Evaluation of GOCE-based Global Geoid Models in Finnish Territory

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Abstract

The gravity satellite mission GOCE made its final observations in the fall of 2013. By then it had exceeded its expected lifespan of 20 months with 35 additional months and observed the Earth's gravitational field from a lower orbit as originally planned during the last 6 months of its mission lifetime. Thus, the mission collected more data from the Earth's gravitational field than expected, and more comprehensive global geoid models have been derived ever since. The GOCE High-level Processing Facility (HPF) by ESA has published GOCE global gravity field models annually. We compared all of the 13 HPF-models as well as 3 additional GOCE, 12 GRACE and 6 combined GOCE+GRACE models with GPS-levelling data and gravity observations in Finland. The most accurate models were also compared against high resolution global geoid models EGM96 and EGM2008.

The models were evaluated up to four different degrees and order: 150 (the common maximum for the GRACE models), 200, 240 (the common maximum for the GOCE models) and maximum. When coefficients up to degree and order 150 are used, the results from the GOCE models are better than EGM96 (with height anomalies) and are comparable with the latest GRACE models and EGM2008. Similar results are achieved with the coefficients up to 200, as the GOCE models perform clearly better than EGM96 when comparing with the GPS-levelling datasets. When coefficients up to 240 or maximum are used the results of the GOCE-based models are comparable with the high resolution models. The best performance of the satellite-only models is not usually achieved with the maximum coefficients, since the highest coefficients (above 240) are less accurately determined.

Keywords: GOCE, GRACE, Geoid model, GPS-levelling, Gravity, EGM2008, EGM96

1 Introduction

The start of the millennium has been an era of the global gravity satellite missions. It started with Challenging Minisatellite Payload (CHAMP), followed by Gravity Recovery And Climate Experiment (GRACE) and most recently the Gravity field and steady-state Ocean Circulation Explorer (GOCE). GOCE made its final observations in the fall of 2013, by then it had exceeded its expected lifespan of 20 months with 35 additional months due to milder solar winds. The last six months of its mission GOCE flew in much lower orbits than originally planned. Thus, the mission was a huge success, since GOCE not only collected more data but also denser data from the Earth's gravitational field than ever imagined, and more comprehensive global geoid models have been derived ever since.

In this study the global geoid models produced by the GOCE and GRACE satellite missions are studied. Altogether 16 GOCE models, 12 GRACE models and 6 combined GOCE+GRACE models are evaluated using Finnish terrestrial data to see how well the models perform relative to each other, but also to see their absolute agreement with terrestrial data. The latest models are also compared against pre-GOCE high resolution global geoid models EGM96 and EGM2008 to see the effect of the GOCE mission on the longer wavelengths in the lower degrees and orders.

2 Description of satellite gravity field models

In the following we shortly describe the global satellite gravity field models that were evaluated over Finland. The section is divided into three subsections: 2.1 GOCE models, 2.2 GRACE models and 2.3 combined GOCE+GRACE models.

2.1 GOCE models

We analyzed all of the GOCE global gravity field models that were calculated by the GOCE High-level Processing Facility (HPF) of ESA (Rummel et al., 2004). The HPF uses three different gravity field modelling methods resulting in three different models: direct (DIR), time-wise (TIM) and space-wise (SPW). A description of the three methods is given in (Pail et al., 2011). The first two DIR models are calculated starting with an a-priori model (EIGEN-5C for DIR1 and ITG-Grace2010s for DIR2), whereas all the follow-on DIR models use the previous model as an a-priori and complementary (GRACE and Laser Geodynamics Satellites (LAGEOS)) data to improve the lower degrees and orders. The TIM and SPW models are based on GOCE data only, although SPW uses a priori high resolution combined models for variance and covariance modelling. DIR and TIM models have been released for 5 data levels and SPW models for 3 data levels.

In addition to the models by HPF, we analyzed three alternative global gravity field models from GOCE: the ITG model by Schall et al. (2014) and the JYY models by Yi et al. (2013). Table 1 gives an overview of the GOCE models analyzed in this study. More information on the models can be found at the website of the International Center for Global Gravity Field Models (ICGEM, 2015).

Table 1: GOCE global gravity field models.

Model (maximum d/o)	Reference	Model (maximum d/o)	Reference
GO_CONS_GCF_2_DIR_R1 (240)	Bruinsma et al., 2010	GO_CONS_GCF_2_TIM_R4 (250)	Pail et al., 2011
GO_CONS_GCF_2_DIR_R2 (240)	Bruinsma et al., 2010	GO_CONS_GCF_2_TIM_R5 (280)	Pail et al., 2011
GO_CONS_GCF_2_DIR_R3 (240)	Bruinsma et al., 2010	GO_CONS_GCF_2_SPW_R1 (210)	Migliaccio et al., 2010
GO_CONS_GCF_2_DIR_R4 (260)	Bruinsma et al., 2013	GO_CONS_GCF_2_SPW_R2 (240)	Migliaccio et al., 2011
GO_CONS_GCF_2_DIR_R5 (300)	Bruinsma et al., 2013	GO_CONS_GCF_2_SPW_R4 (280)	Gatti et al., 2014
GO_CONS_GCF_2_TIM_R1 (224)	Pail et al., 2010a	ITG-Goce02 (240)	Schall et al., 2014
GO_CONS_GCF_2_TIM_R2 (250)	Pail et al., 2011	JYY_GOCE02S (230)	Yi et al., 2013
GO_CONS_GCF_2_TIM_R3 (250)	Pail et al., 2011	JYY_GOCE04S (230)	Yi et al., 2013

2.2 GRACE models

For the comparison to the lower degrees and orders of the GOCE models, we analyzed 12 GRACE models with 6 alternative solutions: AIUB, EIGEN, GGM, ITG, ITSG and Tongji. An overview of the GRACE models is given in Table 2.

