GPS-based LEO orbit determination with carrier phase cycle slip fixing over long data gaps

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Introduction

Precise GPS-based orbit modeling of Low Earth Orbiting (LEO) satellites is important in many research fields like satellite dynamics, reference frame and gravity field determination. One of the limiting factors for highest modeling precision is the necessity to solve for a large number of LEO carrier phase ambiguities.

To reduce this number, we present here an iterative approach for single-LEO phase cycle slip (CS) fixing over long data gaps. In this method the number of ambiguities to be estimated is reduced significantly, leaving in an ideal case only one per LEO and GPS satellite at the beginning of the orbit arc (approximately ~30 in total).

For validation, the method is applied to simulated GRACE on-board GPS data in a reduced-dynamic and kinematic orbit determination and compared with both float and double-difference (DD) ambiguity fixed solution. The LEO orbit determination is performed here in the so-called two-step approach where the reference GPS orbits and clock offsets are kept fixed.

The CS fixing method is also applied to one month of real GRACE-A/B and TerraSAR-X/TanDEM-X (TSX/TDX) data and validated using Satellite Laser Ranging (SLR), GRACE K-Band range data and precise baselines generated for Synthetic Aperture Radar (SAR) applications (TSX/TDX). The precision of the kinematic orbits is verified by comparison with the dynamic solution.

Method

The classical approach to CS detection and correction is based on the well known and commonly used approach based on geometry-free wide-lane (*WL*) and ionospheric (*LI*) combinations of two frequency GPS data. The integer CS (Δn_1, Δn_2) on the L_1 and L_2 frequencies are computed from following equations:

$$\Delta n_1 - \Delta n_2 = \Delta WL \qquad (1)$$

$$\lambda_1 \Delta n_1 - \lambda_2 \Delta n_2 = \Delta LI \qquad (2)$$

where the wide-lane combination, ΔWL, is computed as a difference of mean *WL* bias before and after the cycle slip, the CS in the ionospheric combination, ΔLI, is computed with the help of an ionosphere extrapolation (polynomial) function. Due to poorly predictable behaviour of the ionosphere, this approach can only be used to connect phase sessions separated no more than a few minutes. To overcome this problem, the CS in the ionospheric combination ΔLI is replaced by the CS in ionosphere-free geometry-based combination ΔL_3. The CS in this combination is computed as a difference of L_3 ambiguities obtained in the POD solution before and after the CS. Equation (2) can be replaced by

$$\frac{f_1^2\lambda_1\Delta n_1 - f_2^2\lambda_2\Delta n_2}{f_1^2 - f_2^2} = \Delta L_3 \qquad (3)$$

where λ_1 and λ_2 are the wavelength, f_1 and f_2 frequencies of the L_1 and L_2 carriers. The CSs are fixed (rounded) iteratively to the nearest integer if their fractional part is smaller than 0.15 cycle (increased to 0.25 in the last iteration). The iterative CS fixing process is performed for phase gaps from 10 minutes and sequentially increased up to 330 minutes (all possible gaps). The CS fixing process is monitored by CS histograms, which, when orbit modeling is precise, should show clear pick around the nearest integer. The efficiency of the CS fixing for the gaps up to 10 min reaches in most cases 100%. For larger gaps efficiency ranges from 95% up to 100%, depending on data quality.

Simulation

For validation and for studying the performance of the method, one day of GPS constellation (30 satellites, 124 ground stations) and GRACE-A/B pseudo-range and carrier phase data were simulated. The noise of the pseudo-range was 50 cm, those of the carrier phase 0.5/0.3 cm for ground stations and LEOs, respectively. The GPS/LEO orbit modeling was the same as used in GFZ Rapid Science Orbits (RSO). For GRACE it includes:

- 1 scaling factor for solar radiation pressure (SRP) modeling
- 5 atmospheric drag scaling factors
- 238 periodic empirical coefficients (sin/cos, transversal/normal, 1/rev, 2/rev, every 45 min)
- 700 ambiguities, epoch-wise clocks.

