GEOFORSCHUNGSZENTRUM POTSDAM
STIFTUNG DES ÖFFENTLICHEN RECHTS

Scientific Technical Report

ISSN 1610-0956

Scientific Technical Report STR 06/07

GeoForschungsZentrum Potsdam

A High Resolution Global Gravity Field Model Combining CHAMP and GRACE Satellite Mission and Surface Data: EIGEN-CG01C

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Abstract:

The striking improvements in long- to medium-wavelengths gravity field recovery achieved with GPS-CHAMP and GPS-GRACE high-low and GRACE K-band range low-low satellite-to-satellite tracking prompted us to combine the satellite data with surface data from altimetry over the oceans and gravimetry over the continents to generate a new, high resolution global gravity field model: EIGEN-CG01C. The model is complete to degree/order 360 in terms of spherical harmonics and resolves half-wavelengths of 55 km in the geoid and gravity anomaly fields. A special band-limited combination method has been applied in order to preserve the high accuracy from the satellite data in the lower frequency band of the geopotential and to allow for a smooth transition to the high-frequency band, dominated by the surface data. Compared to pre-CHAMP/GRACE global high-resolution gravity field models, the accuracy was improved by one order of magnitude to 4 cm and 0.5 mgal in terms of geoid heights and gravity anomalies, respectively, at a spatial resolution of 200 km half-wavelength. The overall accuracy at degree/order 360 is estimated to be 20 cm and 5 mgal, respectively, and benefits significantly from recently released new gravity anomaly compilations over the polar regions. In general, the accuracy over the oceans is better than over the continents reflecting the higher quality of the available surface data.

Key Words:

Earth gravity field model, global gravity field recovery, CHAMP mission, GRACE mission, Surface gravity data

1 Introduction

Since the launch of the CHAMP satellite in 2000 and the twin satellites GRACE in 2002 with its dedicated payload for global gravity field recovery, satellite-only gravity field models became available, which resolve the geoid with an accuracy of 1 cm for half-wavelengths down to 1000 km using CHAMP and down to 270 km using GRACE data. The most recent CHAMP and GRACE gravity models, generated at GFZ Potsdam, are EIGEN-CHAMP03S, an improved version of EIGEN-3p (Reigber et al., 2004a) and EIGEN-GRACE02S (Reigber et al., 2004b), respectively. An accuracy improvement by a factor of 30 (CHAMP) and by more than two orders of magnitude (GRACE) has been achieved at the given levels of spatial resolution with respect to the latest pre-CHAMP satellite-only gravity model GRIM5-S1 (Biancale et al., 2000).

Whereas the long- to medium wavelengths features of the Earth's gravity field are homogeneously resolved from space, the shorter wavelengths are derived from surface data. These data, compiled from satellite altimetry and ship-borne gravimetry over the oceans, and air-borne and terrestrial gravimetry over land and the north polar region, provide apart from Antarctica an almost complete global coverage if condensed to mean block values of a regular equal-angular 30' x 30' grid. Due to inconsistencies between the various data sets and regionally varying accuracies, these data contain imprecise long- to medium-wavelengths gravity information but, when properly combined with the CHAMP and GRACE satellite gravity models, extend the resolution of the global model to 55 km half-wavelength. Such a combination that resulted in the broadly used model EGM96 (Lemoine et al., 1998) has been performed years ago based on the pre-CHAMP satellite-only model EGM96S.

Here, a new high-resolution combination and solution is accomplished which, compared to EGM96, benefits in its long- to medium wavelength part from the unprecedented performance of the CHAMP and GRACE models and it is partly improved in the higher frequency part thanks to the recently released more complete and updated surface data compilation.

2 CHAMP and GRACE satellite data and processing

CHAMP-GPS high-low satellite-to-satellite tracking and accelerometer data collected over a period of 860 days, from October 2000 through June 2003, were processed in the classical orbit perturbation analysis approach (Reigber et al., 2003) to solve for the gravitational coefficients of a spherical harmonic expansion of the geopotential complete to degree/order 120 (except C_{00}) and within CHAMP-resonant orders up to a maximum degree 140. Stabilization of the normal equation system has been applied for all unknowns with a degree higher than 60. This was done by adding pseudo-observations to the normal equation system for all unknowns of a degree higher then 60 with a value of zero and a weight reciprocally proportional to Kaula's degree variance model (Kaula, 1966). The resulting CHAMP-only global gravity field model is called EIGEN-CHAMP03S. EIGEN-CHAMP03S is an improved version of the preliminary solution EIGEN-3p described in Reigber et al. (2004a). For the new solution, the reprocessing of the CHAMP data to account for the failure in the radial accelerometer's axis has been completed for the entire 860 period.

GRACE mission data, i.e. GRACE-GPS high-low satellite-to-satellite tracking data, accelerometer data and, K-band intersatellite range rate data being most important for the much higher performance with respect to CHAMP, have been used to generate a normal equation system for the gravitational coefficients complete to degree/order 150 (except C_{00}). The normal equation system is based on the one used for the EIGEN-GRACE02S GRACE-only gravity field solution (Reigber et al., 2004b), derived from 110 days of GRACE data collected during the five months Aug., Nov. 2002 and April, May, Aug. 2003. This normal equation system has been augmented by another 90 days' worth of data from April/May 2002 and Oct./Nov. 2003 to yield a 200 days GRACE-only solution which is called here for convenience EIGEN-GRACE02S + 90 d. Stabilization of the normal equation system has been applied as mentioned above, but for all unknowns with a degree higher than 100.

