GOCE gravity fields established by the Celestial Mechanics Approach

G43A-0746

American Geophysical Union
2011 Fall Meeting
5–9 December 2011, San Francisco, CA,

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1. The GOCE mission

The Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite mission aims at the determination of the gravity field at small scales of 100 km with the accuracy of 1 mGal. It was launched into a sun synchronous orbit at the altitude of 260 km on March 17, 2009. The onboard gravity gradiometer directly measures the gravity gradients in three directions. It is coupled with a drag free system, which compensates the along-track surface forces acting on the satellite.

2. The key instruments

The GOCE orbit is determined by an onboard GPS receiver allowing for a 3D-accuracy of 2.5 cm. The gradiometer consists of three pairs of accelerometers. The noise spectrum of the measured gradients is only flat within the bandwidth $5*10^{-3}$ Hz to $1*10^{-1}$ Hz. The long wavelength part of the gravity field therefore has to be determined from the kinematic orbits derived with GPS.

3. The Celestial Mechanics Approach (CMA)

The CMA, which treats the gravity field determination as a generalized orbit adjustment problem, has already been successfully applied to the gravity field missions CHAMP and GRACE. A key factor of this approach is to take into account unmodeled effects by frequent stochastic pulses or piecewise constant accelerations. This method was extended to the treatment of the measured gradients. The low frequency noise is absorbed by empirical Piecewise Linear Parameters (PWL, **Fig. 1**). The sampling of the PWLs can efficiently be changed by tightly constraining the second derivative of the PWLs. Alternatively they can be smoothed by slightly constraining consecutive differences (**Fig. 2**). This method allows it to flexibly approximate the noise below the measurement bandwidth.

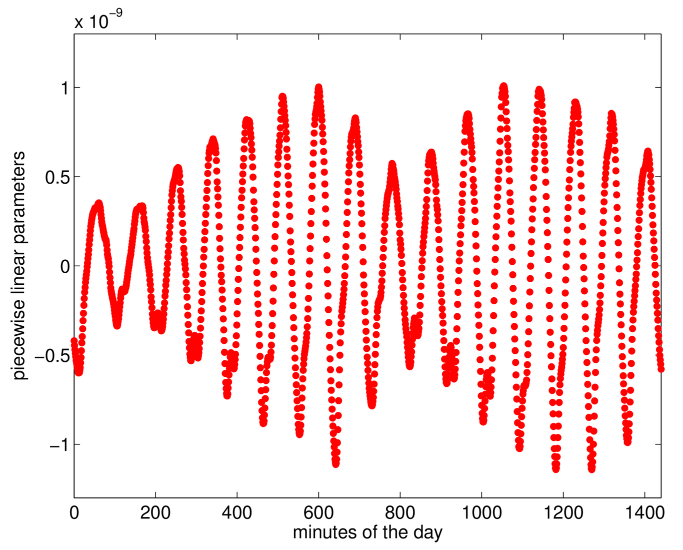

Figure 1: PWLs [$1/s^2$] absorb the dominant 1/rev-signal in the ZZ-gravity gradients.

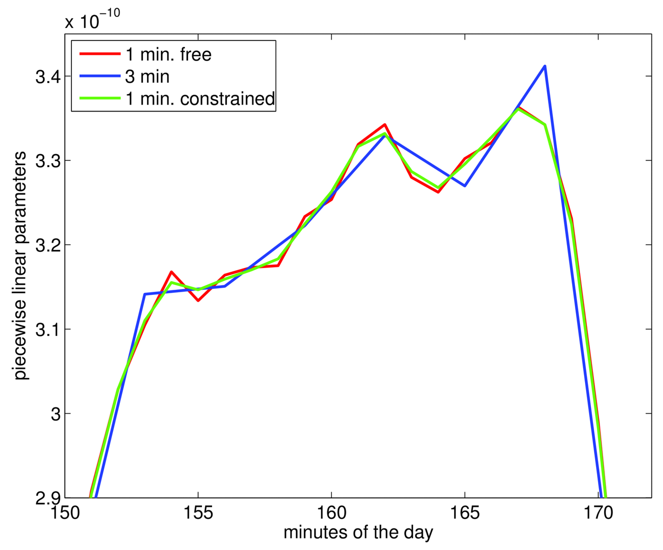

Figure 2: Detail view of Fig. 1 demonstrating the constraining of PWLs [$1/s^2$].

