On the feasibility of phase only PPP for kinematic LEO orbits

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Motivation

- Low Earth Orbiters (LEO): satellites in altitudes up to 1000 km used for Earth observation
- Equipped with many different sensors, positioning and timing are mandatory
- Both is achievable by using GNSS signals
- Uncertainties in the orbit positions directly transfer into the end-products
- Methods for Precise Orbit Determination (POD): reduced-dynamic or kinematic orbits

The GRACE mission

- GRACE: Gravity Recovery And Climate Experiment, launched in 2002 and still in orbit
- Two identical LEOs at ca. 360 km height (in end of March 2016)
- Selection of sensors on-board: star cameras, L1/L2 GPS antenna, BlackJack L1/L2 dual-frequency codeless GPS receiver, Ultra Stable quartz Oscillator (USO)
- GPS raw observations are pre-processed by the Jet Propulsion Laboratory (JPL)
- GRACE positions available from reduced-dynamic orbit done by JPL (Wu et al., 2006)

A method for kinematic GRACE orbits

- Using P-Code and phase observations on both GPS frequencies L1 and L2
- Ionosphere-free linear combinations P3 and L3 to eliminate 1st order of ionospheric delay
- Using high precision GPS satellite orbits and satellite clocks from IGS analysis center CODE
- Precise Point Positioning (PPP) in a batch Least-Squares Adjustment (LSA)
- Observations corrected by PCOs and PCVs, relativistic effects and phase wind-up (PWU)
- Near-field multipath cannot be modeled and subtracted from the observations, therefore it stays as an error source

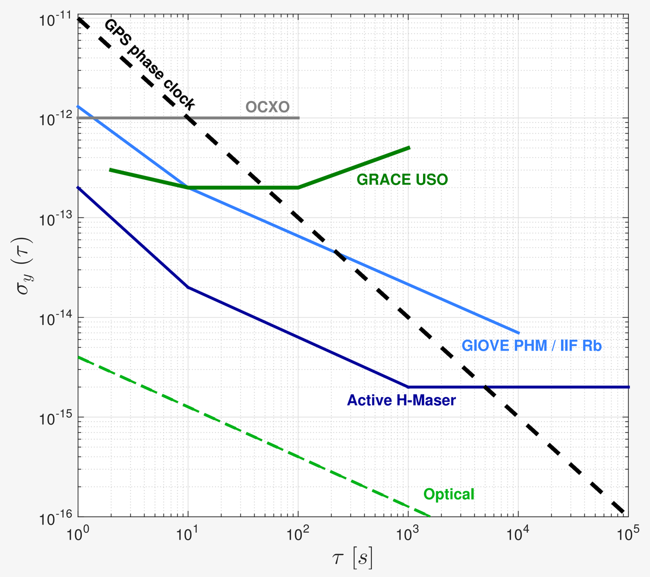

Figure 1: Typical Allan deviations of some chosen high-precision oscillators

- We make use of a concept called GNSS **Receiver Clock Modeling** (RCM)
- RCM in LSA: approximating the behavior of the GPS receiver clock through piecewise linear polynomials
- The coefficients of the polynomials are time offsets o_i and frequency offsets δf_i
- The length $\Delta t = (t - t_i)$ of one polynomial part (the clock modeling interval) is restricted by the frequency stability of the oscillator
- Receiver clock error $\delta t_i = o_i + \delta f_i \cdot (t - t_i)$
- RCM is feasible as long as the Allan deviation of the oscillator is smaller than the white noise of GNSS phase observations (cf. figure 1)
- GRACE GPS receiver is driven by the USO, maximum value of Δt is 60 s
- For CHAMP Montenbruck and Kroes (2003) found that cross-talk between the main GPS antenna and the GPS occultation antenna causes a multipath-like pseudorange error in the aft half of the main antenna, when the occultation antenna is switched on. This phenomena is also present in GRACE GPS data (cf. figure 2)
- The BlackJack receiver has a known code tracking issue which occurs for some code observations leading to 15.5 m bias for C/A, P1 and P2 observations for that specific observation arc (Montenbruck and Kroes, 2003)

