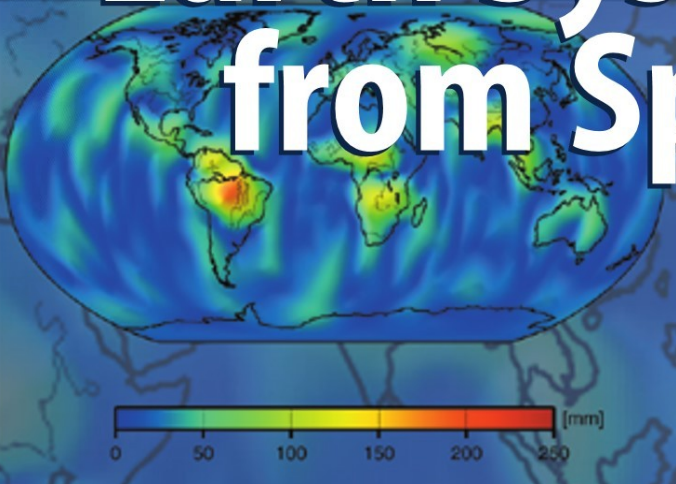
Jakob Flury · Reiner Rummel
Christoph Reigber · Markus Rothacher
Gerd Boedecker · Ulrich Schreiber
Editors

Observation of the Earth System from Space



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Observation of the Earth System from Space

with 249 Figures and 54 Tables

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Preface

In the recent years, space-based observation methods have led to a substantially improved understanding of Earth system. Geodesy and geophysics are contributing to this development by measuring the temporal and spatial variations of the Earth's shape, gravity field, and magnetic field, as well as atmosphere density. In the frame of the German R&D programme GEOTECHNOLOGIEN, research projects have been launched in 2002 related to the satellite missions CHAMP, GRACE and ESA's planned mission GOCE, to complementary terrestrial and airborne sensor systems and to consistent and stable high-precision global reference systems for satellite and other techniques.

In the initial 3-year phase of the research programme (2002-2004), new gravity field models have been computed from CHAMP and GRACE data which outperform previous models in accuracy by up to two orders of magnitude for the long and medium wavelengths. A special highlight is the determination of seasonal gravity variations caused by changes in continental water masses. For GOCE, to be launched in 2006, new gravity field analysis methods are under development and integrated into the ESA processing system. 200,000 GPS radio occultation profiles, observed by CHAMP, have been processed on an operational basis. They represent new and excellent information on atmospheric refractivity, temperature and water vapor. These new developments require geodetic space techniques (such as VLBI, SLR, LLR, GPS) to be combined and synchronized as if being one global instrument. In this respect, foundations have been laid for a substantial improvement of the reference systems and products of the International Earth Rotation and Reference Systems Service (IERS). Sensor systems for airborne gravimetry have been integrated and tested, and a particularly development is a laser gyro dedicated to the measurement of the rotational degrees of freedom of the motion caused by earthquakes. A total sum of about 10 million Euros has been spent by the German Federal Ministry of Education and Research (BMBF) and the German Research Foundation (DFG). The projects were carried out in close cooperation between universities, research institutes, and small and medium sized enterprises.

In this book the results of the first programme phase are collected in 30 scientific papers related to the six core programmes of the theme “Observation of the Earth system from space”. The book provides an overview of the state-of-the-art of this research. At the same time it should provide inspiration for future work, since on many fields research is going on, and a number of projects will continue in the second programme phase. The editors are indebted to all authors and to the publisher for the excellent cooperation in the preparation of this book. The editing process and the compilation of the camera-ready manuscript were coordinated by J. Flury at the German GOCE project bureau at Technische Universität München. The support of the GEOTECHNOLOGIEN programme by BMBF and DFG is gratefully acknowledged as well as the continuous support by the GEOTECHNOLOGIEN coordination office.

Munich and Potsdam, August 2005
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Markus Rothacher
Gerd Boedecker
Ulrich Schreiber

GEOTECHNOLOGIEN

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CHAMP Mission 5 Years in Orbit

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Summary. In the summer of 2000 the geo-research satellite CHAMP was launched into orbit. Its innovative payload arrangement and its low injection altitude allow CHAMP to simultaneously collect almost uninterrupted measurement series relating to the Earth gravity and magnetic fields at low altitude. In addition, CHAMP sounds the neutral atmosphere and ionosphere using GPS observations onboard. After 60 months in orbit one arrives at a very positive conclusion for the CHAMP mission. The CHAMP satellite and its instruments have been operated almost uninterruptedly since launch. The great performance of the satellite subsystems and of the mission operation specialists has made it possible to keep CHAMP in the science operation mode for most of the time and in addition to lift its orbit two times. After a series of calibration and validation activities in the course of the mission, which included a number of onboard software updates and parameter adjustments, CHAMP has been providing excellent measurements from its state of the art instruments for now more than 4 years. The effective and steadily functioning of the CHAMP Science Data System and the supporting tracking networks has made it possible to provide large quantities of pre-processed data, precision data products and auxiliary information to hundreds of registered users in an almost uninterrupted manner. This was only possible due to the funding of the project DACH (CHAMP Data Acquisition and Data Use) within the 'GEOTECHNOLOGIEN' R+D programme of the BMBF. With the orbit altitude being presently about 60 km higher than originally planned for mid 2005, CHAMP will very likely orbit the Earth for another 3 years at quite low altitude. This mission extension at low altitude will make CHAMP a pioneering long-duration mission for geo-potential research and sounding of the atmosphere.

Key words: CHAMP, Mission overview, Science Data System achievements

1 Introduction

The geo-research mission CHAMP (**CHA**llenging **M**inisatellite **P**ayload), launched on July 15, 2000 from the Russian cosmodrome Plesetsk into a near polar, circular and 455 km altitude orbit, was established in 1997 as a Principal Investigator (PI) institution led project, with the PI (C. Reigber) and his institution (GFZ Potsdam) being fully responsible for the successful implementation and execution of the mission. During the various CHAMP mission phases, until the end of the commissioning phase, the project was funded by the German Federal Ministry of Education and Research (BMBF), the German Aerospace Centre (DLR) and the GFZ Potsdam. In mid 2001, 9 months after launch, the CHAMP overall system, consisting of the space and ground segment components, was commissioned and validated and ready to deliver high quality data and data products to the international science and application community. In order to stimulate additional calibration/validation activities and to trigger as many scientific studies and application investigations on the basis of CHAMP data and routinely generated products, an Announcement of Opportunity (AO) was issued in May 2001 for the international geo-science community. At this point of the mission timeline the operational phase of the CHAMP mission started, with the primary CHAMP Science Data System (SDS) funding being provided by the 'GEOTECHNOLOGIEN' R+D programme of the BMBF under grant 03F0333A for the first phase.

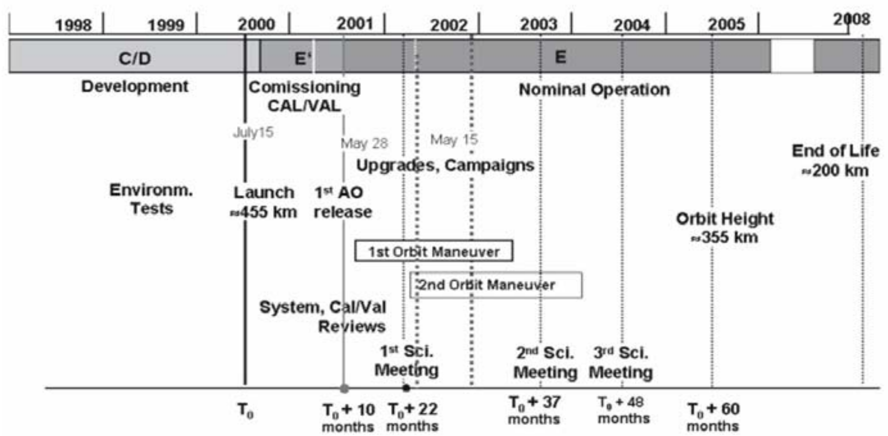

Fig. 1. CHAMP mission timeline.

The exceptionally good performance of all CHAMP system components over the past 5 years and the AO-triggered involvement of a large and still growing number of users around the globe has made it possible not only to provide unprecedented long, uninterrupted and well calibrated data series for various investigations, but also to apply new data reduction and analysis methods and to come up with new and value-added products besides those routinely generated in the CHAMP science data processing system. Many of the scientific achievements with CHAMP data are presented in the proceedings of the 1st CHAMP Science Meeting (Reigber et al., 2003) and the 2nd Science Meeting (Reigber et al., 2004).

The CHAMP mission, originally designed for a 5 years lifetime, will last a few years longer than initially planned, thanks to the smooth functioning of all mission elements, the successful execution of two orbit rises and the availability of still enough cold gas for the operation over a number of additional years. The purpose of this contribution is to shortly describe the status of the mission at this 5-year milestone and to elucidate the science instrument data and data products, which have been delivered in large quantities to the more than 500 scientists and application users worldwide.

2 Spacecraft, Instrumentation and Orbit Evolution

When the CHAMP spacecraft was designed it was optimized in the sense that it should best satisfy the requirements of the gravity and magnetic field objectives simultaneously, which are at times quite different. Design drivers in this respect were a well-determined and constant position of the centre of gravity, a three-axes stabilized attitude control causing only negligible lateral accelerations, a sizable boom for magnetic cleanliness and a long mission lifetime at low altitude.

In order to optimize the aerodynamic behaviour and magnetic field observation environment, the satellite was build as a relatively heavy trapezoid body of dimensions 430x75x162 cm^3 (l/h/w) with a 404 cm long deployable boom in flight direction (see Color Fig. I on p. 286). The spacecraft weighed 522 kg at the beginning of the mission, including 34 kg of cold gas for attitude control and orbit manoeuvres, of which nearly 21 kg have been consumed in the meantime. The average power consumption of 120 W (payload 46 W) is comfortably provided by 7 m^2 of solar cells and a 16 Ah NiH^2 battery. No degradation is detectable so far in the power system.

CHAMP is kept in an Earth-oriented attitude with the boom pointing in flight direction. For calibration experiments the spacecraft was steered in a number of occasions into quite different orientations, from perpendicular to the velocity vector to anti-flight direction. Three magnetic torquers are used to orient the spacecraft within a control band of ± 2 degrees. In case of dead-band exceedance, 12 cold gas thrusters restore the nominal attitude. Prime attitude sensors are star trackers and an onboard GPS receiver. Every 10 seconds the GPS receiver provides a new position and updates the onboard clock. A highly autonomous control and data handling system guarantees a save operation during longer periods (up to 12 h) of no contact with ground stations. Data are stored in a mass memory of 1.2 Gigabit capacity. The 4 m long boom, installed for magnetic cleanliness reasons, consists of three segments: the outer part with the scalar Overhauser magnetometer at the tip, the middle segment with the rigid optical bench on which two star sensor heads and two Fluxgate vector magnetometers are mounted, and the inner segment incorporating the deployment hinge.