4. Gradiometer-only and GPS-only solutions

Four different gradiometer-only solutions using two months of ZZ-gradients are shown in **Fig. 3**. In a first experiment the colored noise was taken into account by empirical covariances (from auto-correlation of post-fit residuals). Then PWLs with 1 min and 3 min spacing where introduced and finally a solution with smoothed 1 min pulses was computed. The last solution equals the one with empirical covariances in quality, but is more transparent from a methodical point of view. **Figure 4** shows GPS-only solutions in comparison to an 8 year CHAMP field. While CHAMP is superior at low degrees due to the orbit geometry and the larger amount of data, it is remarkable that already a few months of GOCE GPS data are superior above degree 80 (due to the low altitude and high quality of GOCE kinematic orbits). Near degree 120 the omission error starts to become visible.

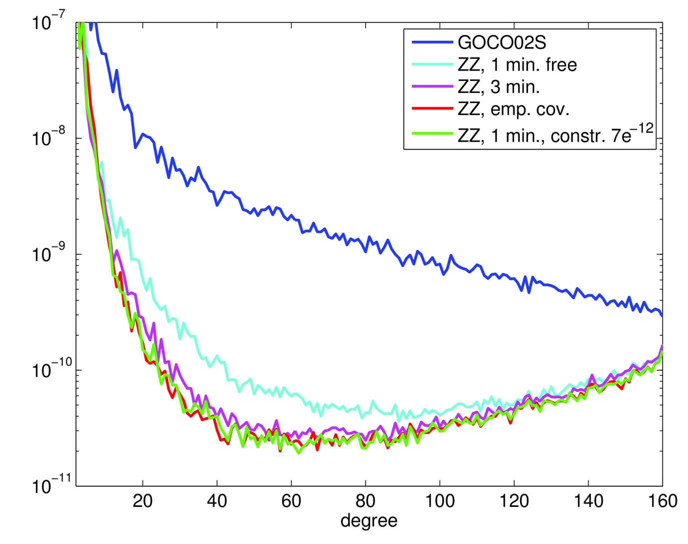

Figure 3: Effect of spacing and constraining of PWLs on the quality of the gravity field solution.

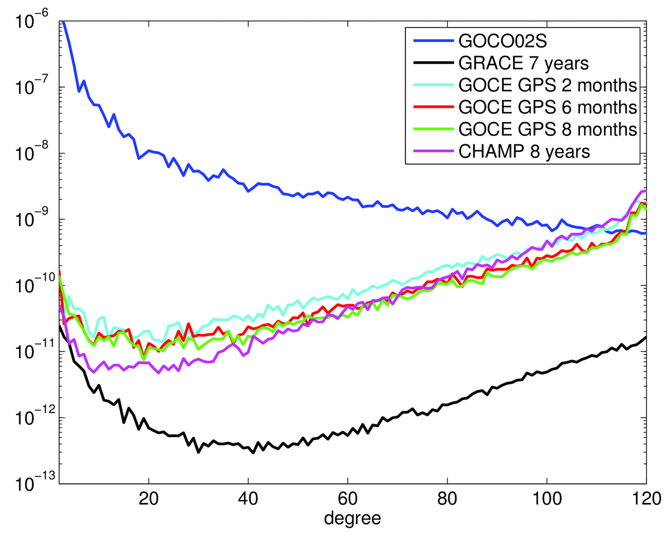

Figure 4: GPS-only gravity field solutions from GOCE and CHAMP and a combined GPS/K-Band range-rate solution from GRACE for reference (shown are difference degree medians with respect to GOCO02S).