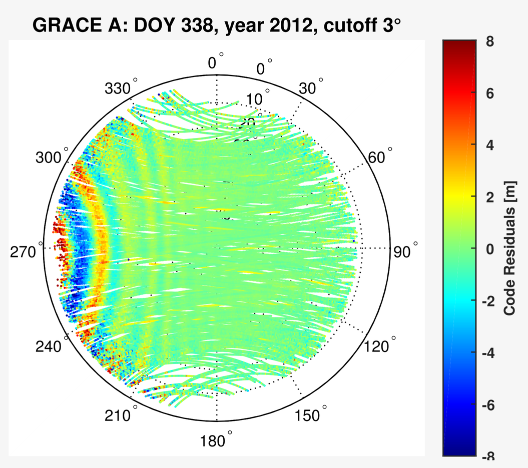

Figure 2: Tailing GRACE A

Benefits for kinematic GRACE orbits from RCM

- Strengthened observation geometry due to smaller DOP values, decorrelation of radial coordinate and receiver clock error, clock parameters are no longer epoch-wise parameters
- Improved mean daily RMS values of high-pass filtered coordinate differences between kinematic and reduced-dynamic orbits without and with epoch-wise clock modeling by 5% to 24% (Weinbach and Schön, 2013)

IfE kinematic GRACE orbits with RCM using P3 and L3

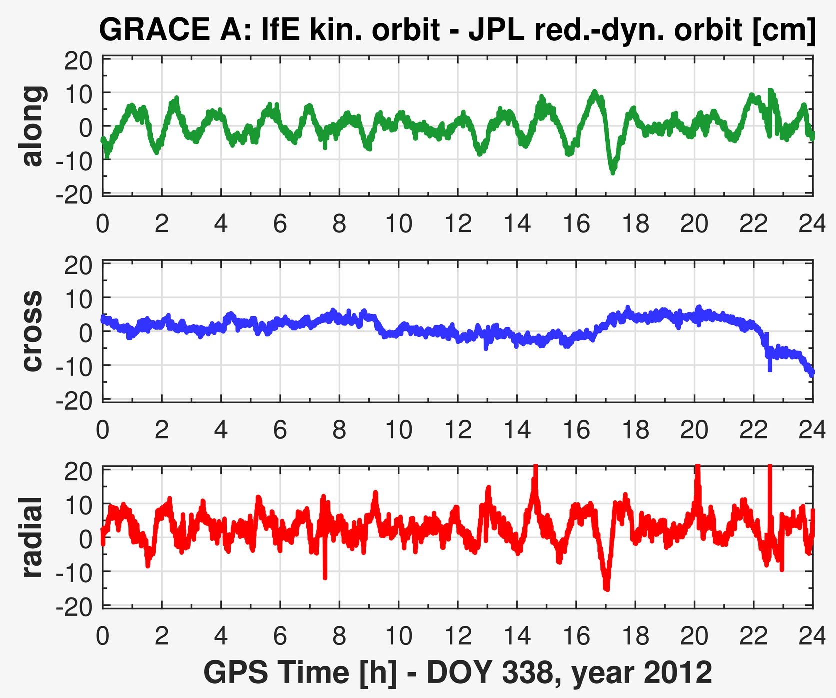

Figure 3: IfE orbit using P3 and L3 observations w.r.t. JPL reduced-dynamic orbit for 3rd Dec. 2012

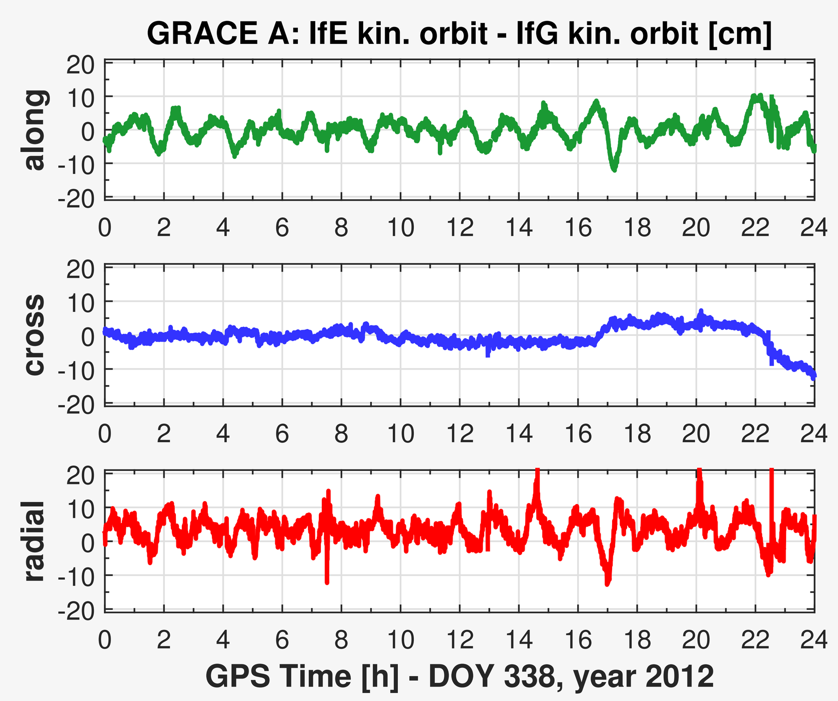

Figure 4: IfE orbit using P3 and L3 observations w.r.t. IfG kinematic orbit for 3rd Dec. 2012