In total CHAMP is equipped with seven different scientific instruments, the data of which are processed in an operational mode since May 2001 (see Color Fig. I on p. 286).

The NASA Jet Propulsion Laboratory (JPL) has provided the state-of-the-art "Blackjack" GPS space receiver. Accommodated for the first time onboard a LEO satellite as a mission control support and satellite-to-satellite (SST) gravity recovery instrument, it delivers NAV solutions accurate to about 6 m rms with an average availability of >99.5 %, the time tag for all science instruments within 1 ms and precision orbit ephemeris (POD) results for gravity recovery with phase residuals in the order of <3 cm (König et al., 2004). Since June 2001 radio occultation measurements have routinely been obtained with C/A measurements at high rates (50 Hz sampling frequency). The obtained profiles for atmospheric humidity and temperature (nearly 250 per day) reach close to the Earth surface and are in good agreement with operational meteorological analysis results (Wickert et al., 2004).

The STAR accelerometer, which was provided by the Centre National d'Études Spatial (CNES) and manufactured by the Office National d'Études et de Recherches Aérospatiales (ONERA), had its maiden flight on CHAMP. It meets the specified resolution of $<3\text{x}10^{-9}$ m/s^2 for the two highly sensitive axes (Förste and Choi, 2004) and has been delivering since autumn 2000 valuable information on the surface forces accelerations, an information which is highly important for the accurate gravity field modelling and the development of air density models.

The GFZ-built CHAMP Laser Retro-Reflector (LRR) has demonstrated impressively the possibility to use a densely packed array with the minimum number of 4 prisms for a LEO satellite to obtain a sufficiently high return signal for easy target acquisition under both night and daytime conditions. Due to its compact design, the target signature of the CHAMP LRR is negligible and single-shot accuracies below 5 mm have been reported by the most advanced laser trackers (Grunwaldt and Meehan, 2003).

CHAMP was also the maiden flight for the Advanced Stellar Compass (ASC) used in dual-head configuration. Combined with the aberration correction capability – first time applied in orbit with CHAMP – this has led to a highly accurate attitude of approximately 15" of the raw data onboard. The instrument has been operating fully autonomously for 5 years already and directly outputs the final quaternions. On-ground post processing improves the accuracy to about 2" (Rother et al., 2003).

The Digital Ion Drift Meter and Langmuir Probe were provided by the Air Force Research Laboratory (AFRL) in Hanscom MA, USA. This newly developed instrument monitors the ion dynamics like the drift velocity, density and temperature along the orbit.

Since its first switch-on on the second day of the mission the Fluxgate magnetometer has been operating flawlessly. Thanks to the magnetic cleanliness of the spacecraft, the ambient magnetic field is measured at a high rate of 50 Hz and a resolution of 0.2 nT in all three axes. After having applied all necessary transformations and corrections to the vector field measurements on the basis of attitude and position observables, absolute vector accuracies of less than 2 nT have been reported (Rother et al., 2003).

The Overhauser magnetometer provides absolutely calibrated readings of the scalar field strength at a rate of 1 Hz and a resolution of 0.1 nT. It serves as measurement standard and calibration unit, and fully satisfies since the beginning of the mission the scientific requirements.

As stated, all CHAMP instruments are in a very good state and function even after 5 years in operation as foreseen. The only exception is the less sensitive radial component of the accelerometer, the observations of which cannot fully be used because of a malfunctioning of one of the six electrode pairs of the STAR accelerometer (Perosanz et al., 2004).

After a series of calibration and validation activities in the course of the mission, which included a number of software updates and parameter adjustments, and the scientific results obtained so far, it can be stated that CHAMP has been providing the best possible measurements from its state-of-the-art instruments for now almost 5 years, making CHAMP a pioneering mission in many respects.

In addition CHAMP is at the moment the lowest orbiting geo-research satellite, continuously tracked by GPS and continuously providing accelerometer and magnetic field data. CHAMP was injected into an almost circular ($e = 0.004$), near polar ($i = 87°$) orbit with an initial altitude of 454 km. This initial altitude was chosen as the best compromise to guarantee on one hand a five-year mission duration even under high solar activity conditions, predictable by models at the time prior to launch, and to account on the other hand for the requirements imposed by the scientific goals of the mission. Due to the extremely high solar flux and the corresponding high atmospheric drag acting on the satellite throughout the time period from mid 2001 to the end of 2002, the orbit decay was considerably faster than had been predictable, with the danger that the mission would have been finished already in 2004. To avoid this, a first orbit change manoeuvre was performed on June 10/11, 2002. Through a sequence of thruster firings at apogee the orbital altitude of CHAMP was increased by about 16 km. A second orbit change manoeuvre of the same type was carried out on December 9/10, 2002, resulting in a second rise of the orbit by about 20 km (see Color Fig. II on p. 286).

Now, in July 2005, CHAMP has lost almost exactly 100 km of its original orbital height and is orbiting at an altitude of about 355 km. After the two orbital manoeuvres the eccentricity e changed to the very small value of 0.0002, which means that CHAMP is now on an almost perfect circular path around the Earth.

The present orbital height is still 55 km above the originally for July 2005 planned height of about 300 km. With the solar flux predictions presently available, the 300 km altitude floor will be reached in autumn 2007 and this

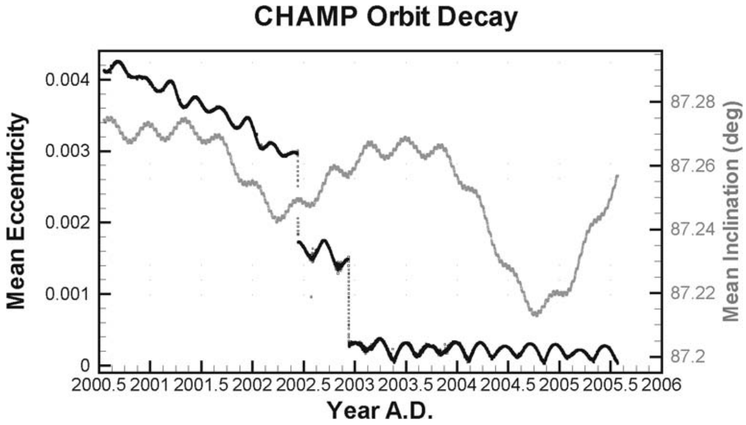

Fig. 2. Changes of mean eccentricity and inclination since launch.

will bring the CHAMP mission to a definite end in the spring to summer 2008 timeframe.

In the course of its free-drifting orbit periods CHAMP passed through many different commensurabilities and resonant regimes, with high sensitivity to 15th and 16th order terms of the geo-potential and overtones. Due to the orbit changes the satellite passed through a number of repeat cycles more than once (e.g., a 2-days repeat in May 2002, October 2002 and in May 2003) and will experience during the second mission part at low altitudes largely enhanced perturbations in the orbital motion.

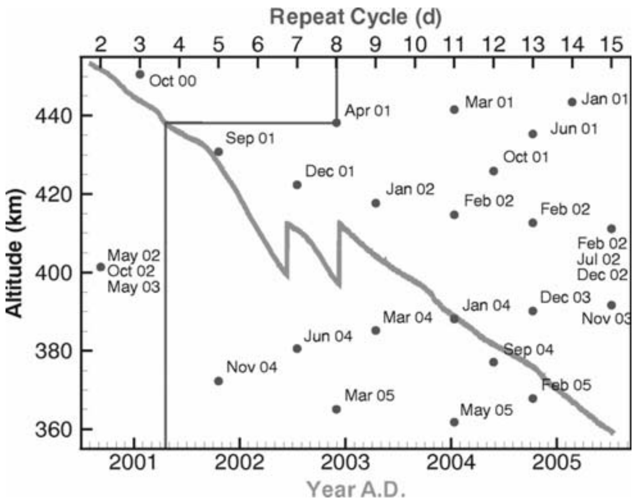

Fig. 3. Repeat cycles (in days) through which CHAMP passed since launch.

3 Ground System Performance

CHAMP's ground segment comprises all ground-based components which perform the operational control of the spacecraft and instruments, the data flow from the onboard memory and supporting ground tracking networks to the processors, the standard science product generation and the dissemination of data and products to the users. Color Figure III on p. 287 shows the general scheme of the ground segment for CHAMP.

DLR has been running for 5 years with great success the *Mission Operation System* (MOS) consisting of the Mission Control Centre (MCC) at the German Space Operation Centre (GSOC), Oberpfaffenhofen, and the Raw Data Centre (RDC) at DLR's German Remote Sensing Data Centre (DFD), Neustrelitz. The *Science Operation System* (SOS) at GFZ constitutes the interface between the science experimenters and satellite operation. It is responsible for mission scheduling, command preparation, and mission and orbit analysis.

CHAMP's on-board instruments continuously produce science and instruments' house-keeping data with an overall rate of 10.8 kbit/s, and the satellite adds 2.2 kbit/s of spacecraft house-keeping data, which makes a total of 141 MByte/d. These data are downloaded three to four times a day to the 7.3 m ground antenna of the DLR receiving station in Neustrelitz (53.5 N, 13 E), Germany, and for almost every pass to the GFZ/DLR 4 m receiving station in Ny Ålesund (78.9 N, 11.8 E), Spitsbergen. A third ground station, the DLR ground station in Weilheim (48 N, 11 E), is operated as the commanding and satellite control station. It also serves as a back-up station to Neustrelitz. It receives 'real-time' science and H/K data at a bit-rate of 32 kbit/s and sends commands at 4 kbit/s. A great number of command sequences were prepared and successfully transmitted to the spacecraft in the meantime. The number of commands executed by the CHAMP satellite since launch nears the 290,000 mark. After 5 years of science data gathering in orbit, approximately 6,700 times telemetry data sequences were downloaded to the three aforementioned ground stations.

CHAMP's *Raw Data Centre* is running, almost uninterruptible since launch, at the receiving station Neustrelitz with the following functions: telemetry data reception (transfer frames) and long-term storage in the *Raw Data Archive*, demultiplexing and extraction of science and H/K application packets (level-0 data), immediate transfer of H/K packets to GSOC, and temporary storage of all level-0 data in the *level-0 rolling archive* for access by the Decoding Centre of the Science Operation System (SOS-SD) at GFZ Potsdam. Here the *level-0 long-term archive* for CHAMP is located.

In addition to the spacecraft data, all CHAMP related ground station network data are accessed and archived at GFZ Potsdam: low rate (30 s, 10 s) and high rate (1 s), low latency GPS ground-based observations from individual GPS stations and the data centres of the International GPS Service (IGS), and CHAMP laser tracking data from the international laser data centres of the Inernational Laser Ranging Service (ILRS). The high-rate GPS ground-station data of the GFZ and JPL dedicated CHAMP GPS subnets, altogether about 25 stations, are mutually exchanged. All data transfer happens via the public Internet network.

The SOS-SD component is carrying out in a semi-automatic process all decoding of CHAMP level-0 data to level-1, that means the conversion from telemetry code into user-defined physical units.