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5. Combination of GOCE gradiometer and GPS

In a first step the GOCE gradiometer and GPS normal equations were accumulated using the ratio of the RMS of the post-fit residuals of the individual solutions as relative weight. This, however, leads to a degradation of the combined field. Downweighting the GPS-part cured the problem (**Fig. 5**), see Jäggi et al (2011). **Figure 6** illustrates the improvement of the combined solution with the amount of data (following approximately the SQRT(n)-law above degree 20).

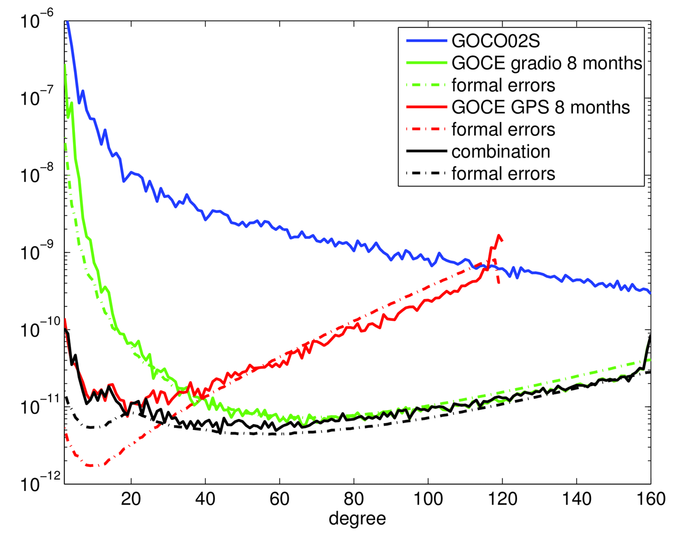


Figure 5: GOCE gradiometer-only, GPS-only and combined solution with formal errors.

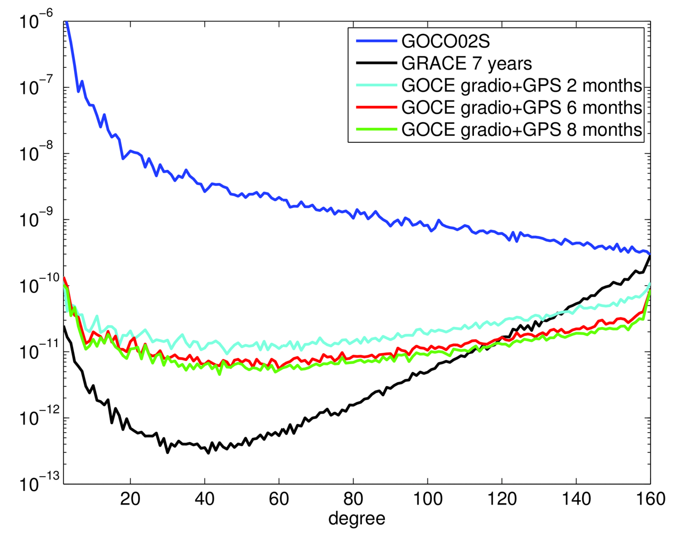


Figure 6: GOCE gradiometer/GPS-combined solutions, GRACE for reference.

6. Combination of GRACE and GOCE

GRACE and GOCE observations are combined on the normal equation level. The GRACE part includes 6 years of GPS and K-Band range-rate data (from July 2003 to December 2009), the GOCE part 8 months of gradiometer data (November 2009 to June 2010). The relative weighting is determined by the ratio of the RMS of the post-fit residuals of the two separate solutions. The formal errors indicate improvement of the GRACE-only solution from degree 80 on (**Fig. 7**), the difference degree variances to GOCO02S (Pail et al, 2011a) even profit from degree 61 on (**Fig. 8**).