Table 2: GRACE global gravity field models.

Model (maximum d/o)	Reference	Model (maximum d/o)	Reference
AIUB-GRACE02S (150)	Jäggi et al., 2009	GGM05S (180)	Tapley et al., 2013
AIUB-GRACE03S (160)	Jäggi et al., 2011	ITG-Grace02s (170)	Mayer-Gürr et al., 2006
EIGEN-GRACE02S (150)	Reigber et al., 2005	ITG-Grace03 (180)	Mayer-Gürr et al., 2007
EIGEN-5S (150)	Förste et al., 2008	ITG-Grace2010s (180)	Mayer-Gürr et al., 2010
GGM02S (160)	Tapley et al., 2005	ITSG-Grace2014k (200)	Mayer-Gürr et al., 2014
GGM03S (180)	Tapley et al., 2007	Tongji-GRACE01 (160)	Chen et al., 2013

2.3 *Combined GOCE+GRACE models*

In addition to the GOCE and GRACE models, we analyzed 6 combined GOCE+GRACE models with 3 alternative solutions: EIGEN, GOCO, and GOGRA. An overview of the combined GOCE+GRACE models is given in Table 3.

Table 3: Combined GOCE+GRACE global gravity field models.

Model (maximum d/o)	Reference	Model (maximum d/o)	Reference
EIGEN-6S2 (260)	Rudenko et al., 2014	GOCO03S (250)	Mayer-Gürr et al., 2012
GOCO01S (224)	Pail et al., 2010b	GOGRA02S (230)	Yi et al., 2013
GOCO02S (250)	Goiginger et al., 2011	GOGRA04S (230)	Yi et al., 2013

3 Datasets of the ground truth in Finland

The GOCE- and GRACE-based global gravity field models, described in section 2, were evaluated over Finland. In the evaluation, GPS-levelling data and gravity data of Finland were used for the comparison of height anomalies and gravity anomalies, respectively. Below, in sections 3.1 and 3.2 the data are described.

3.1 *GPS-levelling data*

For the comparison of the height anomalies, two GPS-levelling datasets were used: The European Vertical Reference Network - Densification Action (EUVN-DA) dataset and a dataset of the National Land Survey (NLS) of Finland.

The EUVN-DA dataset consists of the 50 Finnish EUVN-DA GPS-levelling points (Ollikainen, 2006). The points have EUREF-FIN GPS coordinates as well as N2000 heights (Bilker-Koivula, 2010). The dataset of the NLS of Finland consists of 526 GPS-levelling points taken from the register of the NLS. The accuracy (classes 1 to 3) and distribution of the points is not homogenous and the dataset partly overlaps with the EUVN-DA dataset. The coverage of the datasets in the Finnish territory is presented in Figure 1 (left and middle).

Both GPS-levelling datasets were corrected for the land uplift taking place between the epoch of the N2000 levelling data (2000.0) and the epoch of the EUREF-FIN GPS data (1997.0). The GPS data was transformed to epoch 2000.0 using vertical velocities taken from the NKG2005LU land uplift model (Vestøl, 2005; Ågren and Svensson, 2007). For a more detailed description of the GPS-levelling datasets see Bilker-Koivula (2015).

3.2 *Gravity data*

For the comparison of the free-air gravity anomalies the gravity database of the Finnish Geospatial Research Institute (FGI, former Finnish Geodetic Institute) was used (see Figure 1, right). The database contains gravity observations from early 20th century to present. Observations include terrestrial gravity measurements as well as measurements at sea, mainly on ice.

All of the gravity data in the gravity database of the FGI were transformed from epoch 1963.0 to 2000.0, which is the epoch of the current national height system of Finland N2000. In addition, the tide system was changed from mean tide to the zero tide. Gravity data from before 1938, mainly pendulum data, was removed from the used dataset. The coverage of the gravity dataset (altogether 39 318 points) is presented with the GPS-levelling datasets in Figure 1.

