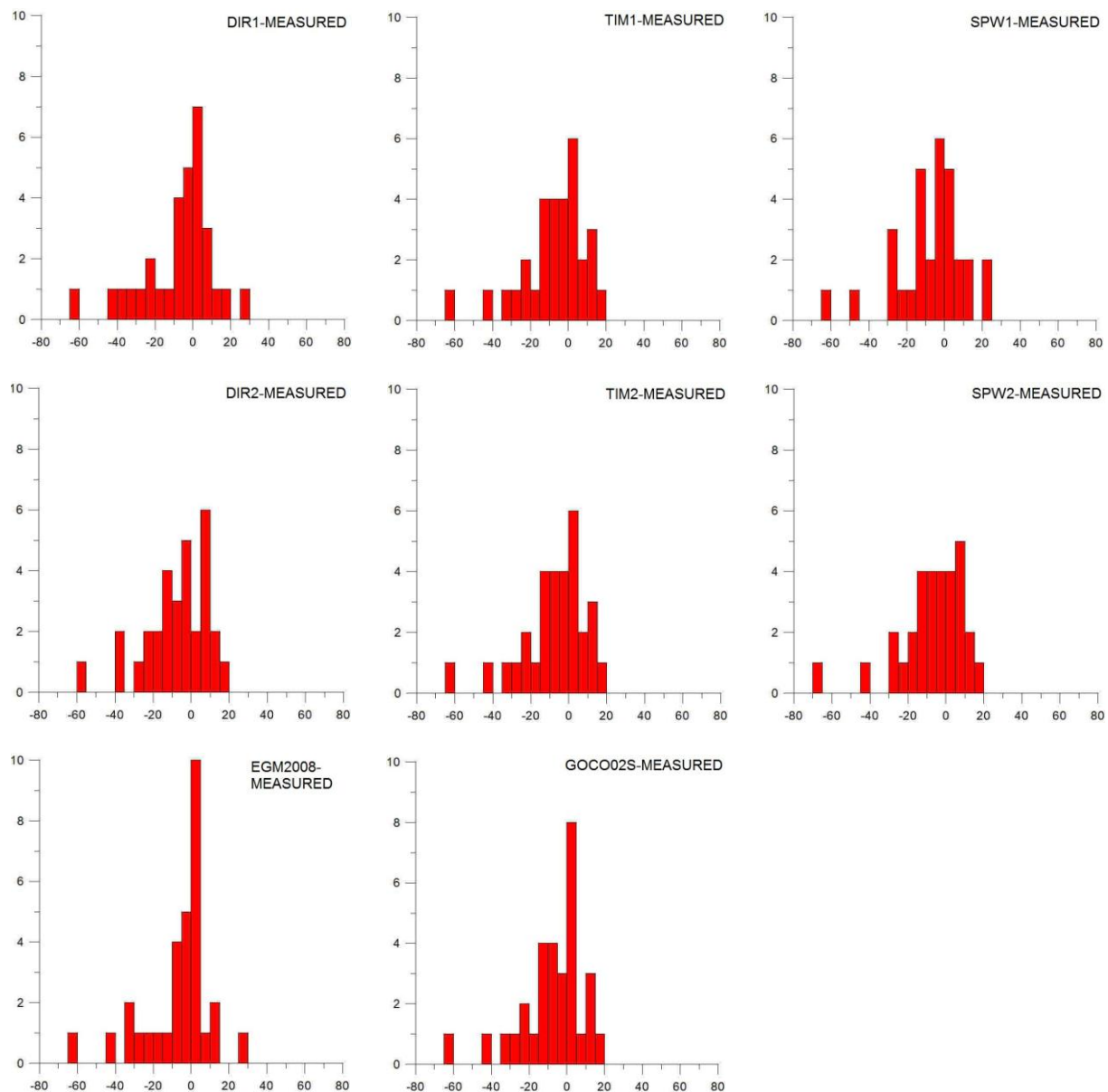


Figure 11. Histograms of differences between the free-air gravity anomalies (computed from global models – measured) at 31 SKTRF stations. Interval: 5 mGal.

measurements have different sources of errors. This is probably also the reason why the histograms for the free-air gravity anomalies, Fig. 11, and for the height anomalies, Fig. 12, are so different.

