Global combination gravity field model based on GOCE and GRACE data




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Abstract

A high-accuracy and detailed global map of the Earth's gravity field is an essential product in many branches of Earth system sciences. A main research interest at the Institute of Theoretical Geodesy and Satellite Geodesy, TU Graz, is the generation of high-resolution global gravity field models by combining data from the satellite gravity missions GOCE, GRACE and CHAMP with complementary gravity field information represented by terrestrial and air-borne data, satellite altimetry, and satellite laser ranging (SLR). These different data types are complementary with respect to their measurement principle, accuracy, spatial distribution and resolution, and spectral (error) characteristics. By means of data combination, benefit can be taken from their individual strengths and favourable features, and in parallel specific deficiencies can be reduced. The combination is performed by means of the weighted addition of the normal equation system of each data type. Within a simulation scenario it could be demonstrated that the method of variance components estimation is well suited for weights estimation. The models are parameterized in terms of coefficients of a spherical harmonic expansion including a proper error description in terms of a variance-covariance matrix. Together with our partners within the international GOCO (Gravity Observation Combination) consortium, the first satellite-only gravity field model GOCO01S was released in July 2010. The model is a combination solution based on 2 months of GOCE data, and 7 years of GRACE data, resolved up to degree and order 224 of a harmonic series expansion. GOCO01S has been validated against external global gravity models and regional GPS-levelling observations. The comparison to existing models revealed improvements especially in mountainous regions and in areas where only a few or less accurate terrestrial observations are available. With the continuously increasing availability of GOCE and GRACE data further improvements in global gravity field recovery will be achieved.

Keywords: Combination gravity field models, GOCE, GRACE

Kurzfassung

Die genaue Kenntnis über das Schwerefeld der Erde bildet die Basis für verschiedene Forschungsgebiete, wie Ozeanographie, Geophysik, Meeresspiegeländerung und Klimaveränderung. In der Geophysik können damit geodynamische Prozesse im Erdinneren besser modelliert und verstanden werden. Auf dem Gebiet der Ozeanographie dient das Erdschwerefeldmodell zusammen mit Beobachtungen von Satellitenaltimetrie-Missionen der Bestimmung von Meeresströmungen, welche wesentlich für den Energietransport auf der Erde verantwortlich sind. Gleichzeitig können auch Meeresspiegeländerungen erfasst werden, die u.a. aufgrund von Abschmelzvorgängen in den Polregionen hervorgerufen werden. Auch die Geodäsie profitiert von einem hochauflösenden Schwerefeldmodell, z.B. in der globalen Vereinheitlichung von Höhensystemen.

Terrestrische Schwerefeldmessungen wurden schon seit jeher durchgeführt. Vorteil dieser Beobachtungen ist die hohe erreichbare Messgenauigkeit. Nachteile sind jedoch, dass zum einen ein homogenes und globales Beobachtungsnetz kaum realisierbar ist und zum anderen, dass aufgrund des Einsatzes unterschiedlichster Messinstrumente die Beobachtungen entsprechend unterschiedliche Messgenauigkeiten aufweisen. Der Start der Satellitenmissionen CHAMP (2000), GRACE (2002) und GOCE (2009) im letzten Jahrzehnt revolutionierte die Modellierung des Erdschwerefeldes. Aufgrund der kontinuierlichen Beobachtung aus dem Weltraum kann eine globale Abdeckung mit homogener Messgenauigkeit erzielt werden. Die Missionen unterscheiden sich prinzipiell anhand des individuellen Orbitdesigns und des Messkonzepts. Somit erhält man komplementäre und voneinander komplett unabhängige Beobachtungstypen, welche sich hinsichtlich räumlicher Verteilung, Auflösung und spektraler Eigenschaften ergänzen. Ein weiterer Beobachtungstyp stellt das Konzept des Satellite Laser Ranging (SLR) dar. Hierbei kann die vom Gravitationsfeld der Erde beeinflusste Trajektorie von Satelliten mittels Entfernungsmessung von der Erde aus im cm-Bereich ermittelt werden. Eine genaue Kenntnis über die Bahn ermöglicht in einem weiteren Schritt die Bestimmung des auf den Satelliten wirkenden Erdschwerefeldes.

Mittels Datenkombination können nun die individuellen Stärken und Vorteile der einzelnen Datentypen genutzt und gleichzeitig etwaige Defizite reduziert werden. Daraus sollen letztlich hochgenaue, hochauflösende globale Modelle des Gravitationsfeldes der Erde, parametrisiert durch sphärisch harmonische Koeffizienten einer Kugelfunktionsreihe und eine zugehörige Beschreibung der Genauigkeit mittels Varianz-Kovarianz-Matrix resultieren. Mathematisch erfolgt diese Kombination auf Basis einer gewichteten Summation der Normalgleichungssysteme eines jeden Datentyps. Zur Berechnung der individuellen Gewichte bietet sich z.B. die Methode der Varianzkomponentenschätzung an, welche aus den gerechneten Residuen und der Redundanz einer jeden Beobachtungsgruppe in einem iterativen Vorgang einen Gewichtsfaktor ableitet.