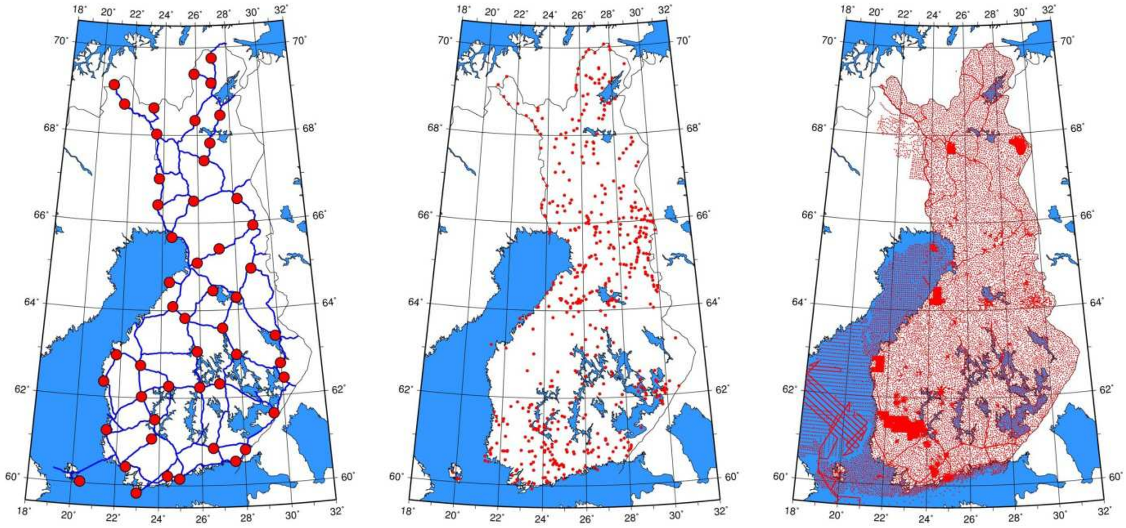

Figure 1: The coverage of the GPS-levelling and gravity datasets over Finland: EUVN-DA with 1st order precise levelling network (left), NLS (middle) and gravity database of the FGI (right).

4 Evaluation of the height and gravity anomalies

The global satellite gravity field models, described in section 2, were compared with the ground data described in section 3. For the comparison, height anomalies and free-air gravity anomalies were calculated from the global models by using the pyGravsoft-software (Forsberg and Tscherning, 2008).

To take care of the omission error, global models are commonly complemented with coefficients of the high resolution model EGM2008 (Pavlis et al., 2012). However, Bilker-Koivula (2015) has shown that there are problems with the EGM2008 model in the Eastern part of Finland. East of the 29 degree longitude line larger discrepancies are found in comparisons with GPS/levelling and gravity data than in the rest of the country. This is most probably due to the lower resolution gravity data used in EGM2008 over Northern Russia. This data was used east of the 29 degree longitude line, which lies for most part within Finnish borders. Using EGM2008 to take care of the omission error would introduce the problems of the EGM2008 into our results. We therefore decided not to complement the models with coefficients of the EGM2008 model. As a result, the omission error is still present in our results. However, when all models are evaluated to a common maximum degree, the omission error will be common for all the models and differences in results can be interpreted as coming from differences in the models.

To remove a possible offset and tilt, a first order polynomial is fitted through the comparison differences and then removed from the differences. Then the standard deviation is calculated from the remaining differences. Results are presented and discussed in the sections below.

4.1 GOCE models versus GPS-levelling and gravity data

At first, all of the GOCE models by HPF were calculated up to degree and order 200 as well as 240 (where models that have maximum degree and order lower than 240 were excluded) and compared against GPS-levelling and gravity data. The results of the comparisons can be seen in Figure 2 (d/o 200) and Figure 3 (d/o 240), where the standard deviations of the height anomalies compared to EUVN-DA and NLS data are presented with columns (primary axis) and the gravity anomalies compared to terrestrial gravity data with dotted line (secondary axis).

The performances of the HPF models are quite similar when developed up to degree and order 200. There are no significant improvements to be seen between the later models comparing to earlier models. However, when the models are developed up to degree and order 240 it is clearly seen how the later models perform better, with the exception of DIR1 where higher resolution combined model EIGEN-5C was included as an a-priori. This improvement of later models was expected, as they include more GOCE data leading to a better determination of the higher degrees and orders above 200.

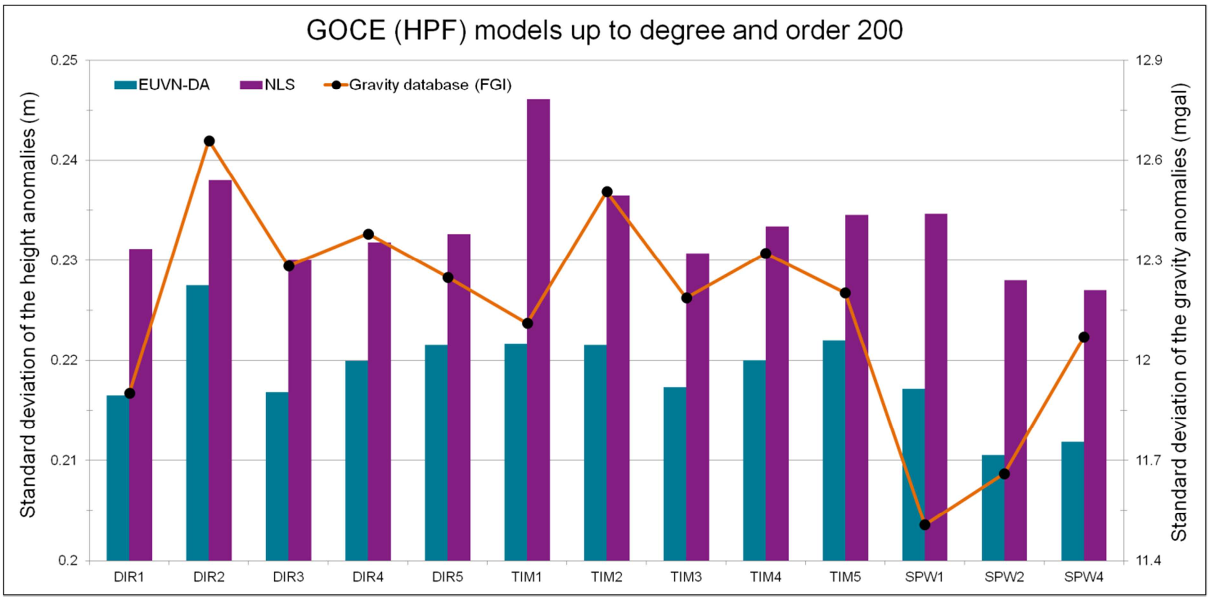

Figure 2: Comparison of the height and gravity anomalies from the GOCE (HPF) models using coefficients up to 200 against GPS-levelling and gravity data: standard deviations of the differences (m) and (mgal).