Finally, the CHAMP and GRACE normal equation systems have been added together to form the basis for the combination with the surface data. The overall CHAMP/GRACE satellite-only solution following from the CHAMP/GRACE normal equation system and obtained after stabilization in the same manner as for GRACE-only is called here EIGEN-CG01S. Thanks to the near-polar orbits of CHAMP (inclination I = 87°) and GRACE (I = 89°) observations extend over all latitudes with a negligible polar gap.

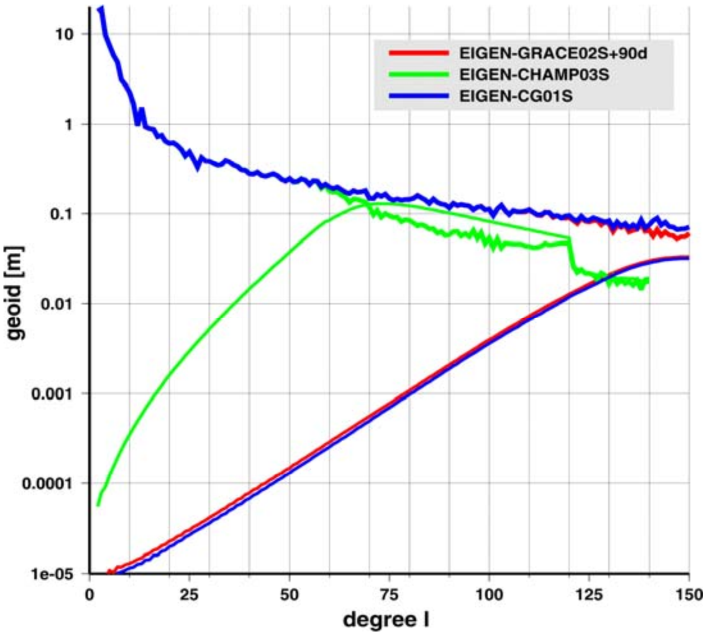

Fig. 1. Signal (thick lines) and error (thin lines) amplitudes per degree in terms of geoid heights for the gravity models EIGEN-CHAMP03S (green), EIGEN-GRACE02S+90d (red) and EIGEN-CG01S (blue), errors are the formal ones as resulting from the adjustment.

Figure 1 shows the signal and error amplitudes in terms of geoid heights per degree of the solved-for spherical harmonic coefficients for the CHAMP-only, GRACE-only and the CHAMP plus GRACE gravity field solutions. The error degree amplitudes are the formal ones, i.e. computed from the coefficients' standard deviations as resulting from the adjustment. It can be seen from Figure 1 that the signal power of the CHAMP solution significantly diminishes beyond degree 60, whereas the GRACE solution resolves fully the gravity field up to degree/order 100. The higher degree coefficients are affected by the stabilization of the normal equation system. Looking at the signal and error degree amplitudes, it becomes clear that it's basicly GRACE data that determines the gravity field model in the long- to medium-wavelength range.

Figure 2 shows the signal degree amplitudes, again in terms of geoid heights, for the CHAMP plus GRACE satellite-only gravity field solution and the pre-CHAMP combination solution EGM96, and the difference degree amplitudes between both solutions. EGM96 is mainly reflecting the altimetric and gravimetric surface data information content, at least beyond degree 70, where only these data enter into the solution. Inspecting the difference degree amplitudes one can therefore deduce that for degrees higher than 110, where the difference degree amplitudes attain a minimum at the 3 cm level, the CHAMP + GRACE data contribution is inferior to that of the surface data.

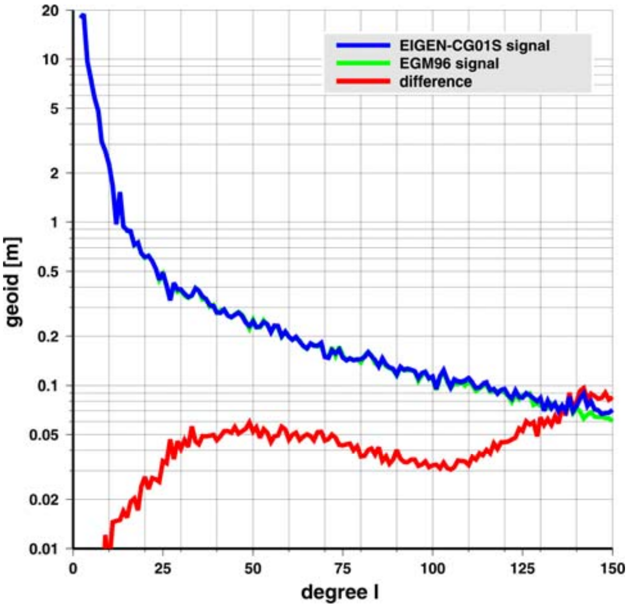

Fig. 2. Signal amplitudes per degree in terms of geoid heights for the gravity models EIGEN-CG01S (blue) and EGM96 (green) and the degree amplitudes of the differences between both models (red).

