Gravity Field Models beyond CHAMP, GRACE and GOCE: A Synergetic View of Global Gravity Field Computation

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Abstract

With the successful launches of the German gravity and magnetic field mission CHAMP in July 2000 and of the US/German twin satellite gravity field mission GRACE in March 2002, a new era of gravity field mapping from space has been started. As the next step in 2006 the European Space Agency's gradiometric mission GOCE is scheduled for launch and will further enhance the gravity field in terms of accuracy and resolution. All three missions provide valuable information in different spectral domains and will contribute to the overall goal to determine the global gravity field from space with highest accuracy and best resolution as possible. It has to be noted that only by a synergetic processing of data from all three missions this goal can be reached. Synergies between the missions can be identified mainly in the area of time dependent gravity field variations with frequencies from a few hours to months and longer, but also in the measurement bandwidth of the missions themselves. Further synergies can be identified with other missions, either in orbit or planned, such as ENVISAT, JASON-1, CRYOSAT, ICESAT, SMOS and others. All of them can contribute significantly to the goals of the gravity field missions by providing useful ancillary observations.

A further enhancement of the satellite derived gravity field models can be reached by the inclusion of available surface and altimeter data as it was done in the past by a few groups, who computed combined and high resolution gravity field models. With the gravity field missions the role of the surface gravity and altimeter data has to be re-assessed. It has to be identified, if the currently available data are sufficient in accuracy and resolution and what are the requirements for the surface data when they are combined with the new missions gravity field solutions. New airborne gravity data like that from the Arctic Gravity Project, could significantly improve the quality and coverage of the surface observations and could be valuable for various purposes in combination with the gravity missions observations.

The first part of the paper focuses on the identification of synergies between the CHAMP, GRACE and GOCE missions with special emphasis on the time variable effects. It also investigates what other Earth observation missions can contribute to the data analysis in order to further improve the gravity field model. The second part of the paper focuses on the future role of surface/airborne gravity and altimeter data in combination with the satellite derived gravity field models.

Mission Synergies

The three satellite missions designed for gravity field recovery, CHAMP, GRACE and GOCE are complementary in observation technique, sequence, coverage, spatial and time resolution. While CHAMP and specifically GRACE have global coverage (with orbit inclinations of 87,28º for CHAMP and 89º for GRACE) GOCE will have to fly in a sun-synchronous orbit (inclination 96.5º) due to solar power constraints. This means on one hand that CHAMP and GRACE will help to fill the polar gap for GOCE and on the other hand that GRACE and GOCE will complement each other with their expected error characteristics in their measurement bandwidths. Figures 1a and 1b illustrate the synergy effects in accuracy for the three missions by showing the square root of degree and cummulative degree variances in terms of geoid heights.

Figure 1a shows the error predictions for the single satellite missions together with the error estimates of currently best gravity field models. It immediately becomes obvious, that all three missions will improve significantly our current knowledge and that by combination of the missions (especially GRACE and GOCE) a further enhancement can be expected. This was the baseline for computing the combined cummulative degree variances shown in figure 1b. There, for a each spectral range (degree) the best error estimates were combined and propagated to cummulative geoid height errors. From our current knowledge we can find that the mean geoid error up to degree 360 is about 70 cm. With the combination of CHAMP (up to degree 70) and the a current geoid error, a global improvement to about 60 cm can be reached. The same combination with GRACE (up to degree 150) provides a global error estimate of about 45 cm for this resolution. Finally by combination of GRACE errors (up to degree 60), GOCE errors (from degree 61 to 260) and the errors from current gravity field models (from degree 261 to 360), we can improve the mean global geoid height error down to about 20 cm. This shows that at least from a theoretical standpoint the combination of the missions will provide the best results. This implies a lot of efforts during ground processing of the data. For the combination of missions common standards have to be applied and the data have to be analyzed very carefully in order to guarantee homogeneity of the missions.