- We compare our solution with the reduced-dynamic orbit from JPL, the kinematic orbit from Institute of Geodesy (IfG) from the TU Graz (Zehentner and Mayer-Gürr, 2013) and the kinematic orbit from the Astronomical Institute of the University of Bern (AIUB)
- Mean value of radial coordinate shows +2.8 cm offset for GRACE A w.r.t. JPL orbit
- Mean values of along and cross fit within 8 mm compared to all other orbits
- Mean standard deviations w.r.t. JPL reduced-dynamic orbit for GRACE A for two days in December 2012: 3.6 cm (along), 3.5 cm (cross), 3.9 cm (radial)

New approach for GRACE kinematic orbits

- Measured distances are directly linked with the receiver clock error δt_i
- Each phase measurement contains an ambiguous number N of whole phase cycles
- Columns for time offsets o_i in the design matrix are linear depended from columns for estimated phase ambiguities N_i
- In the conventional case the code observations rectify the column singularity
- Idea: the receiver clock time offset can be seen as a part of the phase ambiguity
- Time offsets o_i and ambiguities N_i are put into one common parameter, the column singularity in the design matrix vanishes even without using code observations
- Each clock polynomial does not have its own time offset o_i but is now attached relatively to its previous polynomial (cf. figure 5)

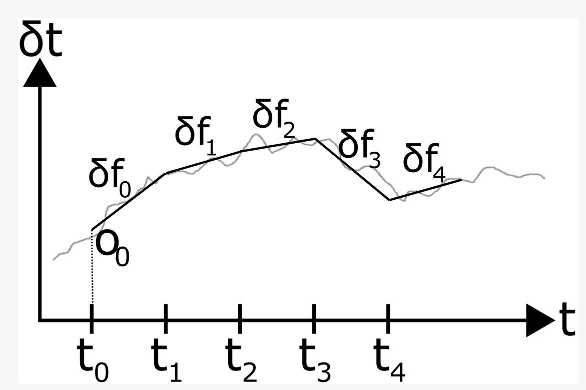

Figure 5: RCM with phase only

- The overall time offset o_0 is set to zero. The introduced error is absorbed by the parameters for the ambiguities N_i
- A parameter adjustment only with phase observations in the design matrix is possible
- This works out for GRACE data because of the pre-processing. GPS observations are time corrected w.r.t. the GPS system time and phase observations are bias-adjusted so that they "are close to the range counterparts" (Wu et al., 2006)
- Furthermore the a-priori coordinates for every observation epoch are known by a few centimeters, coming from the JPL reduced-dynamic orbit
- Benefits: less precise (and partly biased) code observations (compared to the high accurate phase measurements) are no longer used. No near-field code multipath and no multipath-like code errors are introduced into the adjustment (cf. figure 2)

References

Wu et al., 2006 Algorithm Theoretical Basis Document for GRACE Level-1B Data Processing V1.2. *GRACE 327-741 (JPL D-27672).*
Montenbruck and Kroes, 2003 In-flight performance analysis of the CHAMP BlackJack GPS Receiver. In: *GPS Solutions, 7:74-86.*
Weinbach and Schön, 2013 Improved GRACE kinematic orbit determination using GPS receiver clock modeling. In: *GPS Solutions, 17:511-520.*
Zehentner and Mayer-Gürr, 2013 Kinematic orbits for GRACE and GOCE based on raw GPS observations. *Poster presented at the IAG Scientific Assembly 2013, 1.-6. September 2013, Potsdam, Germany.*