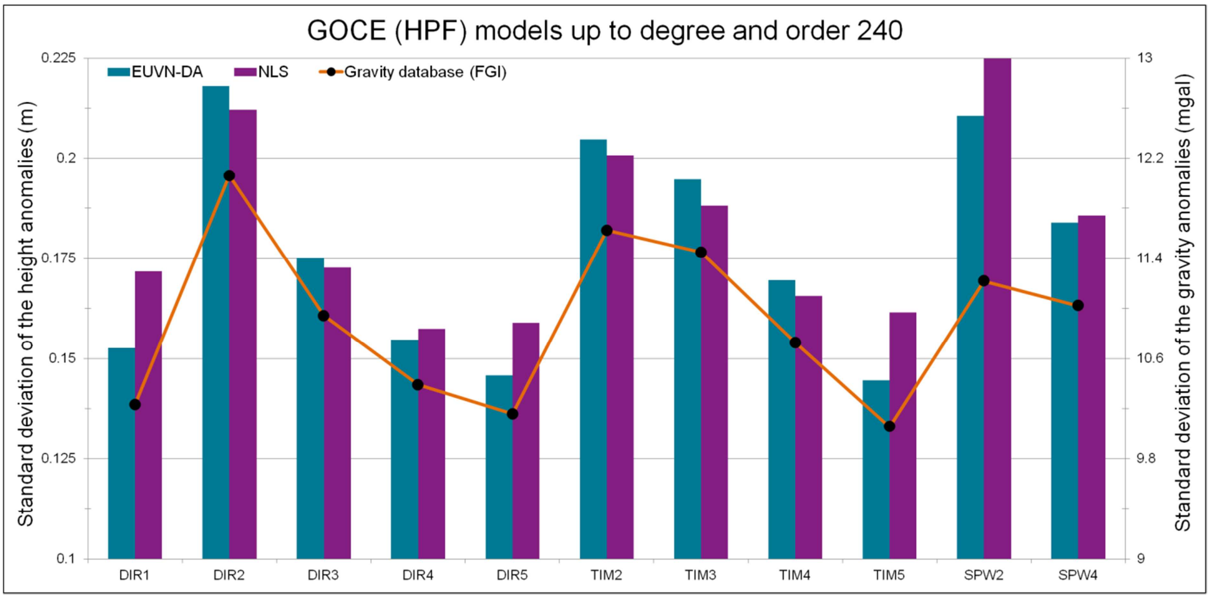

Figure 3: Comparison of the height and gravity anomalies from the GOCE (HPF) models using coefficients up to 240 against GPS-levelling and gravity data: standard deviations of the differences (m) and (mgal).

Generally, the DIR models agree better with the GPS-levelling and gravity data, most probably due to the use of complementary data from the observations of GRACE and LAGEOS. However, an interesting behavior of SPW models is seen from the Figure 2 and 3, as SPW models seem to be superior at degree 200, but deteriorates significantly when comparing with the other HPF models at degree 240.

Next, we calculated the height and gravity anomalies from all of the GOCE models, described in Table 1, using all available coefficients and compared them with the GPS-levelling and gravity data.

The results are presented in Figure 4. The best results with maximum coefficients are achieved with the latest DIR and TIM models, where the standard deviations of the height anomalies are for the DIR5 model 0.163 m (EUVN-DA) and 0.165 m (NLS), and for the TIM5 model 0.163 m (EUVN-DA) and 0.179 m (NLS). Standard deviations of the gravity anomalies behave in a similar fashion: 9.91 mgal (DIR5) and 10.14 mgal (TIM5). However, the best results are obtained with the latest models developed to degree and order 240 (Figure 3). One should keep this in mind when using GOCE-only models e.g. in geoid calculation or in the unification of height systems.