Im Juli 2010 wurde zusammen mit unseren Partnern innerhalb des GOCO (Gravity Observation Combination) Konsortiums das erste Kombinationsmodell aus Satellitenbeobachtungen veröffentlicht und trägt den Namen GOCO01S. Dieses Modell beruht auf sieben Jahren GRACE Daten und zwei Monaten GOCE Daten und hat eine Auflösung bis sphärisch-harmonischem Grad 224, was einer halben Wellenlänge von ca. 90 km entspricht. Die Kombination erfolgte auf Basis der Normalgleichungssysteme. Aufgrund einer angemessenen stochastischen Modellierung der GRACE und GOCE Beobachtungen gingen die beiden Komponenten mit einem Einheitsgewicht in die Kombination ein. Vergleiche zu bereits existierenden Modellen zeigen Verbesserungen speziell in gebirgigen Regionen und in Regionen in denen nur wenige und ungenaue terrestrische Messungen vorliegen. Durch die kontinuierlich zunehmende Beobachtungsdauer von GOCE und GRACE kann eine ständige Verbesserung der Schwerefeldmodelle erwartet werden. Derzeit arbeiten wir bereits an Nachfolgemodellen, welche sechs Monate an GOCE Daten, SLR Beobachtungen und terrestrische Datensätze beinhalten werden.

Schlüsselwörter: Schwerefeldmodelle, Kombinationsmodell, GOCE, GRACE

1. Introduction

The knowledge about the Earth's gravity field essentially supports research activities in oceanography, geophysics, geodesy and sea-level research, and further contributes to studies about climate change. In geophysics it is an important product to improve the modeling of the Earth's interior and of geodynamic processes. In oceanography gravity information is merged with satellite radar altimetry to derive models about ocean circulations, which are important for a better understanding of the global energy transport and climate regulation. It also contributes to observe sea-level change as a result of melting ice sheets. Finally, various fields of geodesy benefit from a unified definition of physical height systems. For these reasons the science and application communities are interested in a high-accuracy and detailed global map of the gravity field.

In the last century models of the Earth's gravity field were mainly derived based on satellite orbit perturbations and in-situ terrestrial observations. Major drawbacks of this type of observation are the inhomogenous data distribution and the varying measurement accuracy. In the last decade satellite gravity missions have been launched (CHAMP [13], GRACE [15], GOCE [14]) and are dedicated to provide a uniform picture of the gravity field. Depending on the individual mission design the derived models are limited to a certain spatial resolution and accuracy. Therefore, the objective of global gravity field modeling is the combination of all observation types to overcome the individual deficiencies and exploit the individual advantages.

Large efforts are made by different teams to compute combination models like the well-known EGM2008 ([12]) or EIGEN-5C ([3]) models. In 2009 the GOCO (Gravity Observation Combination) consortium was established, comprised by the Institute of Theoretical Geodesy and Satellite Geodesy at TU Graz (Austria), the Institute of Astronomical and Physical Geodesy at Technical University of Munich (Germany), the Institute of Geodesy and Geoinformation at University of Bonn (Germany), the Astronomical Institute of the University of Bern (Switzerland), and the Space Research Institute of the Austrian Academy of Sciences in Graz (Austria). The objective of the GOCO consortium is to provide global gravity field models with high accuracy and spatial resolution together with a consistent and reliable error description in terms of a covariance matrix to the user community. In this context the satellite-only model GOCO01S ([11]) was released in July 2010 which is the first combination model incorporating data of the GOCE satellite.

The model is represented by a spherical harmonic series expansion of the gravitational potential V at spherical coordinates with radius r, co-latitude ϑ, and longitude λ according to

$$\mathrm{V}(\mathrm{r},\vartheta,\lambda) = \frac{\mathrm{GM}}{\mathrm{R}} \sum_{l=0}^{l\max} \left(\frac{\mathrm{R}}{\mathrm{r}}\right)^{l+1} \sum_{m=0}^{l} \bar{\mathrm{P}}_{lm}(\cos\vartheta) \cdot \cdot\left[\bar{\mathrm{C}}_{lm}\cos(m\lambda) + \bar{\mathrm{S}}_{lm}\sin(m\lambda)\right] \quad (1)$$

where G is the gravitational constant, M the mass of the Earth, R the mean Earth radius, $\bar{\mathrm{P}}_{lm}$ the fully normalized Legendre polynomials of degree l and order m, and $\{\bar{\mathrm{C}}_{lm}, \bar{\mathrm{S}}_{lm}\}$ the spherical harmonic coefficients which should be determined up to a maximum degree $l_{\max}$.