Change in the design matrix A

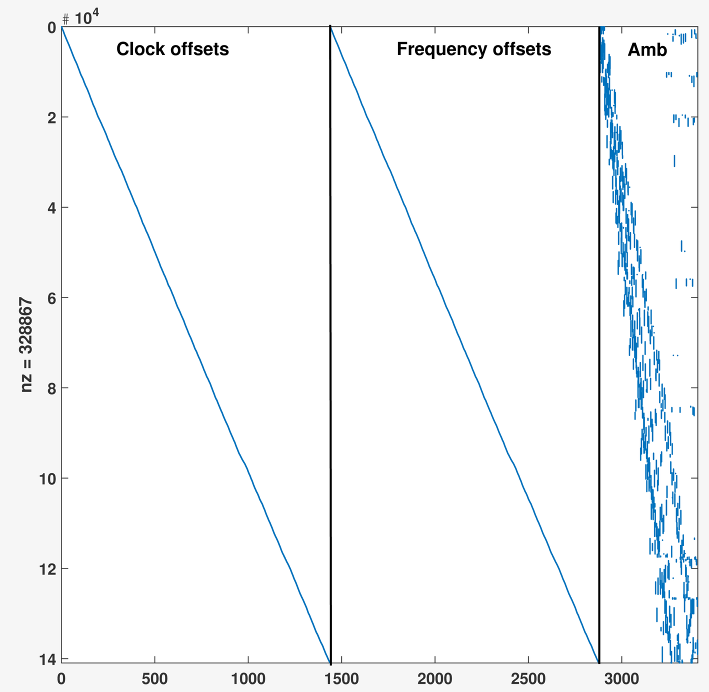

Figure 6: Part of the design matrix A for code and phase observations with RCM

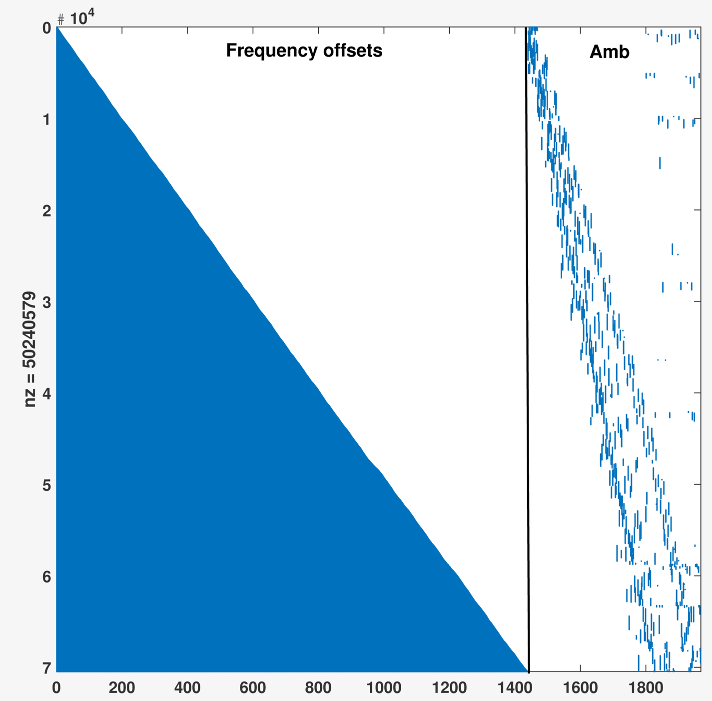

Figure 7: Part of the design matrix A with RCM using phase observations only

IfE kinematic GRACE orbits with RCM using L3 only

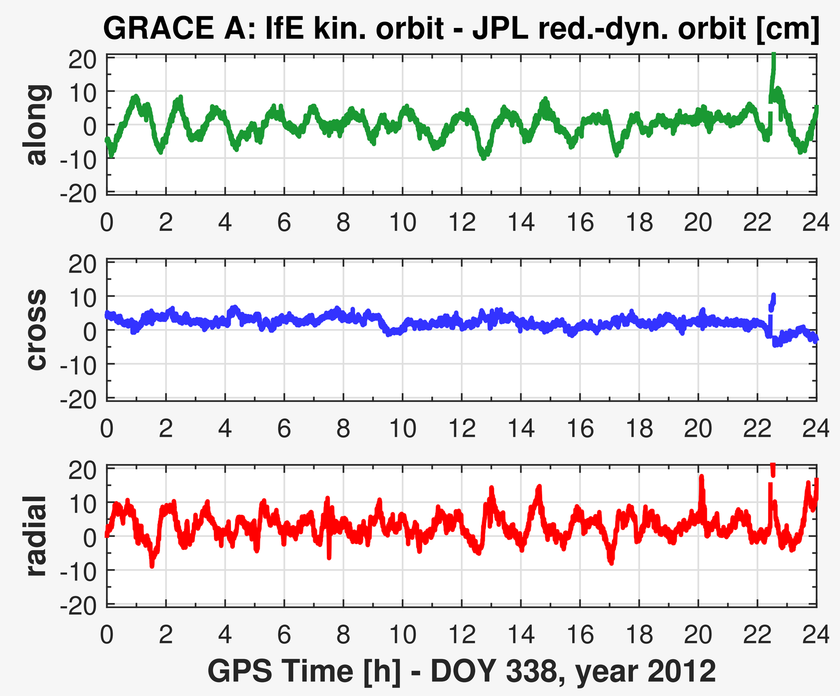

Figure 8: IfE orbit using only L3 observations w.r.t. JPL reduced-dynamic orbit for 3rd Dec. 2012