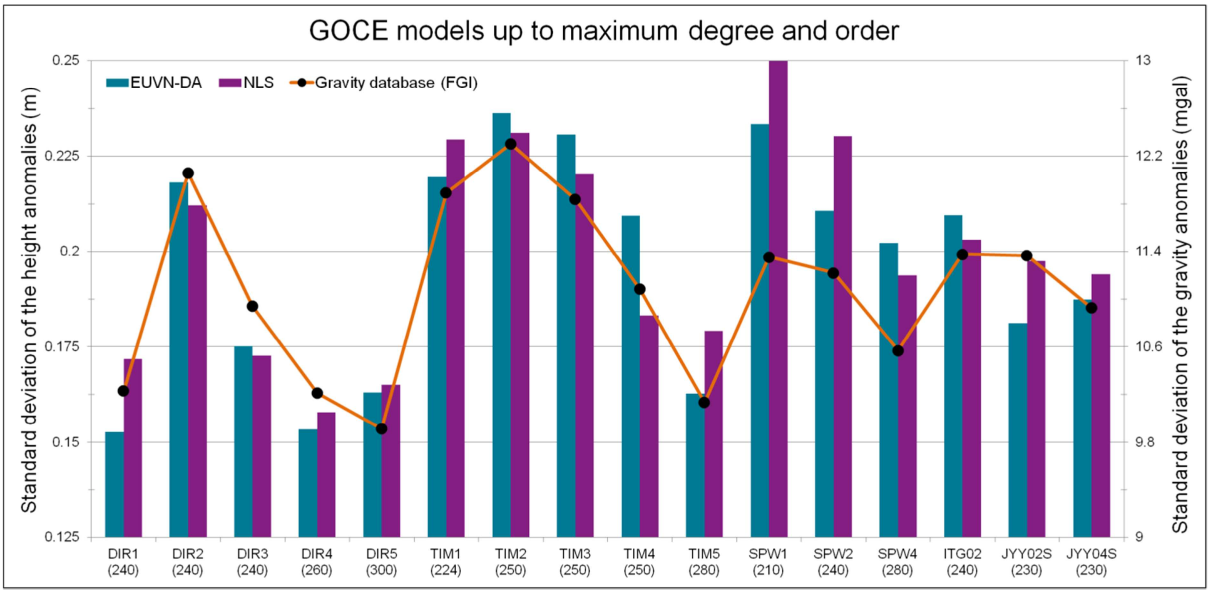

Figure 4: Comparison of the height and gravity anomalies from the GOCE models using all available coefficients against GPS-levelling and gravity data: standard deviations of the differences (m) and (mgal).

4.2 GOCE models compared with GRACE models

In the next comparison we include the GOCE HPF models, the GRACE models (described in Table 2) and the pre-GOCE high resolution geoid models EGM96 (Lemoine et al., 1998) and EGM2008 (Pavlis et al., 2012). The high resolution models are included to show the impact of the GOCE mission for the lower degrees and orders.

The models were developed up to degree and order 150 and the calculated height and gravity anomalies were compared with those of the GPS-levelling (only EUVN-DA results are shown here) and gravity datasets. The results are presented in Figure 5, where the color of the column represents different type of models: teal for GOCE, purple for GRACE and lime for high resolution. The results of the GRACE models vary, especially with the earlier models where the standard deviations of the height anomalies were near half a meter. However, the latest GRACE models perform well, particularly for gravity anomalies, and quite consistently.

All of the GOCE models give more or less similar results when only the coefficients up to degree and order 150 are used. When comparing with the GPS-levelling (EUVN-DA) data, the results from the GOCE models are better than EGM96 and are comparable with the latest GRACE models and EGM2008. The result for the EGM2008 could be expected as the model already includes GRACE data for these wavelengths.

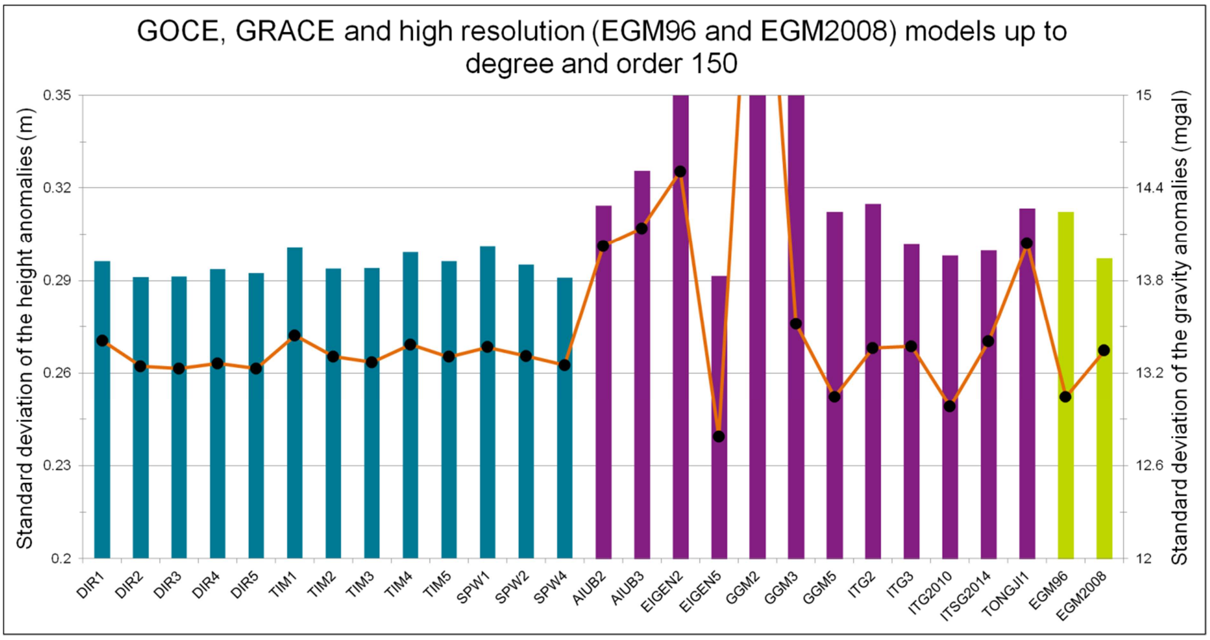

Figure 5: Comparison of the height and gravity anomalies from the GOCE (teal), GRACE (purple) and high resolution (lime) models using coefficients up to 150 against GPS-levelling (only EUVN-DA) and gravity data: standard deviations of the differences (m) and (mgal).

