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THE CHAMP-ONLY EARTH GRAVITY FIELD MODEL EIGEN-2

Ch. Reigber [1], P. Schwintzer [1], K.-H. Neumayer, [1], F. Barthelmes [1], R. König [1], Ch. Förste [1], G. Balmino [2], R. Biancale [2], J.-M. Lemoine [2], S. Loyer [2], S. Bruinsma [2], F. Perosanz [2] and T. Fayard [2]

[1] *GeoForschungsZentrum Potsdam (GFZ), Dept. 'Geodesy and Remote Sensing', 14473 Potsdam, Telegrafenberg A 17, Germany*

[2] *Groupe de Recherche de Géodésie Spatiale (GRGS), 18 Avenue Edouard Belin, 31401 Toulouse, France*

ABSTRACT

The German small geoscientific satellite CHAMP flies around the Earth since July 2000 in a highly inclined orbit with an altitude of initially 450 km and meanwhile at about 400 km. From the gravitational orbit perturbations, exploiting GPS-CHAMP satellite-to-satellite tracking and on-board accelerometer data over a time span of altogether six months, a new long-wavelength global gravity field model, called EIGEN-2, has been derived in a German/French effort. Thanks to CHAMP's dedicated orbit configuration, continuous GPS tracking and in-orbit measurement of non-gravitational satellite accelerations, the new CHAMP-only solution provides the geoid and gravity with an accuracy of 10 cm and 0.5 mGal, respectively, at a half wavelength resolution of 550 km. This is an improvement by almost one order of magnitude compared to any multi-satellite pre-CHAMP satellite-only gravity field model.

CHAMP MISSION CHARACTERISTICS FOR GRAVITY FIELD RECOVERY

Compared to all former geodetic satellite missions used for global gravity field recovery, the CHAMP mission (Reigber et al., 2002a; Figure 1) combines the following principal advantages: a very low altitude below 450 km for an increased sensitivity to gravitational perturbations; a near-polar orbit for a complete coverage of the Earth surface; a dedicated payload consisting of NASA/JPL's BlackJack GPS (Global Positioning System) space receiver providing continuously two-frequency code and carrier phase range information (Kuang et al., 2001) to up to twelve GPS satellites simultaneously and the French three-axes STAR accelerometer (Touboul et al., 1999) measuring the non-gravitational satellite accelerations caused by air density, wind and radiation pressure (surface forces). This up-to-now unique payload combination allows the reconstruction of gravitational satellite orbit perturbations all along the orbit (Figure 2). Two star sensors measure the orientation of the accelerometer's axes with respect to a celestial reference system. The Earth oriented attitude of the satellite is controlled by cold gas thrusters within two arc-degrees for all three axes.

With this configuration it became possible for the first time to derive a global gravity field model based upon only one satellite and from only a few months' worth of data. Moreover, the resulting model, which is demonstrated in the following, is by one order of magnitude superior in accuracy compared to any pre-CHAMP satellite-only model like GRIM5-S1 (Biancale et al., 2000) or EGM96S (Lemoine et al., 1998), which were derived from multi-year tracking records of some tens of satellites. The new CHAMP-only model EIGEN-2 (European Improved Gravity Field Model of the Earth by New Techniques), described here, is based on CHAMP data covering six months out of the time periods July to December 2000 and September to December 2001. A meanwhile improved processing of all the data, the two times enlarged data period and the lower altitude of CHAMP in 2001 (420 km vs. 450 km in 2000) led to a significant improvement in the resulting model with respect

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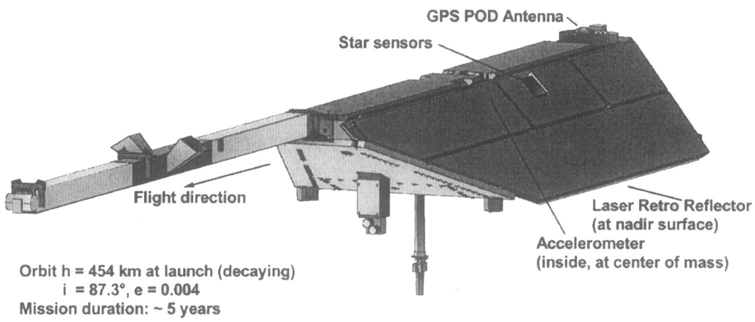

Fig. 1. Sketch of the CHAMP satellite, orbit/gravity payload accommodation and mission parameters.

