



ELSEVIER

Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

Journal of Geodynamics xxx (2004) xxx–xxx

JOURNAL OF
GEODYNAMICS<http://www.elsevier.com/locate/jog>

An Earth gravity field model complete to degree and order 150 from GRACE: EIGEN-GRACE02S

Christoph Reigber*, Roland Schmidt, Frank Flechtner, Rolf König, Ulrich Meyer,
Karl-Hans Neumayer, Peter Schwintzer, Sheng Yuan Zhu

*Department 1 'Geodesy and Remote Sensing', GeoForschungsZentrum Potsdam (GFZ),
Telegrafenberg, 14473 Potsdam, Germany*

Received 23 January 2004; received in revised form 12 July 2004; accepted 14 July 2004

Abstract

A new medium-wavelength gravity field model has been calculated from 110 days of GRACE tracking data, called EIGEN-GRACE02S. The solution has been derived solely from satellite orbit perturbations and is independent from oceanic and continental surface gravity data. This model that resolves the geoid with an accuracy of better than 1 mm at a resolution of 1000 km half-wavelength is about one order of magnitude more accurate than recent CHAMP-derived global gravity models and over two orders of magnitude more accurate than the latest pre-CHAMP satellite-only gravity models. This progress in accuracy together with an increase in resolution are the result of the dedicated instrumentation of the twin GRACE satellites. The instrumentation allows for continuous GPS–GRACE high–low satellite-to-satellite tracking, on-board measurement of non-gravitational accelerations, precise attitude determination, and—being the most important component—the observation of the intersatellite distance and its rate of change.

© 2004 Elsevier Ltd. All rights reserved.

1. Introduction

Tracking data from some tens of satellites at different altitudes and orbit inclinations have over the last three decades gradually improved the knowledge of the Earth's gravity field. While these conventional methods have provided accurate information, especially long wavelengths, they have insufficient

* Corresponding author. Tel.: +49 331 288 1100; fax: +49 331 288 1111.
E-mail address: reigber@gfz-potsdam.de (C. Reigber).

accuracy and time resolution to support a wide range of applications. The limitations are due to the attenuation of the gravitational signal with altitude, the sparse tracking data coverage and the difficulties in modeling the non-gravitational forces for most of the satellites (Biancale et al., 2000). With the CHAMP mission, launched in 2000, for the first time a dedicated configuration has been realized: a low and near-polar orbit, an on-board accelerometer, and a continuous precise tracking simultaneously by up to 10 high-orbiting GPS satellites. These characteristics led to a break-through in the determination of the long-wavelength gravitational field (Reigber et al., 2002) already from a limited amount of mission data.

It was noted already decades ago by Wolf (1969) that the intersatellite signal between a pair of satellites orbiting the Earth in the same orbit plane has significant information on the medium to shorter wavelength components of the Earth's gravitational field and, if this relative motion can be measured with sufficient accuracy, this approach will provide significant improvement in the gravity field modeling. This mission concept was proposed for the early GRAVSAT experiment by US scientists (Fischell and Pisacane, 1978) and the SLALOM mission in Europe (Reigber, 1978). Both of these experiment proposals as well as the follow-on US Geopotential Research Mission GRM and the European POPSAT and BRIDGE mission proposals were not successful in being accepted for funding. The break-through came with the acceptance of the Gravity Recovery and Climate Experiment (GRACE) mission, proposed by Tapley et al. (1997) as a joint US–German partnership mission (Tapley and Reigber, 2001) within NASA's Earth System Science Pathfinder (ESSP) program.

The GRACE is a dedicated satellite mission whose objective is to map the global gravity field with unprecedented accuracy over a spatial range from 400 km to 40,000 km every 30 days. The measurement precision will provide a mean gravity field whose accuracy in this frequency range is between 10 and 100 times better than our current knowledge.

