Identification of Processing and Product Synergies for Gravity Missions in View of the CHAMP and GRACE Science Data System Developments

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ABSTRACT

At GeoForschungsZentrum Potsdam (GFZ) currently the orbit and gravity science data system for CHAMP is in the validation phase and will shortly begin with the nominal operations. In parallel at GFZ, in cooperation with University of Texas Center for Space Research and NASA's Jet Propulsion Laboratory, also the GRACE science data system is under development. For CHAMP as well as for GRACE the science data systems consist of the complete processing chains from raw data to precise orbits and gravity fields, with several intermediate product levels, and separate information systems and data centers for each mission. GRACE developments are based to a large extent on the CHAMP heritage in order to take advantage from synergies between both missions.

Synergy effects can also be identified between the CHAMP/GRACE developments and the planned GOCE processing systems for products in various processing steps. These are:

- Reduction of high frequency (shorter than monthly) gravity variations in CHAMP, GRACE and GOCE observations from mass re-distributions in, on and above the Earth (atmosphere, ocean, hydrology as main sources). Experiences gained during CHAMP and GRACE data processing are fully applicable to GOCE data reduction.
- Reduction of monthly to seasonal gravity variations in GOCE observations. The GOCE mission profile foresees two 6 monthly measurement periods separated by 5 months. This means, that GOCE products will contain seasonal effects, which have to be reduced. The GRACE science data system will produce monthly gravity solutions, which could be basis for the GOCE data reduction of monthly to seasonal effects.
- Combined CHAMP/GRACE/GOCE gravity model. All missions are complementary in their mission profiles and their time-space sampling and can provide valuable information in different spectral and spatial domains. The combination of all data, which have to be processed by using the same standards, enables the determination of an ultimate static gravity field model after completion of the GOCE mission.
- CHAMP and GRACE information and data system developments could be the basis for a similar system to be designed for GOCE. A centralized archive and user interface for all the gravity mission data and products facilitates the user access and information and would help to attract as many users as possible to all the missions.

INTRODUCTION

With the launch of CHAMP [1] in July 2000 and the upcoming GRACE [2] and GOCE [3] missions, planned to be launched end of 2001 and end of 2005 respectively, a new era of gravity field determination from space will begin. Table 1 summarizes the baseline mission scenarios for the three missions. From the scenarios it immediately becomes obvious, that all three missions are to a large extent complementary, what concerns the objectives, the instrumentation, the orbit configuration and the processing and archiving elements. In the following chapters synergies between these missions in three categories are identified more detailed. These three categories are:

1. Mission scenario synergies, related to their sequence, their orbital parameters and their predicted performance.
2. Processing and archiving element synergies, related to the ground segments of the three missions and their operational performance.
3. Data processing synergies, related to specific processing tasks to be performed for all missions in a similar way.

Table 1: CHAMP, GRACE and GOCE Mission Parameters and Characteristics

Mission	CHAMP	GRACE (2 Satellites)	GOCE
Observation Period (planned)	7/2000-2005	11/2001-2006	2006-2007
Inclination [degree]	87.277	89	96.5
Eccentricity	0.004	<0.005	<0.0045
Initial Semi Major Axis [km]	6823	6843	6613
Height Decay during Mission Lifetime [km]	460-300	480-300	250 (constant)
Main Mission Objectives	Gravity Field (static and time variable) Magnetic Field Atmospheric Profiling	Gravity Field (static and time variable) Atmospheric Profiling	Gravity Field (high resolution static)
Primary Instruments	GPS Receiver 3-Axis Accelerometer Fluxgate Magnetometer Overhauser Magnetom. Digital Ion Driftmeter	Microwave Ranging System GPS Receiver 3-Axis Accelerometer	3-Axis Gradiometer GPS Receiver
Processing & Archiving	GFZ Potsdam	GFZ Potsdam Center for Space Research University of Texas (UTCSR) NASA Jet Propulsion Laboratory (JPL)	ESA European GOCE Gravity Consortium (EGG-C)

