SLR and the CHAMP Gravity Field Mission

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Abstract

The restitution of the CHAMP orbit during launch and early orbit phase in a fast and reliable manner was only possible on the basis of data from two microwave tracking systems: the skin radar tracking and the high-low GPS-CHAMP SST tracking, not yet calibrated. Soon SLR tracking joined in and the on-board GPS data could be calibrated in the following weeks with the help of the SLR data. Nowadays, during the operational phase, SLR data are used to evaluate the precise orbit recovery before solving for the gravity field and to assess the quality of the solution. Based primarily on CHAMP observations, a new class of gravity field models can be computed. The EIGEN-1S and the EIGEN-2 models are published, both showing an order of magnitude accuracy improvement in comparison to former global gravity models from space. As such the long wavelength geoid becomes recoverable from just a few months of CHAMP data only and, by this, temporal variations of the geoid will become detectable by evaluating the full mission time span.

The CHAMP Mission

CHAMP (CHAllenging Minisatellite Payload) is a German multi-purpose geoscientific mission with a complementary payload in order to study the global geopotential fields of the Earth and to perform atmospheric/ionospheric sounding. The main mission objectives are the long wavelength Earth gravity field mapping and investigations of the Earth's magnetic field with respect to both the main and the crustal field components as well as contributions from ionospheric currents. For this reason the satellite is equipped with payload packages for gravity and atmospheric research and a dedicated magnetometry instrumentation consisting of both scalar and vector magnetometers. This magnetometry package is located on a four meter long deployable boom (for the satellite configuration see Figure 1).

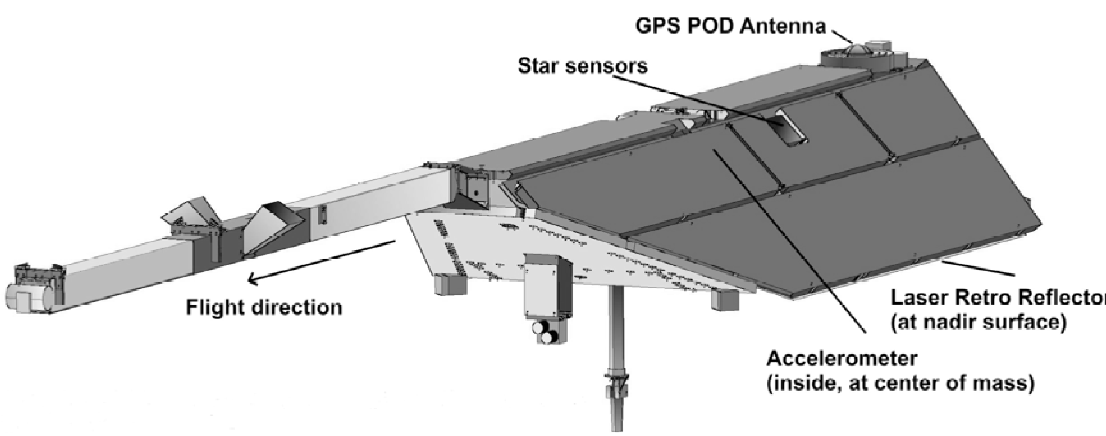

Figure 1. CHAMP satellite configuration.

The gravity and atmospheric payload consists of

- a state-of-the-art GPS receiver with a set of four antennas: a zenith choke ring antenna for Precision Orbit Determination (POD), a helix antenna for GPS radio-occultation measurements in anti-velocity direction, a backup patch antenna which can serve for both POD and occultation measurements, and a nadir-directed helix antenna for a GPS altimetry experiment
- a highly sensitive triaxial electrostatic accelerometer which is located at the centre of gravity of the satellite and measures all non-gravitational forces acting on the satellite body with high accuracy
- a Laser Retro Reflector (LRR) consisting of four prisms in a dense package which serves as an external reference for the radiometric orbit determination by means of GPS measurements [*Grunwaldt et al., 2000*].