The twin GRACE satellites, based on CHAMP heritage, were launched on March 17, 2002 into an almost circular, near-polar orbit (inclination 89.0°) with an initial altitude of 500 km. The natural decay of the orbital altitude since launch is about 1.1 km/month. The GRACE configuration consists of two identical satellites with extremely high temperature and alignment stabilities (Davis et al., 1999). The satellites differ only in the S-band radio frequencies used for ground communication and K-band inter-satellite ranging frequencies. Both satellites follow each other on the same orbital path and are interconnected by the K-band microwave link to measure the exact separation distance and its rate of change with an accuracy of better than $10\ \mu\text{m}$ and $1\ \mu\text{m/s}$, respectively. Both satellites are equipped with the highly advanced BlackJack GPS flight receiver instrument (Yunck, 2003) for high–low satellite-to-satellite tracking, a three-axis SuperSTAR accelerometer (Touboul et al., 1999) to observe the non-gravitational forces, and two star-cameras to measure the inertial orientation of the satellites. The instrumentation and on-board instrument processing units are described in detail in Dunn et al. (2003).

In the following, the GFZ Potsdam-derived global gravity field solution EIGEN-GRACE02S (European Improved Gravity model of the Earth by New techniques solely from GRACE Satellite data) is described and related to latest pre- and post-CHAMP-launch developments in global gravity field recovery (Table 1). The results demonstrate the improvement in quality and resolution of GRACE-derived gravity field models and show the enhanced capabilities of the GRACE mission concept compared to a single satellite mission like CHAMP.

The GRACE data high-level processing is shared by the Center for Space Research of the University Texas in Austin (CSR/UTEX) and the GFZ Potsdam. Global gravity field models from GRACE data are

Table 1
Global geopotential models quoted in this paper

Model	Description	Complete to degree	Reference
EGM96S	Pre-CHAMP, multi-sat.	70	Lemoine et al. (1998)
EGM96	Pre-CHAMP combined: EGM96S plus surface data	360	Lemoine et al. (1998)
GRIM5-S1	Pre-CHAMP, multi-sat.	99	Biancale et al. (2000)
EIGEN-CHAMP03Sp	CHAMP only: 25 months	120	Reigber et al. (2004)
GGM01S	GRACE only: 111 days	120	Tapley et al. (2003)
EIGEN-GRACE01S	GRACE-only: 39 days	140	Reigber et al. (2003b)
EIGEN-GRACE02S	GRACE only: 110 days	150	This paper

generated at both centres. The first CSR GRACE-only solution is called GGM01 (Tapley et al., 2003) and comparable to GFZ's early model EIGEN-GRACE01S. While the actual EIGEN-GRACE02S solution benefits from a meanwhile improved processing, both early versions are about a factor of two worse in terms of geoid heights.

2. GRACE instrument data

For the gravity field solution GRACE mission data have been exploited in a dynamic precision orbit determination (POD) process, discussed in Section 3. POD processing is based on GPS high–low and K-band inter-satellite range-rate observations. The GPS BlackJack receiver on-board GRACE delivers carrier phase (resolution 0.2 cm) and code pseudo-ranges (resolution 30 cm) for up to 10 GPS satellites simultaneously at 10 s time intervals. The GRACE orbit parameters and receiver clock biases are determined relative to the orbits and clocks of the GPS satellites. These are computed from GPS data received at dedicated CHAMP/GRACE mission ground stations (Galas et al., 2001) and stations of the International GPS Service (IGS) network. Because the IGS stations measure at a rate of 30 s, the GRACE SST data are down-sampled to this rate for use in POD. The K-band link provides 10 Hz range, range-rate and range-accelerations, one way from each satellite. Here only range-rate data, accurate to 1 $\mu\text{m/s}$, are used that are down-sampled to 5 s during preprocessing. The non-gravitational forces are directly measured on-board in all three axes using the ONERA built SuperSTAR accelerometer. The linear accelerations are measured with a 10 Hz rate and digitally filtered to get 5 s samples. As the accelerometer's proof mass is located within 0.1 mm at the center of mass of the satellite, perturbing linear accelerations induced by the frequent (about every 2 min) attitude maneuvers are measured by the accelerometer. The precision of the accelerometer is about 10^{-10} ms^{-2} within the bandwidth of 4×10^{-2} to $5 \times 10^{-5} \text{ Hz}$ for the along-track and radial directions and one order of magnitude worse for the cross-track direction. Two star-cameras provide the orientation of the accelerometer axes and the K-band bore sight vector in a celestial reference frame. Additionally each satellite is equipped with a laser retro-reflector. The ground stations of the International Laser Ranging Service (ILRS) observe approximately three SLR passes per day and satellite, which are used for independent POD quality control. Fig. 1 shows a sketch of one of the satellites with the location of the instruments and gives the order of magnitude for the inter-satellite range variations along the orbit.