For the estimation, a mis-modeling of the GPS SRP was simulated by fixing wrong Y-biases of the SRP model and estimating GPS orbits/clocks again, resulting in around 3 cm RMS orbit differences. These GPS orbits/clocks were used as fixed in the subsequent GRACE orbit determination using float ambiguity solution, DD ambiguity fixing or the iterative CS fixing. The results for the GRACE orbits and baselines are given in Table 1.

The simulation results show, that DD ambiguity fixing does not improve the orbits, but is very efficient for the baseline determination. For the dynamic orbits, the CS fixing improves orbits and for the baseline it can be equally efficient as DD ambiguity fixing (provided ~100% CS fixing). For the kinematic orbits the CS fixing gives the best results for the orbits, the baseline in radial direction is, however, less accurate.

	Float ambiguities		DD ambiguity fixing		Cycle slip fixing (100%)	
	Dynamic orbits					
	Orbit	Baseline	Orbit	Baseline	Orbit	Baseline
R	3.62	1.04	4.34	0.28	2.36	0.29
C	8.24	2.37	11.48	0.50	4.18	0.55
A	6.13	2.57	6.98	0.48	4.93	0.50
	Phase RMS 4.40		Phase RMS 4.71		Phase RMS 9.58	
	Kinematic orbits					
	Orbit	Baseline	Orbit	Baseline	Orbit	Baseline
R	12.61	5.99	14.15	4.53	10.37	8.03
C	10.48	3.76	13.40	2.10	4.82	2.76
A	10.52	4.13	11.54	2.14	5.51	3.15
	Phase RMS 3.85		Phase RMS 4.09		Phase RMS 9.34	

Table 1. RMS (mm) of orbit and baseline differences between simulated and estimated GRACE A+B orbits in radial (R), crosstrack (C) and alongtrack (A) directions. SRP of GPS constellation is mis-modeled. Green: improvements, red: deteriorations in comparison with the float ambiguity solution.

TerraSAR-X/TanDEM-X

The same three POD approaches as in the simulation case were used for one month of real TSX/TDX GPS data (May 2016, maneuvers excluded). For the reference GPS constellation the GFZ RSO orbits were taken (~4-5 cm 3D accuracy). The LEO modeling was similar to the simulation case except denser, highly constrained empirical coefficients (every 20 min) in 3 directions (radial, along- and cross-track). Fig. 1 provides a typical example of the distribution of the original CSs for all gap lengths obtained for orbits before and after iterative CS fixing for the TDX satellite on May 1, 2016. The clear peak in the middle indicates the integer nature of the CSs, regardless of data gap length. Figs. 2-5 provide the results concerning number of ambiguities, comparison of the baseline with GFZ precise baselines (accuracy < 1 mm) generated for SAR, as well as validation with SLR and kinematic-dynamic orbit differences.

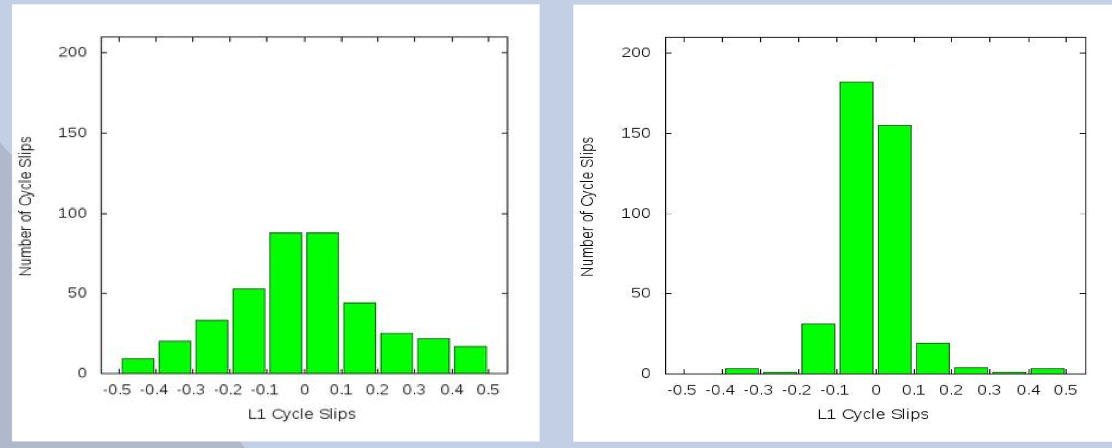

Fig. 1. TDX CS distribution for the orbit before (left) and after (right) CS fixing