In order to fulfil the tasks of a global field mission with optimum performance CHAMP has to fly on a low, nearly polar orbit with low eccentricity which is expected to decay over the anticipated mission lifetime of five years by means of the air drag finally to about 300 km altitude. Additionally, the orbit has to deviate from a sun-synchronous one in order to drift through all local times which allows for an unambiguous separation of solar-driven, local time and seasonal variations from other geophysical effects. The satellite is actively stabilized with the magnetometry boom in flight direction and the LRR pointing towards nadir by means of magneto-torquers and cold gas thrusters within a deadband of ±2° in all three axes. CHAMP has a high degree of onboard autonomy which reduces the command and control efforts to a minimum. The software of most of the payload instruments can be corrected or even exchanged in-orbit by means of telecommands thus making the mission profile even more flexible. The total amount of raw data delivered by the continuously running scientific instruments is more than 100 Mb/day.

Launch and Early Orbit Phase

The CHAMP satellite was launched on July 15th, 2002 from the cosmodrome Plesetsk in Russia aboard a COSMOS launch vehicle. About thirty minutes after the lift-off time of 12:00 UTC the CHAMP satellite was separated from the second stage of the COSMOS launcher and injected into its low-altitude (~454 km), high-inclination (~ 87.3 degree) and almost circular orbit. In the following so-called early orbit phase, approximately the first 24 hours after separation, the satellite operations consisted of orbit monitoring and the activation of all satellite systems and successive activation of science instruments. Until the planned switch-on of the GPS receiver, approximately 24 hours after separation, no accurate GPS tracking data was available and orbit determination for the mission operations as well as for the generation of orbit predictions for the ILRS ground station network was based on less accurate skin radar tracking data. Successful SLR tracking could not be initiated before the incorporation of ephemerides data from the so-called GPS navigation solution of the GPS flight receiver.

Two types of radar tracking information were used in the early orbit phase. One kind was the so-called angle tracking data of the telemetry stations of the NASA Polar Network (Svalbard, Poker Flat, Wallops Island, McMurdo) and the two DLR facilities (Neustrelitz, Weilheim) in Germany. Angle tracking data are azimuth and elevation angles of the S-band telemetry antennae measured during the passes at the individual telemetry sites. Such data were treated similar to optical data from star cameras (i.e., in terms of right ascension and declination) within the GFZ orbit determination software EPOSOC. The accuracy of angle tracking data is given at about 1.5 arc minutes, which corresponds to approximately 200 m in position in the zenith above the telemetry station. The second type of radar tracking data consisted of so-called two-line elements (TLE) for CHAMP computed at a German military radar station located near Bonn/Germany (FGAN). At GFZ, these TLEs were transformed into 8-minute-long short-arc ephemerides and were incorporated into orbit determination (OD) as pseudo-observations. The accuracy of TLE-derived ephemerides was assessed to be about 300 m in position derived from the pre-flight studies and experiences gathered during the GFZ-1 mission. Based on these two types of radar tracking data continuous OD and orbit prediction for satellite operations and orbit control could be conducted with sufficient accuracy. RMS values of the orbital fit of the radar tracking data indicated an orbit accuracy of a few hundred meters. Successful SLR tracking however was eventually initiated after the incorporation of the first available data of the so-called GPS navigation solution from the onboard GPS receiver (switch-on July 16th, 2000 12:57 UTC). The accuracy of the GPS-NAV data of the order of 30 meters significantly improved the accuracy of the orbit predictions. Finally, the first SLR pass was observed on July 17th, 2000 at 00:11 UTC at the SLR station 1884 at Riga in Latvia.

Soon after the continuous delivery of the GPS navigation solution was established, a fully automated orbit prediction processor based on the GPS-NAV and precise SLR was set up, yielding a quite remarkable amount of SLR tracking data throughout the CHAMP mission. To further improve the performance or to simply maintain it in view of lower orbital altitudes, several refinements were made: adoption of a CHAMP-tailored gravity field, software upgrade of the GPS flight receiver improving the accuracy of the onboard derived positions from about 30 to 6-7 meters, refined parametrization in POD, and routine operations of a high-latitude dump station in Ny Alesund in Spitzbergen. For more details on the development and status of the orbit prediction processor see *Schmidt et al.* [2000] and *Schmidt et al.* [2002].