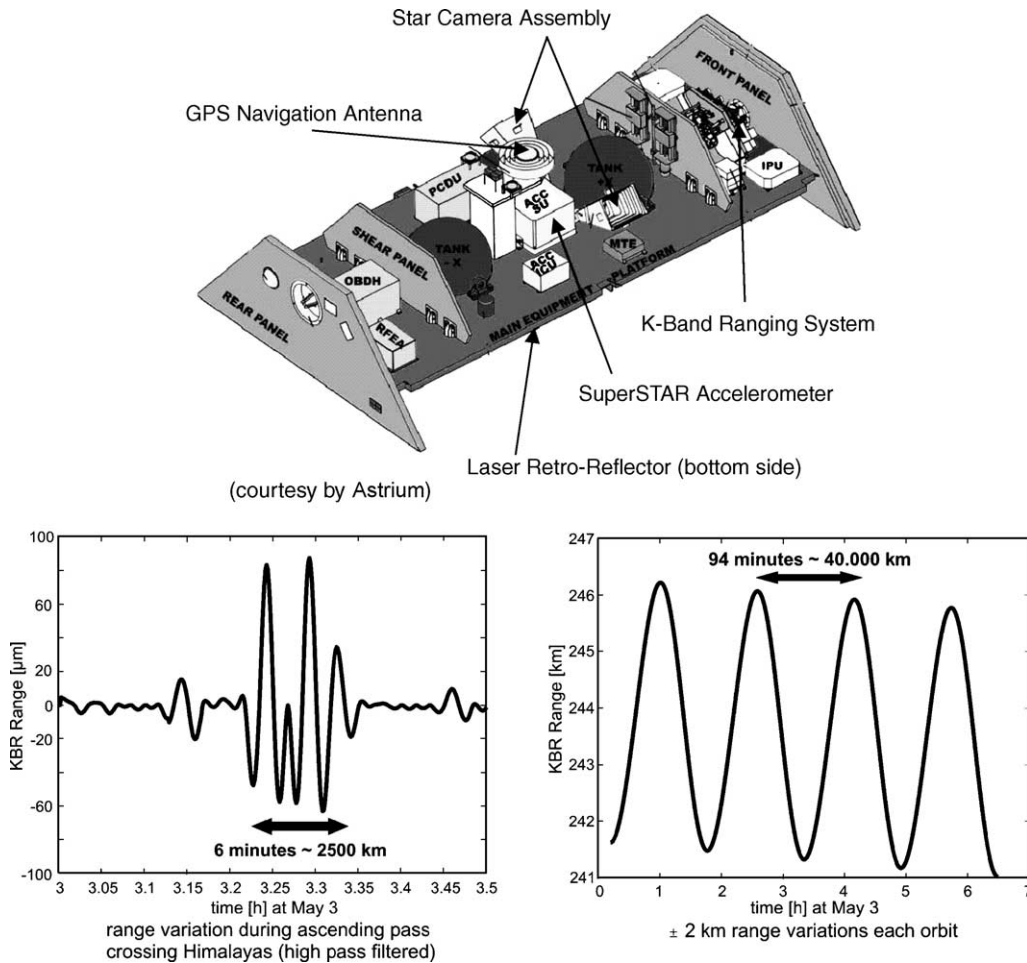


Fig. 1. GRACE gravity recovery relevant instruments (top) and low–low K-band ranging (KBR) tracking signature, coarse resolution (bottom left) and fine resolution (bottom right).

3. Gravity field model determination

The GRACE gravity field model determination is based on the same principle as used to derive the EIGEN-CHAMP models (Reigber et al., 2003a). First, the two GRACE satellite orbits are—based on an initial force field (Earth gravity, third bodies, observed SuperSTAR sensor accelerations)—numerically integrated. Then, the linearized observation equations of the high–low GPS–GRACE and low–low K-band intersatellite tracking data, which provide the relationship to the various unknowns such as the gravity field spherical harmonic coefficients, the orbit state vector at epoch per arc and sensor-specific parameters, are set up, leading after accumulation over the evaluation period to a normal equation system in a least squares sense to be eventually solved by matrix inversion.