3 Surface gravimetry data and their processing

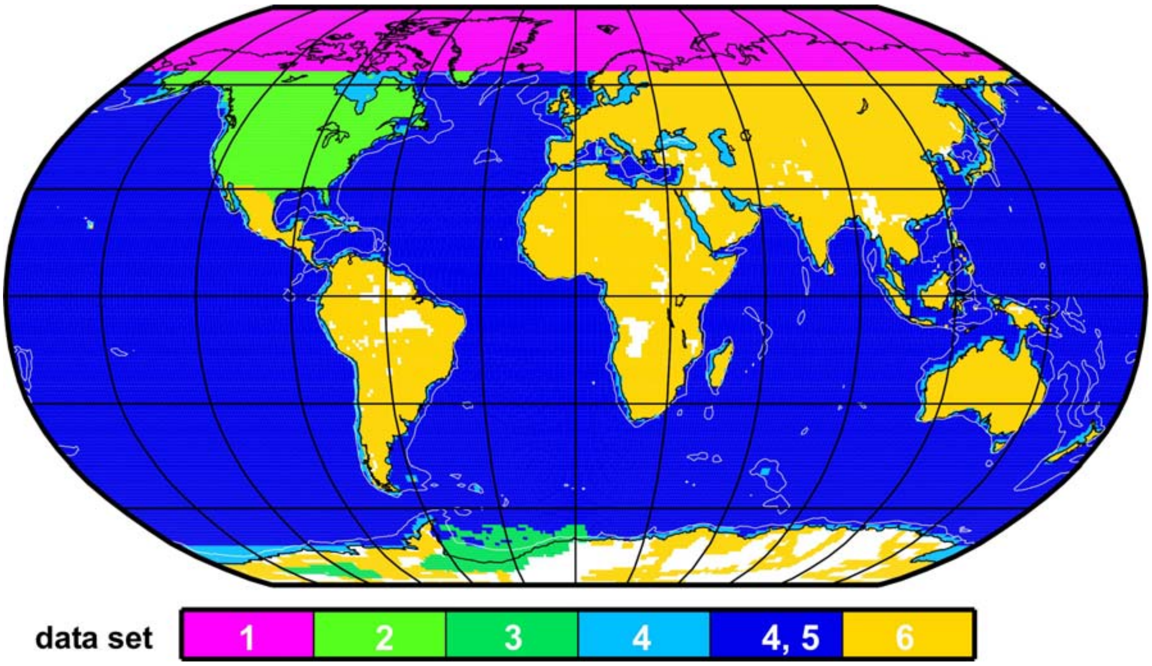

Fig. 3. Coverage of surface data sets 1 through 6 (cf. text); white lines mark used ship gravimetry data (data set 7) over water depths less than 2000 m; white areas are not covered with surface data.

The following surface gravimetry data were used for the combination with the CHAMP and GRACE satellites' normal equations (s. Figure 3 for coverage):

(1) Arctic Gravity Project (ArcGP) gravity anomalies (Forsberg, Kenyon 2004), for regions with $\varphi \geq 64°$,
(2) NRCan gravity anomalies (Véronneau 2003, pers. comm..), covering North America,
(3) AWI (Studinger 1988) and LDO (Bell et al., 1999) gravity anomalies over two small areas of Antarctica and, in the case of AWI, adjacent sea ice,
(4) NGA (National Geospatial Intelligence Agency, formerly NIMA) altimetric gravity anomalies over the ocean, including standard deviations,
(5) Geoid undulations over the oceans by using CLS01 altimetric Sea Surface Heights (Hernandez et al., 2001) and the Sea Surface Topography from the ECCO simulation (Stammer et al., 2002),
(6) NGA terrestrial gravity anomalies (if not covered by data sets 1 to 3) including standard deviations, almost worldwide continental coverage, except for Antarctica and some smaller data gaps, and
(7) NGA ship-borne gravity anomalies over water depths less than 2000 m.

All data sets are available in their original form or after averaging as block mean values on an equal angular 30' x 30' grid, except data sets 5 and 7 which are provided with a 1° x 1° resolution. The NGA data sets (Kenyon, Pavlis 1997) are those already incorporated in the EGM96 solution.

In order to conserve computer resources, the normal equation system for the unknown spherical harmonic coefficients were generated from these data in two essentially different ways for the lower frequency part (up to degree/order 120) and the higher frequency part (up to degree/order 359), respectively: For the lower frequency part, a rigorous normal equation system with individual data weighting was set up using geoid undulations (data set 5) over the oceans and gravity anomalies (data sets 1 to 3 and 6) elsewhere. Data out of data set 4 were used to fill the gaps in near-coastal areas. Shipborne gravimetry (data set 7) was allowed to overlap with the altimeter derived geoid undulations and NGA gravity anomalies, in order to strengthen the transition between geoid undulations and gravity anomalies. For the higher frequency part a block-diagonal normal equation system using gravity anomalies only (data sets 1 to 4 and 6) with a latitude-dependent block area weighting was created (Gruber 2001). In both cases EIGEN-GRACE02 derived gravity anomalies were used to fill the blocks (8.6 %) not covered by surface data.

To generate the normals for the lower frequency part, the 30' x 30' gridded data were averaged to form 1° x 1° block mean values. These were then filtered to suppress the contribution from the spectral gravitational constituents higher than degree 120. The unknowns in the resulting normal equation system took into account spherical harmonic coefficients up to degree/order 140 to avoid aliasing and cut-off errors induced by the data filtering. The data were evaluated (as given) on the Earth surface, i.e. no downward continuation due to topographic heights became necessary (Molodensky approach).

The block-diagonal normal equation system was set up for all coefficients up to maximum degree/order 359 using the 30' x 30' block mean values downward continued to the ellipsoid and reduced for topographic masses.

Prior to the data evaluation, all data sets were transformed to a common reference ellipsoid and the correction for the quadratic terms of the normal gravity gradient and ellipsoidal corrections were applied to the gravity anomalies that are given in spherical approximation (Rapp, Pavlis 1990). The coefficients for degree 360, which are not obtainable from a 30' x 30' data grid in the block-diagonal approach, are computed from the same data by numerical integration.