4.3 Latest GOCE and combined GOCE+GRACE models versus GPS-levelling and gravity data

The comparisons in the final section include the latest GOCE (DIR5, TIM5, SPW4 and JYY04S) and combined GOCE+GRACE (EIGEN-6S2, GOCO03S and GOGRA04S) models as well as high resolution geoid models EGM96 and EGM2008. First, the satellite-only models were developed together with the high resolution models up to degree 200 (Figure 6) and 240 (Figure 7) and compared against the GPS-levelling and gravity datasets. Lastly, the satellite-only models were developed up to degree 240 and maximum (Figure 8), to compare the differences at the higher degrees and orders of the models.

The results in Figure 6 indicate that the GOCE-based models perform better than EGM96 and quite equally with EGM2008 when developed up to degree and order 200. This proves that GOCE has improved the knowledge of the long wavelengths of the Earth's gravitational field. When developed up to degree and order 240 the best satellite-only (DIR5, TIM5 and EIGEN-6S2) models are at the same level as the high resolutions models in Finland: at 15 cm for the height anomalies and at 10 mgal for the free-air gravity anomalies.

The comparisons of Figures 6 and 7 show that the high resolution EGM96 and EGM2008 models perform surprisingly well over Finland even when looking at the lower degrees and orders of the models, which are the weak points of the high resolution models. The excellent performance is due to the good high resolution terrestrial data that was already available in the area of Finland for the EGM96 and EGM2008 (the same gravity data was used for both models), the latter including also the GRACE data. Globally, however, these models do not perform equally well everywhere due to the inhomogeneous distribution of the terrestrial gravity data, whereas the satellite-only models will perform homogeneously everywhere on the globe. Also a small tilt may be present in the EGM96 over Finland due to long wavelength errors in the model, but this is removed in our results by fitting a 1st order polynomial tilt. The satellite-only models do not show significant tilts over Finland.

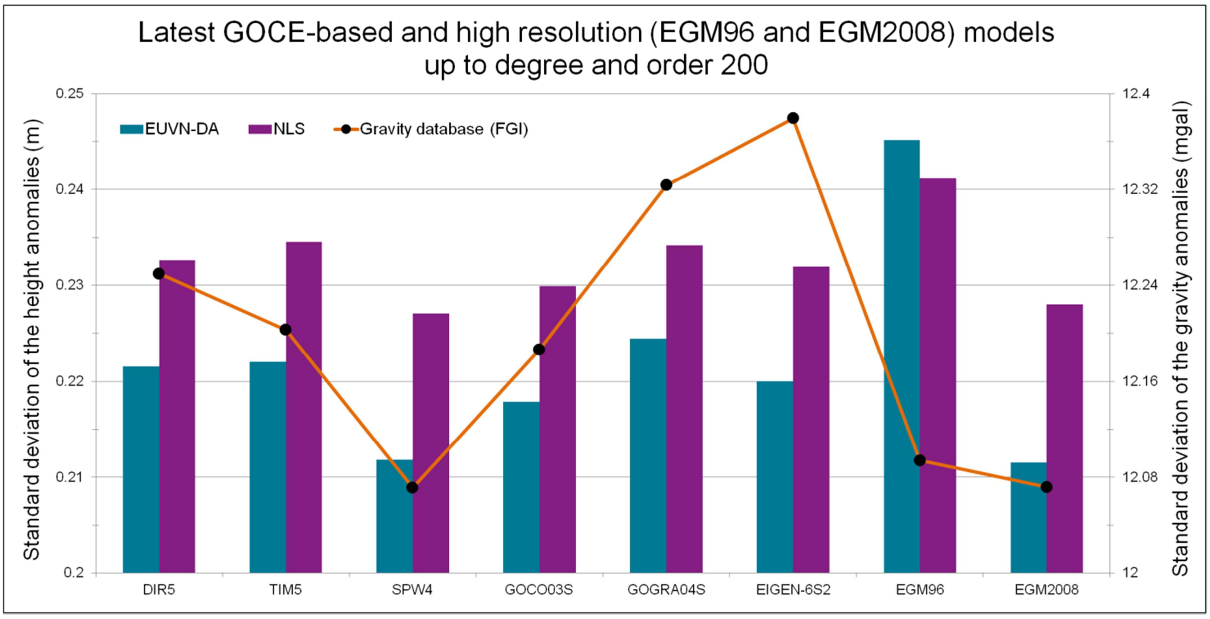

Figure 6: Comparison of the height and gravity anomalies from the latest GOCE-based satellite-only models (GOCE and GOCE-GRACE) and high resolution (EGM96 and EGM2008) models using coefficients up to 200 against GPS-levelling and gravity data: standard deviations of the differences (m) and (mgal).

