CAN GOCE HELP TO IMPROVE TEMPORAL GRAVITY FIELD ESTIMATES ?

Roland Pail [(1)], Thomas Fecher[(1)], Adrian Jäggi[(2)], Helmut Goiginger[(3)]

[(1)] TU München, Institute of Astronomical and Physical Geodesy, Arcisstraße 21, 80333 München, Germany, Email: pail@bv.tum.de, fecher@bv.tu-muenchen.de

[(2)] University of Bern, Astronomical Institute, Sidlerstraße 5, 3012 Bern, Switzerland E-Mail: adrian.jaeggi@aiub.unibe.ch

[(2)] Graz University of Technology, Institute of Theoretical Geodesy and Satellite Geodesy, Steyrergasse 30, 8010 Graz, Austria, Email: h.goiginger@TUGraz.at

ABSTRACT

The main objective of the GOCE mission is to determine the static part of the Earth's gravity field with unprecedented accuracy and spatial resolution. As opposed to the original schedule, it turned out that it is technically feasible to probe the Earth's gravity field continuously also during the long eclipse (hibernation) phases, and due to the mission extension until December 2012 even for a much longer time period. In this feasibility study a first analysis shall be done (a) to what extent GOCE can support and improve time-variable GRACE gravity field estimates, and (b) if the GOCE orbit information alone is sensitive enough to detect temporal gravity signals. Comparing a combined temporal gravity model from GRACE and GOCE with a pure GRACE-only solution, it turns out that GOCE indeed has the potential to improve the solution by reducing the typical GRACE striping pattern significantly. GOCE-only temporal gravity field solutions based on kinematic precise orbits seem feasible for the very low degrees, presuming that the systematic errors in current solutions could be reduced, and longer GOCE orbit time series were available.

1. INTRODUCTION

The typical striping pattern as it can be observed in temporal gravity field models derived from GRACE has two main reasons. The first one is related to aliasing effects from short-periodic temporal gravity field signals. Since these tidal and non-tidal signals can not be perfectly reduced due to errors in the geophysical background models, they alias into the resulting temporal gravity field models. The second issue is related to the fact that the error structure of GRACE is highly anisotropic due to the observation type of along-track range measurements between the twin satellites. The first issue affects only the right-hand side, i.e. the observation vector, of the corresponding normal equation systems, the second one is also reflected in the normal equation matrix expressing the specific observation type. While GOCE will not be able to contribute significantly to reduce the first error source, it shall be investigated whether contributions are possible to reduce the problems related to the second error type.

Correspondingly, we build our study hypothesis that GOCE can indeed support and improve time-variable gravity field estimates derived from GRACE on 2 pillars:

- *In contrast to GRACE, the error structure of the GOCE observation type is isotropic.*
  Since GRACE takes measurements only in one direction (along-track), the resulting error structure is highly anisotropic. In contrast, GOCE is measuring gravity gradients uniformly in all three spatial directions, thus resulting in an isotropic error structure. The combination of data from both missions could thus help to reduce the dominant striping pattern which is inherent in GRACE solutions.
- *The amplitude of regional mass variations is often highly underestimated.*
  Frequently, the amplitude of time-variability of the gravity field is estimated from geophysical models (e.g., [14]), and is expressed in terms of degree variances or degree medians. However, this representation is a global average of the temporal gravity field changes (for certain periods), and has the tendency to underestimate the true amplitude of interesting hydrological or cryospheric features on a regional to local scale by up to one or two orders of magnitude.

2. PROBLEM DEFINITION

2.1. (Non-)isotropy of the observation error

It is important to mention that in GRACE gravity field models the striping pattern can not only be observed in coefficient deviations of monthly gravity field solutions from a static gravity field, but also in the corresponding error estimates. This fact can also be demonstrated by covariance propagation applied to a GRACE variance-covariance matrix based on a monthly solution of ITG-Grace2010s ([8]).

