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Observation of the Earth System from Space

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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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GEOTECHNOLOGIEN

Contents

Part I

CHAMP
CHAllenging Minisatellite Payload

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.

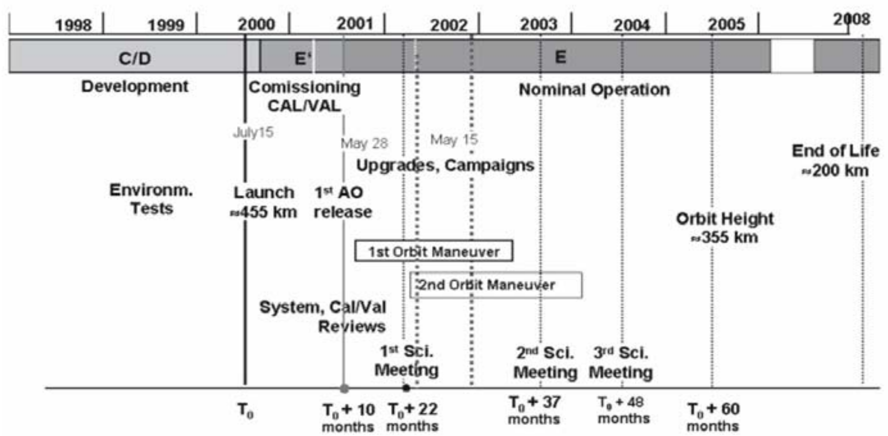

Fig. 1. CHAMP mission timeline.

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 $<3 \times 10^{-9}$ 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

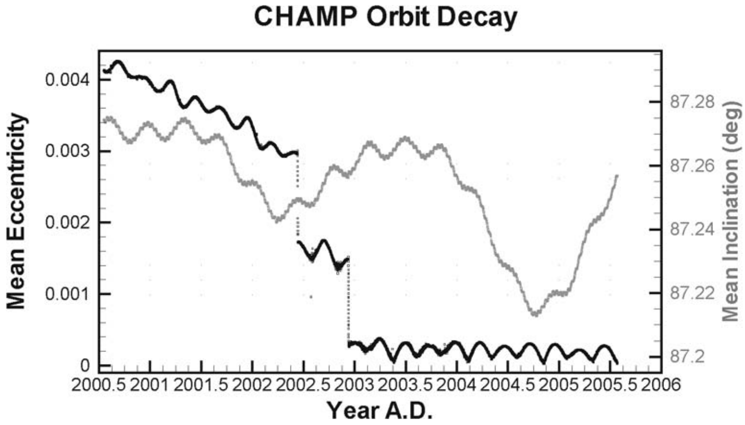

Fig. 2. Changes of mean eccentricity and inclination since launch.

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.

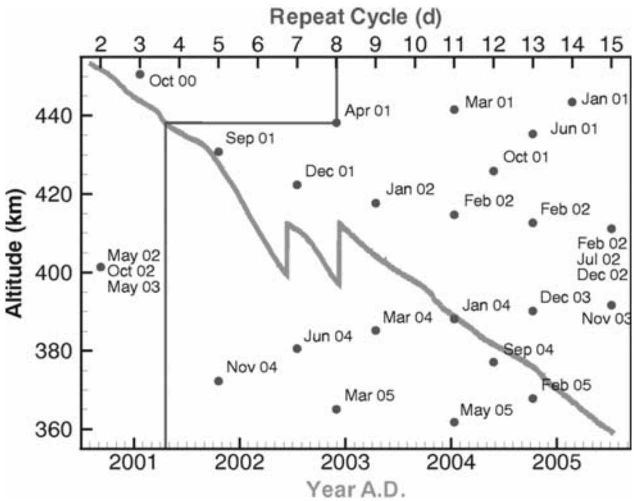

Fig. 3. Repeat cycles (in days) through which CHAMP passed since launch.