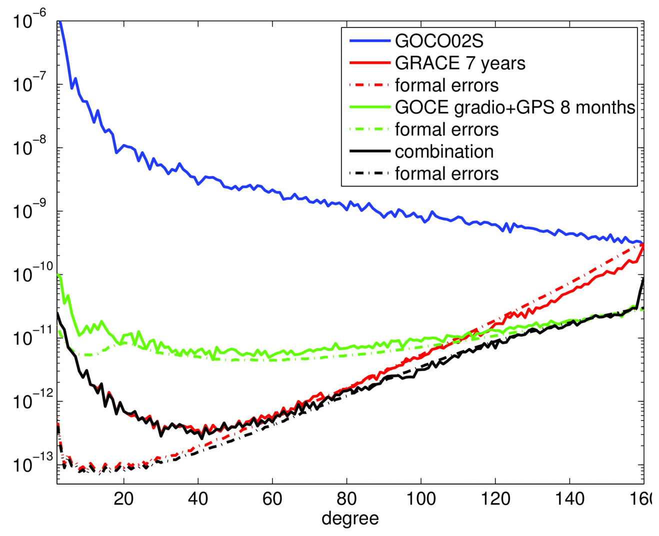


Figure 7: GRACE- and GOCE-only solutions and their combination (medians).

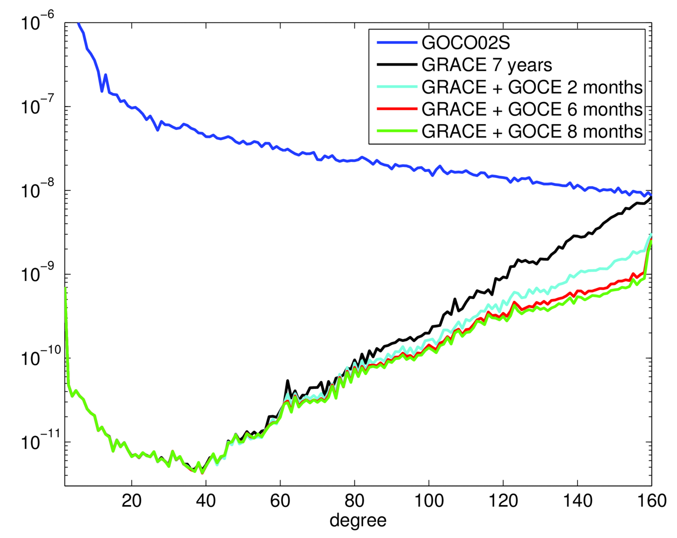


Figure 8: GRACE-only and GRACE/GOCE combined solutions (degree variances).

7. Validation with external models

The 2-month and 8-month GOCE-only fields (gradiometer + GPS) are compared to the two independent solutions computed with the time-wise approach (GO_CONS_GCF_2_TIM_R1 and R2 (Pail et al, 2011b)) and with the direct approach (GO_CONS_GCF_2_DIR_R1 and R2 (Bruinsma et al, 2010)). The 2-month solution is only competitive at low degrees up to approx. 60, confirming the good quality of the GPS part (**Fig. 9**). The 8-month solution is competitive throughout the whole spectrum, but suffers from the omission error near degree 160 (**Fig. 10**).

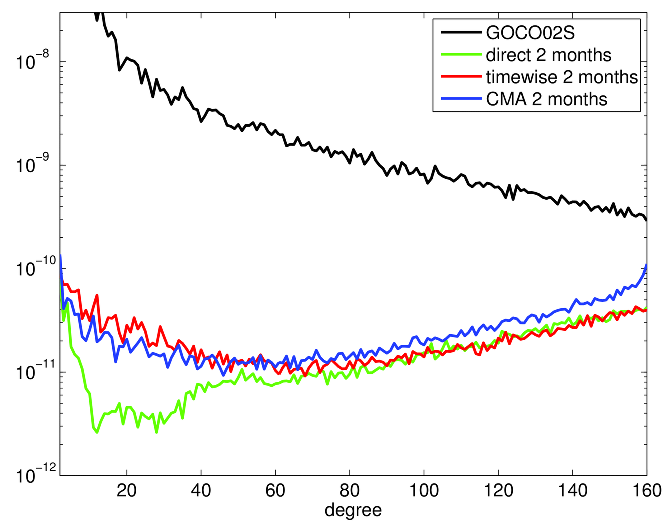


Figure 9: Comparison of different two months GOCE-only gravity field models (medians).