The higher level scientific products are generated within the *Science Data System* (SDS) consisting of the

- Orbit and Gravity Field Processing System (SDS-OG),
- Magnetic and Electric Field Processing Systems and (SDS-ME)
- Neutral Atmosphere Profiling System (SDS-AP)

at GFZ Potsdam, and the

- Ionosphere Profiling System (SDS-IP)

at DLR's Institute for Communication and Navigation (IKN), Neustrelitz.

Data and data product archiving, administration and retrieval is managed by the CHAMP *Information System and Data Centre* (ISDC), located at GFZ Potsdam, which is also the users' www- and ftp-based interface for access to CHAMP data and scientific products. The number of users and user groups, registered at ISDC and retrieving data, data products and ancillary information from the archive, has continuously grown with time. Four years after having issued the Announcement of Opportunity, this number has reached the value of about 560, with more than 50% of these users originating from Germany, the USA and China (see Color Fig. IV on p. 287).

CHAMP's standard science products are labelled from level-1 to level-4 according to the number of processing steps applied to the original data. Decommutation and decoding of level-0 data results in level-1 products. These are daily files, associated with each individual instrument and source aboard CHAMP, with the data content being transformed from the telemetry format and units into an application software readable format and physical units. Level-1 products also include the ground station GPS and laser data. Level-2 products are pre-processed, edited and calibrated experiment data, supplemented and merged with necessary spacecraft housekeeping data and arranged in daily files. Level-3 products comprise the operational rapid products and fine processed, edited and definitely calibrated experiment data. Finally, level-4 leads to the geo-scientific models derived from the analysis of CHAMP experiment data, supported and value-added by external models and observations.

At the time of writing this contribution, the numbers of product files given in Table 1 have been reported by the ISDC to exist in the data base for each of the levels 1 to 4. Each additional year of CHAMP operation adds about 1.4 Terabyte of data to the total amount.

Table 1. Total amount of stored data/product files since launch

	number of files	total
Level-1	3570365	3109 GByte
Level-2	244017	599 GByte
Level-3	807744	1767 GByte
Level-4	7708	1723 GByte
total	7786533	7198 GByte

4 Mission Goals and Science Data System Achievements

The science goals of the CHAMP mission are to gain improved sources of information about the nature and composition of the Earth, about evolutionary processes continuing to shape it, as well as to gain information on dynamic processes taking place in the near Earth space, in the neutral atmosphere and the ionosphere. Precise global gravity and magnetic field models are of main importance for studying and understanding the structure and composition of the solid Earth, whereas evolutionary processes, influencing global change, express themselves either directly or indirectly through changes in gravity and magnetic field signals and changes of key parameters of the atmosphere and ionosphere.

The mission goals for CHAMP, as defined in the pre-launch period, were:

1. to acquire long-term, uninterrupted and well calibrated data series from CHAMP's gravity field, magnetic field and atmosphere sensors,
2. to produce on the basis of high-low SST and accelerometer observations a long-term mean estimate of the Earth's gravity field for the spectral components >1,000 km with an at least one order of magnitude improvement and to contribute to the determination of the time variability of the longest wavelength components of the field by comparing three-monthly models,
3. to measure and model the main and lithospheric magnetic fields of the Earth as well as secular variations and ionospheric currents with unprecedented spatial resolution and precision through high-precision scalar/vector magnetic field and electric field observations,
4. to probe the neutral atmosphere and ionosphere as global as possible, using GPS limb soundings with improved technology,
5. to give all interested science and application users free access to the CHAMP data and data products through a dedicated CHAMP data and information system.

After 5 years in orbit and after 51 months of routine operation it can be stated that the CHAMP mission succeeded in achieving the aforementioned mission goals. More than 98 % of all possible observations have been acquired and stored in the raw data archives. Within the three fields of research and application pursued with CHAMP, the following number of standard products have been made available to the general user community via the ISDC (see Color Figs. V and VI on p. 288) up to now:

(1) Orbit and Gravity Field Processing System (SOS-OG)

- level-1: 21 GByte of GPS to CHAMP satellite-to-satellite phase and code tracking observations (0.1 Hz),
- level-2: 8 GByte of preprocessed *accelerometer* observations (0.1 Hz) and linear and angular accelerations with attitude information plus the thruster-firing time events,
- level-3: 15 GByte of *predicted, ultra-rapid and rapid science orbits* of CHAMP and the GPS satellites in the Conventional Terrestrial System, and processed with a short time delay of a few hours to days after data download,
- level-4: global *Earth gravity field models*, represented by the adjusted coefficients of the spherical harmonic expansion: progressively accumulated solutions, named EIGEN-1S, EIGEN-2, EIGEN-3p and EIGEN-CHAMP03S (see http://www.gfz-potsdam.de/pb1/op/champ/results/index_RESULTS.html).

(2) Magnetic and Electric Field Processing System (SOS-ME)

- level-2: 38 GByte *magnetic field* observations, both scalar and vector field, in the sensor system as well as in local coordinates (North, East, Down), all at 1 Hz rate; 17 GByte precise attitude derived from Advanced Stellar Compass both for the spacecraft and for the boom instrumentation at a 1 Hz rate,
- level-4: *main field and lithospheric field models* by the spherical harmonic expansion coefficients, derived from spacecraft data and its secular variation coefficients from space and ground-based observations; recent models are named POMME 1.4 and MF3 (see: http://www.gfz-potsdam.de/pb1/op/champ/results/index_RESULTS.html).

(3) Atmosphere/Ionosphere Profiling Systems (SOS-AP/IP)

- level-1: 75 GByte *GPS-CHAMP radio occultation* measurements (50 Hz for AP and 1 Hz for IP),
- level-2: 272 GByte of *atmospheric excess path delays*; time-tagged atmospheric excess path of the occultation, link annotated with SNR and orbit (position and velocity), information of CHAMP and the occulting GPS satellite for each occultation event,
- level-3: 16 GByte of *vertical profiles* of atmospheric bending angle and geopotential, profiles of refractivity, *dry air*-density, -pressure and -temperature, and – adopting temperature from global analyses – specific and relative humidity, partial pressure and mixing ratios of *water vapour* in the troposphere. 9 GByte of occultation link related *Total Electron Content* data values and 0.1 GByte of *vertical TEC profiles.*

In addition, more than 2,000 GByte of High Rate GPS ground data are provided to the users via the ISDC.

The SDS team at GFZ has achieved a number of outstanding scientific results in the course of the 5 years operation of CHAMP and has made these results quickly available to the community:

- For the first time in space geodesy's history with the EIGEN solutions global gravity field models with full power up to degree/order 65 of the spherical harmonic expansion could be derived from observations of a single satellite and largest-scale temporal gravity variations could be extracted from 3 years worth of data (Reigber et al., 2004).
- With POMME, a series of field models for the accurate description of the main and external magnetic field has been introduced (Maus et al., 2004). Employing data of the CHAMP scalar and vector magnetometers, a detailed global model up to degree/order 90 of the crustal magnetic field was derived (Maus et al., 2005). This model MF3 is providing important information for studies of the crustal magnetisation. In addition, from two years of high-precision CHAMP satellite magnetic measurements it has been possible to map for the first time the magnetic signal of ocean tidal flow (Tyler et al., 2003).
- Unprecedented continuous long series of atmospheric and ionospheric profiles are derived by the SDS AIP team from CHAMP's GPS radio occultation data. More than 300,000 atmospheric occultation measurements are presently available as well as more than 200,000 ionospheric occultation data. Currently the delay time from data reception to the generation of key parameters of the neutral atmosphere and ionosphere is only a few hours and the quality of the data products as derived from inter-comparisons with independent observations and analyses is impressively high (Wickert et al., 2004; Jakowski et al., 2004).

Finally, with the CHAMP ISDC a modern tool for the management of system data of a space geodetic mission was introduced, which has found its extension into the GRACE era (see http://isdc.gfz-potsdam.de/champ/). More than 500 scientists and application users are registered at the moment, which are making intensive use of this service. With the continuous annual increase of CHAMP data users over the last four years, this number is likely to further grow in the next few years.

5 Conclusion and Outlook

After 5 years of mission operation the main conclusion is that the CHAMP mission fully meets the demands defined by the project team in the design and development phase for the space and for the ground segment. The CHAMP mission has already now provided an unprecedented set of data for geo-potential, atmospheric and ionospheric research and has marked a new era of LEO satellites with onboard GPS receivers, accelerometers and magnetometers. Many scientists from various fields of geosciences and the application area make intensive use of data and products provided by the CHAMP Science Data System for their own analyses and investigations. CHAMP has served in many respects as pathfinder for the GRACE mission and will do so for the next generation of magnetic field missions such as SWARM. CHAMP is likely to remain in orbit until mid 2008. With the decreasing orbital altitude and the extension of the observation period by additional three years, more sensitivity and precision will be gained in particular for the gravity field and magnetic field modelling. With its companion mission GRACE and a CHAMP observation period extended to seven or eight years, highly valuable information on the variability of the Earth gravity and magnetic fields and on long-term changes of key quantities of the atmosphere and ionosphere will be obtained. This information will support a better understanding of the mass balances in the Earth System and may help in future to early detect global changes and to understand their underlying mechanisms.

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Remarks on CHAMP Orbit Products

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Summary. The GeoForschungsZentrum Potsdam (GFZ) runs an operational system for the CHAMP mission that provides precise orbits on a regular basis. Focus is put on recent analyses and achievements for the Rapid and Ultra-rapid Science Orbits.

Key words: CHAMP, GRACE, SAC-C, Precise Orbit Determination, Orbit Products

1 Introduction

Since the beginning of the CHAMP mission (Reigber, 2005) in 2000, the GeoForschungsZentrum Potsdam (GFZ) operationally provides precise orbits. These products comprise orbit predictions (the PreDicted Orbits or PDOs), rapidly available orbits (the Rapid Science Orbits or RSOs and the Ultra-Rapid Science Orbits or USOs), and offline generated orbits (the Post-processed Science Orbits or PSOs). All these routine orbits are dynamically integrated and differentially corrected for certain parameters to fit to the observations being available at the time of generation and being appropriate to meet the objectives the orbit is intended for. The orbits are provided at different frequencies, latencies, and accuracies depending again on their intention. And they are published at the CHAMP data center at GFZ (ISDC, 2001).

Developments in CHAMP Precise Orbit Determination (POD) have recently been discussed in König et al. (2005). The following concentrates therefore on newest improvements in accuracies and latencies, on new considerations regarding accuracy assessments of the RSOs of the GPS satellites, and on the accuracy of GRACE RSOs which have been invented newly to support radio occultation analysis with GRACE enhancing the CHAMP and SAC-C data set. Also given are some tests on the impact of ambiguity fixing and dense GPS clocks. These approaches are due next for the upgrade of the operational processing system.