Proc. of '4th International GOCE User Workshop', Munich, Germany 31 March – 1 April 2011 (ESA SP-696, July 2011)

Rigorous covariance propagation was applied to the full GRACE variance-covariance matrix to derive geoid height errors for different maximum degrees. This study was performed for the monthly solution of August 2009. (It was checked that the near 7 days GRACE sub-cycle in this period does not have an impact by repeating this procedure for data from August 2008, yielding very similar results.) The evaluation was performed regionally for an area covering whole South America. Figure 1 shows the results for maximum degrees of 30, 40, 60 and 120 of the series expansion. Obviously, also in the error estimates this striping pattern is visible, starting already at degrees 30 to 40.

This is a key conclusion for our study idea, because the error estimates reflect only the orbit configuration and measurement type (in our case along-track ranging), but not the right-hand side of our normal equation system. In contrast, aliasing problems affect only the observations (and thus the right-hand side). Thus, we can conclude that a significant part of the striping pattern is related to the GRACE observation type.

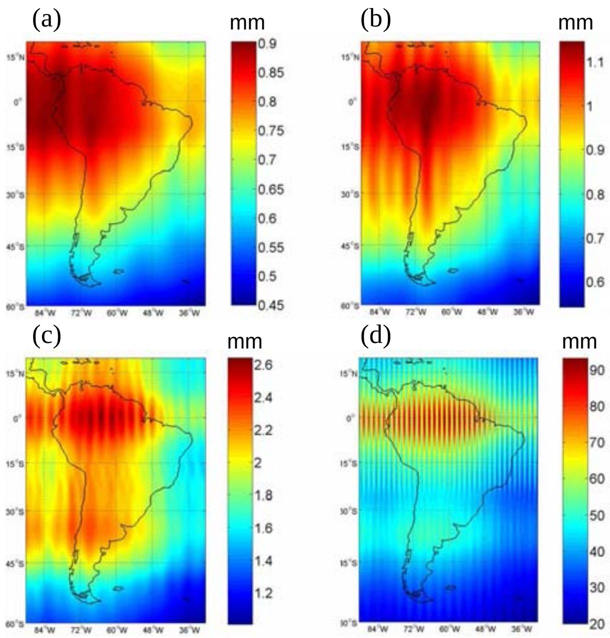

Figure 1. Geoid height standard deviations [mm] derived by rigorous error propagation based on the full variance-covariance information of the monthly ITG-Grace2010s model for August 2009: expansion up to maximum degree (a) 30; (b) 40; (c) 60; (d) 120.

2.2. Amplitude of temporal gravity field variations

Frequently the time variability of gravity field signals of a certain geophysical source is estimated from geophysical models by means of a global analysis. The corresponding spectral representation of the rms variability is given in degree variances. This global representation of time variability, however, underestimates the true amplitude of regional features dramatically.

Figure 2 shows the rms variability of the global gravity field related to land hydrology and ice mass variations. It was derived from geophysical models for a period of 11 years between 1995 and 2005. Concerning hydrology, the large-scale model PCR-GLOBWB (PCRaster GLOBal Water Balance), which is driven by ECMWF ([1]) and ERA-40 ([12]), has been used, while for the ice sheets the time series is composed of mass fluxes derived from ERA-40 up to 2001, and ECMWF Operational Analysis beyond. These data sets have been created in the course of the ESA project “Monitoring and Modelling Individual Sources of Mass Distribution and Transport in the Earth System by Means of Satellites” ([13]).

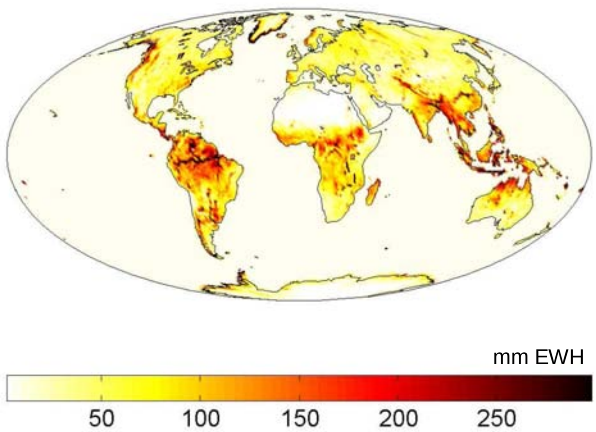

Figure 2. Global distribution of rms variability [mm EWH] of temporal hydrology and cryospheric signals.