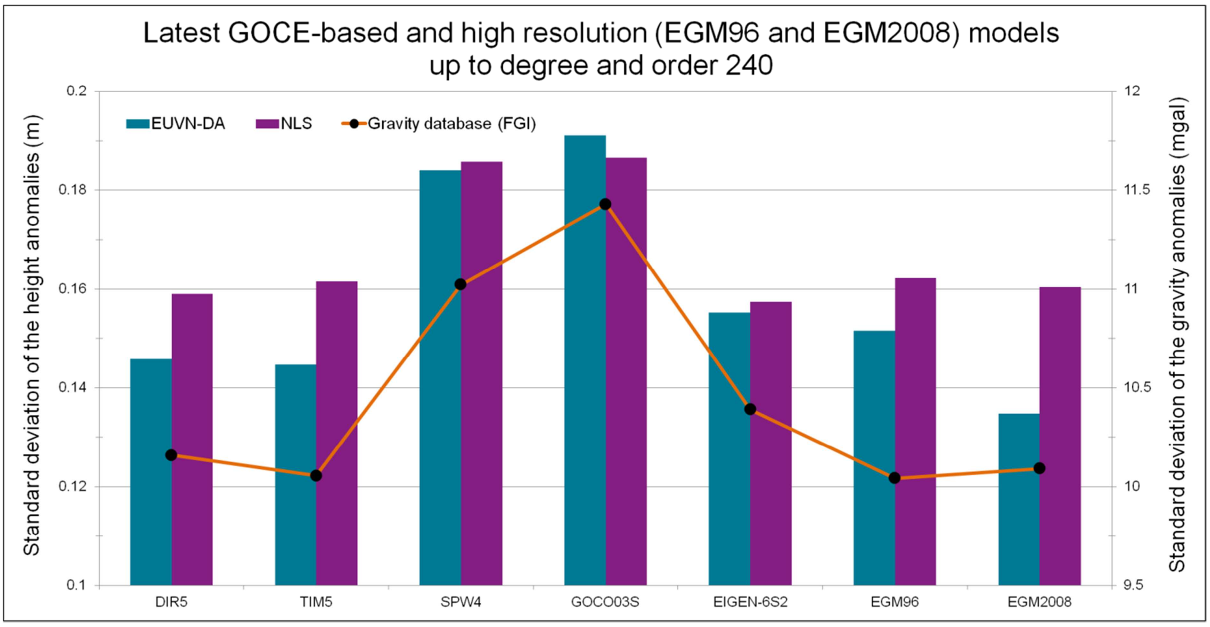

Figure 7: Comparison of the height and gravity anomalies from the latest GOCE-based satellite-only models (GOCE and GOCE-GRACE) and high resolution (EGM96 and EGM2008) models using coefficients up to 240 against GPS-levelling and gravity data: standard deviations of the differences (m) and (mgal).

At the final comparison the models were evaluated by using coefficients up to 240 as well as maximum and the calculated height and gravity anomalies were compared once again with the datasets. The results of the final comparison are presented in the Figure 8. All of the models give standard deviations of the height anomaly differences of less than 20 cm and of gravity anomaly differences of around 10 mgal over Finland. In addition, Figure 8 expresses that the best performance of the satellite-only models is not usually achieved with the maximum coefficients, since the highest coefficients (above 240) are less accurately determined.

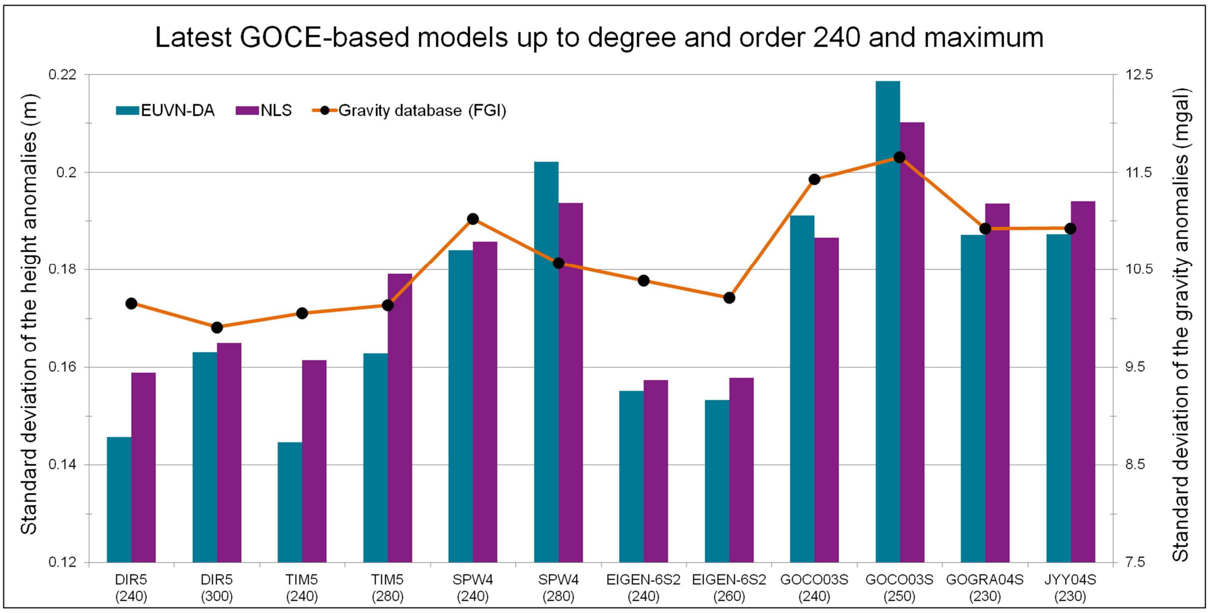

Figure 8: Comparison of the height and gravity anomalies from the latest GOCE-based satellite-only models (GOCE and GOCE+GRACE) using coefficients up to 240/maximum against GPS-levelling and gravity data: standard deviations of the differences (m) and (mgal).