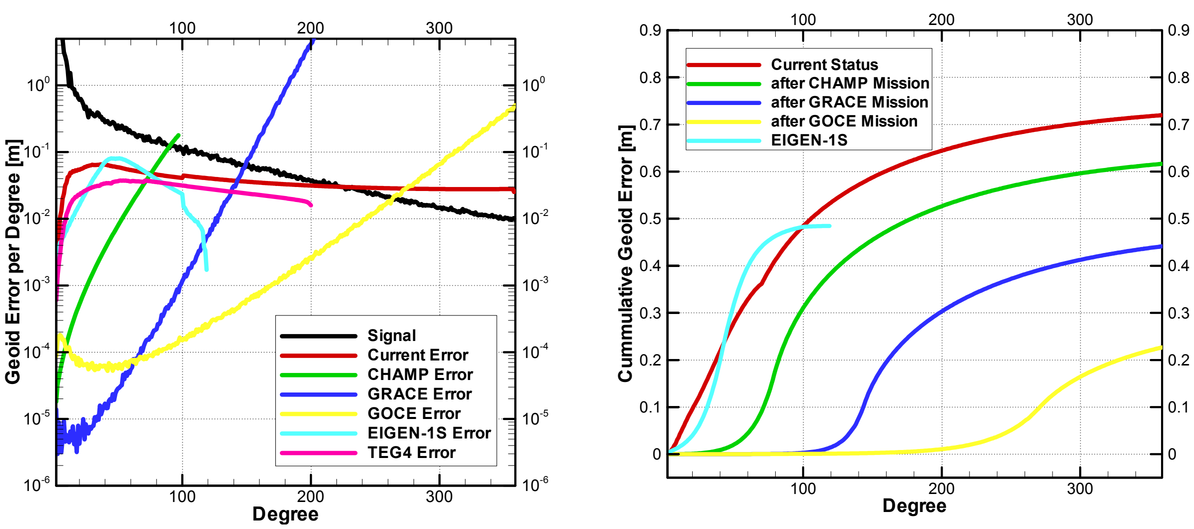

Fig. 1: a) Mission performance in terms of square root degree variances in geoid heights derived from pre-mission estimates (left). b) Square root of cummulative degree variances in terms of geoid heights by combination and error propagation of the best performance per degree (right).

Another area where synergies between the gravity field missions and also with other Earth observation missions can be identified is the time variable gravity field. We have to distinguish here between seasonal and high frequency mass variations. Figure 2 for example shows high frequency variations caused by atmospheric and oceanic mass redistributions as well as monthly variations caused by hydrology over Europe. As we can see from the comparisons with the mission error predictions, GRACE and also to some extent CHAMP are significantly influenced by such mass variations, while for the GOCE gradiometry only solution, only the atmosphere plays a significant role (at least for the high frequency variations). But, because GOCE will also carry a GPS receiver and because GOCE will fly significantly lower than CHAMP (250 km versus 300-500 km) we can expect some influence also from the other time variable sources on the GOCE high-low SST gravity field solution.

One of the main goals of the GRACE mission is to provide monthly global gravity field solutions in order to determine the time variable gravity field. These monthly solutions can be used on the other hand as correction during the GOCE data processing. For GOCE two observation periods of about 6 months with a hibernation phase of 5 months in between are planned. The hibernation phase is necessary due to power consumption constraints during the long eclipse season for the sun-synchronous orbit. This means that with GOCE we only can determine some kind of a biased gravity field from observations taken during the same seasons. Now monthly gravity field variations from GRACE can help to bridge the hibernation phase in order to be able to compute a mean gravity field from GOCE, which is valid for the whole year.

High frequency mass variations have to be corrected beforehand during satellite-to-satellite and gradiometer data analysis. The space-time sampling characteristics of the satellites tracks do not eliminate such short term variations by computing e.g. monthly mean fields. Therefore, strategies for correcting these effects have to be developed and applied. This can be done simultaneously for all three missions with the same approach.