CHAMP Gravity Field Solutions

The satellite CHAMP with its payload components (GPS receiver and accelerometer) and its orbit configuration (low altitude at 87 deg inclination) is the first satellite especially dedicated to probing the Earth gravitational potential. With this configuration the CHAMP mission has the following advantages compared to all former low-Earth orbiting satellites being exploited for global gravity field recovery:

- GPS-CHAMP satellite-to-satellite tracking (cf. Figure 2) provides a continuous coverage of the orbit with multi-directional ranging observations allowing a complete and homogeneous recovery of the gravitational orbit perturbation spectrum contrary to one-directional ground-based tracking of only short orbit fragments during station over-flights.
- The 3-D accelerometer that is accommodated at the center of mass of the satellite does not sense gravitational accelerations but non-conservative (surface) forces due to air-drag and radiation pressure. Subtracting the observed surface force induced orbit perturbations from the GPS measured overall orbit perturbations delivers the purely gravitational signal along the orbit. Without an accelerometer one would have to model the surface forces. But then, especially with regard to air-drag at low altitudes, CHAMP's accuracy requirements could not be met because atmospheric density models do not account for short-time density fluctuations.
- The orbit configuration of CHAMP guarantees for a free-flying satellite a minimum attenuation with altitude of the Earth's gravitational signal, and a complete coverage of the Earth's surface with ground tracks thanks to the almost polar orbit.

Global gravity field recovery with CHAMP relies on the analysis of gravitational orbit perturbations. For this purpose the CHAMP orbit is numerically integrated over successive 1.5 d arcs using up-to-date standards for the dynamic and reference frame related models and the accelerometer observations (at each 10 s integration step) for the non-conservative forces. The gravitational force is modelled by an initial global gravity field model. The integrated orbital arcs are then fitted to the observations (GPS satellite-to-satellite code and phase observations every 30 s from up to eight GPS satellites simultaneously) in a least squares adjustment solving for the arc-dependent parameters, i.e., the initial state vector, accelerometer calibration parameters (bias and scale factor per axis and arc), GPS phase ambiguities, receiver clock corrections, and empirical parameters to model unknown linear accelerations induced by attitude thruster firing events (about one event per every 10 min). After solution convergence, the normal equation system again is set up, but this time also taking into account the partial derivatives for the common parameters, representing the gravitational geopotential. These are the Stokes' coefficients C_{lm} and S_{lm} of a spherical harmonic expansion of the potential, complete up to degree/order 120 and up to degree 140 for the sectorial terms and the CHAMP resonant orders. The solution space also includes some 100 parameters to model the time-varying diurnal and semi-diurnal ocean tidal potential. The arc-wise created normal equation systems are added to form one resulting normal equation systems which then is solved by inversion to provide the almost 16,000 spherical harmonic coefficients of the Earth's gravitational potential.

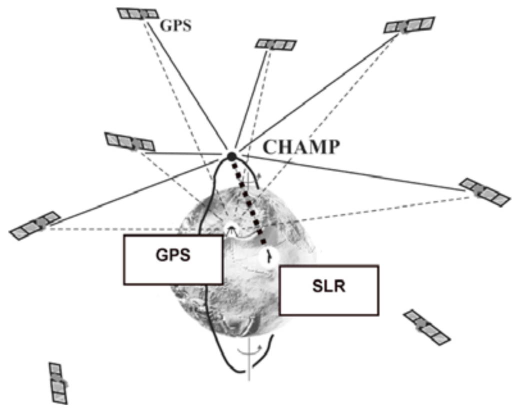

Figure 2. High-low GPS-CHAMP satellite-to-satellite and ground based GPS and SLR tracking.