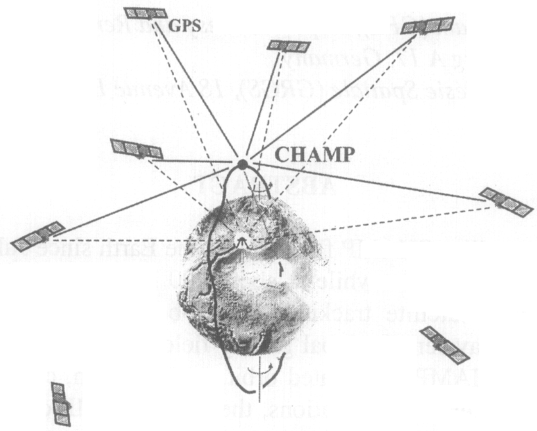

Fig. 2. High-low GPS-CHAMP satellite-to-satellite tracking for gravity field recovery.

to EIGEN-1 (Reigber et al., 2002c) and EIGEN-1S (Reigber et al., 2000b). EIGEN-1S is a combination of EIGEN-1 with other satellite tracking data and the GRIM5-S1 data base.

DATA PROCESSING AND SOLUTION METHOD

Global gravity field recovery from satellite orbit perturbations relies on a precise numerical orbit integration taking into account all reference system and force model related quantities (Reigber, 1989). The integrated orbit is then fitted to the tracking observations (here: GPS-CHAMP GPS code and carrier phase ranges) in a least squares adjustment process solving iteratively for the satellite's state vector at the beginning of the arc and for other observation- and configuration-specific parameters, in particular GPS receiver clock offsets, phase ambiguities and calibration parameters for the accelerometer (c.f. Reigber et al., 2002b). The term 'arc' refers to the time-length of the integrated orbit starting with one initial state vector. In this case one arc extends over nominal 1.5 days, which has been found to be long enough to retain longer-period gravitational orbit perturbations and short enough to avoid an accumulation of systematic force models' errors. When integrating CHAMP's orbit, the on-board accelerometer readings are part of the force model, i.e. these data are not treated as observations but directly taken as disturbing accelerations caused by surface forces.

After convergence of the initial orbit adjustment with the a priori force field models, the observation equations are extended by partial derivatives for the looked-for global parameters, i.e. the unknowns describing the gravitational potential. Arc-by-arc normal equation systems are generated in this way from the observation equations and accumulated over the whole time period to one overall system which is eventually solved by matrix inversion.

When processing GPS-CHAMP satellite-to-satellite tracking data, the precise ephemerides and clock parameters of the 24 GPS satellites have to be known. These are determined before-hand using GPS tracking data from the CHAMP mission stations (Galas et al, 2001) and the IGS (International GPS Service) ground station network and then held fixed in the subsequent CHAMP orbit adjustment process.

For the EIGEN-2 gravity field solution 182.5 days of CHAMP data were processed covering the periods 2000, July 30 to Aug. 10 and Sept. 24 to Dec. 31 and 2001, Sept. 1 to Dec. 31 with some data gaps in-between due to mission events and system unavailability. The processing was split into 113 arcs of 1.5 days length and 13 arcs of 1 day length. The processing involves the following data received from CHAMP: GPS-CHAMP satellite-to-satellite tracking data (2.8 million code and carrier phase observations, respectively), accelerometer data, star camera quaternions for precise attitude knowledge and the attitude control thruster events (about 10 per one revolution) to model disturbing linear accelerations. For a more detailed description see Reigber et al. (2002b).

The gravitational geopotential is mathematically described in the spectral domain by a spherical harmonic expansion (Heiskanen and Moritz, 1967). The Stokes' coefficients C(l,m) and S(l,m) of degree l and order m are the solve-for parameters. The selected solution space is complete to degree and order 120 with an increased resolution up to maximum degree 140 for zonal and sectorial coefficients and for terms within CHAMP orbit specific resonant orders. These altogether 15,793 unknowns are assumed to have a significant effect on CHAMP's orbit. Another 96 unknowns are associated with periodic temporal field variations of 8 diurnal and semi-diurnal ocean tidal waves. Besides, the high-frequency temporal gravitational field variations, caused by atmospheric mass redistributions, are taken into account during the orbit determination process using 6-hourly global air pressure fields from the European Centre for Medium Range Weather Forecasting (ECMWF).

Before solving the finally accumulated normal equation system, the system is stabilized by stochastic a priori information for all gravitational coefficients with a degree $l \geq 30$, because at CHAMP's altitude the gravitational signal gradually fades out for these higher degree terms. The stabilization, following Kaula's degree variance model (Kaula, 1966), constraints the resulting coefficients towards a value of zero if there is no information at all in the observation data.