In order to evaluate the local variability (and thus the detectable signal) in the frame of a global analysis based on degree variances, the following procedure has been executed. First, a certain hydrological basis was selected, and the signals outside this region were set to zero. Then a harmonic analysis was performed, and the corresponding degree variances based on the rms variability have been derived. In the final step, these (global) degree variances were normalized by the area of the hydrological basin relative to the total global definition domain. Thus a more realistic magnitude for the regional variation signal is obtained. Figure 3 shows the resulting degree variance estimates.
Evidently, the temporal variation signals of these three regions of interest are above the current GRACE error curve up to degree and order 50 to 60. However, it has been demonstrated by the numerical studies described

before that the GRACE solutions are affected by stripes already at degree 40. Since we expect that they can be reduced significantly by the inclusion of GOCE, a cleaner signal representation and a reduction of striping artefacts might be achievable.

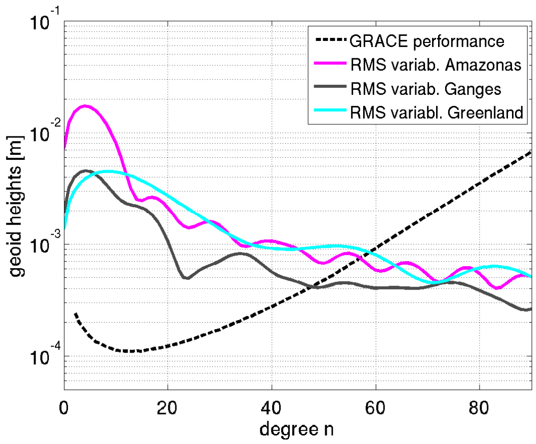

Figure 3. Degree rms of temporal variation signals in selected regions.

3. CASE STUDY 1: IMPROVEMENT OF GRACE GRAVITY FIELD ESTIMATES

In this case study it shall be investigated if GRACE temporal gravity field estimates can be improved by the inclusion of GOCE data. The study logic is to compute first a GRACE-only gravity field solution, which shall then be combined with GOCE in order to analyze the impact.

For this study we chose to compute bi-monthly gravity field solutions, but this case study can be reduced to monthly solutions without major changes in the results or conclusions, because the global coverage of GOCE is already sufficient after one month.

Of course, one pre-requisite of this study is that full GRACE and GOCE normal equations are available for the same time period. Since no ITG-Grace2010s gravity field solutions (the only model that provides also variance-covariance information, from which the normal equations can be reconstructed) are available after August 2009, there is no overlapping period with the GOCE operational phase starting in October 2009. Therefore, GRACE monthly solutions for November and December 2009 have been generated up to degree/order 120 using the celestial mechanics approach ([2], [3], [7]). It should be emphasized that during this period GRACE flew a 7-days sub-cycle, which might slightly decrease the quality of the GRACE solution. We will come back to this issue later on.

Concerning GOCE, full normal equations up to degree/order 224 from satellite gravity gradiometry (SGG) have been generated applying the time-wise method ([9], [10]) for this bi-monthly period, while the GPS satellite-to-satellite (SST) component based on kinematic precise orbits was evaluated by the celestial mechanics approach up to degree/order 120 ([6]). These two normal equations have been optimally combined to result in a consistent full GOCE normal equation system up to degree/order 224.

As a next step, the two monthly GRACE normal equations complete to degree/order 120 have been jointly inverted to obtain a GRACE-only solution. Finally, this solution has been combined, again by addition of normal equations, with the GOCE normal equations to obtain a bi-monthly combined global gravity field estimate.

The dashed curves in Figure 4 show the formal errors in terms of degree medians of the individual GRACE and GOCE solutions, as well as the combined model. The cross-over of the GOCE and GRACE performance curves occurs at degree 85. The GRACE-only estimates (red dashed) could only slightly be improved by GOCE (green dashed), resulting in the blue dashed curve of the combined model. Additionally, the coefficient differences to the independent static GRACE model ITG-Grace2010s are displayed as solid curves of the corresponding color. Concerning GOCE, the most obvious deviation from the formal errors occurs in the low degrees, which is mainly due to non-parameterized systematic errors in the GOCE SST solution. Also the GRACE as well as the combined solution deviate significantly from the formal errors, but the main reason here is that beside observation errors also time-variable gravity field signal is inherent. As a reference, also the degree medians of the temporal variation signals, as shown in Fig. 3, are displayed.