The solution of the gravity field parameters using GRACE tracking data is based on a two-step approach: (1) adjustment of the high GPS constellation orbits and clock parameters from ground-based tracking data

Table 2

Parameterization of GRACE normal equation system (solve-for parameters)

Arc-dependent parameters

Orbit: state vector at epoch of arc

GPS receiver: clock offset (1/30s), phase ambiguities (~ 500 /d/satellite)

Accelerometer: 3D biases (offset and drift per arc) and scale factors (offset and drift per arc)

K-band ranging system: range-rate bias and drift (every 90 min), periodic terms (every 180 min)

Common parameters

Gravitational potential: 22,797 fully normalized spherical harmonic coefficients \bar{C}_{lm} , \bar{S}_{lm} complete to degree, order $lm = 150$ (\bar{C}_{00} and degree 1 terms were fixed to 1 and 0, respectively)

and (2) GRACE orbit determination and computation of observation equations with fixed GPS spacecraft positions and clocks as from step 1. The GRACE data used for EIGEN-GRACE02S cover the months August and November 2002 and April, May and August 2003 and were split into arcs of maximum 1.5 days length each. Due to data gaps and mission operation events in total 111 arcs could be processed covering 110 days over this 5-month period with an average arc length of almost 24 h. These data comprise about 6.8 million GPS code and phase measurements, respectively, and 1.8 million K-band range-rate observations. A nominal arc length of 1.5 days was selected as a compromise between the need for a short arc in order to prevent an increase of mismodelling errors, and a longer arc to cover at least one half of GRACE's primary gravitational orbit resonance period. Besides Earth and ocean tidal potential temporal variations, short-term atmospheric and oceanic mass variations are taken into account in the POD process by applying forward models of the mass transport in these systems that are routinely calculated by GFZ on the basis of 6-h 0.5° ECMWF meteorological fields and a barotropic ocean model provided by JPL (Flechtner, 2003). The gravity field solution then follows the general least squares solution strategy as outlined in Reigber (1989).

One individual normal equation system is created from each individual arc for the set of unknown parameters listed in Table 2. After reduction of the arc-dependent parameters, the 111 individual GRACE normal equation systems were summed up. The resulting overall normal equation system needs a moderate regularization before its solution, because of the attenuation of the gravitational signal with altitude and the remaining high correlations between a number of high degree coefficients. Pseudo-observations with a value of zero and a weight reciprocally proportional to Kaula's degree variance model (Kaula, 1966), i.e. increasing with increasing degree, were added to the system for all spherical harmonic coefficients starting at degree 100. The pseudo-observations serve as a mild constraint on the adjusting size of the coefficients where applied. The inversion of the resulting system provides the gravity field coefficients up to degree and order 150.

4. Gravity field solution: EIGEN-GRACE02S

The gravity field solution resulting from the least squares adjustment described above is called EIGEN-GRACE02S. Fig. 2 shows the estimated signal and error amplitudes per degree for EIGEN-GRACE02S, EGM96 (Lemoine et al., 1997) and the CHAMP model EIGEN-CHAMP03Sp. The GRACE solution provides full power almost up to degree 120 as can be seen from the comparison with EGM96,

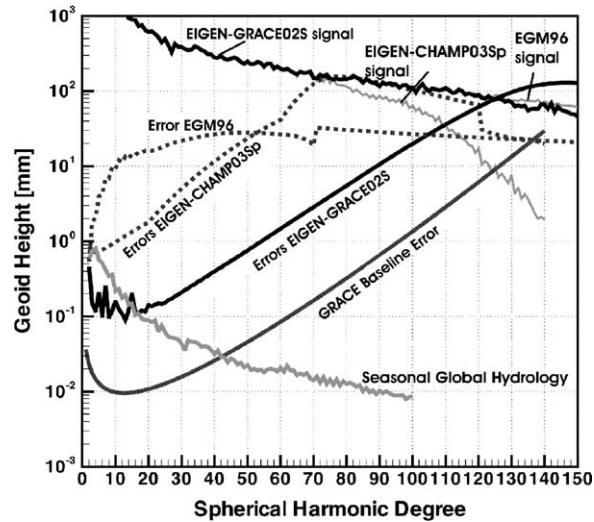


Fig. 2. Signal and error amplitudes per degree in terms of geoid heights.