MISSION SYNERGIES

Error predictions for the CHAMP, GRACE and GOCE missions show an improvement in accuracy and in spatial resolution by including observation data for each mission to the previous solutions. This can be expressed by accumulating the best individual error degree variances for each degree to cummulative geoid height errors. For example the final geoid accuracy after the GOCE mission in terms of the cummulative geoid height error is composed by the error degree variances from GRACE (up to approximately degree 60), from GOCE (between degree 60 and approximately 270) and from a state of the art high resolution gravity model (above degree 270). Figure 1a shows the square root of the individual error degree variances, while figures 1b and 1c show the cummulative geoid height errors for combinations of the missions in their sequence of launch.

Combining table 1 and figures 1a-c the following mission synergies can be identified:

- The sequence of missions enables a step by step improvement of the gravity field. CHAMP is the first operational high-low satellite-to-satellite tracking (SST) and accelerometer mission and will provide a strongly improved long wavelength gravity field as starting point for GRACE data analysis. GRACE as first low-low SST and accelerometer mission will provide a further improved medium wavelength gravity field as basis for GOCE, which is the first space gradiometer mission. GRACE and GOCE together will provide the ultimate gravity field accuracy by combining GRACE long wavelengths with GOCE medium and short wavelength solutions.

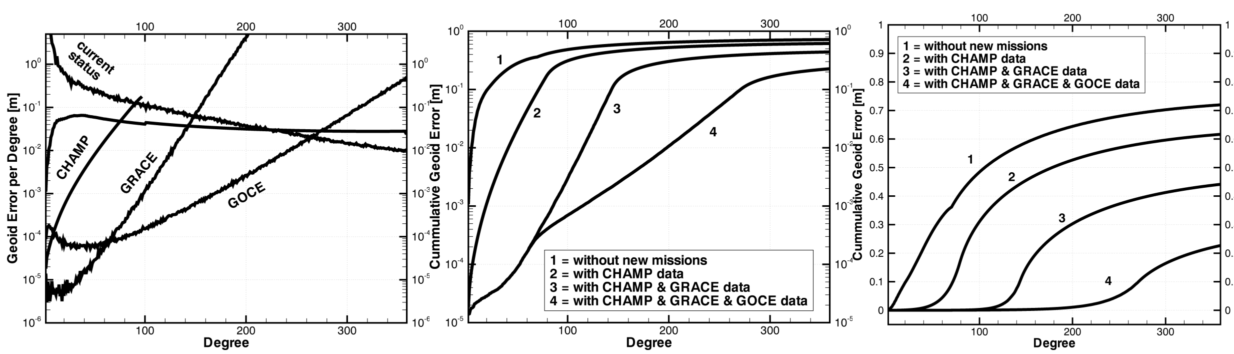

Figure 1: Predicted Performance of Gravity Field Missions (from left to right): a) Square Root of error degree variances, b) cummulative geoid height error logarithmic scale, c) cummulative geoid height error linear scale.

- The sequence of missions enables a step by step gain in data analysis expertise, especially what concerns the accelerometer (gradiometer) behavior in space.
- Overlapping observation periods especially for GRACE and GOCE enable the reduction of monthly to seasonal gravity variations in GOCE observations by using monthly long wavelength GRACE gravity field solutions. The seasonal bias in GOCE observations due to the mission profile (6 months observations, 5 months hibernation, 6 months observations) requires a good knowledge of the seasonal gravity field variations, which are determined with GRACE.
- Due to the different inclinations of all three missions, the polar gap in GOCE can be filled with CHAMP and GRACE observations. This represents a strong synergy of the missions, because especially in the Antarctic area the coverage and quality of surface and airborne gravity observations is insufficient.

PROCESSING AND ARCHIVING ELEMENT SYNERGIES

For each mission a separate processing and archiving element is in operation, under development or planned. These so-called science data systems are structured in different ways, such that mission specific features are reflected in their organization. While the CHAMP science data system was developed by a single institution (GFZ), the GRACE and GOCE science data processing systems are developed in a cooperation between various partners. The following list summarizes the tasks and characteristics of the processing systems for each mission.

