GRACE Orbit Determination using GPS and K-Band Data

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Motivation

The two GRACE satellites provide a unique platform to study precise orbit determination (POD) strategies for constellations of low Earth orbiters (LEOs) using GPS and additional inter-satellite observations. Although the GPS data are well suited to establish the "geodetic datum" of the GRACE orbits, the precision of the relative positions is restricted to only about 1cm when using the GPS data in the zero-difference mode.

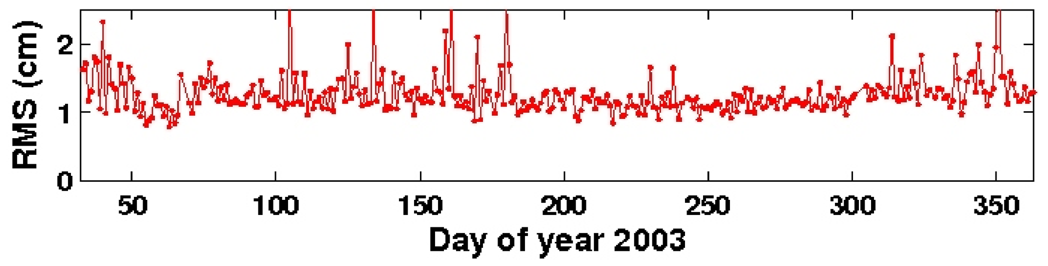

Figure 1: RMS of the K-Band validation of reduced-dynamic orbit positions computed from zero-difference GPS carrier phase observations by Jäggi et al. (2007) with the gravity field model EIGEN-CG03C (Förste et al., 2005).

Combined POD procedure

We use the GPS-based reduced-dynamic orbit positions computed by Jäggi et al. (2007) as pseudo-observations and the ultra-precise Level 1B inter-satellite K-Band range or range-rate data as observations for a combined reduced-dynamic POD procedure with the gravity field model EIGEN-CG03C. The individual steps performed are

- Set up of two normal equation systems based on the GRACE A and GRACE B position pseudo-observations as part of a reduced-dynamic POD procedure. The orbit parameters set up are six initial osculating elements, empirical accelerations in the radial, along-track, and cross-track direction which are constant over 24h, and pseudo-stochastic pulses acting in the same directions every 15min.
- Set up of one normal equation system based on the Level 1B K-Band range or range-rate observations. Apart from necessary K-Band range bias parameters, exactly the same parameters are set up as in the first step. Due to the presence of the orbit parameters of both GRACE satellites, the K-Band normal equations are singular when using them alone.
- Combination of the three normal equation systems. A measurement-type specific weighting ratio has to be applied, e.g., $1:10^4$ between the position pseudo-observations and the K-Band range observations.

Impact on the absolute orbit

It is important to note that the quality of the combined orbit solution is not degraded w.r.t. the GPS-only solution in an absolute sense. The two figures below show that

- The mean RMS values of the orbit differences are rather small, namely 3.9mm for the radial direction, 6.8mm for the along-track direction, and 0.3mm for the out-of-plane direction when using K-Band range observations. For K-Band range-rate observations the corresponding RMS values are 3.5mm, 6.5mm, and 0.02mm.
- K-Band observations change the GPS-based orbit solutions of GRACE A and GRACE B in a perfectly anti-correlated way for the radial and the along-track direction. The out-of-plane component remains essentially unchanged when taking the K-Band data as additional observations into account.