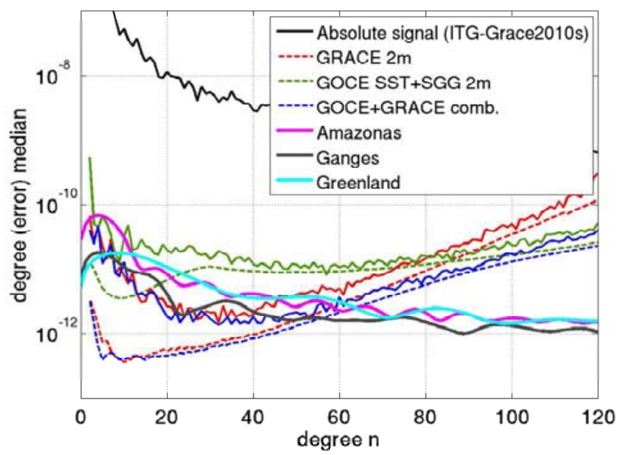

Figure 4. Degree medians of GRACE-only, GOCE-only and combined gravity field models; formal errors (dashed curves) and differences to static reference model ITG-Grace2010s (solid curves).

An even more stunning result can be observed when analyzing the global field of the estimated temporal gravity field signals. Figure 5 shows deviations of the bi-monthly solutions from the static ITG-Grace2010s reference field in terms of equivalent water height for (a) the GRACE-only and (b) the combined GRACE+GOCE solution up to degree/order 30. Evidently, the striping structure of the GRACE-only solution can be significantly reduced when including GOCE normal equations.

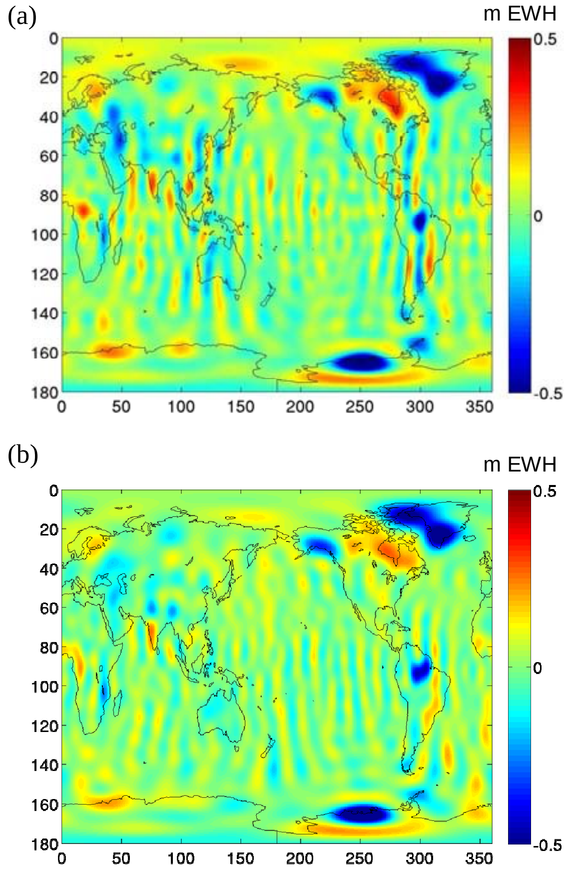

Figure 5. Temporal gravity field signals in terms of equivalent water heights [m] evaluated up to degree/order 30: a) GRACE-only; b) GRACE+GOCE combination.

This effect appears even more clearly when analyzing the difference fields at degree/order 40. The results are shown in Fig. 6. It should be emphasized that this significant improvement is not related to the fact that GOCE can introduce much additional temporal gravity field information, but it is rather an indirect effect, by stabilizing the GRACE normal equations. Here, the isotropic error structure of the GOCE normal equations supports the reduction of the striping pattern. In this sense, it can be interpreted as an additional constraint. Compared to any other "regularization" approach, the true additional value lies in the fact that a completely independent normal equation system based on a complementary gravity mission for exactly the same time period is used. In this sense, the inclusion of (bi-)monthly GOCE normal equations is more consistent. Again it should be emphasized that a similar result is expected when reducing the scenario to monthly solutions, because the performance of both GRACE and GOCE scale down in an analogous way, and the monthly ground track coverage of GOCE is highly sufficient.