From the comparison a systematic effect of approximately -7.3 mGal for the free-air gravity anomalies and 44 cm for the height anomalies is evident. The first systematic effect is probably due to insufficient modelling of the omission error as the frequencies above the degree and order 2160 were neglected. The second

systematic effect is certainly caused by the inconsistency of the Kronstadt vertical datum with the global vertical datum.

For the free-air gravity anomalies all the GOCE solutions are approximately at the same level of consistency with the ground-based values. The Release 2 solutions gives slightly better results than the Release 1 even better than the EGM2008. For height anomalies, the DIR1 solution is by far the best. We think it is because of its high correlation with the EGM2008 which is very good in central Europe and also partially because the omission

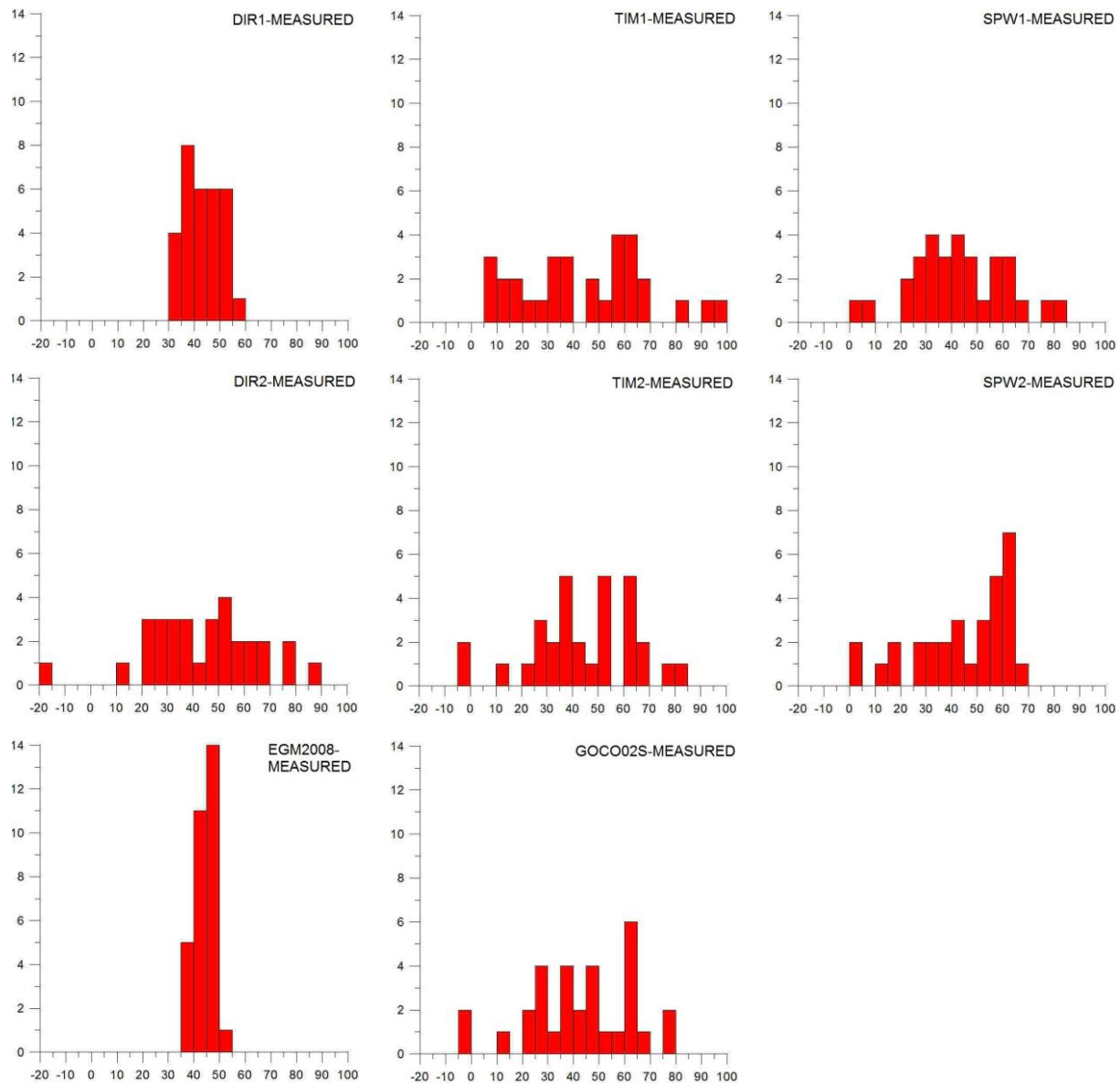


Figure 12. Histograms of differences between the height anomalies (measured – computed from global models) at 31 SKTRF stations. Interval: 5 cm.

error has been computed from the EGM2008 model itself. The second best GOCE solution for height anomalies seems to be the SPW2 because it has a significantly lower range of the differences than the rest of the GOCE solutions.

5. Conclusion

The ambition of this paper was to estimate the quality of the global GOCE solutions over the central Europe and specifically to show the improvement of the Release 2 solutions against the Release 1 solutions. We hope this aim was fulfilled. From the first test, presented in Section 3, it follows that the Release 2

solutions TIM2 and SPW2 computed up to degree and order 210 improve significantly against the Release 1 solutions TIM1 and SPW1 when compared with the EGM2008, see Tables 5–8. The positive thing with the DIR2 solution, although it performs worse than DIR1 when compared with the EGM2008, is that it is less dependent on the EGM2008 than DIR1 and it is approximately at the same level of consistency with the EGM2008 as the TIM2 and SPW2 solutions. Comparing the Release 2 solutions with GOCO02S the improvement against the Release 1 solutions is even more significant.

Table 10. Basic statistics of differences of height anomalies. Total number of differences in each set: 31

Differences	Min	Max	Mean	Range	St. d.	n _{max}
	(mGal)					