- CHAMP science data system: Responsible for operating the orbit and gravity field, the magnetic and electric field and the atmosphere processors. Results are products in different levels, which are finally stored in the product archive. The science data system is supported by the science operation system, responsible for science data decoding, science data control and mission to science operation interface. The science data system is linked to the CHAMP information system and data center (ISDC), responsible for long term products archiving and the user interface.
- GRACE science data system: Developed and operated by GFZ, UTCSR and JPL in a cooperative effort [4]. Generation of gravity field products from level 0 (raw data) via level 1 (corrected and filtered instrument data) to final level 2 products (gravity field solutions). Long term archiving of all products in two project archives (GFZ and JPL). Details of individual tasks see figure 2.
- GOCE science data system: The GOCE science data processing system is separated into two major elements. The processing and archiving element located at ESOC, which is responsible for level 1 products processing (corrected instrument data including precise orbit), archiving and delivery to the scientific consortia [3]. The European GOCE Gravity Consortium (EGG-C), which is responsible for computing the GOCE gravity field products [6].

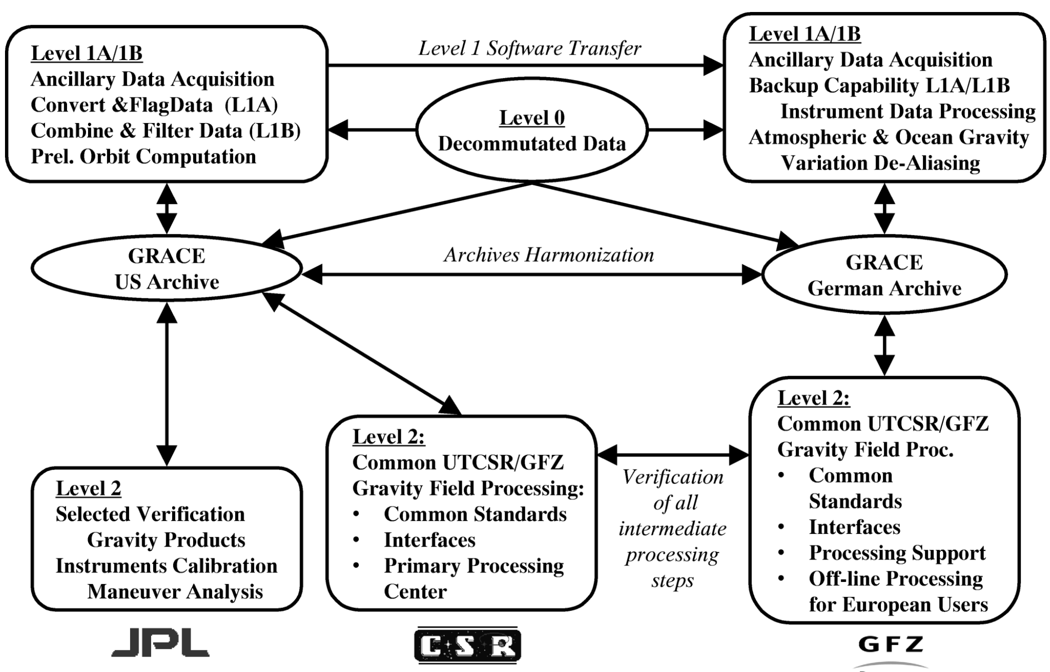

Figure 2: Organization of the GRACE Science Data System with identification of tasks for all contributing partners

For development of the GRACE science data system at GFZ, synergies with developments already made for the CHAMP processing system have been identified and are taken into account.