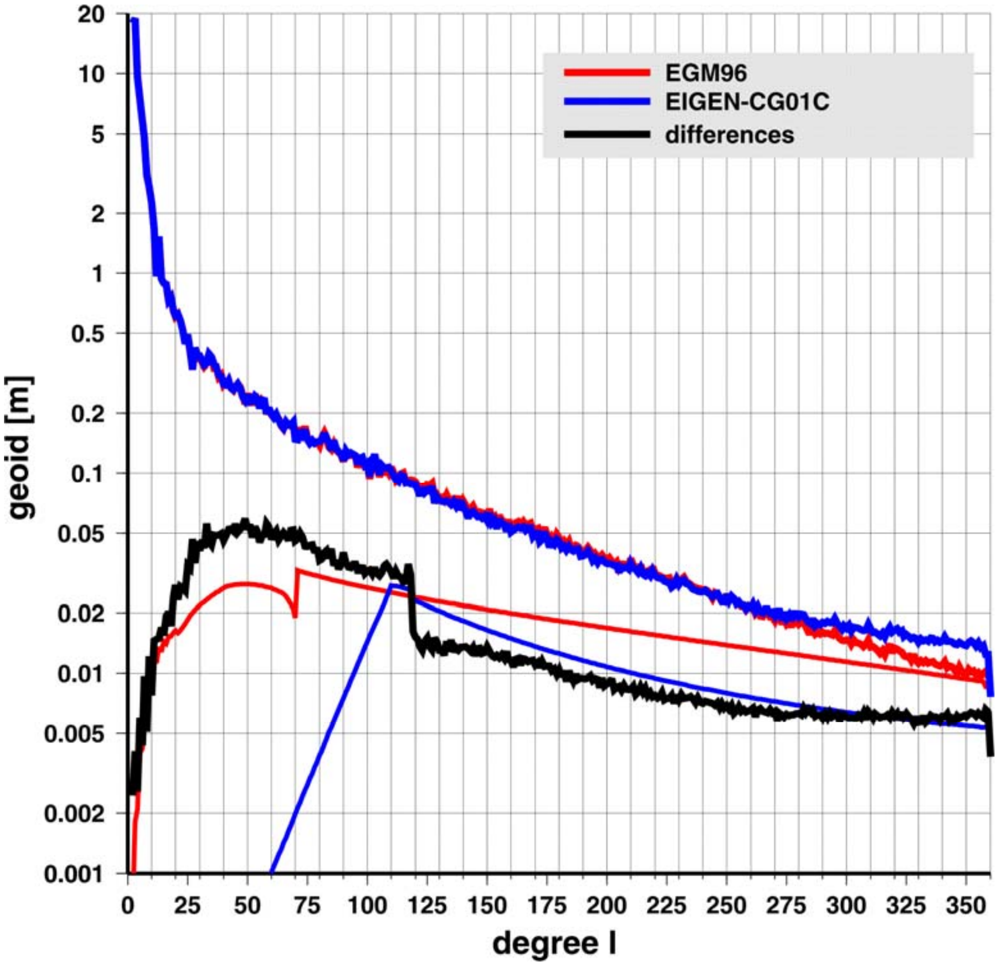

Fig. 4. Signal (thick lines) and error (thin lines) amplitudes per degree in terms of geoid heights for the gravity models EIGEN-CG01C (blue) and EGM96 (red) and the degree amplitudes of the differences between both models (black), the errors are the a posteriori calibrated ones.

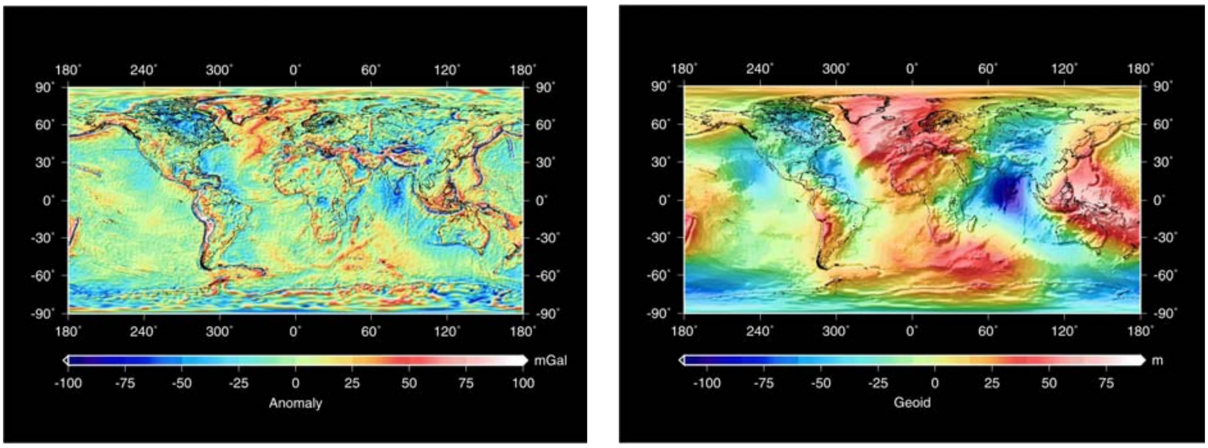

Fig. 5. Geographical distribution of gravity anomalies (left, in mgal) and geoid undulations (right, in m) derived from the high-resolution model EIGEN-CG01C.

4 Combination and solution strategy

The CHAMP+GRACE normal equation system (complete to degree/order 150, no stabilization) was added to the full surface data normal equation system (complete to degree/order 140) in a way that the coefficients up to degree 70 and from degree 110 onwards were kept separate in the resulting normal equation system, i.e. only contributions for the coefficients with degree 71 through 109 were allowed to overlap. Thereby, the surface data normal equation system, initially weighted roughly following the estimated data accuracy, was strongly downweighted by an empirically found optimal factor relative to the satellite-only system. The resulting normal equation system then was solved by inversion taking for the long-wavelength part up to degree 70 the solution coming from the CHAMP+GRACE contributing and from degree 110 to 118 only the solution coming from the surface data contribution. With this procedure, long-wavelength errors in the surface data are not allowed to affect the solution, and the high quality of the CHAMP and GRACE satellite-only gravity field model is kept up to the limit of resolution around degree 110 with a smooth transition within the overlapping part of both normal equation systems.

