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A high-quality global gravity field model from CHAMP GPS tracking data and accelerometry (EIGEN-1S)

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[1] Using three months of GPS satellite-to-satellite tracking and accelerometer data of the CHAMP satellite mission, a new long-wavelength global gravity field model, called EIGEN-1S, has been prepared in a joint German-French effort. The solution is derived solely from analysis of satellite orbit perturbations, i.e. independent of oceanic and continental surface gravity data. EIGEN-1S results in a geoid with an approximation error of about 20 cm in terms of 5 × 5 degree block mean values, which is an improvement of more than a factor of 2 compared to pre-CHAMP satellite-only gravity field models. This impressive progress is a result of CHAMP's tailored orbit characteristics and dedicated instrumentation, providing continuous tracking and direct on-orbit measurements of non-gravitational satellite accelerations. *INDEX TERMS:* 1214 Geodesy and Gravity: Geopotential theory and determination; 1241 Geodesy and Gravity: Satellite orbits; 1243 Geodesy and Gravity: Space geodetic surveys; 1294 Geodesy and Gravity: Instruments and techniques

1. Introduction

[2] The German geoscientific satellite CHAMP ('Challenging Minisatellite Payload') [*Reigber et al.*, 1999] was launched in summer 2000 into an almost circular, near-polar orbit (inclination 87.3°) with an initial altitude of 454 km. The altitude presently decreases by about 1.5 km/month. One major goal of this mission is to improve the knowledge about the Earth's gravity field. For this purpose the satellite has been equipped with highly advanced technology instruments, a GPS flight receiver [*Kuang et al.*, 2001] and a three-axes accelerometer [*Touboul et al.*, 1999]. Compared to all previous satellite missions used for global gravity field recovery, CHAMP has therefore the following significant advantages: (1) The satellite is continuously tracked by a maximum of 12 GPS satellites simultaneously, compared to one-dimensional tracking of only short passes from ground-based tracking. (2) CHAMP experiences an enhanced gravitational signal because of the low altitude with a complete ground track coverage of the Earth thanks to the almost polar orbit. (3) The direct on-orbit measurement of the non-gravitational satellite accelerations replaces the insufficient models of air density and radiation pressure.

[3] The instrumentation allows a precise orbit determination even at the low flight altitude [*Neumayer et al.*, 2000] and the separation of gravitational and non-gravitational accelerations to resolve the gravity field parameters.

[4] Figure 1 shows a sketch of the satellite with the location of the instruments relevant to gravity field determination and gives the characteristic mission parameters. In the following, a first global gravity field solution based on about three months of CHAMP data is described and compared with the latest pre-CHAMP satellite-only models GRIM5-S1 [*Biancale et al.*, 2000] and EGM96S [*Lemoine et al.*, 1998]. The results demonstrate the impressive gain in accuracy with CHAMP compared to the incremental progress over the last decade in global gravity field recovery from satellite orbit perturbation analyses.

2. CHAMP Orbit and Gravity Data

[5] For the first CHAMP gravity field solution, 88 days of mission data out of the period from July to December 2000 have been exploited. The GPS receiver on-board CHAMP delivers carrier phase data (resolution 0.2 cm) and pseudo-ranges (resolution 30 cm) of up to (at that time) 7 GPS satellites simultaneously at 10 s intervals. The CHAMP orbit and clock biases are determined relative to the orbits and clocks of the GPS satellites. These are computed from GPS data received at dedicated CHAMP mission stations [*Galas et al.*, 2001] and stations of the International GPS Service (IGS) network. As the IGS stations measure at a rate of 30 s, CHAMP SST data are downsampled to this rate for use in CHAMP dynamic precision orbit determination (POD). Dynamic POD means numerical integration of the satellite's accelerations and a least-squares fit to the tracking observations by adjusting for orbit parameters. The vector of non-gravitational accelerations is directly measured on-board in three directions at an interval of 1 s and introduced in POD after editing spurious data and averaging over 10 s in order to coincide with the integration step size. The precision of the accelerometer is better than $3 \cdot 10^{-9}$ ms^{-2} within the bandwidth 10^{-4} to 10^{-1} Hz for the along- and across-track directions and one order of magnitude less for the less important radial direction. Due to a hardware problem the measurements in radial direction are affected by systematic errors, which partly could be reduced by solving for additional (empirical) temperature-dependent sensor parameters. The orientation of the accelerometer axes in a celestial reference frame is provided by two star cameras. The data from these instruments are preprocessed like the accelerometer data. As the attitude of the satellite is controlled by thrusters, which may