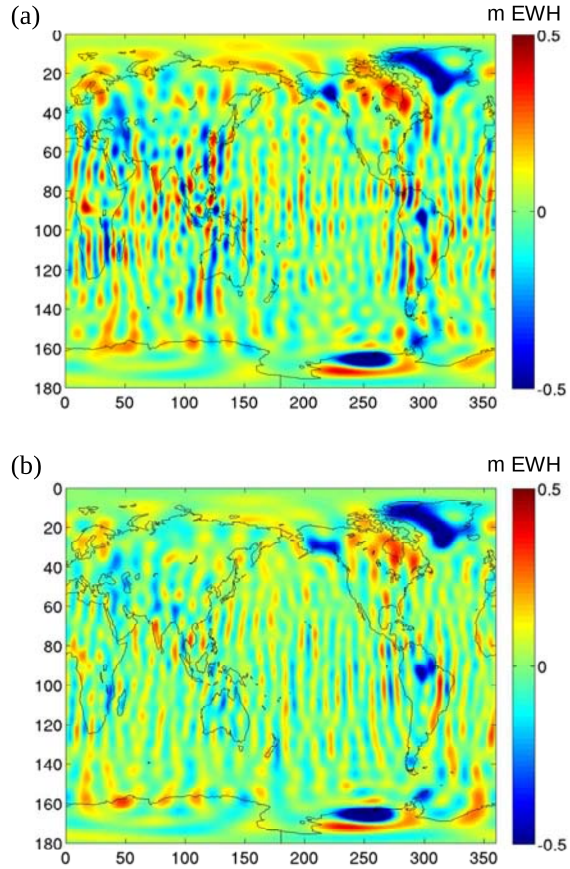

Figure 6. Temporal gravity field signals in terms of equivalent water heights [m] evaluated up to degree/order 40: a) GRACE-only; b) GRACE+GOCE combination.

The impact for a "good" GRACE month, i.e., a month without the 7-days sub-cycle, has been investigated by a numerical study. It turns out that the impact of GOCE is slightly less severe, but still significant.

4. CASE STUDY 2: TEMPORAL GRAVITY FROM GOCE-ONLY

In a second case study, it shall be evaluated whether GOCE can observe temporal gravity field signals by its own. Due to the fact that the GOCE gradiometer works with highest performance only in the bandwidth of 5 to

100 mHz, the long-wavelength gravity field information, where temporal gravity field signals show up most prominently, is derived mainly from the GPS orbit information.

Therefore, we concentrate here on the GOCE SST component. Monthly gravity fields complete to degree/order 120 have been estimated based on the kinematic precise science orbits for the time period from November 2009 to June 2010 applying the celestial mechanics approach ([2], [3]). If at all, temporal gravity field effects will be detectable only in the very low degrees. Therefore, difference fields to the static gravity field model ITG-Grace2010s have been computed up to degree/order 10. As reference solutions, the temporal gravity field models of GFZ RL04 ([5]) up to the same degree/order have been analyzed. Reductions of atmosphere and oceans (products GAC and GAD) have been added back.

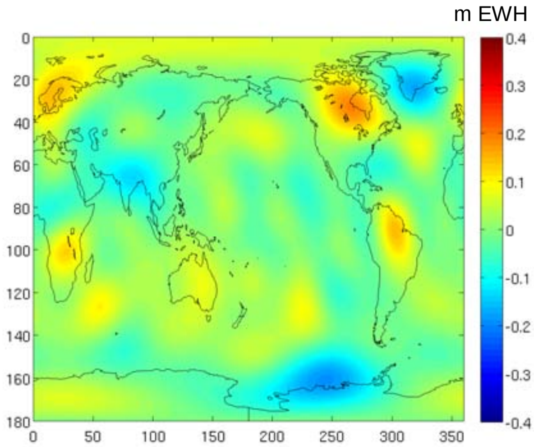

Figure 7. Temporal gravity field signals in terms of equivalent water heights [m] evaluated up to degree/order 10 of the GFZ RL04 model for June 2010.