The solution obtained from the block-diagonal system was then used to extend the spherical harmonic coefficients from degree 118 to degree 359 disregarding the longer wavelength coefficients in the block-diagonal solution, and finally the degree 360 coefficients (from integration) were added for completion, although a drop in power has been realized for this degree compared to the preceding ones.

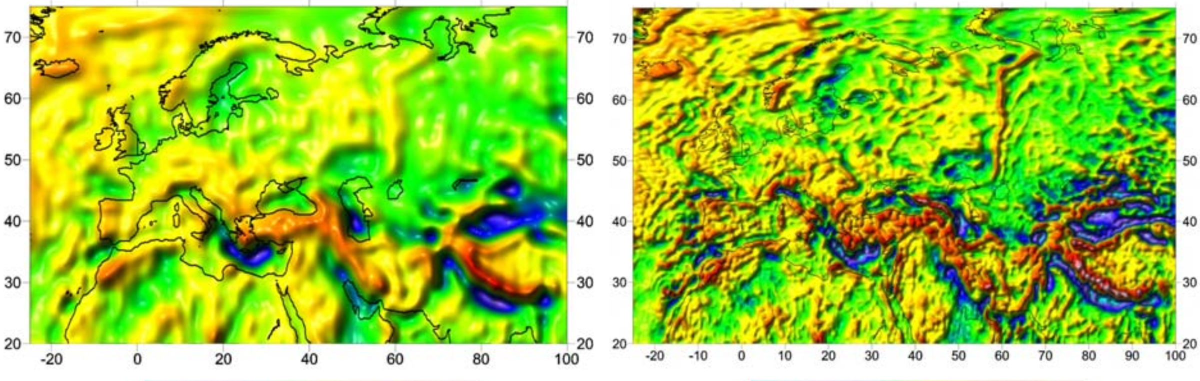

Fig. 6. Gravity anomalies (in mgal) over Europe from the CHAMP/GRACE satellite-only model EIGEN-CG01S (left) and the combined high-resolution model EIGEN-CG01C (right).

5 Result: global gravity field model EIGEN-CG01C

Figure 4 shows the signal and error degree amplitudes of the resulting degree/order 360 EIGEN-CG01C model and for comparison those of the EGM96 model, as well as the difference degree amplitudes between both models. The EIGEN combination solution differs from EGM96 due to the only use of CHAMP and GRACE data instead of the 41 satellites used for EGM96, and, with regards to the surface data, due to the mix of geoid undulations (CLS minus ECCO) and gravity anomalies (up to degree 118) causing the step in the difference degree amplitudes at this boundary; at higher frequencies, EIGEN-CG01C benefits from the new surface data of the Arctic Gravity Project, over North-America and Antarctica which replace older NGA data and close former data gaps, respectively.

The EIGEN-CG01C coefficients' standard deviations as coming out of the adjustment have been calibrated aposteriori in a degree-dependent way in order to produce realistic accuracy estimates. The error degree amplitudes in Figure 4 reflect the huge improvement in accuracy for the long- to medium-wavelengths spectral band thanks to the contribution of the new satellite data.

As an illustration of the high resolution of the EIGEN-CG01C gravity field model, Figure 5 shows the gravity anomalies and the geoid undulations, respectively, resulting from the model's spherical harmonic coefficients, and Figure 6 highligths the contrast in gravity field resolution over Europe between the satellite-only model EIGEN-CG01S and the combined model EIGEN-CG01C.