After stabilization the normal equation system is solved to yield the EIGEN-2 CHAMP-only global gravity field model and the (formal) standard deviations of the estimated parameters.

The main difference in the data processing for EIGEN-2 compared to the EIGEN-1 and EIGEN-1S solutions, which covered only the data out of the year 2000, is the treatment of the radial channel of CHAMP's accelerometer. The readings of this channel are deteriorated by a break of one electrode (CHAMP newsletter No. 9, 2002). Computing now a linear combination of the outputs of two partly redundant electrodes and estimating a radial empirical once per revolution acceleration in every arc provided an about 20 % accuracy improvement in the resulting gravity field model compared to the former approach.

CHAMP-ONLY GLOBAL GRAVITY FIELD SOLUTION 'EIGEN-2'

Figure 3 shows the power spectrum of the EIGEN-2 gravity field solution in terms of geoid heights. For comparison, the power spectra of the pre-CHAMP satellite-only model GRIM5-S1 and of the pre-CHAMP combined model EGM96 (Lemoine et al., 1998) are also plotted. The combined EGM96 model incorporates both satellite tracking data and altimetry/gravimetry surface data and therefore resolves the geoid over the whole spectral range as depicted in Figure 3. The latter two models have no data in common with the EIGEN-2 model and include multi-year records of some tens of satellites, compared to only six months of data for EIGEN-2.

It can be seen from Figure 3, that if compared with the EGM96 power spectrum, EIGEN-2, thanks to the dedicated CHAMP mission and payload configuration, resolves the geoid even better than GRIM5-S1 (up to degree 40 instead of 32 of the spherical harmonic expansion of the geopotential) despite the large difference in the underlying data and number of satellites between these two models. As expected, for higher degree terms the power of EIGEN-2 decreases with respect to the power of the combined solution EGM96 due to signal attenuation with satellite altitude. Although the computational resolution of the EIGEN-2 model extends to degree/order 120, full resolution ends at degree/order 40 in the spectral domain corresponding to a half-wavelength spatial resolution of 500 km at the Earth's surface. Figure 3 also gives the error amplitudes per degree as computed from the coefficients' formal standard deviations resulting from the adjustment. It turns out that above degree 58 the signal-to-noise ratio gets smaller than one for the EIGEN-2 coefficients (root sum of squares over orders per degree).

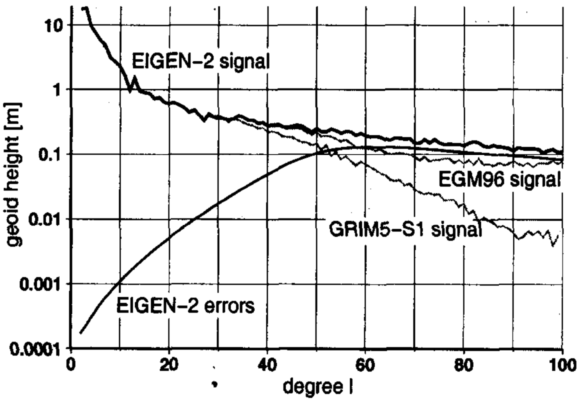

Fig. 3. Signal/error amplitudes per degree in terms of geoid heights.

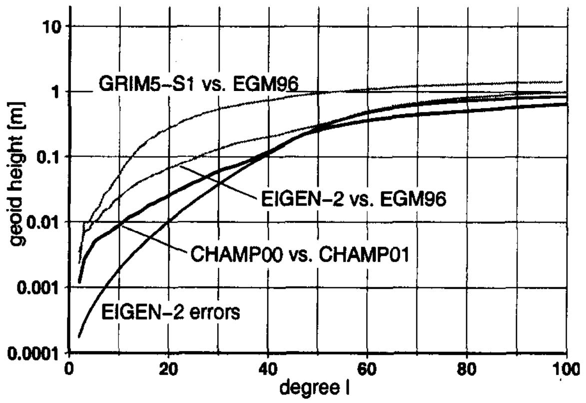

Fig. 4. Difference/error amplitudes as a function of maximum degree in terms of geoid heights.

In order to evaluate the accuracy of EIGEN-2 in relation to the formal (uncalibrated) standard deviations, two subset solutions, one from the three months' worth of data in 2000 (CHAMP00) and one from the three months' worth of data in 2001 (CHAMP01) were generated and mutually compared. The difference amplitudes (root sum of squares over orders and degrees) as a function of maximum degree are given in Figure 4. It turns out that both models fit together on a 8cm-level in terms of geoid heights for all coefficients up to degree/order 36, corresponding to a 5°x5° (550 km x 550 km) spatial resolution. The EIGEN-2 formal error amplitude gives a value of 7 cm at degree 36 (cf. Figure 4) which seems to be a realistic estimate of the model's precision. Because of the modelling environment common to both subset solutions, the error estimate does not necessarily represent a measure for the absolute accuracy. For the longest wavelengths up to degree 20, the formal errors are likely too optimistic.