2. Data combination procedure

The combination concept is based on the fusion of the normal equation systems of each data set which are assembled according to a standard Gauß-Markov model. The resulting combined normal equation system is then solved for the unknown spherical harmonic coefficients (indicated by $\hat{x}$) in terms of

$$\hat{x} = N^{-1}n \quad (2)$$

where the combined normal equation matrices N and the right-hand sides n are composed of the individual components according to

$$N = \sum_i w_i N_i \quad (3)$$

$$n = \sum_i w_i n_i$$

where i denotes the individual data set. The determination of the optimum weights w_i of the individual components is one of the major issues when computing combination gravity field models. There are several methods to deal with this task. Two common strategies are the so-called variance components estimation (VCE, [6]) and the calibration procedure based on subset solutions described by Lerch et al. ([8]). The method of VCE is based on the calculated least squares residuals whereas the latter one is based on the differences between the parameters of the individual solution and the combined solution, and the differences of the variances, respectively. In the next section the two weighting schemes are assessed within a test environment.

3. Simulation scenario

The present test environment was implemented on a single computer to perform basic experiments with focus on the combination methodology. The used test data sets are based on GOCE orbit data and on surface data, respectively. Due to the memory limitation of a single processor only small dimensioned normal equation systems were assembled. Nevertheless, the scenario demonstrates and compares the weights computation based on VCE and on the method of Lerch, respectively.

3.1 Assembling of normal equation systems

GOCE kinematic orbit data

The used satellite-to-satellite tracking (SST) measurements (illustrated in Fig. 1) provided by the GPS receiver are from an end-to-end simulated data set generated by ESA which is based on the reference gravity field model EGM96 ([7]). The resulting GOCE SST-only model is based on 59 days of precise orbit data and accelerometer measurements representing the non-gravitational forces acting on the low orbiting satellite. To assemble and process the normal equation system the energy balance approach ([5]) was utilized. The system is parameterized up to degree and order 70 for this test scenario which corresponds to a normal equation matrix with a dimension of 5041. Note: In the processing of real GOCE data, the SST observations are used to recover the long wavelengths structure of the gravity signal whereas the GOCE satellite gravity gradients (SGG) are able to measure the short wavelengths. Finally, both observation groups are combined to compute a GOCE-only model.

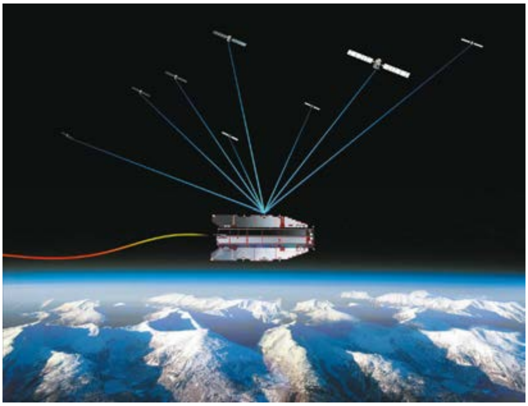

Fig. 1: Satellite-to-satellite tracking concept to determine the GPS position of GOCE and to obtain low-resolution gravity-field data (© ESA – AOES Medialab).

Terrestrial gravity data

To simulate terrestrial measurements covering the whole globe, gravity anomalies are computed based on spherical harmonic coefficients. A special issue of combining different data types is the definition of common reference parameters and numerical standards. For the processing of the gravity anomalies, the global gravity model EGM96 was used. Since the simulated GOCE data described above is also based on this model the issue on homogenization of standards and reference parameters can be circumvented. The processing steps of calculating synthetic gravity anomaly observations are briefly explained in the following. Based on the spherical harmonic coefficients of the EGM96 model, gravity anomalies on a 2°x 2° global grid were derived by series expansion of the gravitational potential complete to degree and order 70 according to Equation 1. In the next step random noise of 0.5 mGal was superposed to the derived grid values which then served as simulated gravity anomaly measurements. Finally, the inverse process was performed to recover the