The instruments of CHAMP provide data for use in POD, such as space-borne Global Positioning System (GPS) Satellite-to-Satellite Tracking (SST) observations, onboard accelerometer measurements, attitude, thruster firing and other POD relevant information from the housekeeping data. The ground based data are GPS data of the CHAMP low latency network, other ground GPS data from the International GNSS Service (IGS, see Beutler et al. (1999), IGS (2005)), and Satellite Laser Ranging (SLR) data from the International Laser Ranging Service (ILRS, see Pearlman et al. (2002), ILRS (2005)). The same holds true for the GRACE satellites, where however the SST observations only are exploited for the RSO. K-band intersatellite range observations as well as the attitude etc. data are omitted because they do not arrive in time. Also in case of SAC-C we must rely on space-borne GPS observations alone.

In all POD applications described in the following, the data are evaluated by GFZ's EPOS-OC (Earth Parameter and Orbit System - Orbit Computation) software system in version 5.4 at the time of writing this.

2 CHAMP Rapid and Ultra-Rapid Orbit Products

Modelling standards and earlier quality results for the CHAMP RSO and USO are given e.g. in Michalak et al. (2003). Recent efforts concentrated on improving and accelerating the pre-processing system. They resulted in more accurate GPS orbits with lower latency. Fig. 1 shows the comparison of the GPS RSO orbits to IGS Rapid Orbits (IGRs) after having applied a Helmert transformation in terms of Root Mean Square (RMS) values of position differences per axis, Fig. 2 the comparison of the GPS USOs to the IGRs. The IGRs are taken as a reference as IGS claims that their accuracy is better than 5 cm (IGS, 2005). Improvements concerned the optimization of the selection of approximately 50 stations of the GPS ground network. In effect since September 20, 2004, (marked by a dashed vertical line in Fig. 1 and 2), indeed less outliers can be noticed for both the RSO and the USO. Currently the GPS RSO shows 7.5 cm RMS versus IGR, the USO 8.5 cm. The USO is slightly less accurate because it is generated with a latency of approximately two hours after the last observation versus a latency of 17 hours for the RSO (the IGR also comes with a latency of 17 hours). Therefore the set of observations for the USO may lack data from some receivers, making the ground station network less optimal.

A validation of the RSOs of the GPS satellites PRN G05 and PRN G06 by SLR observations is performed for orbits since the beginning of year 2004. For that the GPS based orbits are fixed and compared to the SLR observations. Eventually the SLR residuals are compiled in Fig. 3. They exhibit a systematic bias of -5 cm, their standard deviation is 4.9 cm. The bias here is consistent with previously published results (e.g. Urschl et al. (2005)). Con-

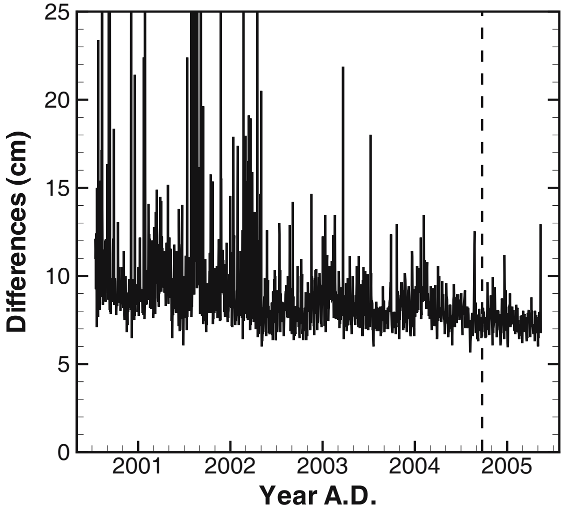

Fig. 1. Comparison of the GPS RSO to the IGR

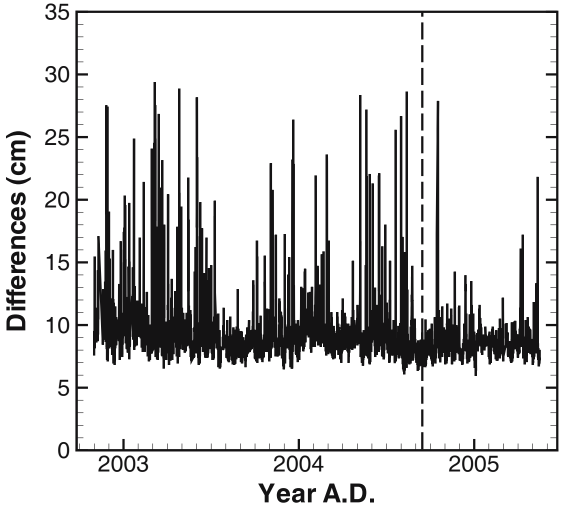

Fig. 2. Comparison of the GPS USO to the IGR

cluding from the SLR validation, a radial accuracy of 5 cm of the GPS RSOs can be assessed.

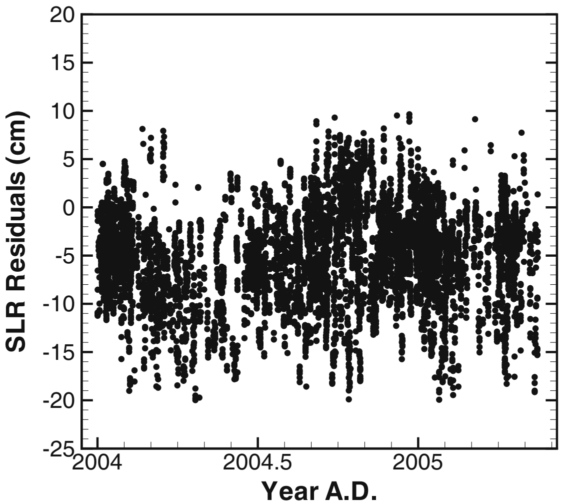

Fig. 3. SLR validation of the RSOs of PRN G05 and PRN G06

For the determination of CHAMP RSO and USO orbits, the respective GPS RSO and USO orbits and clocks are fixed. The resulting accuracies of the CHAMP RSO orbits can again be assessed by SLR validation. For the recent period the RMS is around 5.5 cm. It should be noted here in general, that the SLR data are taken as is, i.e. the RMS values can be contaminated by outliers. In addition, the SLR observations can be located at the beginning or at the end of an arc, which, due to the known dissipations of dynamical orbits at those periods, increases the RMS values as well.

A second assessment of CHAMP RSO accuracy is performed by sampling the position differences of subsequent orbits in the middle of the 2-hour period where the orbits overlap. The recently computed mean of the sampled position differences amounts to 5.0 cm. This is in good agreement with the SLR RMS and validates therefore the possibility to use the overlap analysis as accuracy assessment.

SLR validation and overlap analysis are also used to asses the accuracy of the CHAMP USO. The global SLR RMS is 7.4 cm. This is larger than in case of the CHAMP RSO due to its dependency on less accurate GPS USO orbits and because of more frequent occurences of gaps in the CHAMP SST observations. In Fig. 4 the position differences and their medians of overlapping arcs at epochs distant by 0 to 2 hours from the end of the preceding arc are given. The most critical part of the CHAMP USO orbit is its end, the last 15 minutes, where the median values are quite large, between 13 and 29 cm.

The main reason is found with poor accuracies of GPS USOs for the last 1 hour of the arc due to lacking data. Meanwhile an effort has been started to improve the acquisition of GPS ground data covering the last 1-2 hours of the GPS USO.

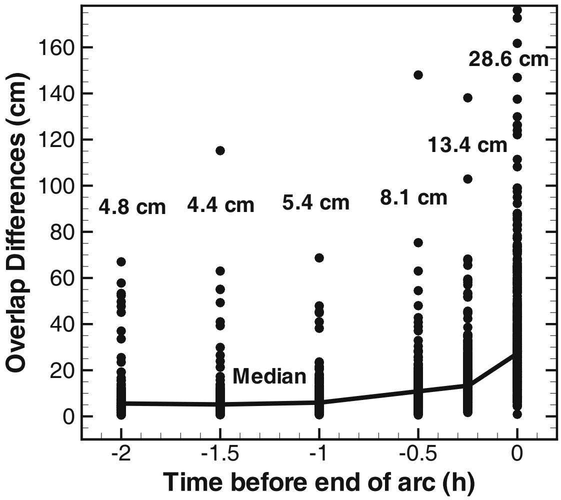

Fig. 4. CHAMP USO orbit accuracies

The GPS and CHAMP USOs are produced as pre-requisite for occultation data processing, which in turn generates atmospheric profiles or related products for use in Numerical Weather Prediction (NWP). The age of input data to NWP applications must not exceed three hours. The latencies of the CHAMP USO are given in Fig. 5. The recent improvement of pre-processing procedures by parallel acquisition and pre-processing of GPS ground data introduced on April 20, 2004, resulted in a reduction of the latency from 3.5h to 2.2h in mean. Further reductions are still possible by switching from a 3-hourly processing interval to dump-dependent processing. In case of CHAMP, the polar receiving station has view of the satellite during each revolution, i.e. approximately each 1.5 hours. Then the onboard data, the GPS SST observations etc., can be sent to the ground or dumped respectively.

3 SAC-C and GRACE Rapid Orbit Products

Recently the CHAMP RSO processing system was extended to generate orbits for three more occultation measuring satellites: SAC-C, GRACE A and GRACE B. The SAC-C satellit has no SLR reflector, so for accuracy assessment the overlap values only are available. The results are given in Table 1.

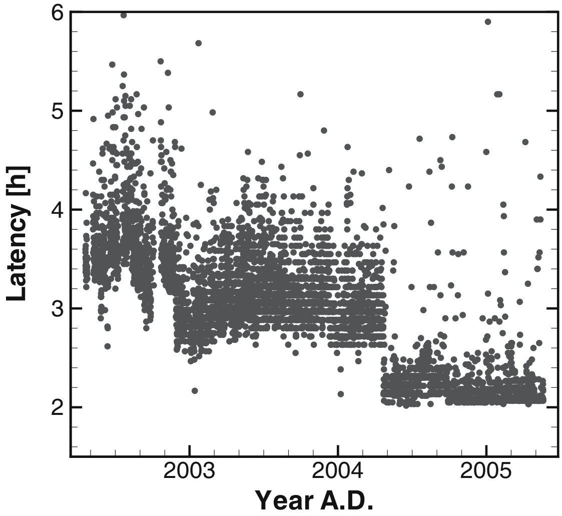

Fig. 5. CHAMP USO latencies

The mean overlap position difference 5.4 cm is close to the value for CHAMP, i.e. 5.0 cm. Since the modelling standards for both satellites are rather similar, it can be concluded from the overlap analysis that the accuracy of the SAC-C orbits is close to that of the CHAMP RSO.

In addition to CHAMP and SAC-C, the RSO for both GRACE satellites is produced since October 2004. Though, at the time being, the GRACE occultation measurements are switched off, permanent switch on is planned. Therefore the generation of the GRACE RSOs keeps going as long as resources allow. Recent accuracy assessments for both GRACE RSOs are compiled in Table 1, too. SLR RMS values are as large as those of CHAMP, but overlaps are about half as large as those of CHAMP and SAC-C. As the GPS receivers onboard the GRACE satellites deliver higher quality data, it can be concluded that the GRACE RSOs are of higher quality than the CHAMP and SAC-C RSOs.