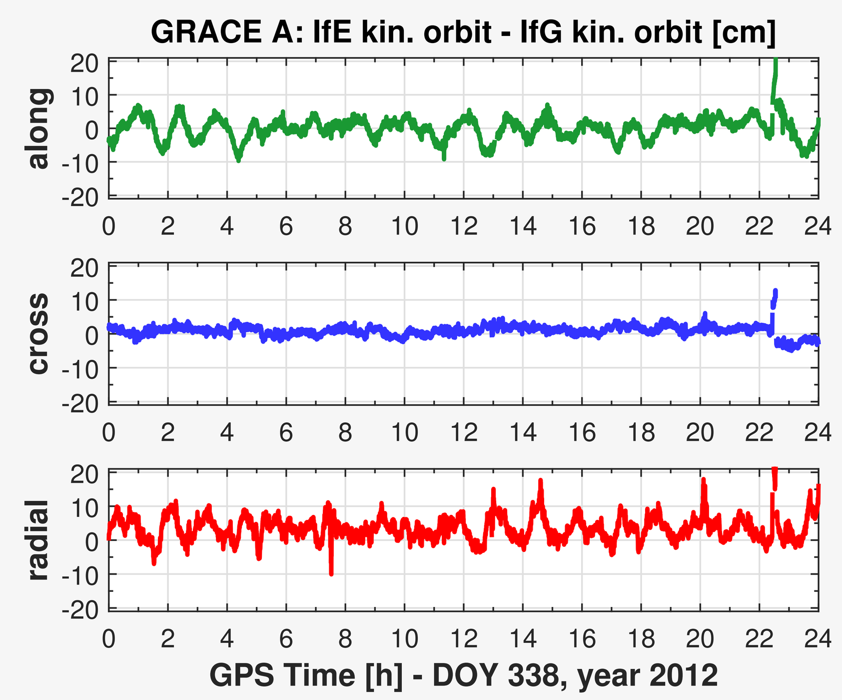

Figure 9: IfE orbit using only L3 observations w.r.t. IfG kinematic orbit for 3rd Dec. 2012

- Mean values of along and cross coordinate fit within 1.2 cm compared to all other orbits
- Mean radial coordinate is +5.2 cm off compared to AIUB kinematic GRACE orbit
- Mean standard deviations w.r.t. JPL orbit for GRACE A for two days in Dec. 2012: 3.6 cm (along), 2.5 cm (cross), 3.6 cm (radial)

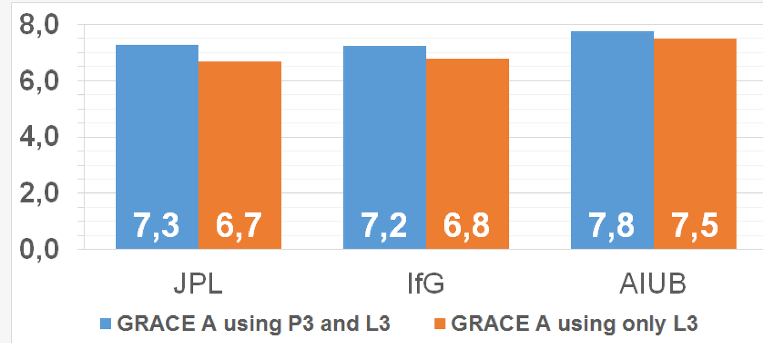

Figure 10: Mean 3D-RMS in cm of IfE kin. orbit w.r.t. other orbits from two day in 2012

Conclusion

- GRACE GPS data suffers from code multipath, occultation antenna cross-talk affecting the code observations and code tracking biases
- GRACE USO offers the opportunity for GPS Receiver Clock Modeling (RCM), leading to improvements in position residuals and DOP values
- Pre-processed GPS data makes a phase only positioning in combination with RCM feasible
- Without the corrupted code observations the position residuals are improved for the GRACE satellite where the GPS occultation antenna is in operation
- Further studies are needed to evaluate the full potential of the phase only PPP with RCM for kinematic orbits

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