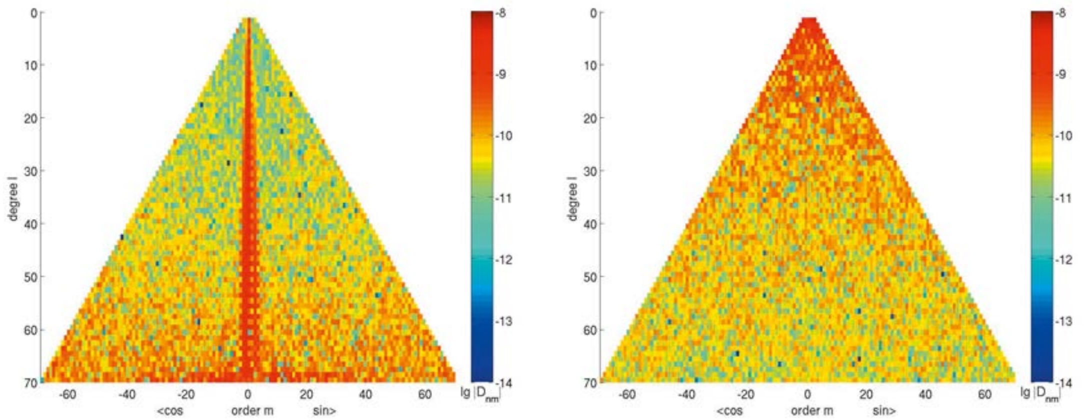

Fig. 2: Coefficient differences of models derived from simulated GOCE SST data (left) and from synthetic terrestrial data (right) w.r.t. EGM96. The colorbar refers to a logarithmic scale.

spherical harmonic coefficients from the noisy observations. In this step the normal equation system was assembled at the same time for the subsequent combination procedure.

3.2 Results of the simulation scenario

The benefit of such a combination is clearly demonstrated by the so-called spectral triangle plots. Fig. 2 (left) illustrates the coefficient differences based on the model computed only from GOCE SST observations with respect to the reference model EGM96. The large differences of the zonal and near-zonal degrees originate from the polar caps which cannot be observed by GOCE because of the particular orbit inclination. However, this is not true for the model based on the terrestrial data (Fig. 2 (right)) since grid values are computed covering the whole globe.

Although the characteristics of the test data sets play only a minor role for this simulation study it can be seen that the coefficients based on terrestrial observations perform worse in the low degrees and become better with increasing degree. For GOCE SST exactly the opposite behaviour can be observed. Now, the task of data combination is to join the strengths of each data type. Fig. 3 (left) displays the coefficient differences of the combination solution based on weights computed by VCE (cf. Table 1).

Obviously, the polar cap problem of GOCE is covered by the terrestrial observations on the one hand, and on the other hand the coefficient differences are very homogeneous over

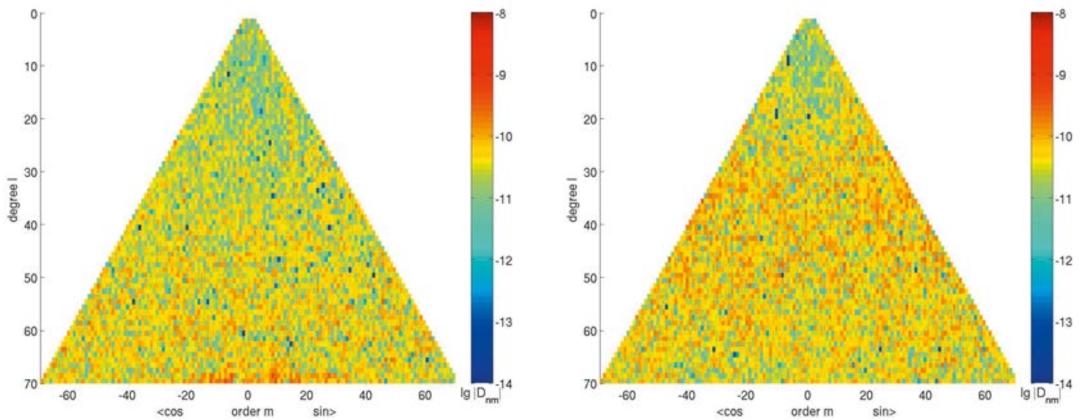

Fig. 3: Coefficient differences of combination models based on weights computed by variance component estimation (left) and on the method of Lerch (right) w.r.t. EGM96. The colorbar refers to a logarithmic scale.

the whole spectral range due to the favourable observations of GOCE SST in the low degrees and the high-quality terrestrial measurements in the higher degrees. The transition of the influence from one data type to the other is rather smooth which should also be a criterion for the quality of the combination. A different picture is shown by the combination solution based on weights computed by the Lerch method (Fig. 3 (right)). The weak estimation of the (near-)zonal coefficients by GOCE also causes strong correlations between these coefficients. Since the approach of Lerch only considers the variances but not the correlations the determined weight of GOCE SST (cf. Table 1) is distorted, whereas VCE computes reliable weights due to the consideration of these correlations.

	VCE	Lerch
GOCE SST	1.00	0.02
Terr. data	0.83	0.74

Tab. 1: Estimated weights for synthetic GOCE SST and terrestrial data sets based on the variance components estimation (VCE) and the Lerch method.