which incorporates altimetry and surface gravity data that are not affected by attenuation. The EIGEN-GRACE02S errors were a posteriori calibrated based on the scattering of subset solutions. Subset solutions are generated from GRACE data covering different time periods. The variances per degree of the coefficients' differences between subset solutions are compared with the formal error degree variances as resulting from the adjustment. Individual calibration factors for bands of the gravitational spectrum are then estimated to scale the too optimistic formal error estimates to more realistic ones. The EIGEN-GRACE02S errors are about one to two orders of magnitude smaller (degrees 5–60) than the corresponding CHAMP and EGM96 errors. But on the other hand the current solution accuracy is still about one order of magnitude off from the anticipated GRACE baseline accuracy predicted from pre-mission numerical simulations. This is partly attributed to residual signals in the very long-wavelength part due to unmodeled seasonal temporal variations that do not completely average out in the present solution. Fig. 2 is complemented by the geoid variability amplitudes per degree due to monthly global continental hydrological mass transports to illustrate the sensitivity of GRACE to temporal field variations.

Fig. 3 shows the error amplitudes as a function of the spatial resolution for the EIGEN-GRACE02S, EIGEN-CHAMP03Sp, EGM96 and GRIM5-S1 solutions and the difference amplitudes as a function of resolution between the GRACE solution and EGM96. The analysis of 110 days of GRACE data results in a largely improved geoid as compared to what is achieved with 25 months of CHAMP data or with the multi-year, multi-satellite GRIM5-S1 and EGM96 solutions. EIGEN-GRACE02S resolves the geoid with a 1 cm accuracy down to 275 km half-wavelength. Also the GRACE error curve remains flat on a level of less than 1 mm down to a half-wavelength resolution of about 600 km while all other gravity models' error curves show a steep increase with increasing resolution even at long wavelengths. The geoid differences as a function of resolution between EIGEN-GRACE02S and EGM96 reflect the combination of the error curves for both models. The improvement in gravity field resolution is also visible from Fig. 4 where a cut of the gravity anomalies deduced from the EIGEN-CHAMP03Sp and the EIGEN-GRACE02S model, respectively, is shown.

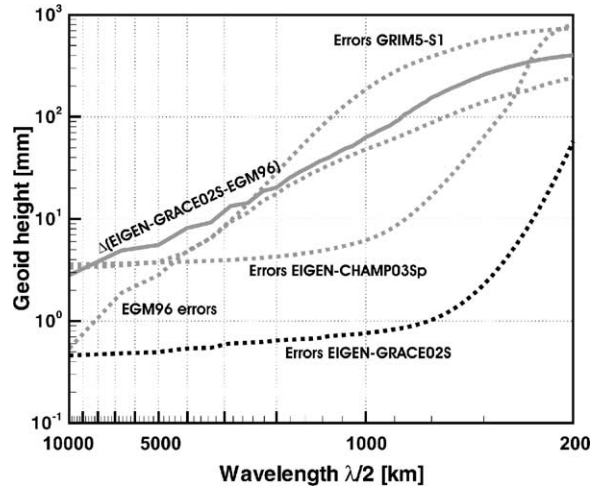


Fig. 3. Error and difference amplitudes as a function of spatial resolution in terms of geoid heights.