The geoid difference amplitudes of EIGEN-2 as a function of maximum degree with respect to the EGM96 model (also shown in Figure 4) reach a value of 18 cm at degree 36, which includes the errors in the EGM96 coefficients. These accumulate according to the coefficients' standard deviations given in Lemoine et al. (1998) to 10 cm at degree 36. The corresponding spectrum in Figure 4 for the GRIM5-S1 vs. EGM96 differences illustrate the new quality of the CHAMP-only solution. In terms of gravity anomalies, the two CHAMP models agree on a 0.35 mGal-level up to degree 36 and EIGEN-2 vs. EGM96 gives a value of 0.76 mGal (not shown here).

Table 1. Gravity field model comparison with altimetry/POCM geoid heights (N); weighted (cos of latitude) root mean square (rms) of differences about mean

Resolution $\lambda/2$	EIGEN-2	GRIM5-S1 wrms (ΔN)	EGM96S
5°	16 cm	41 cm	35 cm

Satellite-only models especially are suited for use in constructing sea surface topography models by subtracting the geoid from an altimetry-derived sea surface. Therefore, the fit of the EIGEN-2 geoid to an oceanic geoid is evaluated in the spatial domain. The oceanic geoid was constructed from ERS/Topex altimetry (GFZ internal mean sea surface solution) by subtracting the sea surface topography resulting from the POCM ocean circulation model (Semptner and Chervin, 1992). The root mean square of the differences (after bias elimination) between EIGEN-2 and the oceanic geoid over a regular grid is given in Table 1. The values were filtered to represent a 5° half-wavelength resolution. For comparison the corresponding values are also given for the two pre-CHAMP satellite-only models GRIM5-S1 and EGM96S.

Table 1 demonstrates that, regarding the small 1.5 m-signal in sea surface topography, EIGEN-2 provides for the first time a geoid which can reasonably be used in oceanography down to half wavelength of 5° x 5° (550 km x 550 km). The fit of 16 cm includes the errors in the EIGEN-2 geoid (Figure 4), in the altimetric sea surface and in the POCM oceanographic model or, in other words, represents the difference between a geometrically derived sea surface topography (altimetry minus geoid) and an oceanographically modelled one (POCM).

From all the above given comparisons the absolute error in the EIGEN-2 geoid is estimated to be on the 10 cm level at a 5°x5° spatial resolution.

The performance of a new global gravity field model in dynamic precise orbit determination of a number of representative satellites usually is taken as a criterion to describe the quality of a gravity field model. As expected, the orbital fit of CHAMP GPS tracking data (carrier phases) improves from 20 cm to 0.8 cm and of laser tracking data from about 1 m to 8 cm, when replacing GRIM5-S1 by EIGEN-2 in the integration and adjustment of CHAMP's orbit with data outside the gravity field processing period. The opposite behaviour can be observed for other low Earth orbiting satellites like GFZ-1, Starlette, Stella and ERS. Because tracking data from these satellites were extensively exploited in the GRIM5-S1 gravity field model, especially the higher degree terms within the orbit specific resonant orders are well resolved in GRIM5-S1 and not well covered by the single satellite model EIGEN-2. Therefore, for the purpose of general precise satellite orbit determination, a combination of a CHAMP-only and GRIM5-S1 normal equation systems is necessary, as it was done for EIGEN-1S.

CONCLUSIONS

The exploitation of six month's worth of CHAMP data has proven that the combination of nearly continuous high-low satellite-to-satellite tracking and accelerometry aboard a satellite in a low altitude and highly inclined orbit allows a drastic improvement in long-wavelength global gravity field recovery. The CHAMP-based gravity field model EIGEN-2 provides the geoid and gravity with an accuracy of 10 cm and 0.5 mgal, respectively, at half wavelengths down to 550 km, which is an improvement by almost one order of magnitude compared to pre-CHAMP satellite-only models. Oceanography and geodesy will largely benefit from this progress when applying the geoid as a dynamic reference surface.

For the first time it became possible to recover the global gravity field with data from one satellite only and from only half a year observation time.

For precise orbit determination of low-flying satellites in different orbits than CHAMP, a combination with normals from tracking data of such satellites is still required.