Table 1. SAC-C RSO and GRACE RSO accuracies

	SLR RMS (cm)	Overlap Mean (cm)
SAC-C	-	5.4
GRACE A	5.2	2.8
GRACE B	4.8	2.9

4 Increasing the Accuracy of GPS and LEO Orbits

Ambiguity fixing (Mervat, 1995) for GPS observations is tested for a small sample of the GPS Post-processed Science Orbits (PSOs, 30 s ephemerides and clocks for sub-sequent gravity field processing). Table 2 summarizes the comparison of the standard and the ambiguity-fixed PSOs to the IGS final orbits for three 1.5-d arcs of May 2002. The IGS final orbits are considered as a reference because IGS claims, as in case of the IGR, that their accuracy is better than 5 cm (IGS, 2005). For further assessment, two out of all individual contributions to the combination of the IGS final orbits, the final orbits of the CODE and GFZ IGS analysis centers, are compared the same way as the PSOs to the IGS final orbits.

From Table 2 it can be conluded that ambiguity fixing improves the accuracy of the PSOs considerably. GFZ final and CODE final orbits should be as close as 2 cm to the IGS final orbits according to the IGS combination reports. However the values in Table 2 differ quite largely from this particularly for the GFZ finals. The reason being the weighting scheme applied in the combination whereas the results in Table 2 are derived from straightforward differences of all satellites being equally weighted.

Table 2. Impact of ambiguity fixing. Differences in position per axis for various orbits versus IGS final orbits

Arc	Standard PSO RMS (cm)	PSO with ambiguity fixing RMS (cm)	GFZ final RMS (cm)	CODE final RMS (cm)
2002.05.01	13.8	9.9	10.2	3.6
2002.05.03	11.4	6.9	8.5	3.2
2002.05.05	9.7	5.7	7.0	3.1
Mean	11.6	7.5	8.6	3.3

The GPS PSO (standard and with ambiguity fixing) was next used to generate CHAMP RSO type orbits for the period 2003.08.01 - 2003.08.14. Some arcs were excluded a priori because of gaps in the GPS clock solutions. Generally the CHAMP RSO is generated using the 5 minutely spaced ephemerides and clocks of the GPS RSOs. The 5-minute clocks are then being linearly interpolated to 30-second clocks. The impact of these different GPS orbits and clocks on CHAMP RSO accuracy can be seen in Table 3. The largest impact comes from proper 30-second clock solutions, case GPS PSO, for which the CHAMP SLR RMS drops drastically. The ambiguity fixed PSOs improve the CHAMP orbits additionally. Ambiguity fixing as well as improved interpolation of the 5-minute clocks of the GPS RSO will be implemented in the next future.

Table 3. Impact of GPS clocks and ambiguity fixing on CHAMP RSO type orbits measured by independent SLR residuals. CHAMP arcs where attitude and thruster data are missing, are marked by (*)

Arc	Standard GPS RSO RMS (cm)	Standard GPS PSO RMS (cm)	PSO with ambiguity fixing RMS (cm)	Number of SLR normal points
030801 10:00	3.68	2.08	2.00	167
030801 22:00	2.94	3.47	4.49	51
030802 10:00	3.81	2.46	2.54	139
030802 22:00	5.29	4.57	4.38	28
030803 10:00*	4.53	2.35	1.40	59
030803 22:00	0.13	1.10	0.04	1
030804 10:00	2.52	2.06	1.68	148
030804 22:00	2.90	2.72	3.59	45
030805 10:00	4.29	4.50	3.54	96
030805 22:00	5.11	3.17	3.47	122
030807 22:00	3.51	1.16	2.54	47
030808 10:00*	4.90	4.90	4.49	120
030808 22:00*	5.60	4.00	4.73	38
030810 10:00*	2.99	4.22	5.79	162
030810 22:00	4.94	5.67	4.33	66
030811 10:00	3.93	3.52	3.06	170
030811 22:00	3.51	3.89	2.93	81
030812 10:00	3.06	3.60	2.86	194
030812 22:00	4.19	3.05	2.25	49
030813 10:00	5.69	2.64	3.18	232
030813 22:00	6.02	3.29	3.48	52
030814 10:00	5.73	5.09	4.58	51
Global SLR RMS				
All arcs	4.24	3.48	3.45	2118
Arcs (*) excluded	4.24	3.30	3.08	1739

Another possibility for improving the LEO orbit accuracies is to use the integrated approach (Zhu et al., 2004) where all LEO and GPS orbits and the ground station coordinates are estimated in one step. Some results for a few GRACE 1.5-day arcs under different observation scenarios are given in the cited article. Here the integrated approach is applied for two months of GRACE A/B 1-day orbits and shown in Table 4. For comparison, also RMS values of SLR residuals are given for GRACE orbits produced during gravity field screening and for JPL reduced dynamic orbits. In the gravity screening runs, accelerometer data and empirical forces were used to achieve good initial orbits. For the integrated solution, solely accelerometer data were used. The independent SLR RMS for the integrated solutions is slightly larger than for the JPL solution. The difference can be deduced to gaps in the accelerometer data in the integrated solution. Therefore the integrated approach can produce LEO orbits accurate on the level of 2-3 cm.

Table 4. GRACE A and B orbit accuracies for three different solutions measured independently by 9872 SLR normal points for the period 2003.07.02-2003.08.31

Solution	RMS (cm)
Routine gravity screening (1.5d arcs, accelerometer + emp. coeff.)	5.15
Integrated (1-step) solution (1d arcs, accelerometer only)	2.92
JPL solution (reduced dynamic)	2.33

5 Summary and Conclusions

Rapid and ultra-rapid GPS, CHAMP, SAC-C and GRACE orbits generated operationally by GFZ e.g. for GPS radio occultation applications are accurate and reliable products. Recent improvements concern the optimized selection of a suitable GPS ground station network that resulted in more reliable GPS RSOs and USOs. Faster procedures for data acquisition and pre-processing led to considerable smaller latencies of the USOs. By applying ambiguity fixing and accurate GPS clock interpolation the LEO orbits can be generated on an operational basis with an anticipated accuracy of 2–3 cm versus the current 4–5 cm. Further accuracy improvements are possible by the integrated approach which, due to its large needs on computational resources, seems at this time to be of practical relevance only if it is applied offline. As demonstrated by the adoption of the SAC-C and GRACE A/B RSOs, the GFZ operational system is prepared to accomodate further future LEO missions carrying onboard GPS where fast and accurate orbits are required.

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Harmonic Analysis of the Earth's Gravitational Field from Kinematic CHAMP Orbits based on Numerically Derived Satellite Accelerations

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Summary. Based on very accurate kinematic CHAMP orbits, a new CHAMP gravitational field model was computed by means of a (point-wise) acceleration approach. In order to implement such an acceleration approach, the satellite's acceleration has to be derived from the kinematic CHAMP orbits by means of interpolation and subsequent numerical differentiation. The iterative method of preconditioned conjugate gradients is implemented to solve the large linear system of equations for the spherical harmonic coefficients. If appropriate preconditioning is applied, convergence can be reached within 7 – 15 iterations. An important topic concerning the accuracy of the gravity field solutions is the detection and filtering or down-weighting of spikes, jumps, outliers and inaccurate data in the kinematic orbits. These problems are adressed by data-preprocessing or robust estimation. Different gravity field solutions up to degree and order 90 were computed, where validation exhibits a signal-to-noise (S/N) ratio per degree of $S/N \geq 1$ for coefficients up to degree 80 and $S/N \geq 2$ for coefficients up to degree 70. Comparisons to different CHAMP-models, which were obtained by application of alternative algorithms, prove that the acceleration approach can compete with other methods of gravity field determination.

Key words: gravity field determination, CHAMP, low earth orbiting satellite (LEO), numerical differentiation, robust estimation, wavelet filter

1 Introduction

The classical, dynamic approach for the analysis of the high-low SST (satellite-to-satellite-tracking) measurements between the low Earth orbiting (LEO) CHAMP-satellite and GPS-satellites is based on the former methods developed for Laser-Ranging-observables and connects the GPS-observables directly with the gravity field parameters (Reigber, 1989). The relation between the satellite orbit and the gravity field parameters is achieved by the integration of the variational equations. With the proceeding CHAMP mission various models, e.g. EIGEN-1S (Reigber et al., 2002), EIGEN-2 (Reigber et al., 2003), EIGEN-3p and EIGEN-CHAMP03S (Reigber et al., 2005a), have been estimated with this method which indeed led to an improvement of state-of-the-art gravity field models. Besides this classical *one-step-method* alternative approaches have been developed in context with CHAMP. These are based on kinematic orbits and can be classified as *two-step-methods* (1. GPS-observations → kinematic orbits; 2. kinematic orbits → gravity field parameters). Applied alternative two-step-methods are the *energy-balance-approach* (Földváry et al., 2005), the *short-arc analysis* formulated as *boundary value problem* (Mayer-Gürr et al., 2005) and *acceleration approaches* (*point-wise*, see Austen et al. (2002), Reubelt et al. (2003a,b) and *average*, see Ditmar and van Eck van der Sluijs (2004)). The implementation of such algorithms is motivated by the fact, that kinematic orbits can nowadays be determined with an accuracy of less than 5 cm (Švehla and Rothacher, 2003, 2004), offering comparable results to the classical approach.

The two-step algorithms working with kinematic orbits can be classified as fast regarding the computation time, which is achieved by the underlying linear system of equations. Especially the acceleration approaches will be efficient, since any kind of integration of the force function is avoided and instead the comparable fast process of numerical differentiation is applied. Numerical differentiation, which normally increases the noise, is a less critical procedure within acceleration approaches, if the orbit is correlated. In this case, the noise may be reduced by numerical differentiation (Reubelt et al., 2003a,b). Indeed the correlation of kinematic orbits can be proven by either a comparison to dynamic orbits (Reubelt et al., 2003a,b) or by error-propagation of kinematic orbits (D. Švehla, personal communication).

Motivated by the explained advantages, detailed simulations and first results from real data analysis (Reubelt et al., 2003a,b), the CHAMP real data analysis within the subproject of the GIS in CHAMP-DACH was performed with a point-wise acceleration approach.

2 The point-wise acceleration approach

The acceleration approach is briefly outlined in this section, detailed explanations including mathematical formulas can be found in Austen et al. (2002) and Reubelt et al. (2003a). Normally, kinematic CHAMP orbits are given with respect to a Conventional Terrestrial System (CTS). In order to obtain accelerations free from frame accelerations, the CHAMP positions have to be transformed into the Conventional Inertial System (CIS). The satellite acceleration vector is derived from the positions by differentiating twice an interpolation function, which was fitted to the orbit. The Gregory-Newton-interpolation turned out to be an appropriated method for application in *numerical differentiation*. By reduction of non-conservative (non-gravitational) and gravitational (tides) disturbing accelerations the terrestrial gravitational acceleration vector can finally be obtained. While tidal effects as the direct attraction of sun, moon and the planets, the solid Earth and pole tides and the ocean tides can be modeled with sufficient accuracy, non-conservative effects caused by satellite surface forces as atmospheric lift and drag, solar radiation pressure and the Earth's albedo are measured with the in-situ CHAMP STAR accelerometer. Calibration parameters - determined by GFZ - for the correction of the bias, tilt and scale of the accelerometer instrument can be downloaded from CHAMP-ISDC at GFZ. Due to some major problems, as explained in Sect. 6, the satellite accelerations were not reduced by the accelerometer measurements. According to Newton's Law of motion, the "reduced" accelerations are balanced by the gradient of a spherical harmonic geopotential model in order to set up the linear system of equations for the determination of the spherical harmonic coefficients of the gravitational field. The gradient is naturally computed by the spherical partial derivatives in the local spherical system (normalized tangential system) and must therefore be transformed into the CIS (via the CTS). A method for the solution of the large system of equations and important aspects of data-preprocessing and weighting are addressed in Sects. 4 and 5.