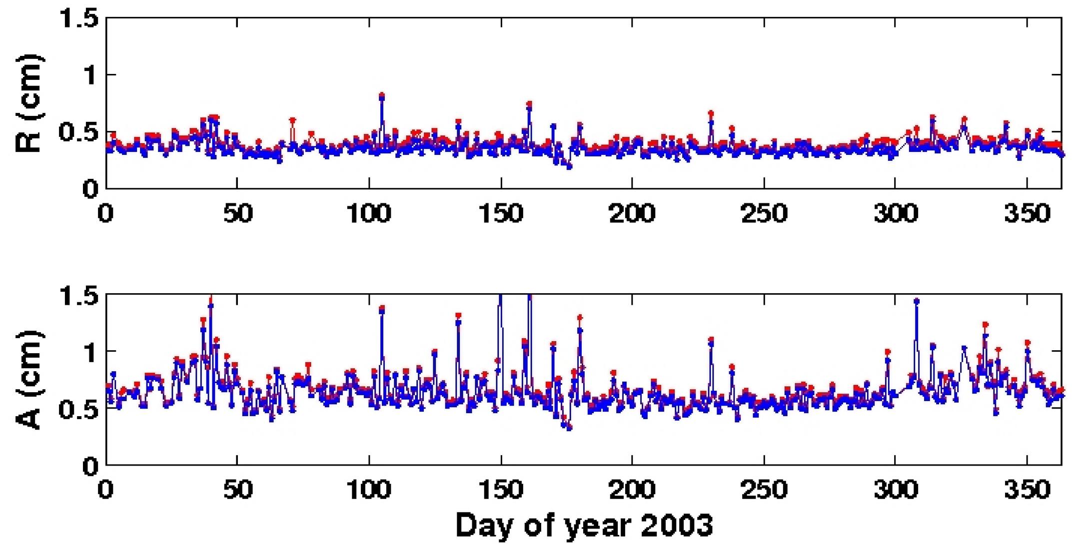

Figure 2: RMS of position differences between the combined reduced-dynamic orbit solution (based on K-Band range or range-rate observations) and the GPS-only solution in the radial (top) and the along-track (bottom) direction.

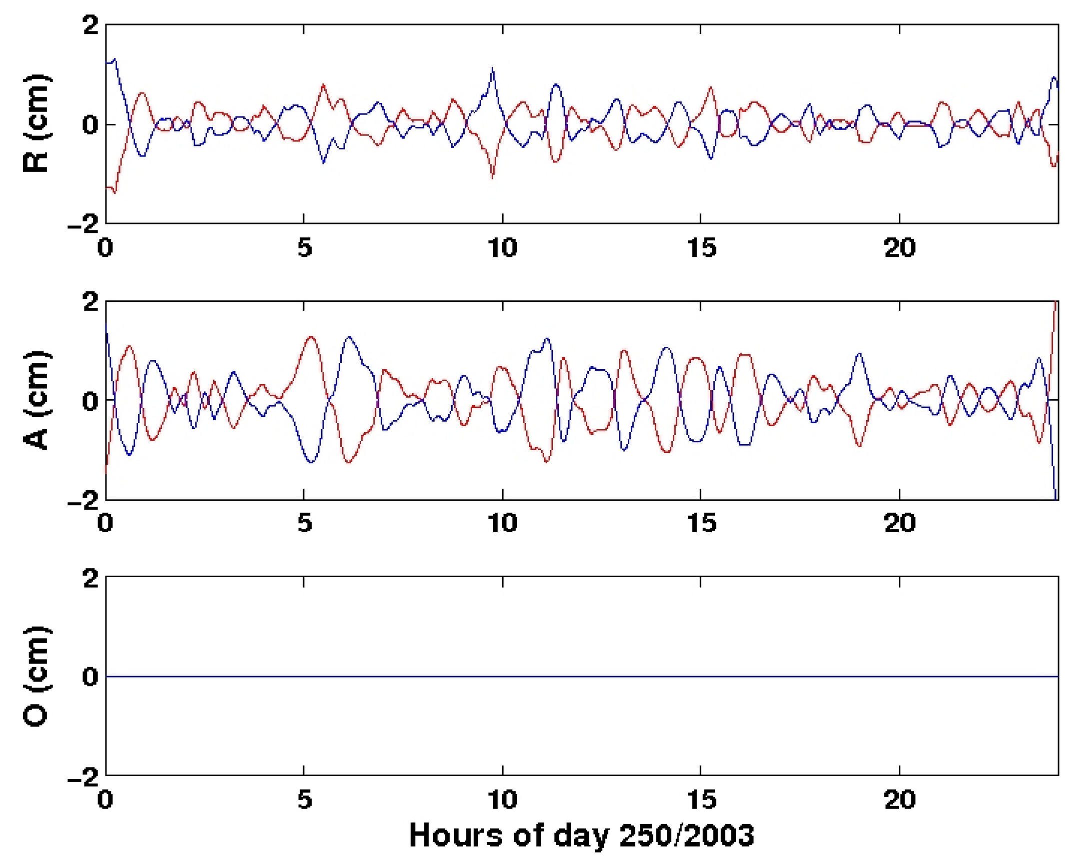

Figure 3: Position differences of the combined solution based on K-Band range-rate observations and the GPS-only solution in the radial (top), the along-track (middle), and the out-of-plane (bottom) direction for GRACE A and GRACE B.

Impact on the relative orbit

The quality of the relative orbit positions primarily depends on the capability to properly model the K-Band observations. The three figures below show that

- The mean RMS error of the K-Band range residuals is 42.3 um (outliers not shown) when using the K-Band range observations for POD with the gravity field model EIGEN-CG03C.
- The corresponding RMS error of the K-Band range-rate residuals is 0.54 um/s. Numerous outliers are present in the first month of the year due to data quality issues.
- The force model is crucial in order to obtain relative orbit positions of highest quality. Further improvements are expected when considering more recent ocean tide models and non-tidal short-term mass variations as background models.