- Archives: Archiving, retrieval and user access procedures, which are based on a data base system and a tape library, have been developed for the CHAMP-ISDC. For product definition the quasi standard DIF format (directory interchange format) is used. The GRACE-ISDC is based on these CHAMP developments by using the same archiving standards and procedures. The GOCE EGG-C products archive also could be based on these developments.
- Processing Software: CHAMP processing strategy and Software (e.g. for high low SST observations and accelerometer preprocessing) partly can be adopted for GRACE as well as for GOCE data analysis. Expertise gained during data analysis of one mission significantly contributes to the development of the processing system for the other missions. Each mission provides new insights for data analysis of follow-on mission.

Similar synergies can be identified for the GOCE science data system. Expertise gained during the CHAMP and GRACE operational phases will contribute significantly for the GOCE science data system development.

DATA PROCESSING SYNERGIES

There are existing data processing synergies for processing data of similar type, as for example accelerometer data and high low SST observations, or for processing ancillary data in the same way for all three missions. As one specific topic, where a lot of synergies between all three missions are obvious, the processing of time variable effects in the gravity field is identified. In this chapter especially high frequency gravity variations due to atmosphere and ocean mass variations are investigated. Both have impact on all three gravity field missions. Seasonal effects are shortly described, because they have impact on the GOCE gravity field solution, due to the mission profile.

Problem Definition

Mass variations in, on and above the Earth's surface cause time variant gravity field forces acting on the orbiting satellites. These time varying forces have to be taken into account during data processing, if they are not eliminated by repeated observations within short periods. Due to the mission profiles this generally is not the case. Therefore, the effect has to be removed prior to or during the gravity field determination process. For computing these time variations in the gravity field mainly external data sources have to be used. In case of the seasonal effect for GOCE, monthly gravity field solutions, as they are planned for GRACE, could be used for data reduction. The following sources for gravity field variations are known:

- High frequency variation sources: Tides (improved tide models are necessary for all missions); Atmosphere; Oceans; Continental water (snow, ice, hydrology).
- Seasonal variation sources: Atmosphere; Oceans; Continental water; Ice mass

Figure 3a shows the effect of some of these mass variations in the gravity field in terms of degree standard deviations in comparison to the expected performance of the three gravity field missions. It clearly becomes visible, that the high frequency mass variations in the atmosphere have impact to all three gravity missions and therefore have to be reduced very carefully. It also becomes visible, that high frequency mass variations in the oceans are much smaller than in the atmosphere, but still have impact on CHAMP and GRACE observations. Because the GOCE gradiometer measures second derivatives of the gravity potential, the sensitivity of the gradiometer to long wavelength mass variations is much smaller. But, as GOCE also carries a GPS receiver, a similar error spectrum as for CHAMP can be expected for the long wavelengths. This means, when combining high-low SST and gradiometer observations of GOCE also oceanic mass variations have impact on the GOCE solution. A similar signal is visible from the monthly hydrology signal over Europe (precipitation minus evaporation). GRACE will detect this long wavelength signal by computing monthly gravity models and comparing them in their sequence of time. It becomes clear, that these monthly variations in the continental water have impact on GOCE, because there are no observations over a full year. Similar signals are caused by seasonal variations in the atmosphere and the oceans. Consequently the monthly GRACE gravity field solutions have to be used for removing this so-called seasonal bias from the GOCE observations. Because of the large signal of high frequency atmospheric mass variations in the following the computation of this effect is described more detailed.

Atmospheric Gravity Variations

Gravity field variations caused by atmospheric mass variations are computed from global atmospheric model data. For our investigation, sample data of three global atmospheric models are available. These are the ECMWF global forecast analysis, the NCEP reanalysis and the DWD (German weather service) global model. Two mathematical approaches are investigated here. A simplified formula immediately transforms the surface pressure to spherical harmonic gravity coefficients by spherical harmonic analysis of a single layer on the Earth surface (up to degree and order 50). A more complicated, but fully correct approach, performs the vertical integration of the atmospheric density and computes then the gravity coefficients by spherical harmonic analysis. Figure 3b shows the gravity variations for different time intervals (6 hour step size, on 23. Feb. 2001) computed from surface pressure of the ECMWF model. All computations are assumed non-inverse-barometer corrected (non IB), what means, that the full signal over the oceans is taken into account. It becomes clear, that already 6 hourly mass variations cause significant effects in the gravity field, which are sensed by GRACE and to some extent by CHAMP and GOCE. Gravity variations in shorter time scales can not be computed, due to the time resolution of the atmospheric models, which is 6 hours.