CHAMP marks the first step in the anticipated dramatic improvement in Earth gravity field recovery with a new generation of dedicated gravity satellite missions followed by the twin satellite mission GRACE (Tapley and Reigber, 2001), launched in March 2002, with its low-low satellite-to-satellite link aiming at a high resolution of temporal field variations, and ESA's mission GOCE (European Space Agency, 1999) scheduled for 2006 with on-board gradiometry so as to obtain an ultimately high spatial resolution and accuracy.

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REFERENCES

Biancale, R., G. Balmino, J.-M. Lemoine, J.-C. Marty, B. Moynot, F. Barlier, P. Exertier, O. Laurain, P. Gegout, P. Schwintzer, Ch. Reigber, A. Bode, R. König, F.-H. Massmann, J.-C. Raimondo, R. Schmidt, and S.Y. Zhu, A new global Earth's gravity field model from satellite orbit perturbations: GRIM5-S1, *Geophys. Res. Letters,* **27**, 3611-3614, 2000.

CHAMP newsletter No. 9, http://op.gfz-potsdam.de/champ, April 2, 2002.

European Space Agency (ESA), Gravity field and steady-state ocean circulation mission (GOCE), Report for mission selection, in *The four candidate Earth explorer core missions*, SP-1233 (1), Noordwijk, NL, 1999.

Galas, R., J. Wickert, and W. Burghardt, H/R low latency GPS ground tracking network for CHAMP, *Phys. Chem. Earth (A),* **26**, 619-652, 2001.

Heiskanen, W. and H. Moritz, *Physical Geodesy*, W.H. Freemann, San Francisco, USA, 1967.

Kaula, W., *Theory of Satellite Geodesy*, Blaisdale Press, Waltham, Mass., 1966.

Kuang, D., Y. Bar-Server, W. Bertiger, S. Desai, B. Haines, B. Iijima, G. Kruizinga, Th. Meehan, and L. Romans, Precise orbit determination for CHAMP using GPS data from BlackJack receiver, in *2001 ION National Technical Meeting Proceedings,* Session E1: Scientific Applications, Timing, and Frequency, Long Beach, California, January, 2001.

Lemoine, F.G., S.C. Kenyon, J.K. Factor, R.G. Trimmer, N.K. Pavlis, D.S. Chinn, C.M. Cox, S.M. Klosko, S.B. Luthcke, M.H. Torrence, Y.M. Wang, R.G. Williamson, E.C. Pavlis, R.H. Rapp, and T.R. Olson, 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, 1998.

Reigber, Ch., Gravity field recovery from satellite tracking data, in *Theory of Satellite Geodesy and Gravity Field Determination,* ed. F. Sansò, R. Rummel, Lecture Notes in Earth Sciences, Vol. **25**, Springer, Berlin, Heidelberg, New York, 197-234, 1989.

Reigber, Ch., H. Lühr and P. Schwintzer, CHAMP mission status. *Adv. Space Res.,* **30** (2), 129-134, 2002a.

Reigber, Ch., G. Balmino, P. Schwintzer, R. Biancale, A. Bode, J.-M. Lemoine, R. König, S. Loyer, K.-H. Neumayer, J.-C. Marty, F. Barthelmes, F. Perosanz, and S.Y. Zhu, A high-quality global gravity field model from CHAMP GPS tracking data and accelerometry (EIGEN-1S), *Geophys. Res. Lett.,* **29** (14), 10.1029/2002GL015064, 2002b.

Reigber, Ch., G. Balmino, P. Schwintzer, R. Biancale, A. Bode, J.-M. Lemoine, R. König, S. Loyer, K.-H. Neumayer, J.-C. Marty, F. Barthelmes, F. Perosanz, and S.Y. Zhu, Global gravity field recovery using solely GPS tracking and accelerometer data from CHAMP, in *Space Sciences Series of ISSI*, Vol. **18**, ed. G. Beutler, M. Dringwater, R. Rummel, and R.v. Steiger, Kluwer Academic Publishers, Dordrecht, NL, accepted, 2002c.

Semptner, A.J. and R.M. Chervin, Ocean circulation from a global eddy-resolving model, *J. Geophys. Res.,* **97**, C4, 5493-5550, 1992.

Tapley, B.D. and Ch. Reigber, The GRACE mission: status and future plans, *Eos Trans AGU* **82** (47), Fall Meet. Suppl., G41 C-02, 2001.

Touboul, P., E. Willemenot, B. Foulon, and V. Josselin, Acclerometers for CHAMP, GRACE and GOCE space missions: synergy and evolution, *Boll. Geof. Teor. Appl.,* **40**, 321-327, 1999.

E-mail address of P. Schwintzer psch@gfz-potsdam.de

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