The simulation scenario revealed that the approach of Lerch is not qualified when working with GOCE data. In contrast VCE computed an optimum solution and thus is further used in the combination of real data.

4. Satellite-only gravity field model GOCO01S

GOCO01S is the first combination gravity field model where GOCE observations are incorporated. The model is comprised by seven years of GRACE data and two months of GOCE satellite gravity gradients (SGG) data.

4.1 GRACE

GRACE (Gravity Recovery and Climate Experiment) is a twin-satellite gravity field mission (cf. Fig. 4) which was launched in March 2002 ([15]). It is a joint project between the University of Texas Center for Space Research, GFZ Potsdam, NASA and Deutsches Zentrum für Luft- und Raumfahrt with the aim to determine the low to medium wavelengths of the Earth's gravity signal and its variability. The basic observations are the range and range rates between the spacecrafts. These measurements are performed by the satellites' key instrument, the K-band Ranging System, which is capable of resolving the one-way distances between the satellites with a high precision of about 1 μm based on microwave technology. The absolute orbit positions at cm-level are derived from GPS-measurements using the onboard GPS receiver assembly mounted on each satellite. The non-conservative forces acting on the satellites are determined by accelerometers, while a Star Camera Assembly is used to derive the actual satellite attitude in space.

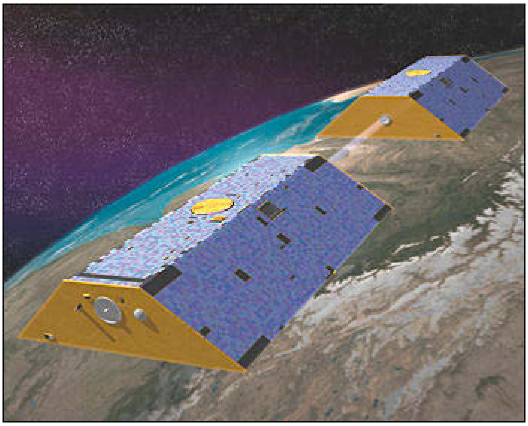

Fig. 4: GRACE tandem configuration with the ranging link between the two spacecrafts (© NASA).

The Institute of Geodesy and Geoinformation at the University of Bonn, our partner within the GOCO consortium, is computing static and time-variable gravity field models from GRACE. GRACE normal equations of the ITG-Grace2010s model ([10]) up to degree and order 180 have been used in the combination procedure which are based on the observation period from August 2002 to August 2009. The model is computed by the integral equation approach using short arcs with a maximum length of 60 minutes based on K-band range rates and kinematic orbits. Additionally, an adequate stochastic model for each short arc was introduced.

4.2 GOCE

The Gravity field and steady-state Ocean Circulation Explorer (GOCE, [2]) is the first Earth Explorer Core mission as part of ESA's Living Planet Programme and is – after the satellite missions CHAMP and GRACE – the third dedicated gravity satellite. The satellite was launched in March 2009. After an in-orbit-calibration phase of 7 months GOCE started to record science data. Integral part of the mission concept and payload is the Electrostatic Gravity Gradiometer (Fig. 5) consisting of three pairs of orthogonally mounted accelerometers. The gradiometer is able to sense short-wavelength structures of the gravity field with unprecedented precision. The measurement principle is based on the analysis of accelerations acting on a proof mass. Each pair is separated by about 50 cm on the gradiometer arm. For the very first time, the principle of satellite gravity gradiometry (SGG) comes into operation.

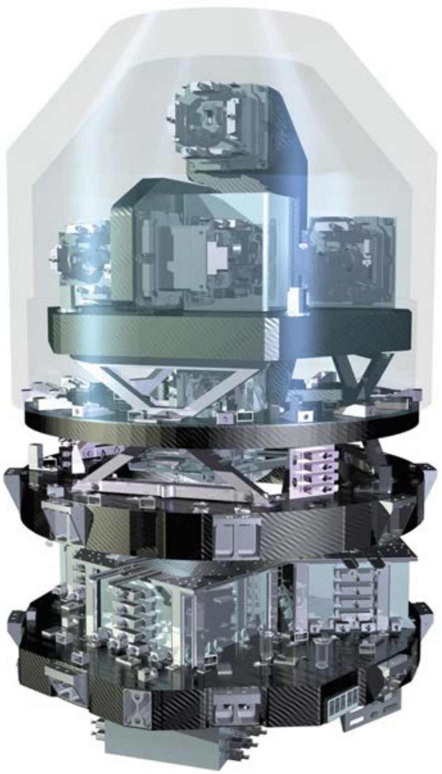

Fig. 5: Electrostatic Gravity Gradiometer carried by GOCE (© ESA – AOES Medialab).