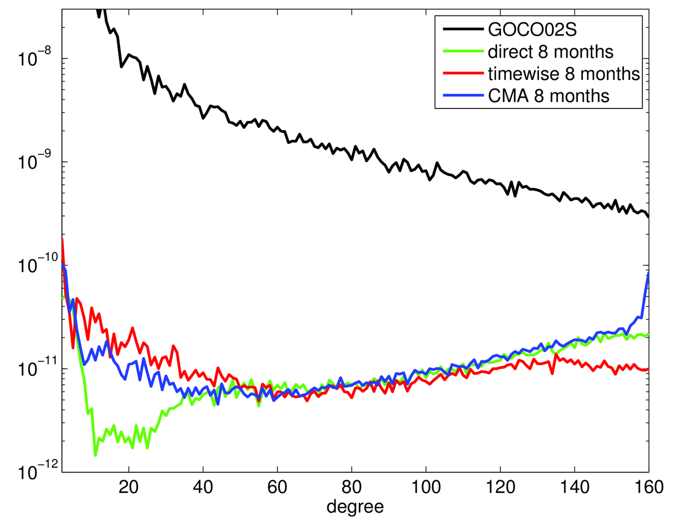


Figure 10: Comparison of different eigth months GOCE-only gravity field models (medians).

8. Analysis of the results

Figures 11 and **12** show comparisons of our 8-month GOCE gradiometer-only and combined solutions to GOCO02S. The deficiencies at low degrees due to the bandlimitation of the gradiometer (**Fig. 11**) and in the near-zonal coefficients due to the polar gap (**Figs. 11+12**) are clearly visible.

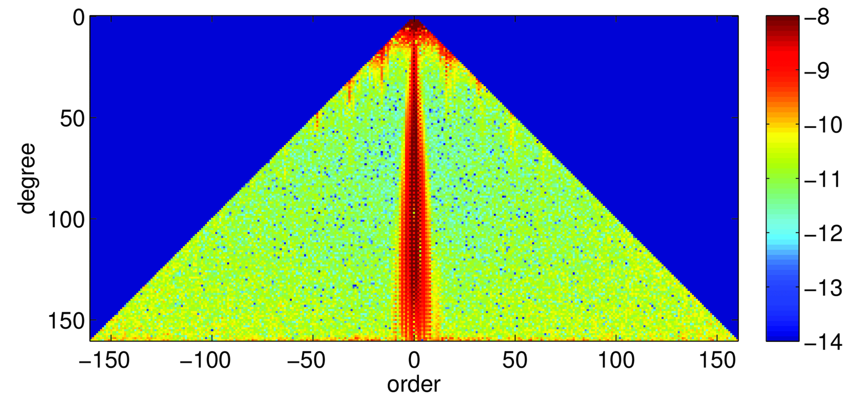


Figure 11: GOCE (gradiometer-only, 8 M) - GOCO02S.