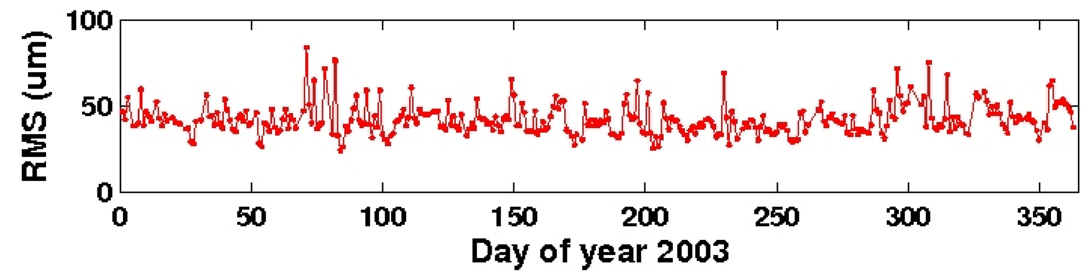

Figure 4: RMS of the K-Band range residuals when using the gravity field model EIGEN-CG03C.

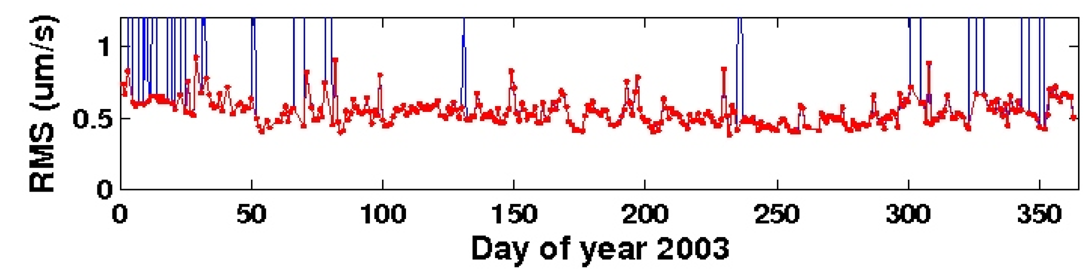

Figure 5: RMS of the K-Band range-rate residuals when using the gravity field model EIGEN-CG03C. Outliers mainly occur in the first month of the year and are often related with problematic attitude data which is needed to correct the K-Band observations.

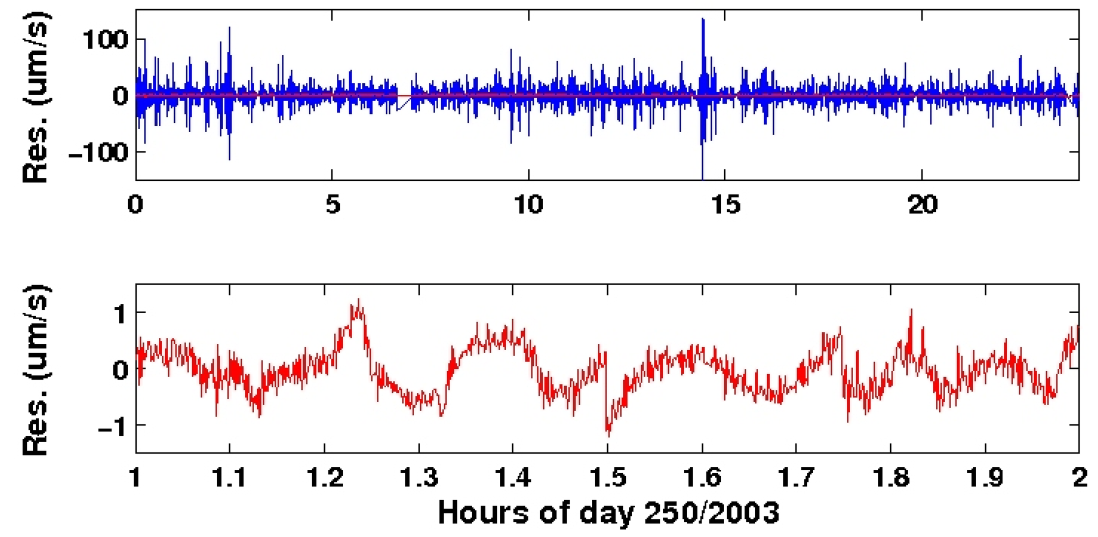

Figure 6: K-Band range-rate residuals when using the pre-GRACE gravity field model EIGEN-2 or the GRACE gravity field model EIGEN-CG03C (top) and zoom on the residuals when using EIGEN-CG03C (bottom). The signals are due to the very limited background modeling and the neglection of the correlations between the Level 1B K-Band observations.