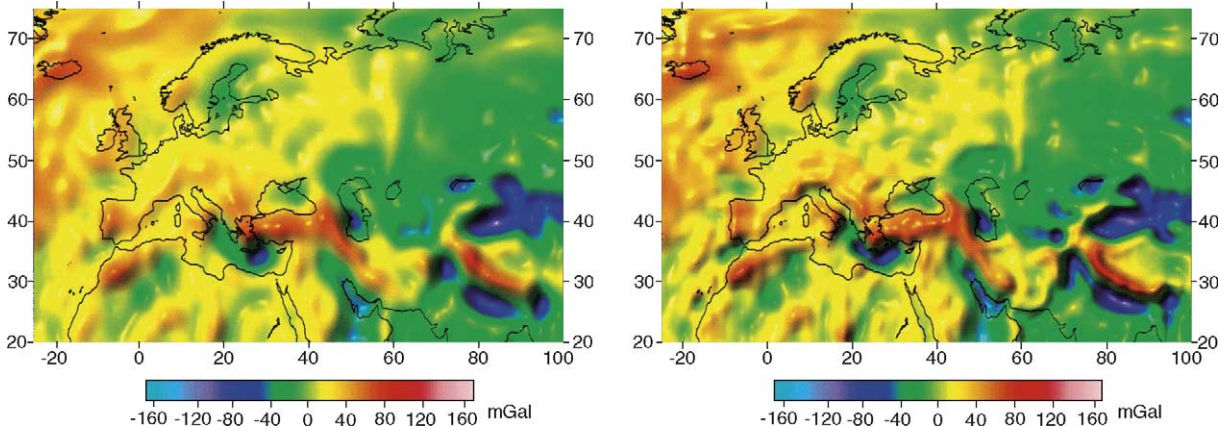


Fig. 4. Gravity anomalies (mgal) derived from the EIGEN-CHAMP03Sp (left) and EIGEN-GRACE02S (right) models.

5. EIGEN-GRACE02S comparison against surface data

Comparisons of a satellite-only gravity field model in the spatial domain against independent gravity anomalies or geoid height data are capable to test the model accuracy homogeneously over all spherical harmonic coefficients up to the considered resolution. Gravity anomalies and geoid heights were computed from the spherical harmonic coefficients of a set of gravity field models as block mean values on an equal-angular global grid with 5° and 2.5° spacing, respectively. These are compared against appropriately filtered geoid heights derived from altimetry over the oceans (CLS01 sea surface (Hernandez et al., 2001) minus ECCO sea surface topography (Stammer et al., 2002)) and altimeter-derived gravity anomalies compiled by US National Imaging and Mapping Agency (NIMA), the set that was used in the EGM96

Table 3

Comparison of satellite only geopotential models with altimeter-derived geoid heights (N , 'CLS01 minus ECCO' oceanic geoid) and gravity anomalies (Δg , NIMA marine gravity anomalies) for a grid spacing of $5^\circ \times 5^\circ$ ($\hat{=}$ degree/order 36) and $2.5^\circ \times 2.5^\circ$ ($\hat{=}$ degree/order 72)

Model	rms (dN), cm		rms (d Δg), mgal	
	$5^\circ \times 5^\circ$	$2.5^\circ \times 2.5^\circ$	$5^\circ \times 5^\circ$	$2.5^\circ \times 2.5^\circ$
EGM96S (pre-CHAMP)	36	70	1.85	5.39
GRIM5-S1 (pre-CHAMP)	44	76	2.00	5.40
EIGEN-CHAMP03Sp (CHAMP-only: 25 months)	15	33	0.56	3.74
GGM01S (GRACE-only: 111 days)	14	18	0.29	1.88
EIGEN-GRACE01S (GRACE-only: 39 days)	14	17	0.28	1.55
EIGEN-GRACE02S (GRACE-only: 110 days)	14	16	0.28	1.25

rms—root mean square of differences about mean.

model generation (Lemoine et al., 1998). The root mean squares of the differences (after bias elimination) as given in Table 3 show the very good agreement between the EIGEN-GRACE02S and the surface geoid and gravity data, but mainly reflect in view of Fig. 3 the long-wavelength errors in the surface data used for comparison. These cannot compete with the GRACE model's accuracy at these levels of resolution. The striking gain in accuracy and resolution with respect to pre-CHAMP and the CHAMP-only models is obvious, also the benefit of improved processing in the EIGEN-GRACE02S solution with respect to the early GRACE solutions GGM01S and EIGEN-GRACE01S.