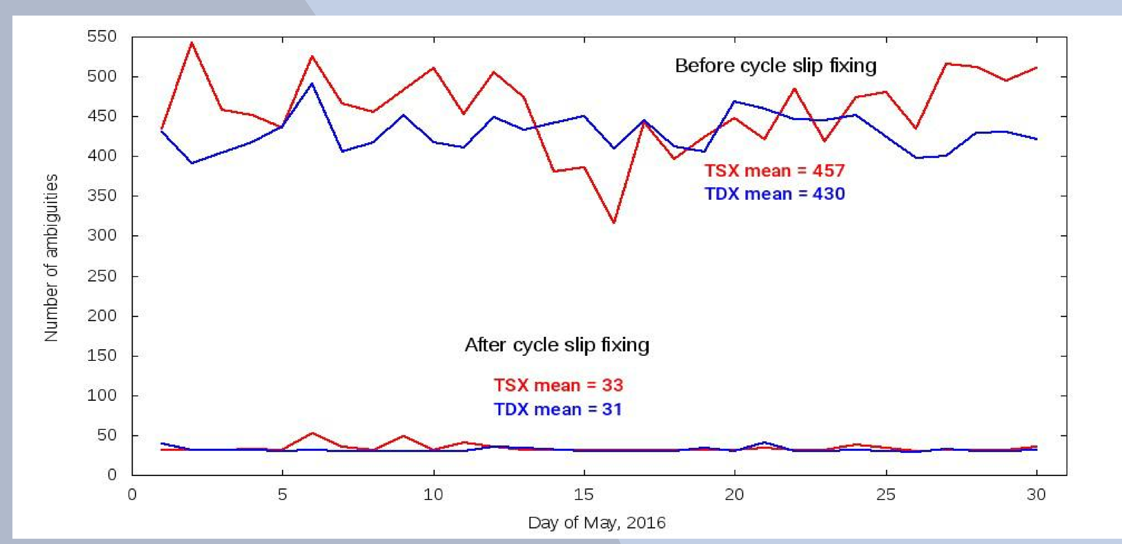

Fig. 2. Number of ambiguities before and after the CS fixing.