Before inversion, the equation matrix is stabilized using stochastic *a priori* information following Kaula's degree variance model for all terms with a degree larger than 29. To be able to perform CHAMP's orbit adjustment, the orbits and clock parameters of the GPS satellites are required. These are adjusted beforehand using GPS ground station data and then are fixed in the subsequent treatment of the CHAMP GPS satellite-to-satellite tracking data.

It soon turned out that with CHAMP it became for the first time possible to resolve the Earth's gravity field from space on a global scale with only one satellite and based on only a short observation period. The first CHAMP-only global gravity field solution incorporates three months' worth of CHAMP GPS and accelerometry data out of the year 2000 and is called EIGEN-1 [*Reigber et al.,* 2003a]. The acronym EIGEN means 'European Improved Gravity model of the Earth by New techniques'. The follow-on model EIGEN-2 [*Reigber et al.,* 2003b] additionally incorporates three months of CHAMP data out of the year 2001 and constitutes a considerable improvement with respect to EIGEN-1, also because all data were reprocessed with a more appropriate procedure to circumvent the failure in one electrode of the radial channel of the accelerometer.

Figure 3 shows the geoid signal and (formal) error degree amplitudes of the EIGEN-2 model and, for comparison, the signal spectra of the models GRIM5-S1 [*Biancale et al.,* 2000] and EGM96 [*Lemoine et al.,* 1998]. GRIM5-S1 is the latest pre-CHAMP satellite-only model (based on tracking data from 24 satellites and multi-year tracking records), whereas the pre-CHAMP model EGM96 includes both satellite data and surface gravity data from altimetry and gravimetry, i.e., representing the complete geoid spectrum over the degrees displayed in Figure 3. It can be deduced from Figure 3, that the resolution of the CHAMP-only model extends to degree/order 45, whereas with GRIM5-S1 full resolution is attained only up to degree/order 30. Beyond these limits the resolution fades out due to signal attenuation with satellites' altitude (signal-to-noise ratio smaller than 1 above degree 55 for the CHAMP solution).

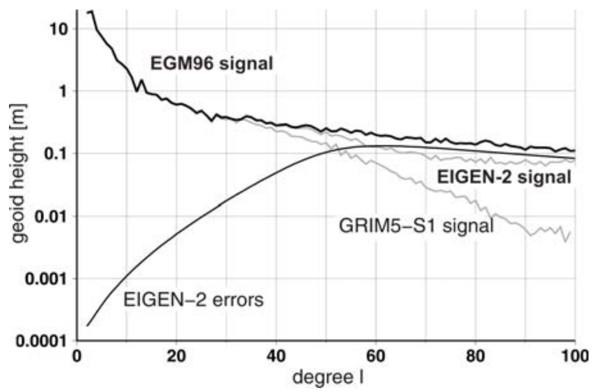

Figure 3. Signal/error amplitudes per degree in terms of geoid heights.

Figure 4 shows the geoid difference amplitudes as a function of maximum degree for EIGEN-2 versus EGM96 and for two CHAMP-only subset solutions CHAMP00 (data out of the year 2000) versus CHAMP01 (data out of the year 2001). For comparison, the spectra of the differences GRIM5-S1 versus EGM96 and of the (formal) errors of EIGEN-2 are also given. Figure 4 demonstrates the enormous gain in accuracy in global gravity field recovery obtained with CHAMP.

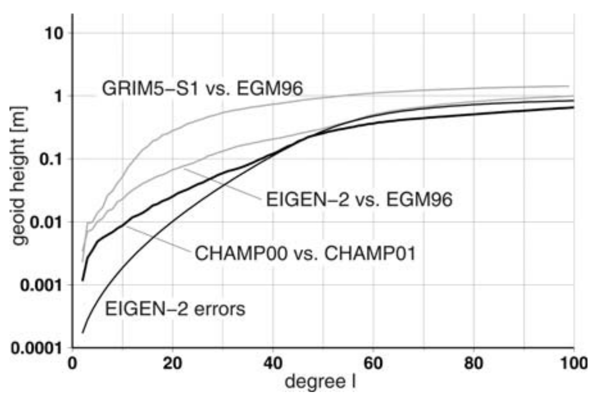

Figure 4. Difference/error amplitudes as a function of maximum degree in terms of geoid heights.