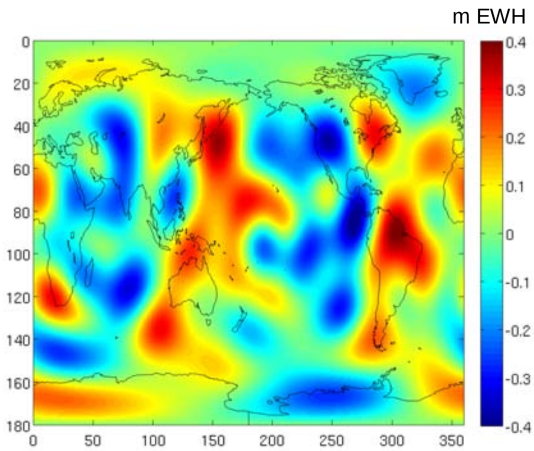

Figure 8. Temporal gravity field signals in terms of equivalent water heights [m] evaluated up to degree/order 10 derived from GOCE SST for June 2010.

Exemplarily, Fig. 7 shows the temporal gravity field signal in terms of equivalent water heights up to degree/order 10 of the GFZ model for June 2010. The corresponding field derived from the same month of GOCE kinematic orbit data is shown in Fig. 8. Evidently, although these fields are on the same order of magnitude, the noise level of the GOCE SST solution dominates the picture. Correlations between Fig. 7 and Fig. 8 seem to appear in certain regions with large temporal variation signals, such as Greenland, South America and the Western ice shield in Antarctica, but similar amplitudes also appear in regions where no strong temporal gravity field signal is to be expected.

One of the main future challenges is to reduce systematic effects in the GOCE SST solutions. As it can be clearly seen in Fig. 4, the actual errors in the low degrees are considerably larger than the formal errors, demonstrating that systematic effects contribute significantly to the total error budget. If we succeeded to reduce these systematic errors by a factor of 5-10, and thus being consistent with the formal errors, it could be expected that temporal gravity field effects can be recovered at least for the very low degrees.

Additionally, longer time series of GOCE orbit data will be needed to estimate them either by co-estimating trend and periodic signals, or by stacking monthly gravity field estimates to reduce the noise patterns, as it has been successfully done for CHAMP ([11]).

Although GOCE orbits the Earth in a much lower altitude than CHAMP, the added value will not be excessively high, because the signal attenuation with altitude is not very strong for the very low degrees, and thus the lower GOCE orbit altitude does not contribute a lot to the higher sensitivity. However, the orbit accuracy of GOCE, which is estimated to be in the order of 2- 2.5 cm 3D rms ([4]), is considered to be a favourable argument for GOCE, once the full potential of this high accuracy can be exploited and systematic errors can be significantly reduced.

5. CONCLUSIONS

Two case studies based on real GRACE and GOCE data have been performed. In the first one, it was investigated whether GOCE can support and improve GRACE temporal gravity field estimates. In fact, the inclusion of full GOCE normal equations for the processing of combined GRACE+GOCE temporal gravity field models indeed can improve the solutions, in terms of significant reduction of the typical striping pattern of GRACE-only solutions. Here, the favourable isotropic error behaviour of GOCE can help to stabilize the combined normal equation systems. In this sense, GOCE normal equations are constraining the solutions. Compared to any other “regularization” method, we consider normal equations derived from a complementary mission for exactly the same period as the ideal candidate for such a constraint.

In a second study, we investigated if GOCE can detect temporal gravity field signal on its own. Due to the weak sensitivity of gradiometry to the low harmonic degrees, if at all, temporal gravity field signals can be derived solely from the precise GOCE orbits. A very first analysis has revealed that the currently achievable accuracies of temporal gravity field solutions, evaluated for the low degrees, is in the same amplitude range as the time-variable gravity field signals, but still exceed them. However, current GOCE SST gravity field solutions are dominated by systematic errors in the low degrees. A reduction of these systematic errors by improved processing techniques (both concerning the orbit and the gravity field processing), together with longer GOCE orbit time series to be analyzed, should result in the feasibility to recover temporal gravity field signals at least for the very low degrees.