6. Conclusion

The first EIGEN gravity model derived solely from 110 days of GRACE data gives a substantial improvement in long- to medium-wavelength Earth gravity field recovery. A 1 cm accuracy geoid model with a spectral resolution up to degree and order 75 has become available, a gain in spatial resolution (half wavelength) from 1000 km to 275 km compared to pre-CHAMP gravity models and from 400 km to 275 km compared to a multi-year CHAMP-only model. The EIGEN-GRACE02S model is independent from ocean and continental surface data, which is of great importance for oceanographic applications, as for example, the precise recovery of sea surface topography features from altimetry. It is expected that upcoming GRACE gravity models, with improved processing methods and computational models, will further increase the gravity field model's accuracy towards the mission's baseline accuracy in order to be able to resolve reliably the tiny signals of climatologically and geophysically induced temporal field variations. These include seasonal and interannual variations in the ocean/atmosphere mass distribution (ocean bottom pressure), in large scale continental water storage as well as in the thickness of the Antarctic and Greenland ice shields. With the completion of the anticipated five-year mission lifetime also secular gravitational signatures due to trends in the ice/water mass balance and due to post-glacial adjustment very likely will be recoverable from space. Also, high resolution global gravity field models from a combination of satellite tracking, altimeter and surface gravity data will benefit from the accuracy improvements in the long- to medium-wavelength part of the gravitational spectrum allowing a more thorough interpretation of the gravity field for geodynamic processes in the Earth's mantle/lithosphere system.

Remark

The spherical harmonic coefficients of the EIGEN-GRACE02S model can be downloaded from the GRACE homepage: <http://op.gfz-potsdam.de/grace/results>.

Acknowledgements

The German Ministry of Education and Research (BMBF) supports the GRACE project within the GEOTECHNOLOGIEN geoscientific R&D programme under grant 03F0326A. Thoughtful reviews by S. Klosko and one anonymous reviewer improved the paper greatly.

References

- Biancale, R., Balmino, G., Lemoine, J.-M., Marty, J.-C., Moynot, B., Barlier, F., Exertier, P., Laurain, O., Gegout, P., Schwintzer, P., Reigber, C., Bode, A., König, R., Massmann, F.-H., Raimondo, J.-C., Schmidt, R., Zhu, S.Y., 2000. A new global Earth's gravity field model from satellite orbit perturbations: GRIM5-S1. *Geophys. Res. Lett.* 27, 3611–3614.
- Davis, E.S., Dunn, C.E., Stanton, R.H., Thomas, J.B., 1999. The GRACE Mission: Meeting the Technical Challenges. American Institute of Aeronautics and Astrophysics, IAF-99-B.2.05.
- Dunn, Ch., Bertiger, W., Bar-Sever, Y., Desai, S., Haines, B., Kuang, D., Franklin, G., Harris, I., Kruizinga, G., Meehan, T., Nandi, S., Nguyen, D., Rogstad, T., Brooks Thomas, J., Tien, J., Romans, L., Watkins, M., Wu, S.-C., Bettadpur, S., Kim, J., 2003. Instrument of GRACE–GPS Augments Gravity Measurements, *GPS World*, 1 February.
- Fischell, R.E. Pisacane, V.L., 1978. A drag-free lo-lo satellite system for improved gravity field measurements, In: Proceedings of the 9th GEOP Conference, Department of Geod. Sci. Rep. 280, Ohio State University, Columbus, pp. 213–220.
- Flechtner, F., 2003. AOD1B Product Description Document. GRACE Project Documentation, JPL 327-750, Rev. 1.0.
- Galas, R., Wickert, J., Burghardt, W., 2001. H/R low latency GPS ground tracking network for CHAMP. *Phys. Chem. Earth A* 26, 619–652.
- Hernandez, F., Schaeffer, P., Calvez, M.-H., Dorandeu, J., Faugère, Y., Mertz, F., 2001. Surface Moyenne Oceanique: Support Scientifique à la mission altimétrique Jason-1, et à une mission micro-satellite, altimétrique, Contrat SSALTO 2945–Lot2–A.1. Rapport final no. CLS/DOS/NT/00.341, CLS, Ramonville St Agne.
- Kaula, W., 1966. *Theory of Satellite Geodesy*. Blaisdale Press, Waltham, MA.
- Lemoine, F.G., Kenyon, S.C., Factor, J.K., Trimmer, R.G., Pavlis, N.K., Chinn, D.S., Cox, C.M., Klosko, S.M., Luthcke, S.B., Torrence, M.H., Wang, Y.M., Williamson, R.G., Pavlis, E.C., Rapp, R.H., Olson, T.R., 1998. The Development of the Joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential model EGM96. NASA Technical Paper NASA/TP-1998-206861. Goddard Space Flight Center, Greenbelt.
- Reigber, C., 1978. Improvements of the gravity field from satellite techniques as proposed to the European Space Agency, In: Proceedings of the 9th GEOP Conference. Department of Geod. Sci. Rep. 280, Ohio State University, Columbus, pp. 221–232.
- Reigber, C., 1989. Gravity field recovery from satellite tracking data. In: Sansò, F., Rummel, R. (Eds.), *Theory of Satellite Geodesy and Gravity Field Determination*, Lecture Notes in Earth Sciences, vol. 25. Springer, Berlin, pp. 197–234.
- Reigber, C., Balmino, G., Schwintzer, P., Biancale, R., Bode, A., Lemoine, J.-M., König, R., Loyer, S., Neumayer, H., Marty, J.-C., Barthelmes, F., Perosanz, F., Zhu, S.Y., 2002. A high-quality global gravity field model from CHAMP GPS tracking data and accelerometry (EIGEN-1S). *Geophys. Res. Lett.* 29 (14), doi: 10.1029/2002GL015064.
- Reigber, C., Balmino, G., Schwintzer, P., Biancale, R., Bode, A., Lemoine, J.M., König, R., Loyer, S., Neumayer, H., Marty, J.C., Barthelmes, F., Perosanz, F., Zhu, S.Y., 2003a. Global gravity field recovery using solely GPS tracking and accelerometer data from CHAMP. *Space Sci. Rev.* 108, 55–66.
- Reigber, C., Schmidt, R., Flechtner, F., König, R., Meyer, U., Neumayer, K.-H., Schwintzer, P., Zhu, S.Y., 2003b. First GFZ GRACE Gravity Field Model EIGEN-GRACE01S, <http://op.gfz-potsdam.de/grace/results>.