At degree 40, corresponding to a half wavelength resolution of 500 km at the Earth's surface, the two CHAMP subset solutions differ by not more than 10 cm in terms of geoid heights, which is an improvement by almost one order of magnitude compared to the latest pre-CHAMP satellite-only model GRIM5-S1 (cf. GRIM5-S1 vs. EGM96). The discrepancy between the two spectra EIGEN-2 versus EGM96 and CHAMP00 versus CHAMP01 may be attributed to long wavelength errors in the pre-CHAMP model EGM96, as the two CHAMP-only subset solutions have no data in common.

The use of a CHAMP-only model in dynamic POD of satellites other than CHAMP reveals a degradation (factor of 2) in performance for satellites at altitudes below 1000 km like Starlette, Stella, ERS, GFZ-1 and Envisat with respect to the use of the multi-satellite model GRIM5-S1 (incorporating tracking data from these satellites) because CHAMP is not capable to resolve higher degree resonant terms specific to these satellites' orbits. For satellites at altitudes above 1000 km, like Ajisai and LAGEOS, both gravity field models perform equally well. The combination of the CHAMP-only gravity field model EIGEN-1 with the GRIM5-S1 normal equation system, resulting in the solution EIGEN-1S [*Reigber et al.,* 2002], eliminates the disadvantage of using a CHAMP-only model in general POD, but on the other hand slightly degrades the excellent accuracy of the CHAMP-only model in representing the geoid and the Earth gravity field.

With CHAMP as a forerunner of the American/German GRACE mission (launch May 2002) and ESA's GOCE mission (planned for 2006) single-satellite global gravity field recovery has become possible with an increased resolution and a largely increased precision (10 cm geoid up to a half wavelength resolution of 500 km) compared to all former satellite-only models. These capabilities are especially important for applications in oceanography to resolve the dynamic sea surface topography with altimetry and for the resolution of large-scale non-tidal environmental temporal gravity field variations, presently being under study.

The role of SLR in the course of developing a gravity field model is twofold. Before the normal equations per arc are set up as described above, the arcs are subjected to a POD with the objective to get all data free of blunders. The orbital fit of the SLR measurements serves as an independent assessment of orbit quality. These quality values serve also as a measure of the quality of the individual normal equation matrices. The second and more important role of SLR data lies in assessing the quality of the gravity field model solutions. For this, the new model is employed for POD of a variety of geodetic satellites besides CHAMP. The orbital fits are compared relatively to PODs for the same satellites with identical data sets and identical parametrizations but with different gravity field models. Improved qualities of the new models show up in decreased RMS values of the orbital fits particularly for the lower altitude satellites. For example, with the GRIM5-S1 model, CHAMP SLR residuals show a root mean square of 80 cm, with EIGEN-1S 7 cm, and with preliminary EIGEN-2S versions approximately 5 cm.

Further Developments

With the CHAMP mission the fast delivery of SLR data was successfully implemented. The GRACE mission and future LEO missions take benefit thereof. The design of the laser retroreflector on-board CHAMP turned out to be very efficient and was also adopted for the GRACE satellites. Future applications of GPS receivers aboard LEO satellites will tend towards fast to real time availability of highly accurate orbits. SLR will offer a commonly accepted base for calibration and validation. For the full integration of SLR during all mission phases it will be necessary to improve the availability of short latency data or even move towards real time data streaming.

Conclusions

CHAMP commences a new era of applications for the SLR technique, i.e., tracking of LEO satellites that are equipped with on-board GPS receivers for high accuracy and high density orbit monitoring. This dense tracking is of particular advantage for gravity field model development, as with just some months of data, models are derived with resolutions and accuracies never reached in the decades before CHAMP. SLR plays an important role in the early phases of such missions as an additional tracking system that supports orbit maintenance and validation and calibration of the on-board GPS receiver. Later on, SLR becomes even more important for the assessment of POD quality and for the assessment of the quality of gravity field model solutions.

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