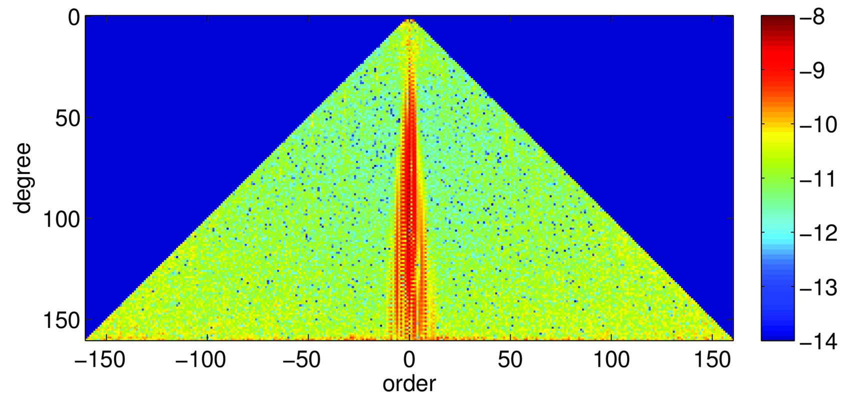
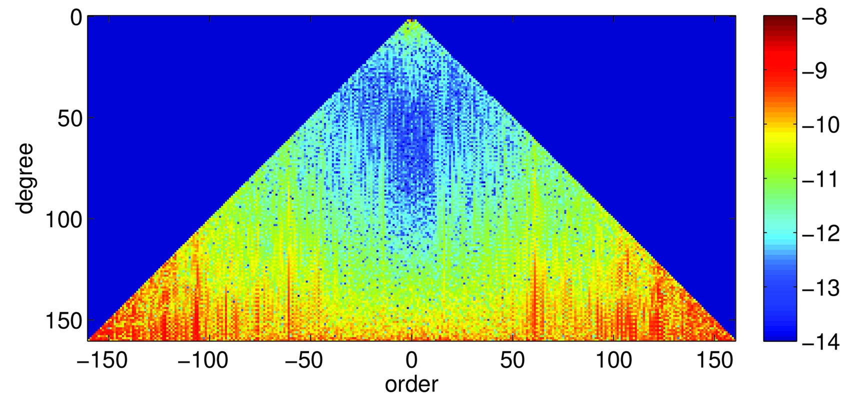


Figure 12: GOCE (gradiometer/GPS, 8M) - GOCO02S.

Figure 13 shows a comparison of a 6 year GRACE solution, also computed with the CMA, to GOCO02S. The limited sensitivity of GRACE at high degrees and orders and aliasing problems in resonance bands are visible. These Problems are cured in the combined GRACE/ GOCE solution (**Fig. 14**).



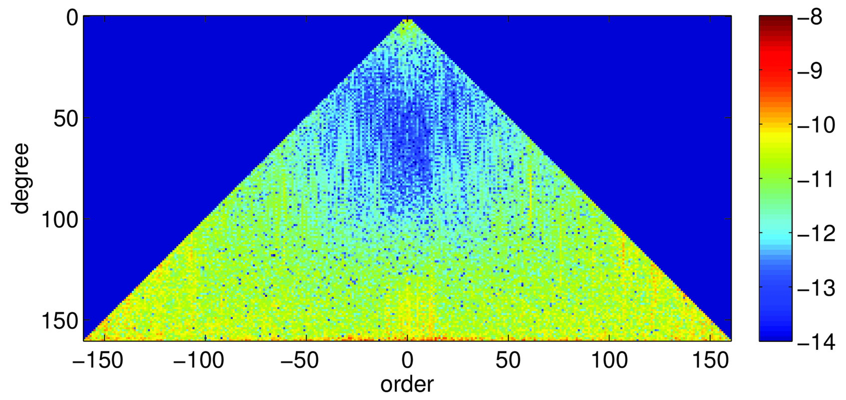


Figure 14: GRACE(6 y)/GOCE (8 M) - GOCO02S.

Figure 15 shows global gravity anomalies, which were derived from the combined GRACE/GOCE solution. All striping artefacts known from the GRACE-only solution have disappeared. The most significant differences to EGM08 (**Fig. 16**) are limited to regions, where poor terrestrial gravity data was incorporated into EGM08. The differences to GOCO02S (**Fig. 17**) show a prominent feature South of Australia, where the observations are known to be affected by heavy winds in the upper atmosphere. Data from this region were excluded in the computation of GOCO02S.

9. New angular-rate determination

C. Stummer kindly provided two months of enhanced gradiometer and attitude data, where the nominal Kalman filtering method for angular-rate reconstruction was replaced by a Wiener filtring method (Stummer et al, 2011). This leads to an improved performance at low degrees (**Fig. 18**) and for near zonal coefficients (**Fig. 19**).