- Reigber, C., Jochmann, H., Wunsch, J., Petrovic, S., Schwintzer, P., Barthelmes, F., Neumayer, K.-H., König, R., Förste, C., Balmino, G., Biancale, R., Lemoine, J.-M., Loyer, S., Perosanz, F., 2004. Earth Gravity Field and Seasonal Variability from CHAMP. In: Reigber, C., Luehr, H., Schwintzer, P., Wickert, J. (Eds.), *Earth observation with CHAMP—Results from the Three Years in Orbit*. Springer, Berlin, pp. 25–30.
- Stammer, D., Wunsch, C., Giering, R., Eckert, C., Heinbach, P., Marotzke, J., Adcraft, A., Hill, C.N., Marshall, J., 2002. Global ocean circulation during 1992–1997 estimation from ocean observations and a general circulation model. *J. Geophys. Res.* 107, C9, 3118, doi: 10.1029/2001JC000888.
- Tapley, B.D., Reigber, C., 2001. The GRACE mission: status and future plans. *EOS Trans. AGU* 82 (47), Fall Meet. Suppl. G41 C-02.
- Tapley, B.D., Chambers, D.P., Bettadpur, S., Ries, J.C., 2003. Large scale ocean circulation from the GRACE GGM01 geoid. *Geophys. Res. Lett.* 30 (22), 2163, doi: 10.1029/2003GL018622.
- Touboul, P., Willemenot, E., Foulon, B., Josselin, V., 1999. Accelerometers for CHAMP, GRACE and GOCE space missions: synergy and evolution. *Boll. Geof. Teor. Appl.* 40, 321–327.
- Wolf, M., 1969. Direct measurements of the Earth's gravitational potential using a satellite pair. *J. Geophys. Res.* 74 (22), 5295–5300.
- Yunck, T.P., 2003. Spaceborne GPS for POD and Earth Science. In: Reigber, Ch., Lühr, H., Schwintzer, P. (Eds.), *First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies*. Springer, Berlin, pp. 42–52.