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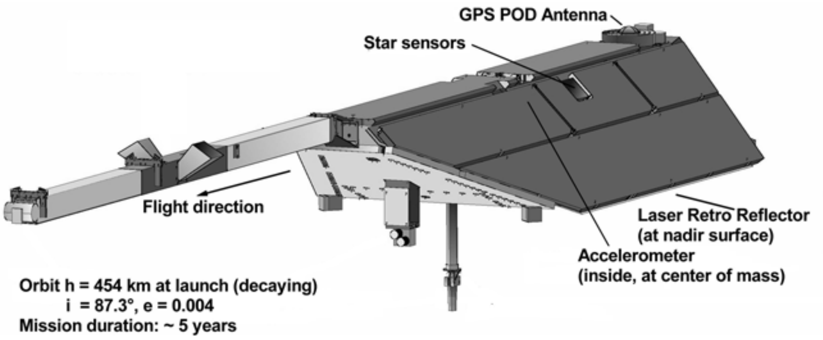

Figure 1. Sketch of the CHAMP satellite, orbit/gravity payload accomodation and mission parameters.

induce unknown residual linear accelerations, the epochs and durations of thruster pulses (about one event every 10 min) are monitored and used when solving for additional unknowns during POD processing.

3. Gravity Field Model Generation

[6] The principle of gravity field recovery from gravitational orbit perturbations is to dynamically integrate a satellite orbit based upon an initial gravity field model, create linearized observation equations linking the satellite tracking data with the solve-for gravity field, orbit and sensor-specific parameters, and derive normal equations in a least squares sense to be solved by inversion.

[7] A two-step approach has been applied for CHAMP data processing: (1) adjustment of the high-flying GPS spacecraft orbit and clock parameters from ground-based tracking data and (2) CHAMP orbit determination and computation of observation equations with fixed GPS spacecraft positions and clocks from step 1. The CHAMP data, which were exploited for the present gravity field solutions, cover the periods 2000, July 30–Aug. 10 and Sept. 24–Dec. 31 with some data gaps of up to several days in between. The 88 days' worth of data, spread out from July to December 2000 (about 1.1 million GPS code and phase measurements, respectively), were split in 50 arcs of 1.5 days and 13 arcs of 1 day length each, depending on the distribution of data gaps and mission events. A nominal arclength of 1.5 days (orbit integration length) was selected as a compromise between the need for a short arc in order to prevent the increase of residual errors in non-gravitational accelerations, and a long arc to cover at least one half of CHAMP's primary resonance period. From the data of each arc, an individual normal equation system was created with the unknown parameters as listed in Table 1. This set of parameters proved to give the best quality for the present gravity field solution.

[8] After reduction of the arc-dependent parameters, the 63 individual CHAMP normal equation systems were summed up and, for an improved stability, eventually combined with the normal equation system of the satellite-only gravity field model GRIM5-S1 and additional normal equations derived from laser ranging data of Lageos-1, -2, Starlette and Stella (year 2000), and Lageos-1, -2 and Starlette constraints for zonal coefficients from long-arc analyses.

[9] For inversion, the resulting system requires a regularization because of the attenuation of the gravity field signal at altitude and the large number of coefficients that need to be independently recovered. It turned out that, with CHAMP, regularization is necessary only for terms $l > 30$, compared to $l > 5$ for GRIM5-S1. The normal equation system then is solved for the gravity field and ocean tide parameters as well as tracking station position parameters in the ITRF96 frame.