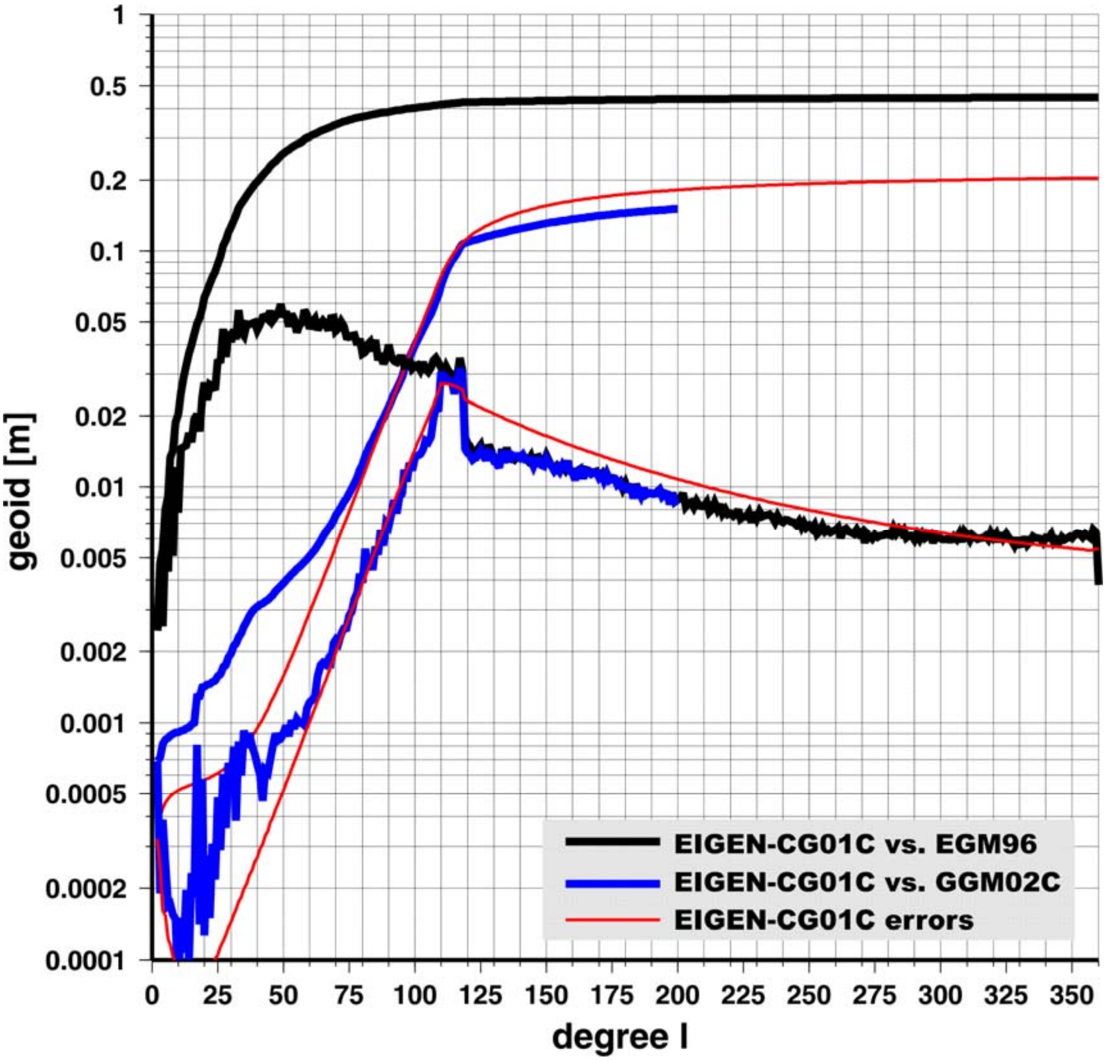

Fig. 7. Amplitudes per degree (lower curves) and degree-wise accumulated (upper curves) in terms of geoid heights of the differences EIGEN-CG01C vs. EGM96 (black) and GGM02C (blue), respectively, and of the EIGEN-CG01C calibrated errors (red).

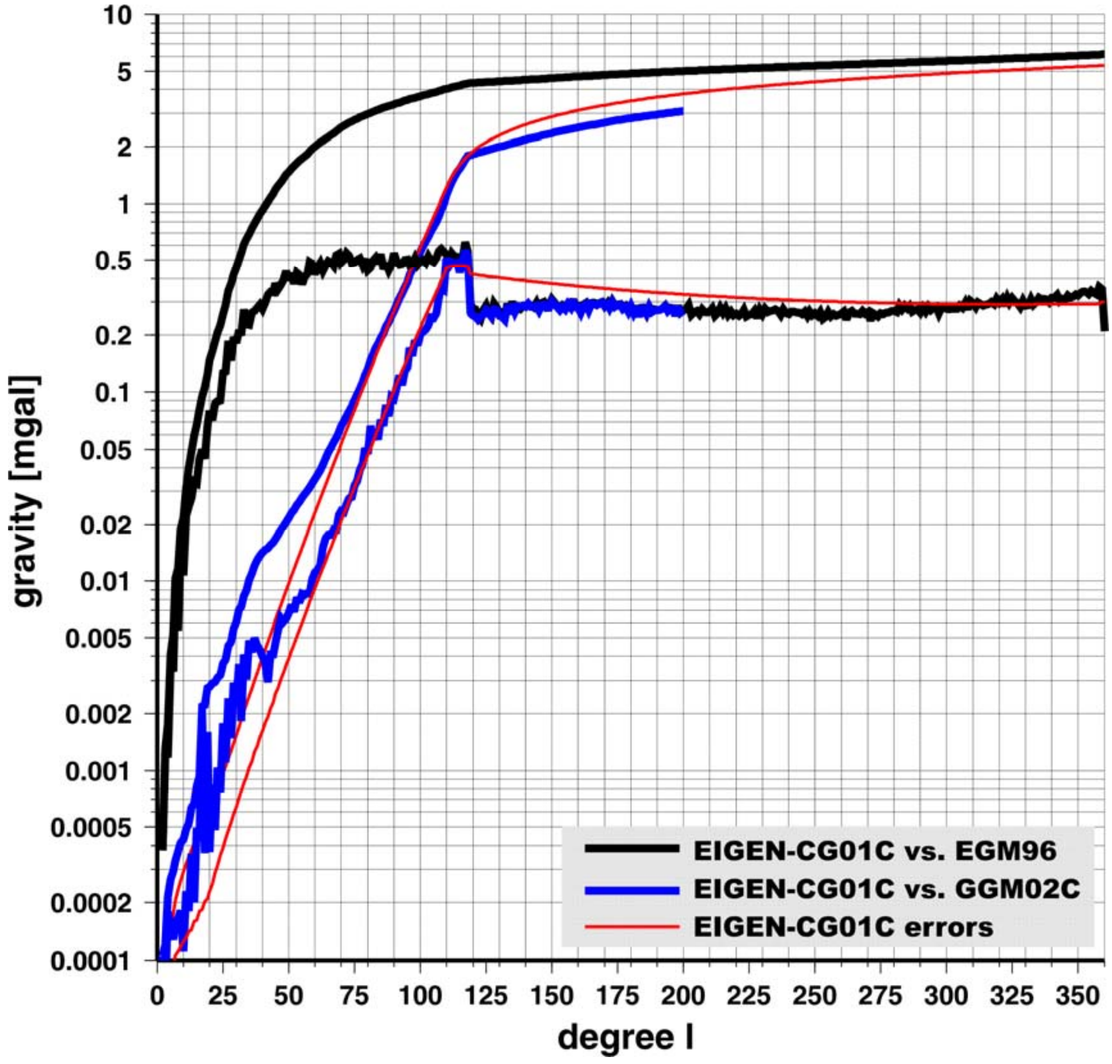

Fig. 8. Same as Figure 7 but in terms of gravity anomalies.