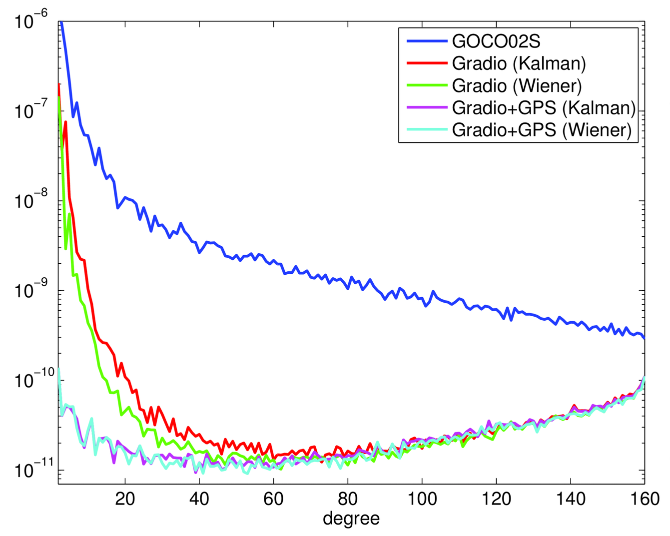
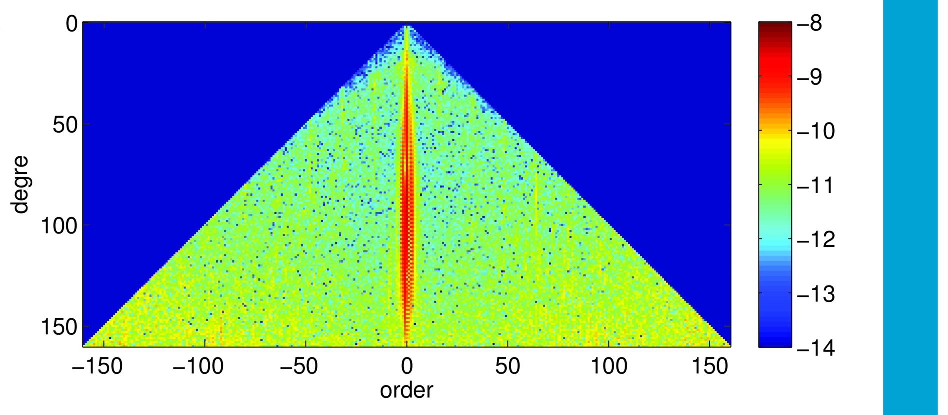


Figure 18: Gradiometer-only and combined gradiometer/ GPS-solutions from two months of original (Kalman) and new (Wiener) observation data respectively. In the low degrees (mainly below the measurement bandwidth of the gradiometer) a significant improvement is visible.

In the combination with GPS these improvements disappear, because the low wavelength part of the field is mainly determined by GPS observations.

Figure 19: Differences per coefficient between combined gradiometer/ GPS-solutions from two months of original (Kalman) or new (Wiener) observation data. Improvements are visible mainly in the near zonal coefficients that are generally degraded due to the polar gap.



10. References

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Stummer C, Fecher T, Pail R (2011): Alternative method for angular rate determination within the GOCE gradiometer processing, J Geod 85:585-596