4. Gravity Field Solution: EIGEN-1S

[10] The gravity field model resulting from the least squares adjustment is called EIGEN-1S (**E**uropean **I**mproved **G**ravity model of the **E**arth by **N**ew techniques). Figure 2 shows the signal and error amplitudes per degree of the spherical harmonic coefficients of EIGEN-1S in terms of geoid heights and, for comparison, the signal amplitudes of the models GRIM5-S1 and GRIM5-C1 [*Gruber et al.*, 2000], both lacking CHAMP data.

[11] GRIM5-C1 is a combination of GRIM5-S1 with altimetric and gravimetric surface data and has gotten full power over the whole spectrum up to degree 120, because the surface data has not the problem of signal attenuation and no regularization is needed for the solution. Compared to this curve, the two satellite-only solutions reveal a decrease in power due to signal attenuation with the satellite altitude beyond approximately degree 30 in case of GRIM5-S1 and degree 40 in case of EIGEN-1S. This reflects the gain in spatial resolution when incorporating CHAMP data. For the higher degree amplitudes, which are more and more affected by regularization, the EIGEN-1S model also retains more power than GRIM5-S1, proving the gain in strength

Table 1. Parametrization of CHAMP Normal Equation System (Solve-for Parameters)

arc-dependent parameters
orbit: state vector at epoch of arc
GPS receiver: clock offset (1/30 s), phase ambiguities (~450/d)
accelerometer: 3-D biases (daily) and scale factors (per arc)
radial channel: plus temp. and temp. gradient dependent bias terms (daily)
thrusters (6 pairs): 3-D linear acceleration vector (3×6 unknowns per day)
gravitational potential (common parameters)
stationary field: 10738 spherical harmonic coefficients $\bar{C}_{l,m}$, $\bar{S}_{l,m}$, complete to l, m = 99 plus selected terms up to l = 119, $\bar{C}_{00}$ and degree 1 terms not solved
temporal field variations: $d\bar{C}_{1,0}/dt$ for l = 2 to 4
ocean tide potential: 106 spherical harmonic coeff. of 11 long-period, diurnal and semi-diurnal waves

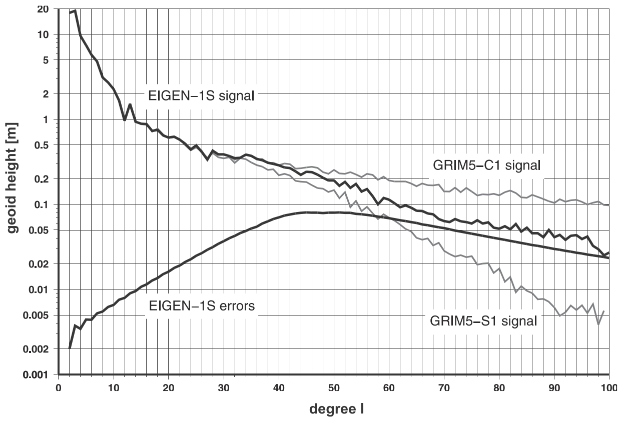

Figure 2. Signal/error amplitudes per degree in terms of geoid heights.

within the normal equation system with the inclusion of CHAMP data.

[12] The error amplitudes per degree in Figure 2 result from the standard deviations of the spherical harmonic coefficients as obtained from the least-squares adjustment, but a posteriori calibrated. The calibration factors have been empirically found from comparisons with independent altimetric geoid heights and from the coefficients' differences between two CHAMP-only gravity field solutions related to separate time intervals. It turned out that the formal standard deviations for the low degree coefficients are much too optimistic and therefore a degree dependent calibration has been applied to get realistic error estimates: 45/l for terms up to degree l = 36 and 1.25 for all higher degree terms. The error curve reflects the commissioning error regardless of the omission error due to the decrease in signal power beyond degree 40. The formal variance-covariance matrix of the spherical harmonic coefficients was accordingly calibrated by left and right multiplications of the diagonal matrix containing the calibration factors.