3 Numerical differentiation

For derivation of the satellite's acceleration from kinematic orbit positions, numerical (double) differentiation has to be applied. In general, several possibilities exist for numerical differentiation, whereas the most important are the Fourier (FFT)-approach and differentiation based on interpolating splines and polynomials. The FFT-approach is not further considered since data gaps and outliers as well as sudden changes in the signal (orbit maneuvers,...) cause serious problems and the result is contaminated from edge-effects and aliasing-effects (Weigelt and Sneeuw, subm.). Due to a less oscillating nature, cubic splines instead of polynomials are generally suggested for interpolation. Problems in using spline-interpolation are the derivation of boundary values and the cause of edge-effects in the case of inaccurate boundary values. Compared with polynomials, a longer time-series is needed to apply spline-interpolation, which can be problematic in the presence of data-gaps and outliers. The aforementioned difficulties can be handled, if polynomial interpolation is adopted. Oscillations are avoided or marginal, when the order of the polynomial is not too high and the polynomial is shifted point-wise for interpolation. In our algorithm, numerical differentiation based on Gregory-Newton-interpolation is implemented. Details exceeding the following brief overview can be found in Reubelt et al. (2003a,b). According to Engeln-Müllges and Reutter (1987), Gregory-Newton-interpolation is a n-point-interpolation-scheme and can be expressed as a product-sum of *binomial coefficients*, containing the time t (sampling time Δt), and *forward-differences* of positions $\mathbf{X}_k$. By means of double-differentiation of the *binomial coefficients* with respect to time (2) and by expressing the *forward differences* $\mathbf{\Delta}^i_{1+i/2}$ in terms of *coordinate dif-*

ferences $\Delta\mathbf{X}_k^{k+1}$ (baselines) (3) the satellite accelerations $\ddot{\mathbf{X}}$ can be determined by numerical differentiation with (1).

second derivative of the Gregory-Newton-interpolation formula

$$\ddot{\mathbf{X}}(t) = \sum_{i=1}^{n-1} \binom{q}{i}^{//} \mathbf{\Delta}^i_{1+i/2} \tag{1}$$

with time difference quotient $q = \frac{t-t_1}{\Delta t}$

second derivative of binomial coefficients

$$\binom{q}{i}^{//} = \frac{1}{\Delta t^2\, i!} \sum_{j=0}^{i-1} \frac{\sum\limits_{k=0}^{i-1} \left(\frac{q-j}{q-k}\right) - 1}{(q-j)^2} \prod_{l=0}^{i-1} (q-l) \tag{2}$$

forward differences in terms of baselines

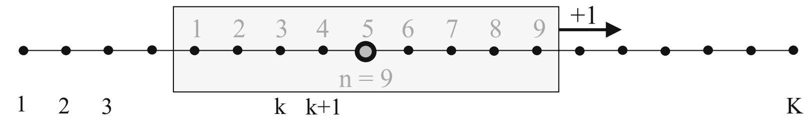
$$\mathbf{\Delta}^i_{1+i/2} = \sum_{k=0}^{i-1} (-1)^{i-1+k} \binom{i-1}{k} \Delta\mathbf{X}_{k+1}^{k+2} \tag{3}$$

with baselines

$$\Delta\mathbf{X}_k^{k+1} = \mathbf{X}_{k+1} - \mathbf{X}_k$$

For reasons of accuracy the accelerations are only determined at the central point of the interpolation scheme. The resulting central difference filter is displayed in Fig. 1a.

(a)



(b)

$-\frac{1}{560\Delta t^2}$	$\frac{8}{315\Delta t^2}$	$-\frac{1}{5\Delta t^2}$	$\frac{8}{5\Delta t^2}$	$-\frac{205}{72\Delta t^2}$	$\frac{8}{5\Delta t^2}$	$-\frac{1}{5\Delta t^2}$	$\frac{8}{315\Delta t^2}$	$-\frac{1}{560\Delta t^2}$

Fig. 1. (a) second derivative of Gregory-Newton-interpolation as filter and (b) its filter coefficients for a 9-point-scheme

To guarantee a good approximation, at least a 7-point-scheme must be used. On the other hand, the propagation of orbit-noise increases with a higher-order-interpolation scheme. The 9-point scheme (Fig. 1b) offers a good compromise between approximation and propagation of errors.

Generally, a major drawback involved with numerical differentiation is an increase of noise. This holds for white noise and it can be shown (Reubelt et al., 2003a,b), that the noise induced errors of the accelerations can be diminished if the coordinates are correlated. To demonstrate this, the *second order formula of Gregory-Newton-interpolation* (1) was expressed in baselines (relative coordinates) instead of absolute coordinates. Due to the correlation of positions, these baselines can be determined with higher accuracy than the absolute coordinates, similar to DGPS. By introduction of such baselines it can be explained why numerical differentiation with (1) enables the damping of noise. The effect of correlation is briefly outlined in Figs. 2a,b,c by means of a simulated erroneous orbit ($\sigma_X = 3\,\text{cm}$, $\rho = 0.97$), which was generated according to earlier real data investigations (Reubelt et al., 2003a,b) and an improved accuracy of real CHAMP kinematic orbits (Švehla and Rothacher, 2004). While the absolute orbit accuracy in Fig. 2a is 3 cm, the accuracy of the baselines is enhanced in Fig. 2b to about $\sigma_{\Delta X} = 7\,\text{mm}$. If the correlation of the orbit is assumed to $\rho_2 = 0.8$, the accuracy of the baselines only improves up to $\sigma_{\Delta X} = 1.9\,\text{cm}$ (not shown in the figure). The higher accuracy of the baselines for $\rho = 0.97$ leads to an accuracy of the accelerations in the level of $\sigma_{accl} = 1.6{\cdot}10^{-5}\ \text{m/s}^2$ (Fig. 2c) in contrast to an accuracy of $\sigma_{accl} = 4.5{\cdot}10^{-5}\ \text{m/s}^2$ for the lower correlated orbit ($\rho_2 = 0.8$). This means, that the level of accuracy of the accelerations and furthermore of the corresponding gravity solution is rather determined by the correlations and the accuracy of baselines than the absolute accuracy of the orbit.

Figs. 2d,e,f try to oppose the behavior and accuracy of a real CHAMP kinematic orbit (Švehla and Rothacher, 2003, 2004) to the simulations. The accuracy of a real kinematic orbit is difficult to judge since the truth is not known. Thus the quality and accuracy of the kinematic orbit, its baselines and accelerations are validated by a comparison to a reduced dynamic orbit (Švehla and Rothacher, 2003, 2004), which is based on the best present-day gravity field model EIGEN-GRACE02S (Reigber et al., 2005b) and which serves due to its smooth behavior as a good reference for evaluation. The orbit/baseline acceleration differences between the kinematic and reduced-dynamic orbit, illustrated in Figs. 2d,e,f, show RMS values of $2\,\text{cm}/6\,\text{mm}/1.5{\cdot}10^{-5}\ \text{m/s}^2$ (outliers and data gaps are neglected) and thus are in good agreement with the results of the simulated correlated orbit, displayed in Figs. 2d,e,f. Additionally the orbit-, baseline- and acceleration differences between two (smooth) reduced-dynamic-orbits (Švehla and Rothacher, 2003, 2004) based on EIGEN-GRACE02S and the less accurate EGM96 (Lemoine et al., 1998) are plotted, which show RMS-values of 2 cm, 3 mm and $3{\cdot}10^{-6}\ \text{m/s}^2$. The small differences between the baselines and accelerations of both reduced dynamic solutions prove that the reduced-dynamic orbits provide a good reference for validating the accuracy of kinematic baselines and accelerations. Only the estimation of the absolute accuracy of the kinematic orbit by a comparison to the reduced-dynamic orbit is difficult, since the absolute accuracy and long wavelength-behavior of the reduced-dynamic orbit may be in the same range,

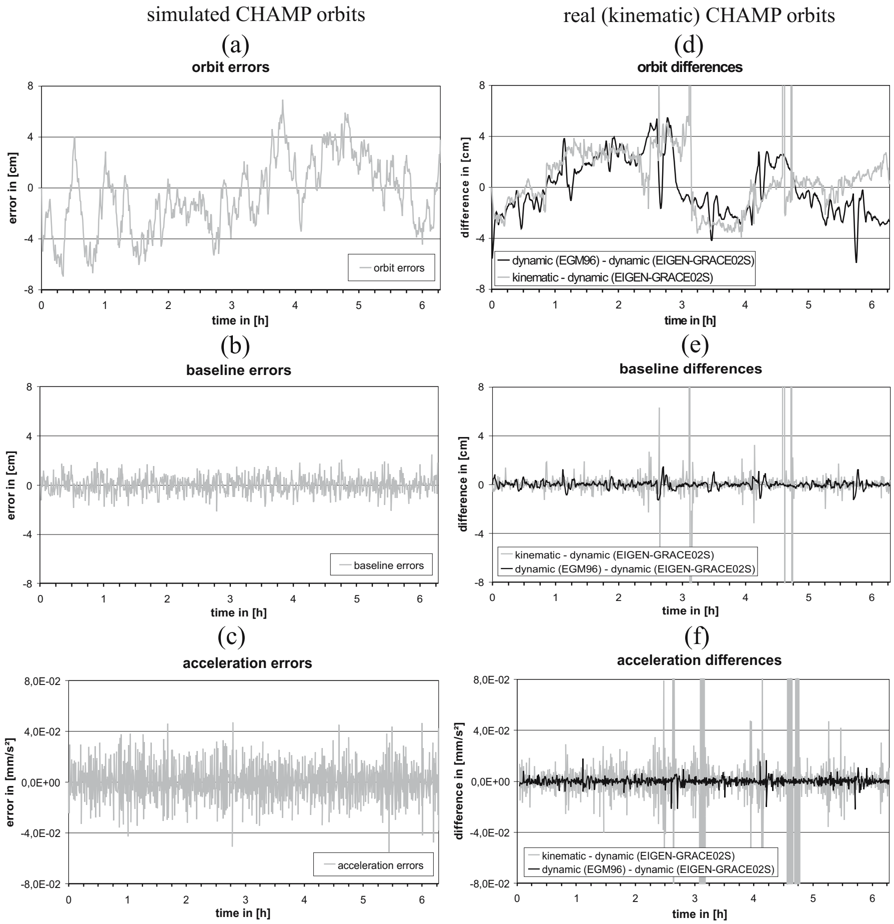


Fig. 2. (a),(b),(c) orbit/baseline/acceleration errors of a simulated CHAMP orbit (h = 470 km, Δt = 30 s, $\sigma_X = 3$ cm, $\rho = 0.97$) in the CIS (x-component); (d),(e),(f) orbit/baseline/acceleration differences between real CHAMP orbits (year 2002, day 200, GPS time, Δt = 30 s) in the CIS (x-component); bright: differences between kinematic and reduced-dynamic orbit (EIGEN-GRACE02S), dark: differences between 2 reduced-dynamic orbits (EIGEN-GRACE02S, EGM96)

as indicated by the orbit-difference between the two reduced-dynamic orbits. From external validation to SLR-data and orbit-adjustment-residuals (Švehla and Rothacher, 2003, 2004) we get the absolute accuracy of the kinematic orbit of about 2 - 3 cm. A comparison of this absolute accuracy to the baseline accuracy of ≤ 1 cm gives a hint, that kinematic orbit data is correlated, although the correlation may differ slightly from the simulations. At least the comparable accuracy of baselines and accelerations from simulations and real kinematic orbits indicate that real data processing will confirm the promising results from simulations (for instance in Reubelt et al. (2003a,b)).