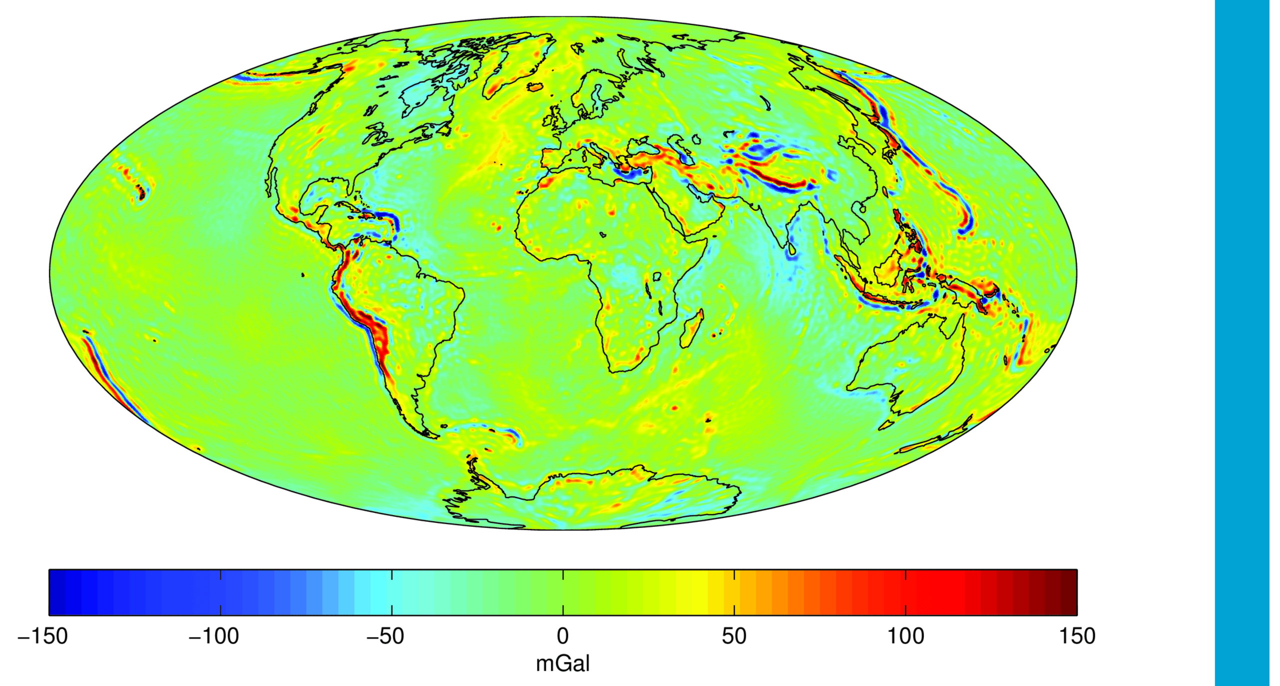

Figure 15: Gravity anomalies computed with the combined GRACE/GOCE (8 M) solution (l_{max}=160).

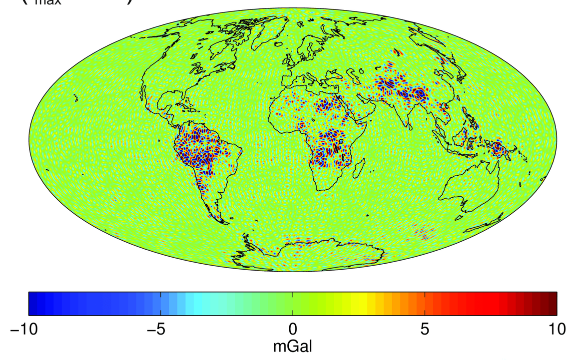

Figure 16: Differences to EGM08 (l_{max}=160).

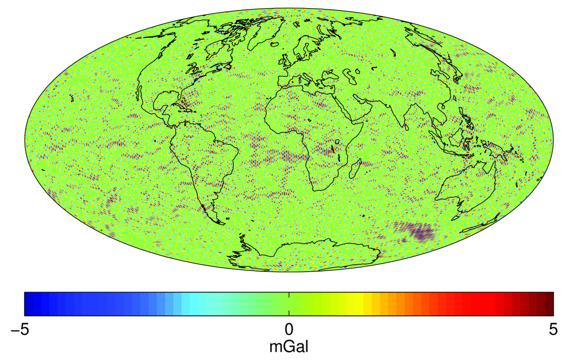

Figure 17: Differences to GOCO02S (l_{max}=160).

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