[13] Figure 3 depicts the spectrum of difference amplitudes as a function of maximum degree of the three satellite-only models EIGEN-1S, GRIM5-S1 and EGM96S with respect to EGM96 [*Lemoine et al.*, 1998], and again the calibrated EIGEN-1S error curve. EGM96 is a combination solution of satellite tracking data (EGM96S) with altimetric and gravimetric surface data. Figure 3 demonstrates that the EIGEN-1S model agrees much better with EGM96 than GRIM5-S1. We assume that, when two almost independent models fit better, then both are closer to reality. One can conclude that the long-wavelength modelling accuracy has improved by at least a factor of two (up to degree 10) to four (up to degree 25) when going from GRIM5-S1 to EIGEN-1S. EIGEN-1S even fits better to EGM96 above degree 8 than EGM96S which is an integral part of the EGM96 model.

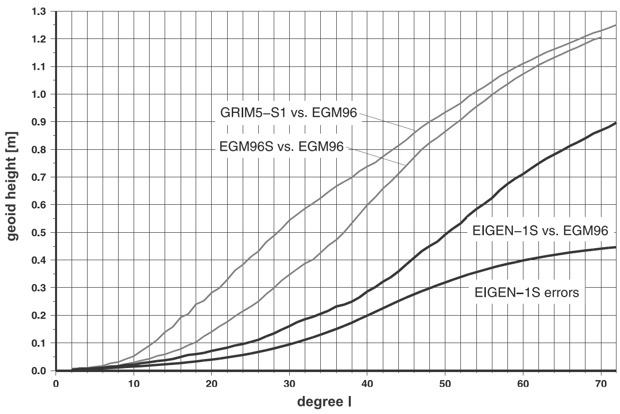

Figure 3. Difference/error amplitudes as a function of maximum degree in terms of geoid heights.

5. EIGEN-1S Model Quality Evaluation

[14] One important application of global gravity field models is the computation of the gravitational acceleration in dynamic satellite orbit determination. The fit of tracking data to a numerically integrated and adjusted orbit usually is used as one criterion to describe the quality of a gravity model.

[15] It turns out that with EIGEN-1S, the orbital fits of SLR, PRARE and DORIS data for all geodetic and altimeter satellites as well as ERS-1 and TOPEX altimeter crossover differences were consistently almost identical to those obtained already with the GRIM5-S1 model, [*Biancale et al.*, 2000] except for the CHAMP satellite itself. In the case of CHAMP itself, an improvement in the average fit from 20 cm to 1.2 cm in GPS carrier phase measurements and from 95 cm to 11 cm in laser ranges (external fit after orbit determination with GPS SST data) was observed for CHAMP orbits not used in the gravity field model.

[16] The EIGEN-1S and GRIM5-S1 calibrated variance-covariance matrices were used to predict by error propagation gravitational radial orbit errors at the altitudes of ENVISAT (777 km) and CHAMP (460 km). Figure 4 gives the resulting standard deviations over a range of orbit inclinations between 20 deg and 160 deg. The minima coincide with the inclinations of satellite orbits being exploited for the gravity field solution. The impact of CHAMP data at an inclination of 87 deg in Figure 4 is very obvious.

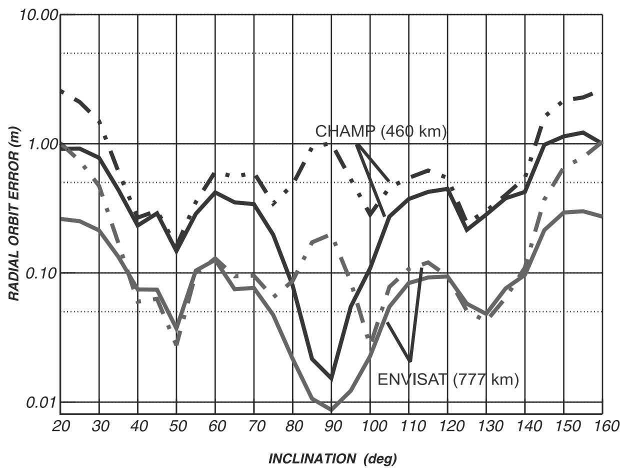

Figure 4. Radial orbit error as a function of inclination and altitude propagated from EIGEN-1S (solid lines) and GRIM5-S1 (dash-dotted lines) covariance matrices, resp.