DIR1-measured	31.0	58.7	43.3	27.7	7.3	240
DIR2-measured	-15.6	85.1	44.2	100.7	21.4	240
TIM1-measured	7.4	95.5	44.4	88.1	24.7	224
TIM2-measured	-4.7	80.3	44.1	85.0	20.9	250
SPW1-measured	4.5	81.5	43.3	77.0	18.3	210
SPW2-measured	0.4	67.7	44.5	67.3	18.9	240
EGM2008-measured	37.0	50.2	44.3	13.2	3.5	2160
GOCO02S-measured	-3.3	78.2	43.0	81.5	20.7	250

Another important thing we can see (mainly from Tables 5–8) is that increasing the resolutions above the degree and order 210 still brings a drastic loss of accuracy except for the DIR1 solution. This problem is known and was already demonstrated for the Release 1 solutions by Gruber et al. (2011) and Hirt et al. (2011). However, a positive indication can be found in Tables 5–8 that the loss of accuracy is in general slower for the Release 2 solutions.

The second test presented in Section 4 represents a comparison with the completely different and independent ground-based measurements and therefore, from this point of view, is more important than the first test. On the other hand it was carried out in a smaller area using only 31 well verified points of the SKTRF network. The results of this experiment suggest that the best GOCE quasigeoid solution for the central Europe is DIR1. However, we should be very careful with such an explicit interpretation. A better conclusion would be that our experiment reveals how much the DIR1 solution is linked to the EGM2008 model. In terms of free-air gravity anomalies we can observe a slightly better performance for the Release 2 GOCE solutions than for the Release 1 solutions and even better than for EGM2008. The best solution, although probably not significantly better, seems to be the DIR2 solution. The analysis of the EGM2008 and GOCO02S models using the SKTRF points shows that their performance in terms of free-air gravity anomalies is at the same level while in terms of height anomalies EGM2008 performs much better in our testing area.

We did not perform a deep joint analysis of the two presented experiments as it would require a significant extension of the paper. Nevertheless, from both experiments it can be seen that the Release 2 GOCE solutions are more accurate and better balanced. The problem with the accuracy of the higher harmonic components still remains although some improvement is visible.

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