6. REFERENCES

1. Andersson, E., Bauer, P., Beljaars, A., Chevallier, F., Holm, E., Janiskova, M., Kallberg, P., Kelly, G., Lopez, P., McNally, A., Moreau, E., Simmons, A.J., Thepaut, J.-N., Tompkins, A.M. (2005). Assimilation and modelling of the atmospheric hydrological cycle in the ECMWF forecasting system, Bull. Amer. Meteor. Soc., 86, 3, 387-401.
2. Beutler, G., Jäggi, A., Mervart, L., Meyer, U. (2010). The celestial mechanics approach: theoretical foundations. Journal of Geodesy, 84:10, 605-624, doi: 10.1007/s00190-010-0401-7.
3. Beutler, G., Jäggi, A., Mervart, L., Meyer, U. (2010): The celestial mechanics approach: application to data of the GRACE mission. Journal of Geodesy, 84:11, 661-681, doi: 10.1007/s00190-010-0402-6.
4. Bock, H., Jäggi, A., Meyer, U., Visser, P., van den IJssel. J., van Helleputte, T., Heinze, M., Hugentobler, U. (2011). GPS-derived orbits for the GOCE satellite. Journal of Geodesy, accepted for publication.
5. Flechtner, F., Dahle, C., Neumayer, K.H., König, R., Förste, C. (2010). The Release 04 CHAMP and GRACE EIGEN Gravity Field Models. In: F. Flechtner et al. (eds.): System Earth via Geodetic-Geophysical Space Techniques, Springer, ISBN 978-3-642-10227-1, doi: 978-3-642-10228-8, 41 – 58.
6. Jäggi, A., Prange, L., Hugentobler, U. (2011). Impact of covariance information of kinematic positions on orbit reconstruction and gravity field recovery, Advances in Space Research, DOI: 10.1016/j.asr.2010.12.009, in press.
7. Jäggi, A., Beutler, G., Mervart, L. (2010). GRACE Gravity Field Determination using the Celestial Mechanics Approach – First Results, in Gravity, Geoid and Earth Observation, edited by S. Mertikas, pp. 177-184, Springer.
8. Mayer-Gürr, T., Kurtenbach, E. & Eicker, A. (2010). ITG-Grace2010 Gravity Field Model; www.igg.uni-bonn.de/apmg/index.php?id=itg-grace2010.
9. Pail, R., Goiginger, H., Mayrhofer, R., Schuh, W.-D., Brockmann, J.M., Krasbutter, I., Höck, E., Fecher, T. (2010). GOCE gravity field model derived from orbit and gradiometry data applying the time-wise method. In: Lacoste-Francis, H. (eds.) Proceedings of the ESA Living Planet Symposium, ESA Publication SP-686, ESA/ESTEC, ISBN (Online) 978-92-9221-250-6, ISSN 1609-042X.
10. Pail, R., Bruinsma, S., Migliaccio, F., Förste, C., Goiginger, H., Schuh, W.-D, Hoeck, E., Reguzzoni, M., Brockmann, J.M, Abrikosov, O., Veicherts, M., Fecher, T., Mayrhofer, R., Krasbutter, I., Sanso, F., Tscherning, C.C. (2011). First GOCE gravity field models derived by three different approaches. Jounal of Geodesy, accepted for publication, doi: 10.1007/s00190-011-0467-x.
11. Prange, L., Meyer, U., Jäggi, A., Beutler, G. (2011). Temporal gravity field solutions at the AIUB. Geophysical Research Abstracts, Vol. 13, EGU2011-6641, EGU General Assembly 2011.
12. Troccoli, A., Kållberg, P. (2004). Precipitation correction in the ERA-40 reanalysis, ERA-40, Project Report Series, 13.
13. Van Dam, T, Visser, P., Sneeuw, N., Losch, M., Gruber, T., Bamber, J., Bierkens, M., King, M., Smit, M. (2008). Monitoring and Modelling Individual Sources of Mass Distribution and Transport in the Earth System by Means of Satellites. Final Report, ESA contract no. 20403, European Space Agency, Noordwijk.
14. Wahr, J., Molenaar, M., Bryan, F. (1998). Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE, J. Geophys. Res., 103(B12), 30,205–30,229.