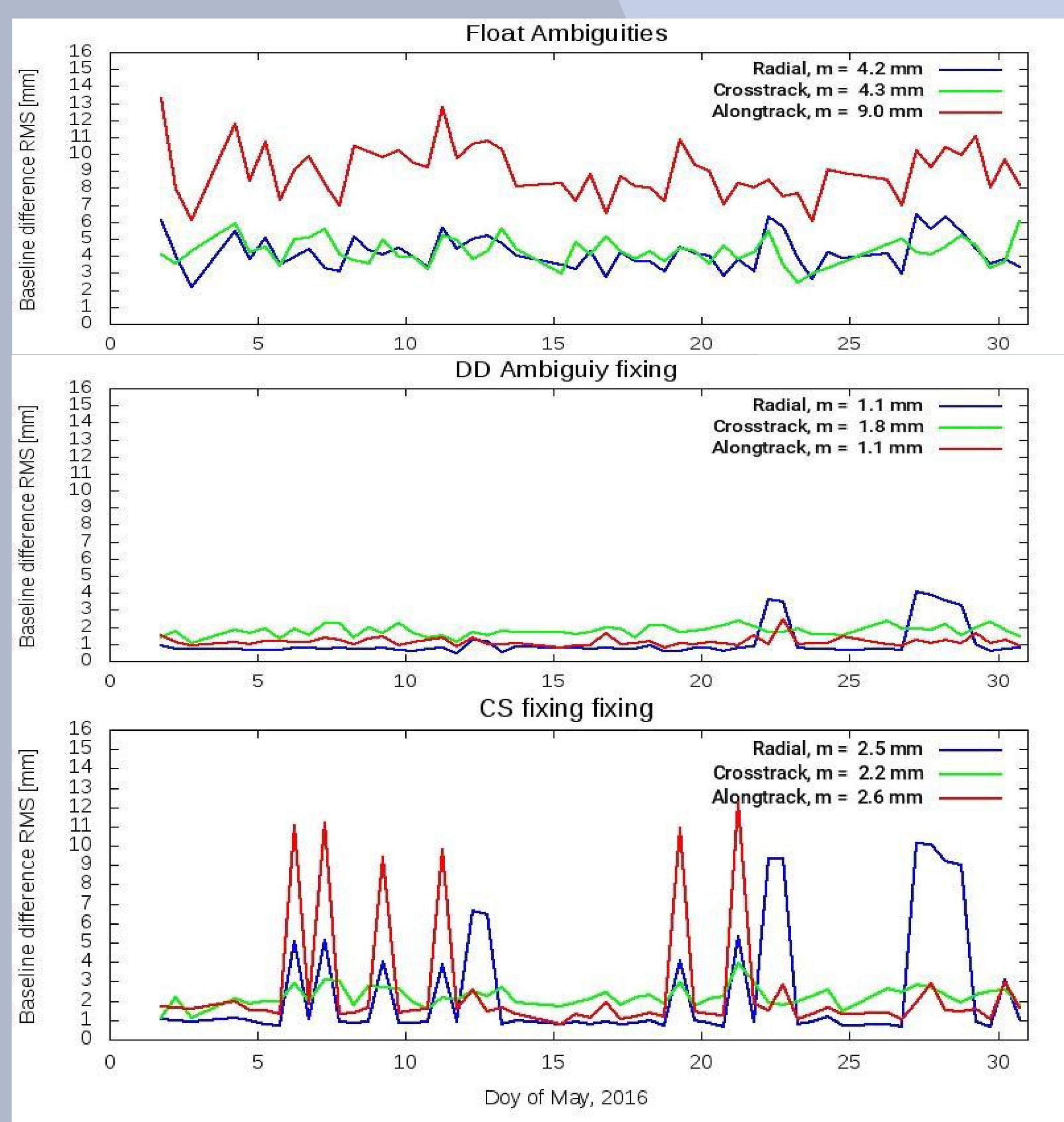

Fig. 3. Baseline comparison with precise GFZ baseline solutions. Large deviations are likely cased by smaller number or incorrectly fixed CSs.

Fig. 4. TSX+TDX SLR statistics for May, 2016. Number of observations is given in (). Average values are computed from indicated subset of stations.