6 Model evaluation

The overall differences in the spectral domain between the EIGEN-CG01C and the EGM96 model amount to 45 cm and 6 mgal in terms of geoid undulations and gravity anomalies, respectively, as can be seen from Figures 7 and 8. Compared to University of Texas' model GGM02C (Tapley et al. 2005) which is a combination solution of GRACE satellite and NGA surface data but complete only to degree/order 200, the differences amount to 15 cm and 3 mgal, respectively, up to the degree of resolution. As the three models are not independent because of having a considerable amount of GRACE data and/or surface data in common, the comparisons should not be over-interpreted. However, the one to two orders of magnitude accuracy improvements from the pre-CHAMP model EGM96 to the new models being visible in Figures 7 and 8 in the long-wavelength part are clearly demonstrated (Reigber et al. 2004b). The difference degree amplitudes between the EIGEN model and the EGM96 and GGM02C models nearly coincide for degrees higher than 109 because nearly the same surface data normal equation systems entered into both external models.

The comparison in the spectral domain doesn't provide a regional discrimination of the model characteristics. Therefore the geographical distribution of the gravity anomaly differences between EIGEN-CG01C and EGM96 is given in Figure 9, representing only the long- to medium-wavelength part (half-wavelengths larger than 200 km, or spherical harmonic degrees 2 to 100), and in Figure 10 for the remaining higher frequency part (half-wavelengths in between 200 km and 55 km, spherical harmonic degrees 101 to 360).

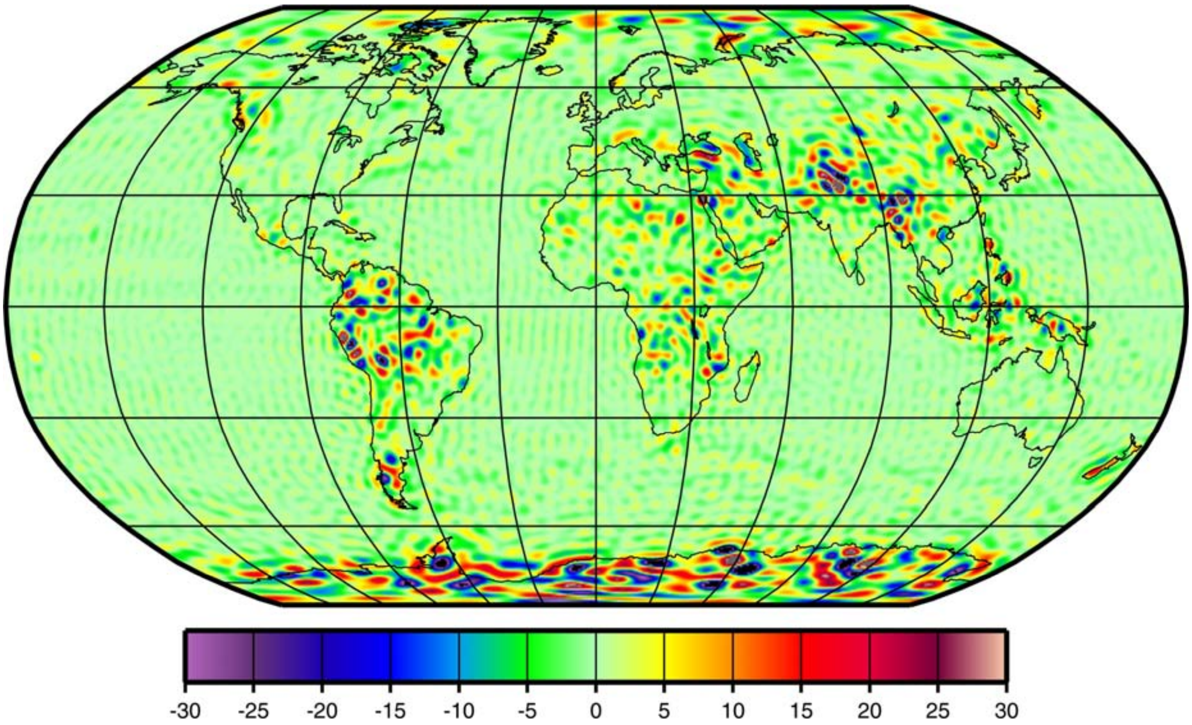

Fig. 9. Gravity anomaly differences between EIGEN-CG01C and EGM96 gravity model for half-wavelengths larger than 200 km (spher. harm. degrees 2 to 100) in units of mgal.

Figure 9 shows the areas where CHAMP/GRACE satellite data contribute most in improving the global gravity field model: the polar caps, previously not resolved by satellite-only models, and the continents of Africa, Asia and South America which are not well and inhomogeneously covered by gravimetric data. Figure 10 mainly reveals the impact of the new gravity anomaly data from the Arctic Gravity Project and over the two regions of Antarctica. Also larger discrepancies appear over the areas where surface data are missing, because these were filled-in in different ways in the two models.

degree	global	oceans	Continents
2 - 360	6.8 mgal	3.9 mgal	11.0 mgal
2 - 100	4.1 mgal	2.0 mgal	6.8 mgal
101 - 360	5.5 mgal	3.5 mgal	8.6 mgal

Table 1. Weighted (cosine of latitude) root mean square (wrms) of gravity anomaly differences between EIGEN-CG01C and EGM96 as a function of spherical harmonic degree range.