The current baseline for computing these corrections is to use global atmospheric and oceanographic model outputs. 6 hourly 3-D atmospheric fields referred to a long term mean value can be used to compute residual gravity field coefficients, which further-on can be applied during data analysis. For this, results of atmospheric analysis from the European Center for Medium Range Weather Forecast (ECMWF) are operationally used for GRACE data analysis. For the ocean mass variations ocean models driven by the same atmospheric fields are used. They provide 6 hourly global sets of ocean bottom pressure, which can also be translated to gravity field correction coefficients. As it was mentioned above, all these computations are based on global atmospheric model analysis and also on some assumptions made in the models (e.g. inverse barometer assumption in the ocean model). It should also be mentioned that the accuracy of the atmospheric parameters strongly depends on input data used. One can for example assume that the mean uncertainty in the ECMWF pressure fields is between 1-2 mbar in surface pressure, which is above the requirements for the gravity field missions (especially GRACE).

By using data from other Earth observation missions these shortcomings of the atmospheric and ocean models could be overcome at least to a certain extent. ENVISAT has two sensors on-board (MIPAS, SCIAMACHY) providing vertical profiles of pressure, temperature and humidity, which are the basic parameters for computation of the center of mass of the atmospheric column. Also GPS limb sounding missions like CHAMP, GRACE, SAC-C and specifically the planned COSMIC missions will provide a large number of vertical profiles for the required parameters. These profiles can be used as in-situ observations to upgrade the atmospheric models or in a later stage may be there are enough observations even to replace the models for this purpose. For modeling oceanic mass variations ENVISAT observations could also play a significant role. While the altimeter provides sea surface heights, the on-board radiometer (AATSR) provides sea surface temperature observations, which, together with salinity, can be used to compute the steric (heat) effect on the sea surface. By subtracting this effect from the altimetric sea surface heights the deviations from a mean sea surface should mainly reflect oceanic mass deviations from a mean ocean state. Salinity at the moment must be taken from ocean models, but could be replaced in a later stage also by observations of the planned ESA mission SMOS. By combining all these data probably also for the oceans most of the model information can be replaced by real observations for this purpose.