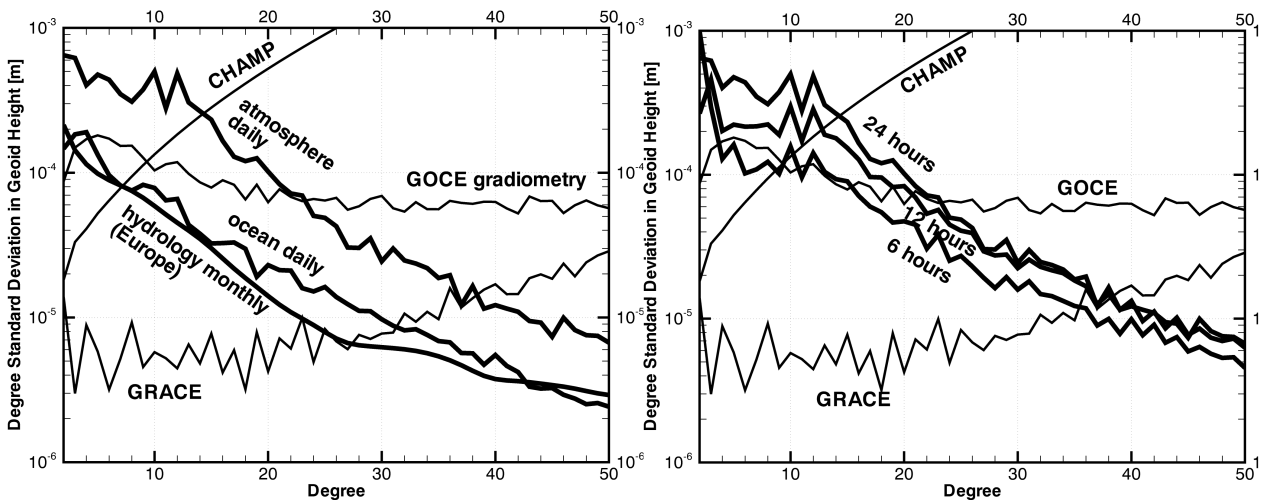

Figure 3: Gravity variation signals from different sources in different time scales compared to mission sensitivities (from left to right): a) Comparison of daily atmosphere, daily oceanic and monthly hydrological signals. b) Comparison of 6, 12 and 24 hourly ECMWF signals.

Comparing gravity variations estimated from surface pressure fields from all three atmospheric models at the same time step, enables the estimation of a level of uncertainty in the resulting spherical harmonic series. For all three models (ECMWF, NCEP, DWD) 6 hourly gravity field spherical series have been computed and converted to geoid heights. Then differences of the geoid height fields have been computed and plotted. Figure 4a,b shows two samples for the NCEP-ECMWF and DWD-ECMWF geoid height differences. Differences are in the range of ±1 mm up to degree and order 50, while the GRACE observations are sensitive to about ±0.1 mm for this frequency range (see figure 1a). This clearly shows that there is a high level of uncertainty coming from the atmospheric model. The differences do not have the meaning of an error, but, because they are above the GRACE sensitivity, they have to be further investigated. Especially a quality estimate for the atmospheric models is necessary, in order to find the best model. Also investigations with the IB case have to be performed, because large uncertainties in the atmospheric models are expected in the Southern oceans, where insufficient observation data are available.