Differences in the free-air gravity anomalies between the latest GOCE models (DIR5, GOCO03S and EIGEN-6S2) and gravity data over Finland are presented in Figure 9, where the comparison has been made with the coefficients up to degree and order 240. Minor differences can be seen between the models. Overall, DIR5 seems to be performing quite smoothly over Finland, especially in the Southern Finland. As for the Northern Finland, EIGEN-6S2 is the most steady satellite-only gravity field model.

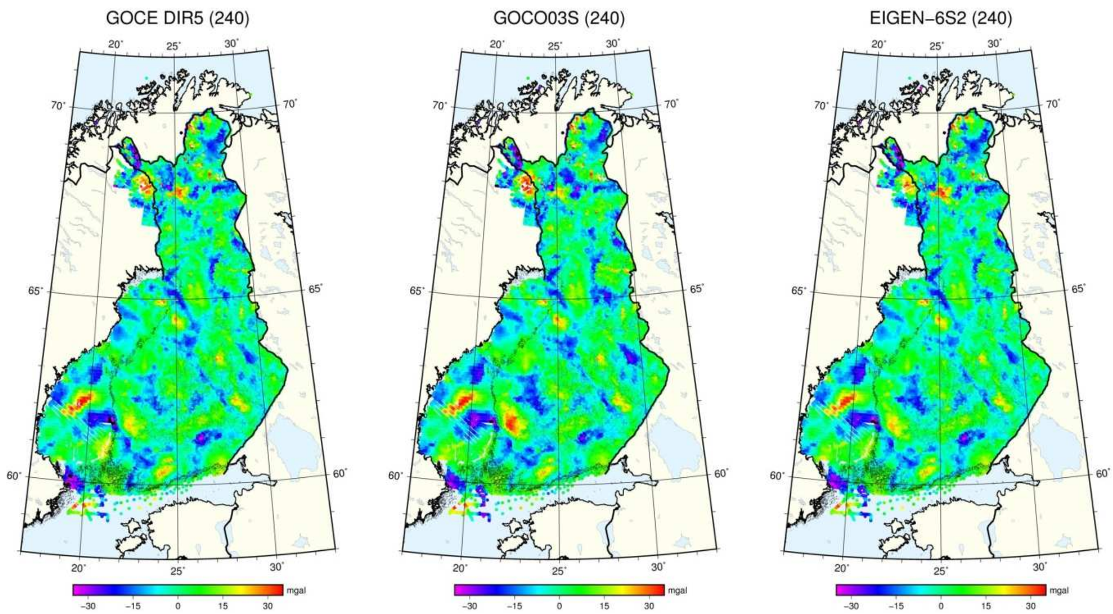

Figure 9: Differences in the free-air gravity anomalies between the latest GOCE models (DIR5, GOCO03S and EIGEN-6S2) and gravity data over Finland. The comparison has been made with the coefficients up to degree and order 240.

5 Conclusions

In this study we compared altogether 16 GOCE models, 12 GRACE models and 6 combined GOCE+GRACE models with GPS-levelling data and gravity observations in Finland. The latest satellite-only models were compared against high resolution global geoid models EGM96 and EGM2008.

The models were evaluated up to four different degrees and order: 150 (the common maximum for the GRACE models), 200, 240 (the common maximum for the GOCE models) and maximum. When coefficients up to degree and order 150 are used, the results from the GOCE models are better than EGM96 (with height anomalies) and are comparable with the latest GRACE models and EGM2008. Similar results are achieved with the coefficients up to 200, as the GOCE models perform clearly better than EGM96 when comparing with the GPS-levelling datasets.

The performances of the GOCE models are quite similar when developed up to degree and order 200. There are no significant improvements to be seen between the later models comparing to earlier models. However, when the models are developed up to degree and order 240 it is clearly seen how the later models perform better. This improvement of later models was expected, as they include more GOCE data leading to a better determination of the higher degrees and orders above 200.

Generally, all of the latest GOCE and GOCE+GRACE models give standard deviations of the height anomaly differences of around 15 cm and of gravity anomaly differences of around 10 mgal over Finland, when coefficients up to 240 or maximum are used. The results are comparable with the results of the high resolution models. The best performance of the satellite-only models is not usually achieved with the maximum coefficients, since the highest coefficients (above 240) are less accurately determined.

Even at the lower degrees and orders, the high resolution EGM96 and EGM2008 models performed very well over Finland when compared to the satellite-only models. The excellent performance is due to the good high resolution terrestrial data that was already available in the area of Finland for the EGM96 and EGM2008. Globally, however, these models do not perform equally well everywhere due to the inhomogeneous distribution of the terrestrial gravity data, whereas the satellite-only models will perform homogeneously everywhere on the globe.

We will continue the study by using the GOCE-only models in combination with the terrestrial gravity data in the calculation of a geoid model for Finland. Then the true value of the GOCE mission for regional geoid modelling can be analyzed. Additionally, we will investigate filtering of the terrestrial data to the same resolution as the GOCE models in order to remove the problem of the omission error in the comparisons.

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