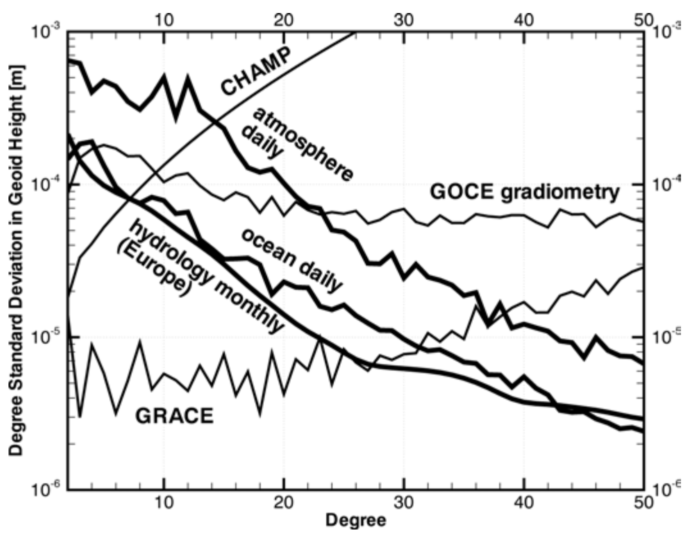

Fig. 2: Sources signal of time variable gravity effect

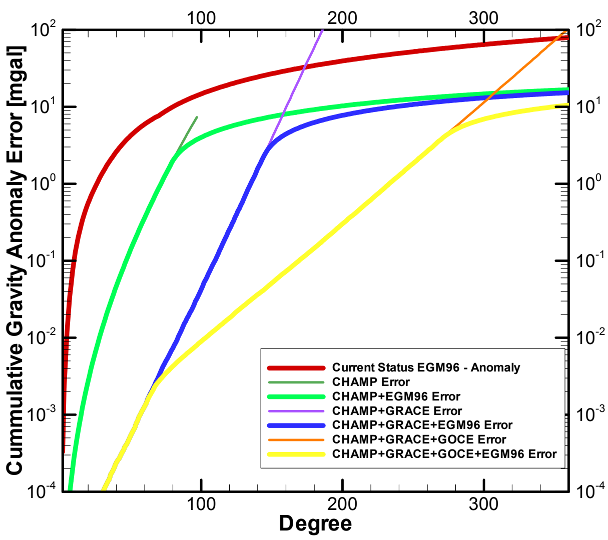

Fig. 3: Square root of cumm. degree variances

Future Role of Surface & Airborne Gravity Data

As it can be identified in figure 1a the new missions promise huge improvements in the global geoid. Now we can ask ourselves what is the role of surface and airborne gravity observations for future global high resolution models (of the EGM96 type) ? Because at the moment 90% of the Earth's surface is covered by more or less high quality mean 30' gravity anomalies (EGM96 data sets from NIMA) we restrict this investigation to degree and order 360.

Figure 3 shows the square root of cummulative degree variances in terms of gravity anomalies. Different combinations of errors have been computed in order to identify the impact of the surface data (as they were used in the EGM96 solution). The thick lines always show the error based on the mission predictions and the EGM96 error, while the thin lines show the combined mission error predictions without using EGM96 errors as additional constraint. Error predictions are combined by adding always the smaller error for each degree (see also figure 1b for geoid heights).

From figure 3 we can read that for CHAMP we can reach an accuracy level of about 3 mgal up to degree 80. By combining this with existing gravity anomalies the error propagates to about 18 mgal (thick green line). If we want to keep the 3 mgal level from CHAMP for the full 360 solution, we would need global gravity anomalies with an accuracy better than 2-3 mgal starting at degree 80 up to degree 360, what corresponds to half wavelengths of 250 km to 55 km. For GRACE we can reach 3 mgal up to degree 140. The combination with existing data sums then up to about 15 mgal. Similar, for GRACE+GOCE we can reach 4 mgal up to degree 280 summing up to 10 mgal by combining it with the existing gravity data. To keep the accuracy level of GRACE for the full 360 solution we must know gravity anomalies better than 3 mgal for the wavelengths 143km to 55 km and for GOCE we would need gravity anomalies better than 4 mgal for wavelengths between 71 km and 56 km.

Looking to the existing EGM96 half degree gravity anomalies data sets we know that in many continental areas this accuracy level is reached, but we also can identify various areas around the world, where the indicated errors are much larger. As a first consequence a more uniform coverage of gravity anomalies over the continents is necessary. What concerns the oceans we can say that except for the polar ice covered regions we have very uniform gravity anomaly data sets derived from satellite altimetry. There we can reach (at least for the oceans between 60º North and South latitude) the necessary accuracy level of 1-2 mgal. Problems may occur at the continent-ocean boundaries. Missing areas in the polar regions have to be filled by airborne campaigns (e.g. Arctic Gravity Project for the Northern hemisphere).

Conclusions

In the paper we have identified mission synergies between the three gravity field missions CHAMP, GRACE and GOCE as well as with other Earth observation missions, which can contribute to gravity field processing. Concluding we can say that

- CHAMP, GRACE and GOCE are complementary in sequence, observation technique, accuracy level and processing strategy,
- until 2007 the computation of a 1cm geoid with 100 km half wavelength will be possible,
- high frequency gravity field variations (< 1 month) will be the major limiting factor,
- other Earth observation missions like ENVISAT could strongly support the modeling of high frequency mass redistributions.

Further, it was investigated to what extent available continental and altimetric gravity anomalies can contribute to future global gravity field modeling. It was found that

- available surface and altimeter data partly can upgrade the future satellite solutions,
- existing data can not improve the satellite models due to insufficient coverage and accuracy
- global uniform gravity coverage with 30' spatial resolution with an accuracy of about 2 mgal is necessary.