Table 1 gives the statistics of the differences in terms of gravity anomalies between the two high-resolution global gravity field models for the lower (degree 2 to 100) and higher (degree 101 to 360) frequency part as well as for the entire spectrum.

The differences over the oceans are on average lower than over the continents due to the homogeneous coverage with satellite altimeter data.

An independent comparison with external data can be made using geoid heights determined point-wise by GPS positioning and levelling (GPS-Levelling). Table 2 shows the results for the two models under considerations using GPS-Levelling points from the USA (Milbert, 1998), Canada (Véronneau, pers. comm. 2003, Natural Resources Canada, GPS on BMs file, update Feb. 2003,) and Europe (Ihde et al., 2002). The improvement in the new EIGEN-model is visible, but not so dramatic because of the large omission error for spherical harmonic degrees higher than 360, common to both models when comparing point values.

Gravity Model	**GPS-Levelling Geoid Heights**		
	USA (6169)	Canada (1930)	Europe (186)
EIGEN-CG01C	44 cm	35 cm	41 cm
EGM96	47 cm	39 cm	45 cm

Table 2. Root mean square (rms) about mean of GPS-Levelling minus model derived geoid heights (number of points in parentheses).

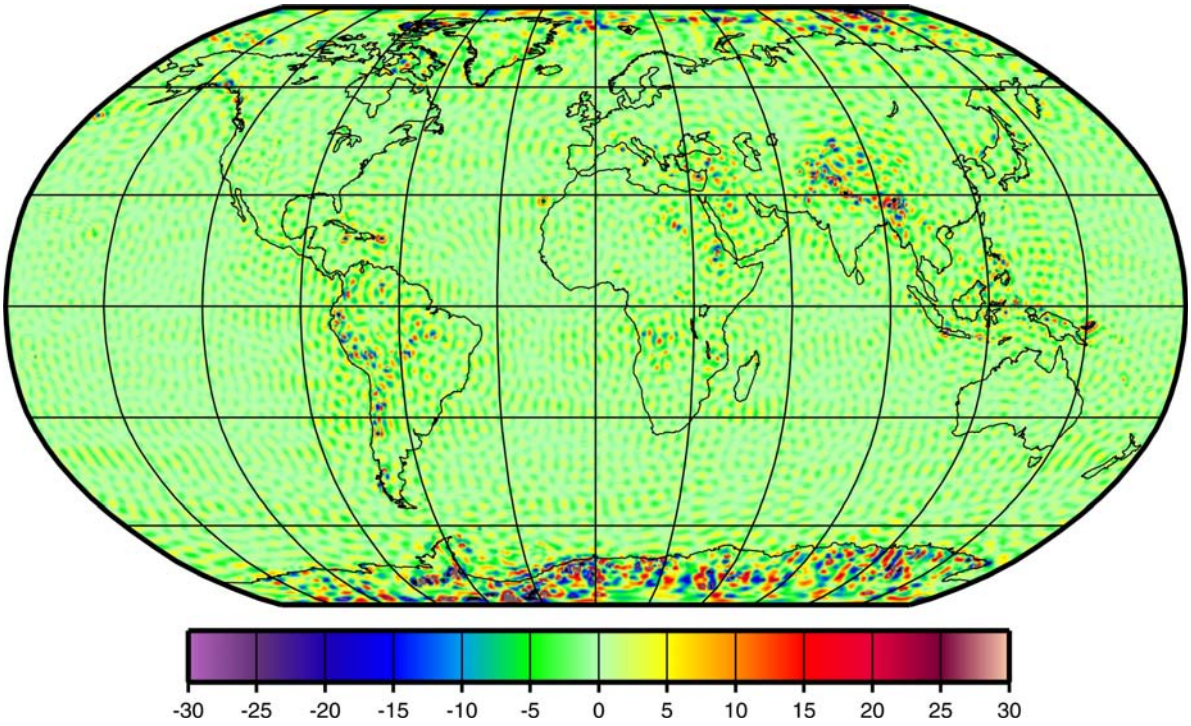

Fig. 10. Gravity anomaly differences between EIGEN-CG01C and EGM96 gravity models for half-wavelengths shorter than 200 km (spher. harm. degrees 101 to 360) in units of mgal.

7 Conclusions

On the basis of CHAMP and GRACE satellite gravity field recovery results, a new high-resolution global gravity field model to degree/order 360 has been developed, incorporating surface data including newly available or improved data sets (Arctic, Antarctica, North-America, altimetry): EIGEN-CG01C. Compared to the pre-CHAMP high-resolution model EGM96, the long- to medium-wavelength ($\lambda/2 > 200$ km) gravity and geoid accuracy now being 0.5 mgal and 4 cm, respectively, was improved by about one order of magnitude, thanks to GRACE's contribution.

The average accuracy of EIGEN-CG01C up to degree/order 360 ($\lambda/2 = 55$ km) is estimated to be on the 5 mgal, 20 cm level, respectively, mainly reflecting the quality of the surface data. In particular, over the high latitude areas EIGEN-CG01C benefits from the better coverage due to the released gravity anomaly compilations. In general, the accuracy over the oceans is better than over the continents (cf. Table 1).

The new model may be applied as a background model in regional geoid modelling and for geodynamic interpretation over a wide range of scales.

Acknowledgements. The German Ministry of Education and Research (BMBF) supports the GRACE and CHAMP projects within the GEOTECHNOLOGIEN geoscientific R+D programme under grants 03F0326A and 50EP9587A. On the French side the research was supported by the Centre National d'Etudes Spatiales (CNES).

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