Table 2. Gravity Field Model Comparison with Altimetric Ocean Geoid Heights (N) and Gravity Anomalies (Δg); Weighted (Cos of Latitude) Root Mean Square of Differences About Mean

grid spacing	N	Δg
	EIGEN-1S/GRIM5-S1/EGM96S	
5 × 5 deg	27 / 50 / 44 cm	3.3 / 3.9 / 3.8 mgal
2.5 × 2.5 deg	60 / 80 / 76 cm	7.5 / 8.2 / 8.2 mgal

[17] The orbit computations and predicted radial orbit errors show that the orbit determination quality for satellites with different inclinations than CHAMP does not benefit from the gravity model improvement. One can conclude that meanwhile for high- and medium-orbiting satellites the mismodelling of non-gravitational effects is dominating the purely gravity induced errors, and for low-orbiting satellites CHAMP is not sensitive enough to improve the higher order terms in the orbit specific resonant spectral bands.

[18] Whereas orbit computations are able to detect at least mismodelling of coefficients within specific orders to which the satellite under consideration is sensitive, comparisons in the spatial domain with independent gravity anomaly and geoid height data are capable to test the model's accuracy homogeneously over all spherical harmonic coefficients up to the considered resolution. Geoid heights and gravity anomalies, both as block mean values in an equal-angular global grid with a spacing of 5 deg as well as 2.5 deg, were computed from the EIGEN-1S, GRIM5-S1 and, for comparison, from the EGM96S Stokes gravitational coefficients and compared to (1) ocean geoid heights from ERS/TOPEX altimetry (GFZ internal solution) after correction for the mean ocean circulation according to the POCM model [*Semptner and Chervin*, 1992] and (2) oceanic gravity anomalies [*Lemoine et al.*, 1998], both data sets averaged to get 5 deg and 2.5 deg grid values. The root mean squares of the differences (after bias elimination) are given in Table 2, showing the very substantial improvement in the EIGEN-1S geoid model compared to the pre-CHAMP satellite-only models GRIM5-S1 and EGM96S.

[19] The spectral resolution of the EIGEN-1S model (full power up to degree/order 36) corresponds to a 5 × 5 deg spatial resolution, i.e. the commissioning error amounts to not more than 20 cm and 2.5 mgal in terms of geoid heights and gravity anomalies, respectively, when reducing the numbers in Table 2 by the errors and higher frequency content of the comparison data. For the 2.5 deg grid spacing, which would correspond to a degree/order 72 gravity field model, the additional omission error due to the loss of power for higher degree terms becomes visible.

6. Conclusion

[20] A substantial improvement in long-wavelength global Earth gravity field recovery has been achieved with the CHAMP mission. A 10 cm-accuracy geoid model with a spectral resolution up to degree/order 30 (cf. Figure 3), corresponding to a spatial resolution of 600 km (half wavelength) at the Earth's surface, is now available by adding only a three month's worth of CHAMP GPS SST and accelerometer data to the GRIM5-S1 normal equations. This resolution threshold is twice as high as for pre-CHAMP satellite-only gravity field models. The EIGEN-1S model is, being important for oceanographic applications, independent of Earth ocean and continent surface data. The real quality of the longest wavelength constituents of the EIGEN-1S model is hard to evaluate as independent high quality test data are lacking.

[21] EIGEN-1S is the forerunner of a new era in global gravity field modelling with ever increased accuracy and resolution by including more CHAMP data and in particular data from the twin satellite mission GRACE [*Tapley and Reigber*, 2001] and later from GOCE [*European Space Agency* (*ESA*), 1999].

6.1. Remark

[22] The spherical harmonic coefficients of the EIGEN-1S model can be downloaded from the CHAMP homepage: op.gfz-potsdam.de/CHAMP/results.

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