The correlation of kinematic orbits originates from the natural correlation of GPS-measurements, from signal delays (ionosphere) and from the procedures (e.g. ambiguity and clock fixing) adopted in the orbit adjustment. Additionally to the comparison between kinematic and reduced-dynamic orbits, the variance-covariance-matrix of kinematic orbits clearly reveals such correlations (D. Švehla, personal contact).

For completeness it should be mentioned, that also smoothing methods like polynomial regression and smoothing splines have been tested in simulations in order to reduce the influence of noisy observations. These methods were not adopted to real data, since the accuracy of the estimated gravity decreased though the internal statistics of the accelerations improved. The reason for this might be, that not only the noise was reduced by smoothing, but also the signal.

4 Iterative solution of linear system of equations

For the determination of the gravity field parameters from the 2-years kinematic orbit, a system of equations consisting of 6 millions of observations and 8278 unknowns for the maximum degree $L = 90$ has to be solved. This may lead to two basic problems, namely the storage of the large design and normal matrices and the time-consuming computation of the normal matrix. The algorithm can be shifted to a super-computer or an iterative solution can be aimed concerning these problems. Iterative methods are able to deal with restricted memory, since the normal matrix must not be built up and the design matrix must not be stored. If iterative solvers in terms of preconditioned conjugate gradients (PCG) are implemented, the computations can be performed on a standard PC. Mathematical details on the method of preconditioned conjugate gradients, which led to a fast and stable convergence within $7 - 15$ iterations in all computations, can be found in Ditmar and Klees (2002). In Reubelt et al. (subm.) the preconditioner, which is implemented as a block-diagonal approximation of the normal matrix consisting of one submatrix per order m, is examined in more details.

5 Data preprocessing and robust estimation

5.1 Data preprocessing

The gravity field determination in this contribution is based on a two years kinematic CHAMP orbit of the period March 2002 – March 2004, which was kindly provided by D. Švehla and M. Rothacher (Forschungseinrichtung Satellitengeodäsie at Technical University Munich). In contrast to (reduced) dynamic orbits, which depend on a model, kinematic orbits are generated purely from the geometric information of GPS phase-observations and pseudoranges. Kinematic orbits thus are not as smooth as (reduced) dynamic orbits and may contain data gaps, outliers and jumps, as visible in Fig. 2d. While the former two phenomena are mainly caused by an insufficient number of observed GPS satellites or a bad satellite-constellation, the latter can be assigned to a changing GPS-constellation.

Since the implemented method of the acceleration approach is very sensitive to outliers and jumps, as proved by simulations (Götzelmann et al., subm.), data-preprocessing is a very important aspect in gravity field determination. In the acceleration approach, the removal of outliers can mainly be applied at two levels. The first opportunity is the preprocessing of the given kinematic orbit (or its baselines) and, since errors propagate into numerical differentiation, the derived accelerations offer a second platform for outlier removal strategies.

The most natural way for data preprocessing would be to detect outliers by means of the variance-covariance matrix of the kinematic orbit, which was propagated from the orbit adjustment. By setting a threshold value for the orbit variances, inaccurate orbit observations can be removed. A weakness of this procedure is revealed by a comparison between orbit variances and orbit differences (kinematic - reduced dynamic): outliers and inaccurate positions do not always coincide with large orbit variances and vice versa. Moreover, jumps in the orbit may hardly be discovered from the orbit variances (only a reduced correlation between two positions may give a hint for the presence of jumps).

To overcome the mentioned problems, data preprocessing by comparisons to the smooth reduced dynamic orbits and accelerations computed from an existing model was tested. A very simple method would be to set a threshold value for the orbit and/or baseline differences between the kinematic and the reduced dynamic CHAMP orbit and remove all observations which exceed this limit. The comparison is more valuable on the level of baselines than on the level of positions, since reduced dynamic baselines provide a better reference for evaluation than absolute coordinates (as already explained in Sect. 3) and jumps can easier be detected. Thus, a kinematic baseline indicating a difference to a reduced dynamic baseline of 5 cm can already be classified as outlier whereas an orbit difference of 5 cm cannot necessarily be interpreted as an outlier. For orbit differences, a higher threshold-value, e.g. 10 cm or 20 cm must be set to ensure, that the difference is not caused by an inaccurate reduced dynamic orbit. In a second step, the determined accelerations can be compared with the accelerations of the reduced dynamic orbit or directly with accelerations computed from existing gravity field models, which were applied for the computation of the reduced dynamic orbits. Here, the direct comparison to accelerations estimated from a gravity field model was chosen. Due to gravity signal attenuation at the satellite orbit, degrees higher than $l \geq 90$ only contribute marginally to accelerations and thus the used gravity field model is only developed up to degree and order 90. From

Sect. 3 it is concluded, that a threshold value of 5 - $10 \cdot 10^{-5}$ m/s^2 for acceleration differences should be applied. This ensures that all outlying accelerations can be removed and the acceleration differences are not caused from errors in the applied gravity-field.

A more elegant and mathematically well-defined method to remove small, temporary occurring outliers from the input data set are wavelet filter techniques, which are based on fast discrete wavelet transformation. Due to their time localizing ability, these are very appropriate for detecting and removing local signal occurrences without effecting the remaining parts of the signal. By means of the fast discrete wavelet transformation the input signal is developed into a consecutive series expansion of approximation signals and detail signals of increasing scales. Fast wavelet transformation is applicable for orthogonal wavelets with compact support (finite number of corresponding filter coefficients). Daubechies wavelets of order 1 (Haar wavelet) and 2 were applied. All local spikes and outliers within the signal are solely mapped to the coefficients on the smallest scales. Considering multiples of the mean signal energy on these small scales, scale-dependent thresholds are computed. By localising the signal points, which correspond to the identified wavelet coefficients, outliers and bad data can be removed from the observation data set. Such wavelet techniques are applied first to the orbit differences between kinematic and reduced dynamic orbits and second to the difference of accelerations derived from the kinematic orbit and from a gravity field model. A comparison on the level of baselines is not necessary since the wavelet-filter enables already the detection of spurious data from orbit differences. For the wavelet-filtering of the accelerations, it proved to be sufficient to develop the reference gravity field model only up to degree 2, see Götzelmann et al. (subm.) Thus it can be ensured at this stage that the signal is not shifted to any structure (of resolution $l > 2$) of the reference field. More details about the applied wavelet-filters can be found in Götzelmann et al. (subm.).

5.2 Robust estimation

The alternative way for data preprocessing in terms of filtering is to use robust methods for parameter estimation, which are less sensitive to outlying observations than least squares estimation. Simultaneously, data weighting is addressed by means of robust estimation.

Gravity field modeling in the acceleration approach is posed as a least-squares parameter estimation problem within the Gauss-Markoff model, which presumes an underlying Gaussian normal distribution. Actually, the errors in the real data are rarely Gaussian normal distributed, and especially in the presence of outliers the probability function will distinctly depart from the Gaussian one. Common least squares is sensitive to gross errors and tends to smear outlying observations by averaging them into the solution. A natural step is to implement parameter estimation methods, whose robustness against spurious observations is superior. According to Huber (1981), robust estimation methods may, similar as least-squares adjustment, be interpreted as maximum-likelihood estimators with a different probability function. An opportunity to attain robust maximum likelihood estimations $\hat{\xi}^{(j)}$ is provided by iteratively reweighting the common least squares solution. Starting with the normal least squares estimation $\hat{\xi}^{(0)} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{y}$ in the first step, the weights $w_{i,i}^{(j+1)}$ of the diagonal weight matrix $\mathbf{W}_d^{(j+1)}$ for each following iteration step are obtained from the residuals $\mathbf{v}^{(j)} = \mathbf{A}\hat{\xi}^{(j)} - \mathbf{y}$ of the preceding iteration step. The weights can for instance be determined with Huber's method: 1 if $|v_i| \leq a$; $a/|\mathrm{v_i}|$ if $|v_i| \geq a$. This means, that all observations, whose residuals lie within the boundary a, are assumed to be Gaussian normal distributed, observations with larger residuals underlie a different probability function. By means of the application of such robust methods, (i) no data preprocessing is necessary since spurious observations are iteratively down-weighted and (ii) data weighting can be implemented easily by means of the estimated diagonal weight matrix in the PCG method. It must be mentioned, that the correlations among the accelerations are neglected in this procedure. However, as mentioned in (Koch, 1996; Xu, 1989), robust methods for uncorrelated data also work well for correlated data. This is confirmed by the following results of robust estimation in comparison to the results of standard least squares estimation including data-preprocessing. For completeness, it must be emphasised that robust methods work, in contrast to the outlier removal and filter strategies, without any other additionally data sources like reduced-dynamic orbits or reference models. Therefore it is guaranteed, that the solution is purely gained from the kinematic orbit data itself and does not display any dependency from the reference signal.

6 Results

Based on the two-years kinematic CHAMP orbit (version 6) of the period March 2002 – March 2004 different gravity field models with application of the strategies explained in the previous section were computed. The gravity field parameters were estimated without any application of regularisation to guarantee an unbiased solution, additionally the accelerations were not reduced from non-conservative disturbing effects. The reason for the latter are results from precedent investigations (Reubelt et al., subm.) of version 3 of the two years kinematic orbit, where the reduction of accelerometer-data worsened the results slightly. This might be due to the fact, that the provided accelerometer calibration parameters are not sufficient to remove the bias and tilt correctly. Here, in future, the inclusion of in-situ-estimation of calibration parameters within the acceleration approach should be investigated, which was not implemented so far.