The scientific data processing (Level 1b to Level 2) is performed by the "European GOCE Gravity Consortium" (EGG-C), a consortium of 10 European universities and research institutes, within the ESA-funded project "GOCE HPF". In the frame of this project the Institute of Theoretical Geodesy and Satellite Geodesy together with partners from the Austrian Academy of Sciences, University of Bonn, and Technical University Munich, is responsible for the processing of an Earth's gravity field model and the corresponding variance-covariance matrix from the precise GOCE orbit and SGG data.

The GOCE contribution to the GOCO01S model is based on two months of satellite gravity gradients (SGG) covering the time span of November 1, 2009, until December 31, 2009. The observed gravity gradients are the second order derivative of the gravitational potential and are directly related to the spherical harmonic coefficients to be estimated. The gradiometer measurements are affected by colored noise and perform best within the measurement bandwidth of 5 to 100 mHz. Thus one key issue is the correct stochastic modeling of the spectral behaviour of the observations ([1]). This is realised by the application of digital auto-regressive moving average filters to the full observation equation, i.e., both to the columns of the design matrix and the observations. Finally the GOCE SGG normal equation system was assembled up to degree and order 224 on a PC cluster.

4.3 Constraints

The third component incorporated in GOCO01S is a Kaula regularization to improve the signal-to-noise ratio in degrees larger than 170. One main objective of the GOCO models is to be completely independent from existing gravity field models. Thus the solution is Kaula constrained towards zero and not towards any a-priori geopotential coefficients.

4.4 Combination solution

The calculation of the final combination solution was performed by the fusion of the individual normal equation systems according to Equations 2 and 3. The weights for the GRACE and GOCE components as well as for the Kaula constraints applied to the high degrees were calculated by means of variance component estimation. The resulting estimated weights for GRACE and GOCE were close to one. This is an indicator for the realistic and correct stochastic modeling of the errors for both, GRACE and GOCE data. The final normal equation system was rigorously solved up to degree and order 224 using the in-house implemented parallel software.

5. Results and validation of GOCO01S

Fig. 6 illustrates the comparison of the GOCO01S model with the well-known EGM2008 model which is also a combination model based on ITG-Grace03s ([9]), terrestrial and altimetry-derived gravity data. As already mentioned, the lack of GOCE observations over polar regions causes a poor determination of the (near-)zonal coefficients. Therefore, to enable a representative comparison the figure displays the robust median difference per spherical harmonic degree.

The black curve indicates the median of the absolute signal per degree whereas the colored curves represent the median of the coefficient