Comparing the vertical integration of density along the atmospheric column (using temperature and humidity at atmospheric model levels) with the single layer surface pressure approach, also differences of ±1 mm in terms of geoid heights are determined. The signal degree variances of this difference shows a sensitivity for GRACE up to approximately degree 20, while for CHAMP and GOCE nearly no impact can be seen. This means, that the surface pressure approach can only be regarded as an intermediate step and that for GRACE data processing in any case the vertical integration has to be performed. This implies a more complicated data analysis and requires access to much more data. The integration is done numerically for the number of model levels of the specific atmospheric model (e.g. 31 levels for the DWD global model). Geopotential heights of these model levels, which are varying over the continents, are computed from temperature, specific humidity and pressure at the model levels in each grid point. The requirements on data transfer, processing time and storage are much higher than using only surface pressure fields as a first approximation. But, as first test computations have shown, all tasks can be performed within reasonable time.

Time Variable Gravity Field De-Aliasing Synergies

- Tides: CHAMP & GRACE gravity field determination will include an update of the initial tidal model. In addition a better initial model from altimetric/hydrodynamic data analysis is necessary. For GOCE a significantly improved tide model based on CHAMP/GRACE and other data will be available.

- Atmospheric and oceanic high frequency gravity variations: The GRACE project will systematically produce gravity field correction coefficients from both sources based on best available atmospheric and oceanic models. Same corrections can also be used for GOCE observation corrections.
- Seasonal gravity variations: Within the GRACE project monthly mean gravity field solutions will be systematically computed. The analysis of this sequence of gravity field models can be used for reducing monthly effects as well as the seasonal bias in the GOCE observations and gravity field solution.

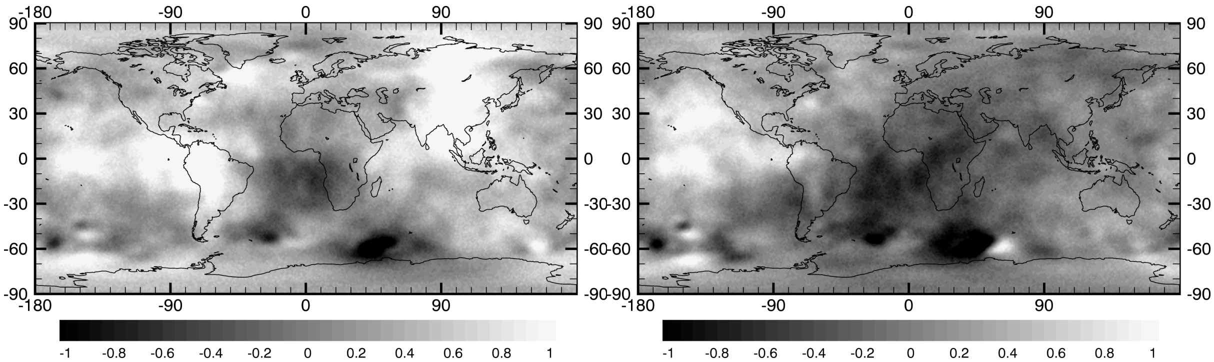

Figure 4: Differences of 6 hourly gravity variations for different atmospheric analysis in terms of geoid heights [mm] (23. Feb. 2001) (from left to right): a) NCEP minus ECMWF 6 hourly variations; b) DWD minus ECMWF 6 hourly variations.

CONCLUSIONS

The CHAMP, GRACE and GOCE gravity field missions have a large potential of synergies in various domains. From the descriptions and investigations in the previous chapters the following main conclusions can be drawn:

- Mission scenarios for all three missions are complementary in sequence, observation period and spatial sampling. In case of a delay of the GOCE mission or a reduced mission lifetime of the GRACE mission no overlapping observation periods are possible, what would cause additional work for the GOCE data analysis.
- A combined gravity model from data of all three missions can enhance single mission solutions.
- Significant project synergies at GFZ and possibly with the EGG-C consortium are obvious. Processing experience, archives and Software will be shared by science data processing systems for all three missions.
- High frequency and seasonal time variable gravity field de-aliasing for GOCE will be based to a large extent on GRACE developments and results.
- CHAMP, GRACE and GOCE should be seen as one tool for improving the knowledge of the Earth gravity field.

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