For the evaluation of the estimated GIS-CHAMP models, comparisons (Fig. 3, Table 1) were drawn to the recently released GRACE gravity field model EIGEN-GRACE02S, which is of superior accuracy for degrees up to

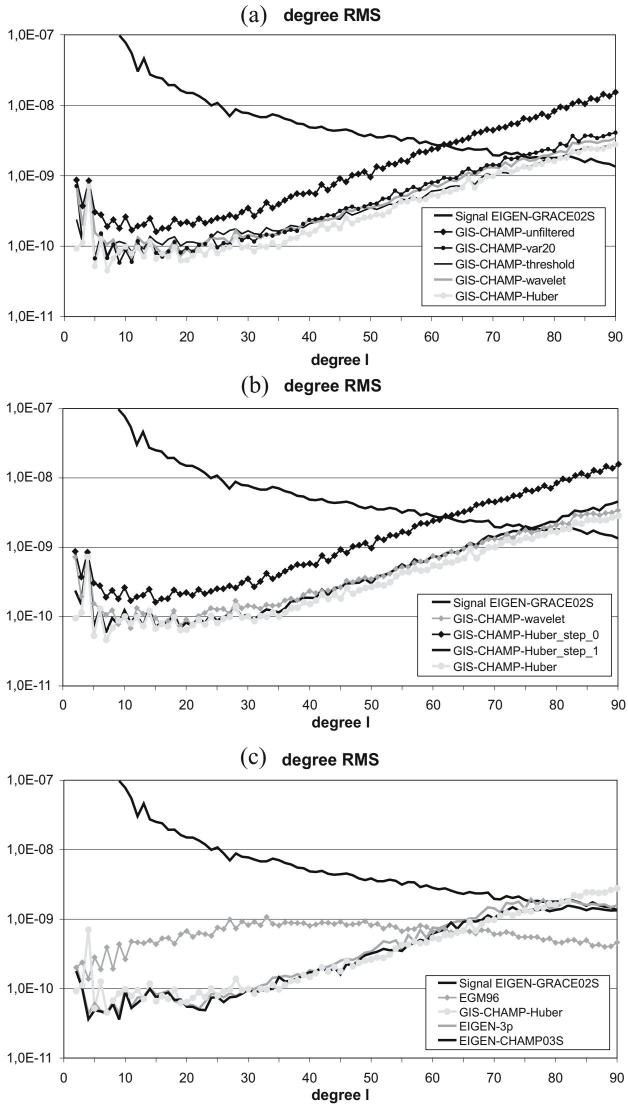


Fig. 3. Validation of different gravity field models GIS_CHAMP by means of a comparison to EIGEN-GRACE02S in terms of degree RMS; (a) comparison of models obtained from unfiltered data, various filtered data and robust estimation; (b) solutions of robust estimation (basic step, first step, final result) compared to wavelet-filtering; (c) result of robust estimation compared to models obtained with the classical approach (from a different observation period!)

100 due to the more sensitive measurement principle. To get an idea of the performance of the acceleration approach, validations of the CHAMP-models EIGEN-3P and EIGEN-CHAMP03S were added, which were estimated from GFZ-Potsdam by means of the classical approach from a time span from July 2000 – June 2003 and October 2000 – June 2003 respectively.

Fig. 3a shows the degree RMS (in comparison to EIGEN-GRACE02S) of different GIS-CHAMP models, which were obtained by application of the outlier removal and downweighting strategies described in the previous section. It can be concluded from these results, that methods for dealing with inaccurate data are very important, since the model computed from completely unfiltered data by means of least squares estimation, GIS-CHAMP-unfiltered, could be significantly improved by the procedures described in the previous section. Already by data-selection in terms of the orbit variances, where about 20% of the orbit data was filtered out (GIS-CHAMP-var20), the accuracy could be explicitly enhanced. A further advance of quality can be gained, especially for degrees > 40, if the wavelet filter is applied to the accelerations computed from the remaining orbit after preselection by means of the orbit variances. In GIS-CHAMP-wavelet, about 5% of the accelerations were additionally eliminated. The improvement by means of the wavelet-filter in contrast to detection by orbit variances can be explained by the fact, that orbit variances are not able to mark all outlying and inaccurate data. A similar result compared to wavelet-filtering can be received by the simple thresholding principle, where a higher accuracy was reached for degrees over 45 accompanied with a lower quality for some lower degrees. The model GIS-CHAMP-threshold (about 20% of the data were filtered out) was estimated by a threshold of coordinates and baselines compared to the EGM96-based reduced-dynamic orbit of 50 cm and 10 cm respectively and by a threshold-value of differences between computed accelerations and EGM96-accelerations of $5{\cdot}10^{-5}$ m/s^2. The best result, outreaching the methods of data preprocessing, especially for degrees 20 - 70, is obtained by means of robust estimation in terms of the Huber method (GIS-CHAMP-Huber, parameter $a = 1.5{\cdot}10^{-5}$ m/s^2). The superiority of robust estimation opposite to data-preprocessing can be explained by: (i) instead of a rigorous threshold all data is used and downweighted according to its accuracy and (ii) the weights are purely gained from the kinematic orbit itself without any additional information. Fig. 3b demonstrates the fast convergence of robust estimation. While the result of the basic step (GIS-CHAMP-Huber_step_0) coincides with the result from the unfiltered orbit (GIS-CHAMP-unfiltered), already in the first step (GIS-CHAMP-Huber_step_1) a comparable accuracy to data preprocessing (here: GIS-CHAMP-wavelet) is reached. With the second step, convergence is almost achieved and only marginal improvements, which won't be visible in the figure, can be gained by further iterations. GIS-CHAMP-Huber corresponds to the model estimated in step 5. Finally in Fig. 3c, a comparison of GIS-CHAMP-Huber and EIGEN-3P/EIGEN-CHAMP3S, estimated by means of the classical method, is displayed. All three models are of similar accuracy. GIS-CHAMP-Huber is slightly superior for degrees 45 – 75 and marginally worse for degrees < 30 compared to EIGEN-CHAMP03S, which is the final version of EIGEN-3P. For completeness, it must be kept in mind that EIGEN-CHAMP03S is estimated from a longer, but earlier observation period, where the satellite was in a higher orbit and thus less sensitive for higher degree terms. This might explain, why GIS-CHAMP-Huber is closer to EIGEN-GRACE02S for the higher spherical harmonic degrees. The remarkable worse accuracy for the very low degrees (2-6) of the GIS-CHAMP models in Figs. 3a,b,c was confirmed by other groups working with the same kinematic orbits, which leads to the assumption that this is an effect due to the data and not a problem related to the applied method. In addition to the CHAMP-models the degree RMS of the most accurate pre-CHAMP global geopotential model, EGM96, are illustrated in Fig. 3c. A clear increase of accuracy of the CHAMP-models in comparison to EGM96 is visible for the coefficients up to degree 60 or 65, which demonstrates the progress in gravity field determination achieved with CHAMP.

Table 1. RMS-value, area-weighted RMS (by $\cos(\phi)$) and maximum absolute value of the geoid-differences between various gravity field models and the reference model EIGEN-GRACE02S, developed up to degree and order 70

model / error (m)	EIGEN-		GIS-CHAMP-			
	CHAMP3p	CHAMP03S	var20	threshold	wavelet	Huber
geoid-RMS	0.356	0.233	0.281	0.211	0.253	0.189
weighted RMS	0.282	0.235	0.305	0.224	0.275	0.204
max. deviation	2.664	1.575	1.258	1.037	1.360	0.915

Table 1 displays the RMS values, the area-weighted RMS values and the maximum absolute values of the geoid differences between the GIS-CHAMP/EIGEN-CHAMP models and EIGEN-GRACE02S. The geoid differences were computed up to degree and order 70 (signal-to-noise ratio per degree is ≥ 1 for all models) on a 1° x 1° grid. Since the area of 1° x 1° grids decreases with shortening distance to the poles, additionally to the normal 1° x 1° - RMS the area-weighted RMS is regarded in order to diminish the influence of polar and near-polar data. If the normal and the area-weighted RMS are similar, the distribution of the geoid differences is quite similar, as it is the case for EIGEN-CHAMP03S. In contrast, the area-weighted RMS of EIGEN-3P is much higher than its normal RMS which is caused by larger differences around the poles. The normal RMS-value of the GIS-CHAMP models is slightly higher than their area-weighted RMS, which points to a lower accuracy at the equatorial areas. This can be explained as follows: (i) since the CHAMP groundtrack converges towards the poles more data per area is available. This means that an area in polar regions gets a higher weight in the solution if all observations are assumed to have equal quality. (ii) more kinematic orbit data was filtered out or downweighted at the equatorial areas.

The interpretation of Figs. 3a,b,c is confirmed by Table 1. The reached accuracy of the GIS-CHAMP-models with robust estimation (weighted RMS of 20.4 cm) is superior to data-preprocessing methods, the best outlier-removal strategy is the simple threshold method (weighted RMS of 22.4 cm). Concerning the weighted RMS, GIS-CHAMP-threshold is of similar accuracy and GIS-CHAMP-Huber is of slightly higher accuracy than EIGEN-CHAMP03S. A very interesting point is the maximum geoid differences. Obviously, the inclusion of outlier removal or downweighting strategies in the acceleration approach reduces larger geoid errors. Even the data selection by means of the orbit variances leads only to a maximum deviation of 1.258 m in comparison to 1.575 m at EIGEN-CHAMP03S. The high performance of robust estimation by means of downweighting inaccurate data is supported by a maximum deviation of only 0.915 m of the corresponding model.

7 Conclusions/Outlook

It has been demonstrated within this contribution and by other groups (Földváry et al., 2005; Mayer-Gürr et al., 2005), that models of the Earth's gravitational potential recovered by gravity field analysis based on kinematic CHAMP satellite orbit data can compete with those models generated by classical integration of the variational equations. A major reason for this is the outstanding quality of currently available kinematic orbits. The capability of kinematic orbit analysis in terms of a point-wise acceleration approach can further be enhanced, if methods are employed, which are either able to filter or to downweight single spurious observations. Exceedingly satisfying results are obtained if robust estimation is applied, which requires neither additional preparatory data preprocessing nor any reference information. Exploiting the full primary data set without rejecting any observation, the quality of models recovered by data-preprocessing was exceeded within a few iteration steps.

Reliable detection of outliers is also achieved by application of the wavelet filter or the simple threshold method. Although the accuracy of the resulting gravity field models remained inferior to robust estimation, filter methods are advantageous with respect to computational effort as no repeated iterative solution of the system of normal equations is required.

The second order numerical differentiation doesn't seem to be the weak point of acceleration approaches due to the correlation of the orbit data and the high accuracy of the baselines. The algorithm can be classified as fast, since the system of equations is linear and numerical differentiation is applied to the data instead of integration. The analysis can be carried out on a standard PC by means of the iterative PCG method, which guarantees fast convergence and is able to cope with restricted memory capacity.

It has been demonstrated in this contribution, that the implemented method of the acceleration approach is a well-suited procedure for gravity field determination. Future investigations and validations can address the following topics: (i) in-situ-estimation of calibration-parameters within the acceleration approach and (ii) external validations based on terrestrial data (GPS/leveling, gravity data, ...).

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