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-

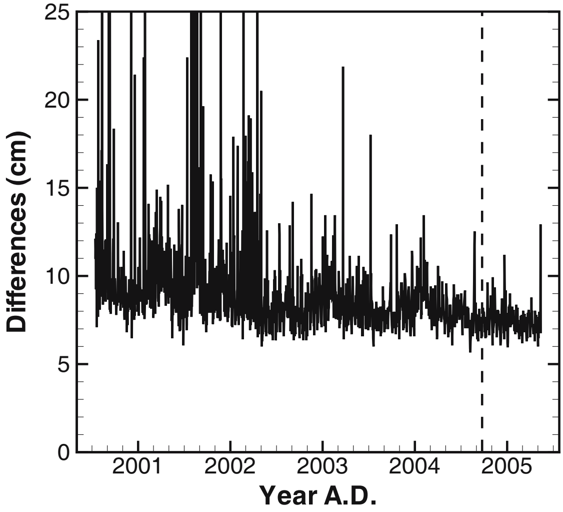

Fig. 1. Comparison of the GPS RSO to the IGR

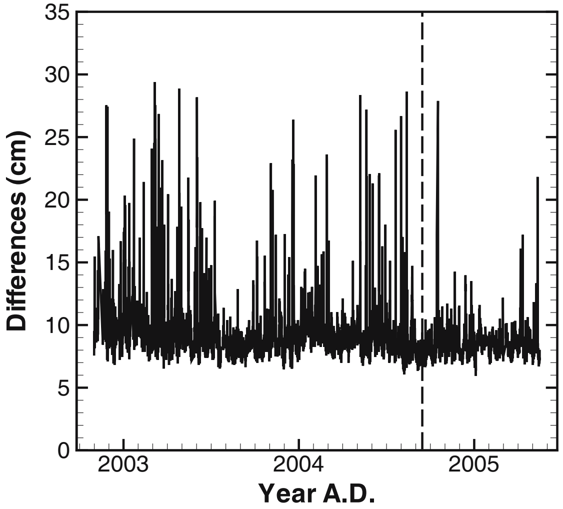

Fig. 2. Comparison of the GPS USO to the IGR

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

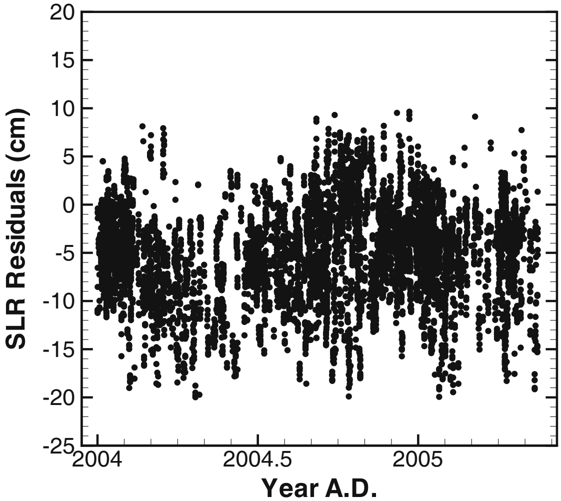

Fig. 3. SLR validation of the RSOs of PRN G05 and PRN G06

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.

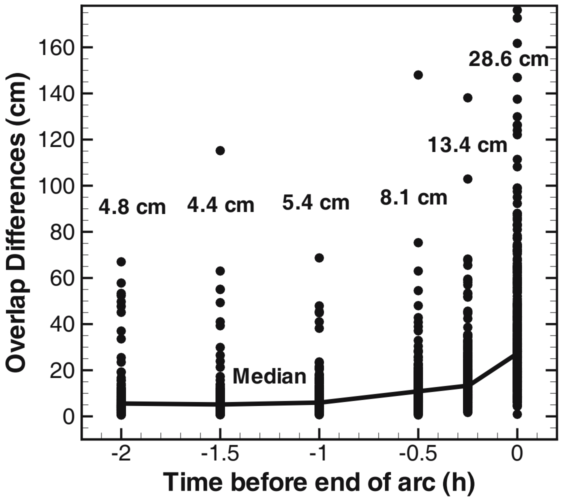

Fig. 4. CHAMP USO orbit accuracies

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.

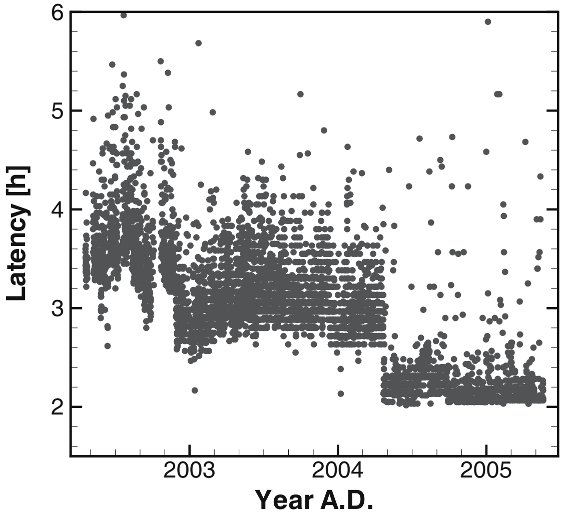

Fig. 5. CHAMP USO latencies

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.