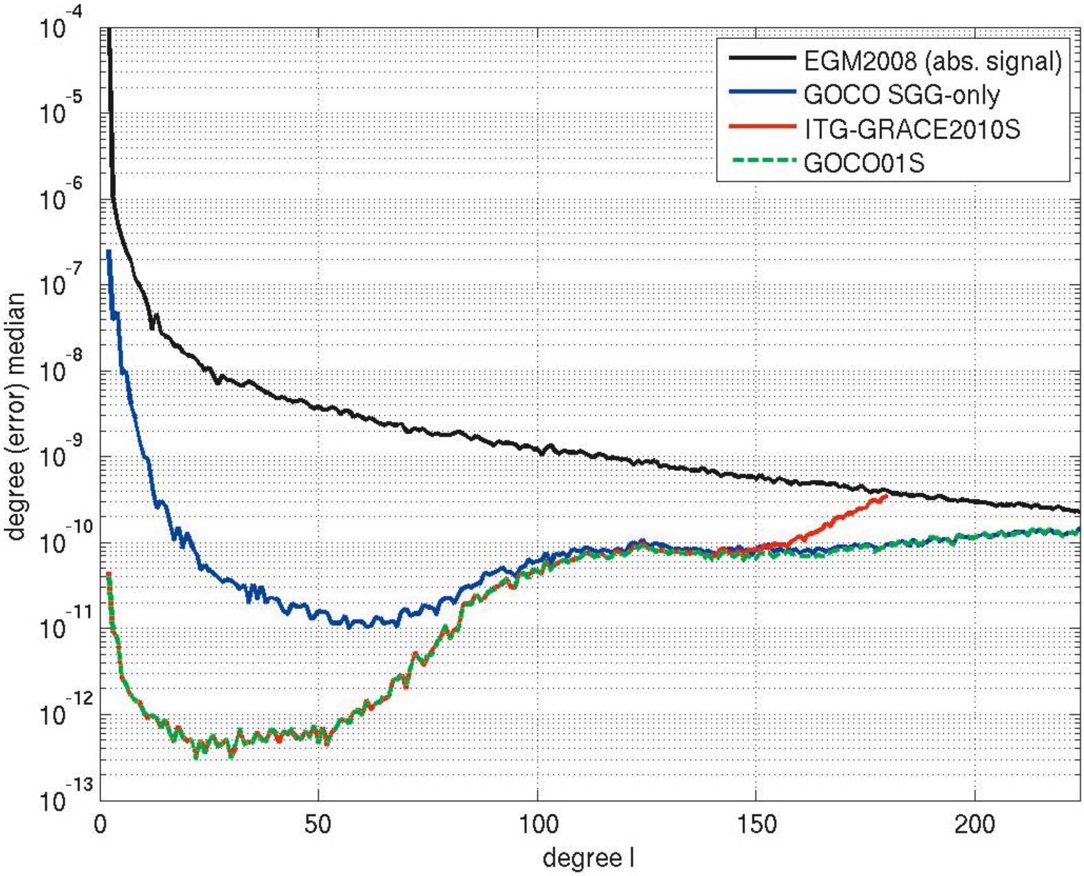

Fig. 6: Degree error medians of the GOCE SGG-only component (blue curve), the GRACE component (red), and the combination solution GOCO01S (green dashed) w.r.t. to the EGM2008 model. The black curve represents the median of the absolute coefficients signal per degree.

deviations per degree of the single solutions and the combination solution w.r.t. EGM2008. The GOCE solution (blue curve) is only based on gravity gradients. Thus the low degree coefficients are poorly estimated because of the limited measurement bandwidth of the gradiometer. As a consequence the combination solution (green dashed curve) clearly demonstrates that the low to medium degrees are mainly determined by GRACE (red curve). The contribution of GOCE SGG starts at about degree 100. Beyond degree 150, GOCE is the dominant contributor.

Fig. 7 displays the geoid height differences of GOCO01S (top) and ITG-Grace2010s (bottom) w.r.t. EGM2008 up to d/o 180. Both plots demonstrate that satellite data deliver additional information especially in mountainous regions (e.g. Himalayas, Andes) and in regions where only a few and less accurate terrestrial measurements are available (e.g. Africa, Antarctica). This benefit is most underlined by the GOCO01S model. Furthermore, the along-track pattern differences, which are typical GRACE errors, disappear when using GOCE data.

For a completely independent validation a comparison of geoid heights derived from GOCO01S and other gravity models with geoid heights determined by GPS and levelling observations was performed (a description of the methodology can be found in [4]). Here, the models were truncated at different degrees N_{max}. The RMS of the geoid height differences are listed in Table 2. As can be noticed, there are regional offsets in the given values because of inconsistencies in the height system definitions. However, compared to the ESA GOCE-only model the GOCO01S model benefits from multi-year GRACE observations in the degrees up to 150. Beyond degree 150 the differences from GOCO01S model are smaller than from ITG-Grace2010s due to the dominant contribution from GOCE.