Numerical stability

The combination of the ultra-precise K-Band observations with the less precise positions may be particularly critical with regard to numerical stability when applying large weights for the K-Band range observations. In order to avoid the loss of significant digits in the GPS-part to some extent, it is beneficial to not set up the original parameters O_A and O_B of GRACE A and GRACE B, but transformed parameters as

$$T_1 = ½(O_A+O_B) \quad \text{and} \quad T_2 = ½(O_A-O_B)$$

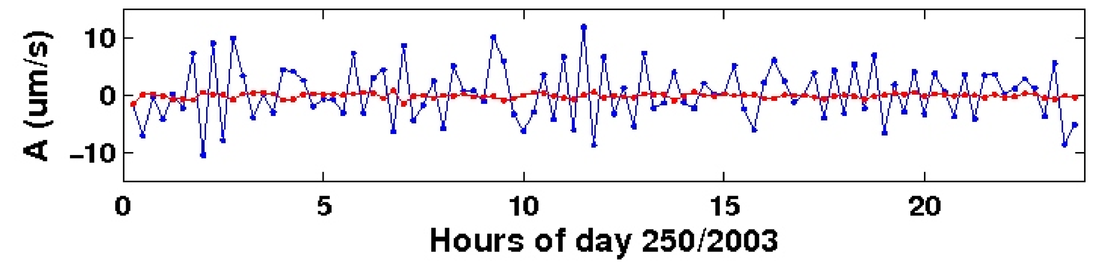

Figure 7: Parameter T_2 for the along-track pulses estimated in the GPS-only or in the combined reduced-dynamic POD. The K-Band observations mainly contribute to the parameter T_2 and, e.g., "naturally" constrain the pulse differences of GRACE A and GRACE B to almost zero.

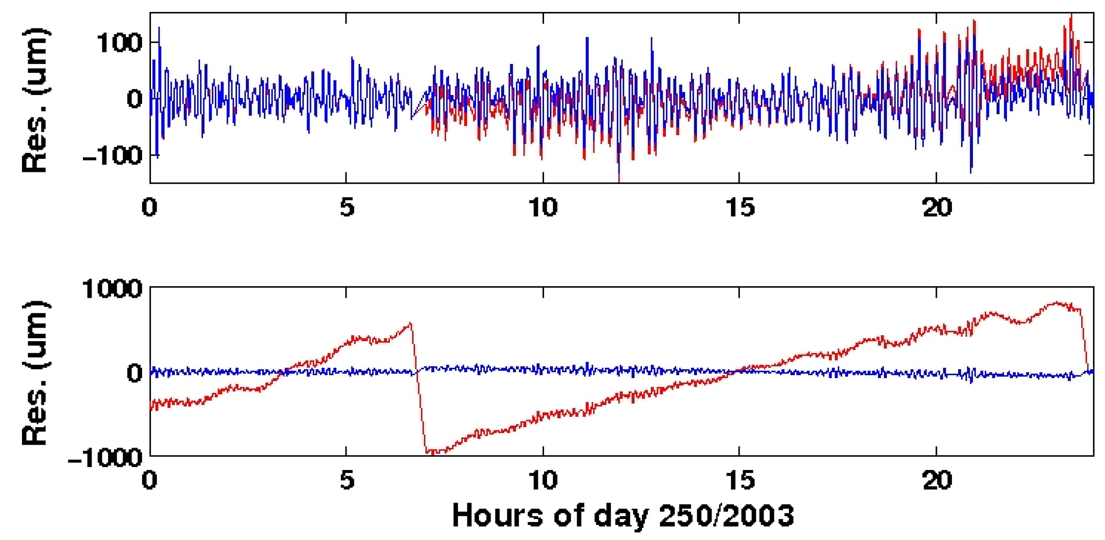

Figure 8: K-Band range residuals when using the original parameters or the transformed parameters for a weighting ratio of $1:10^4$ (top) or $1:10^6$ (bottom). The transformation avoids to some extent numerical problems which may even lead to singularities when applying large weights (bottom).

Summary

Reduced-dynamic GRACE orbits are computed based on GPS-based reduced-dynamic positions used as pseudo-observations and inter-satellite K-Band data used as additional observations. The combined solutions are not degraded w.r.t. the GPS-only solutions in the absolute sense and are much better in the relative sense. Numerical problems are avoided to some extent by a corresponding parameter transformation.

References
Förste C. et al. (2005) A New High Resolution Global Gravity Field Model Derived From Combination of GRACE and CHAMP Mission and Altimetry/Gravimetry Surface Gravity Data. Geophysical Research Abstracts, Vol. 7, European Geosciences Union.
Jäggi A. et al. (2007) Precise orbit determination for GRACE using undifferenced or doubly differenced GPS data. Adv. Space Res. 39(10), 1612-1619.
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