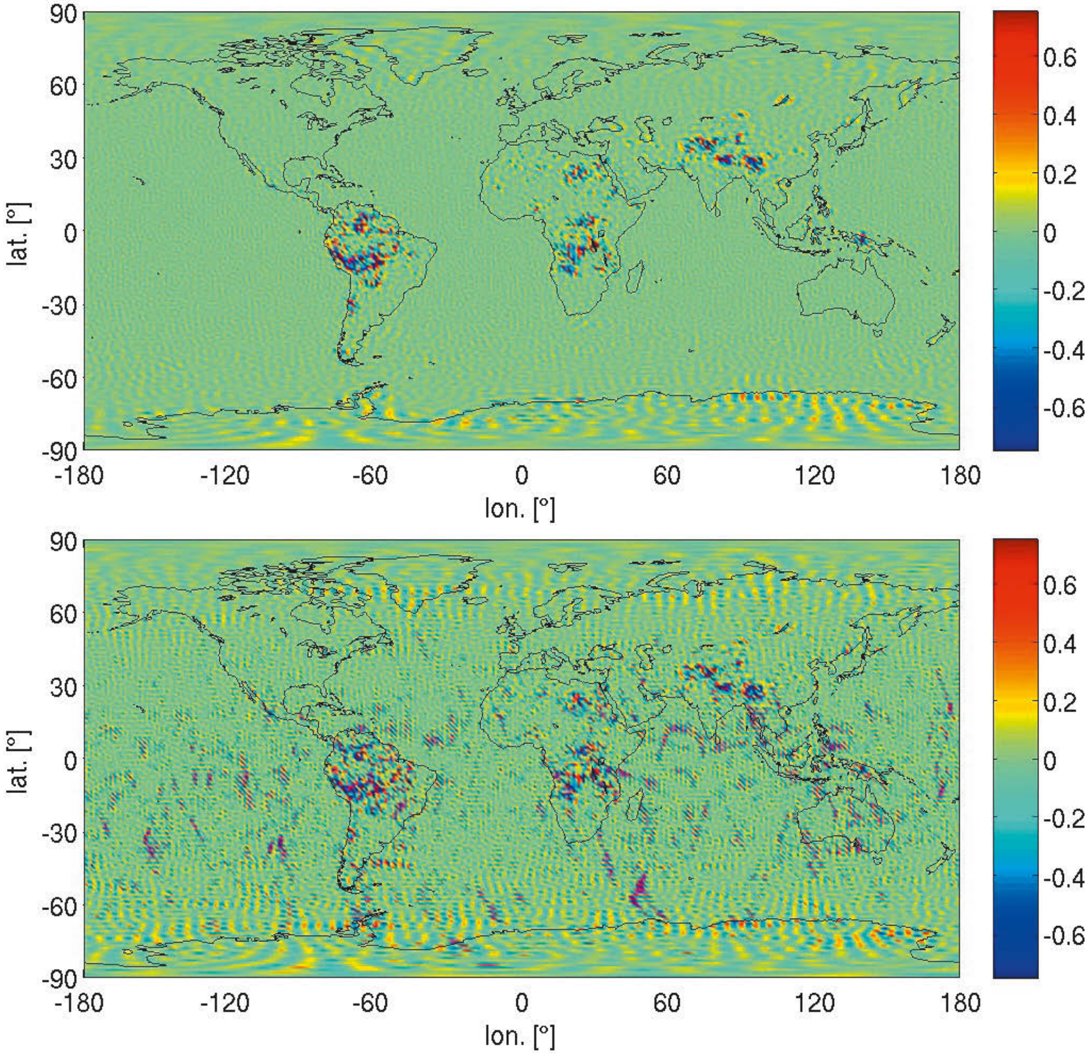

Fig. 7: Geoid height differences [m] of GOCO01S (top) and ITG-Grace2010s (bottom) w.r.t. EGM2008.

6. Conclusions and outlook

The combination procedure is based on the weighted fusion of normal equation systems. Two methods for weights estimation have been implemented and assessed within a test environment. The result based on the variance components estimation has delivered an optimum solution in the sense of a minimum achievable error throughout the whole spectrum. In contrast, the weights estimated by the approach of Lerch has been distorted due to the degraded determination of the zonal and near-zonal coefficients by GOCE. The principle difference between these two weighting procedures is the consideration of the covariances of the coefficients in the case of the variance components estimation method whereas only the variances are used in the case of the Lerch method.

One objective of the GOCO consortium is to process complementary data sets without the use of any prior gravity information to finally provide a consistent combination model to the users. The GOCO01S is the first satellite-only combination model computed by the GOCO consortium. The benefit of a pure satellite-only model is that it is independent of altimetry data and thus it can be used e.g. to derive the dynamic ocean topography. Currently the next generation model GOCO02S is being processed which contains more than 6 months of GOCE data. GOCO02S will have a resolution of up to degree and order 250. Furthermore Satellite Laser Rang-

Model	Germany	Japan	Canada
	RMS [cm]	RMS [cm]	RMS [cm]
N_{max} = 100			
GOCO01S	4.0	9.9	14.0
ITG-Grace2010s	4.1	10.2	14.6
ESA GOCE-only	4.2	10.8	14.6
EIGEN-5C	4.1	10.4	14.5
N_{max} = 150			
GOCO01S	4.6	9.9	14.0
ITG-Grace2010s	4.8	10.5	14.7
ESA GOCE-only	5.3	11.2	14.7
EIGEN-5C	6.3	12.7	16.4
N_{max} = 170			
GOCO01S	4.9	9.7	14.3
ITG-Grace2010s	7.5	13.9	17.7
ESA GOCE-only	5.7	10.7	15.4
EIGEN-5C	5.7	14.4	16.8
N_{max} = 200			
GOCO01S	14.3	13.0	17.0
ITG-Grace2010s	26.5	34.9	30.3
ESA GOCE-only	15.1	13.9	18.2
EIGEN-5C	6.6	17.8	16.6

Tab. 2: RMS of geoid height differences [cm] between gravity field models and GPS-levelling observations for Germany (675 points), Japan (873 points), and Canada (430 points) truncated at degree and order N_{max}.

ing (SLR) data will be used to recover the very low degree coefficients. With the approval of the extension of the GOCE mission until the end of 2012 further improvements of combination models can be expected. In the near future a combination model using also terrestrial and altimetry observations will be processed and published. The GOCO01S model (and the follow-on models) can be downloaded from http://itsg.tugraz.at/goco or from http://icgem.gfz-potsdam.de/ICGEM/ICGEM.html.

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