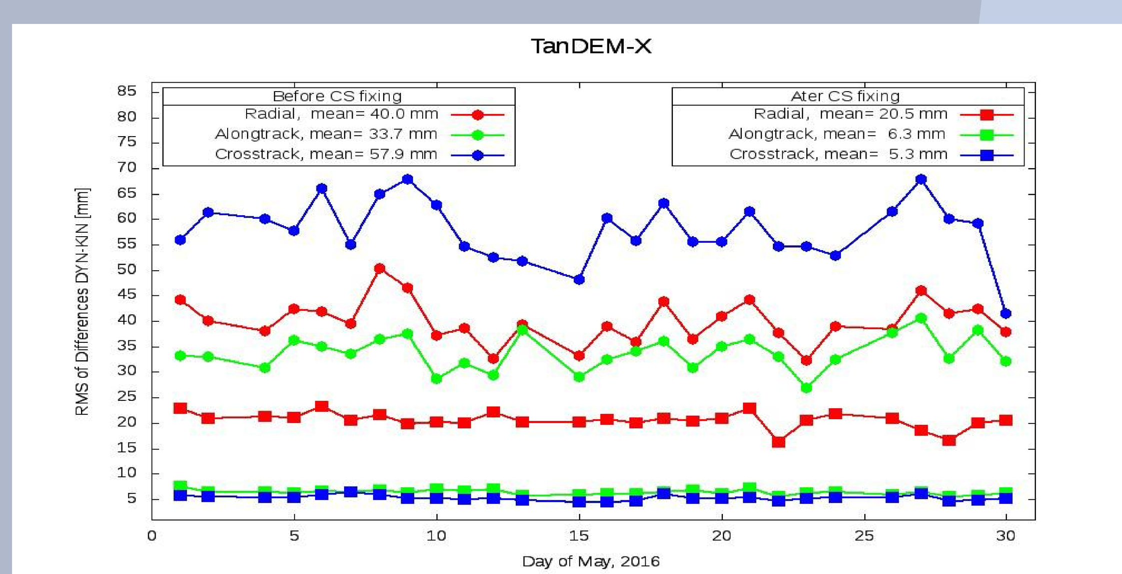

Fig 5. TDX differences between dynamic and kinematic orbits before and after CS fixing. Improvement are mostly pronounced in along- and cross-track direction.

GRACE-A/B

For the GRACE satellites one month (June 2008) of real GPS and K-band range data was selected. The modeling standards were based on those from the GFZ RL05 gravity field processing chain. For the reference GPS constellation the Post-processed Science Orbits (PSO) were taken (~3-4 cm 3D accuracy). In the dynamic modeling the GRACE accelerometer data were used and the following dynamic parameters per LEO were estimated:

- 20 periodic empirical coefficients (sin/cos, transversal/normal direction, spaced every 6 h)
- 75 accelerometer biases (radial/transversal/normal directions, spaced every 1 h)

The results of the processing are depicted in Figs. 6-9. Fig. 7 shows the results of the baseline validation using down-weighted K-band inter-satellite range data.

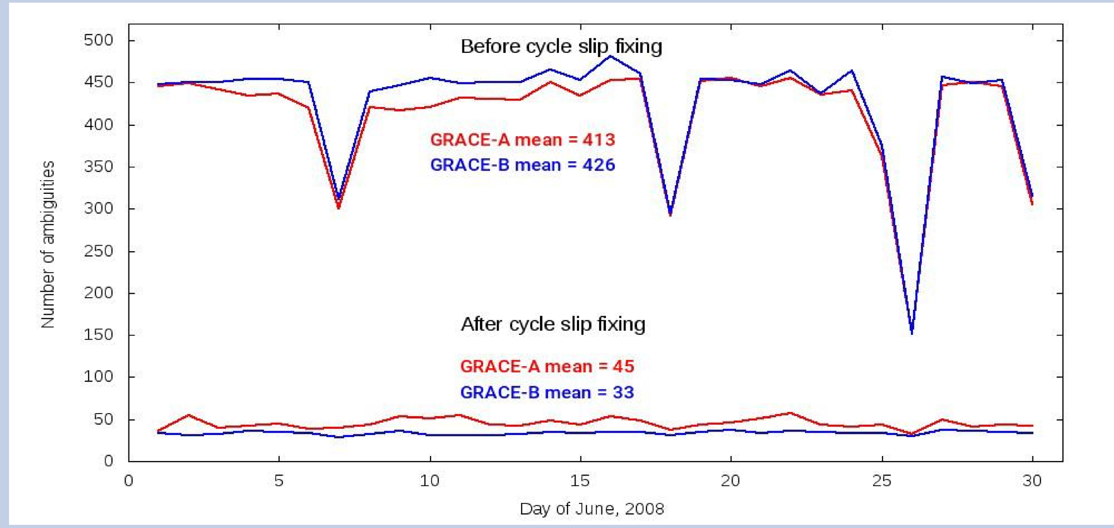

Fig. 6. Number of ambiguities before and after CS fixing.

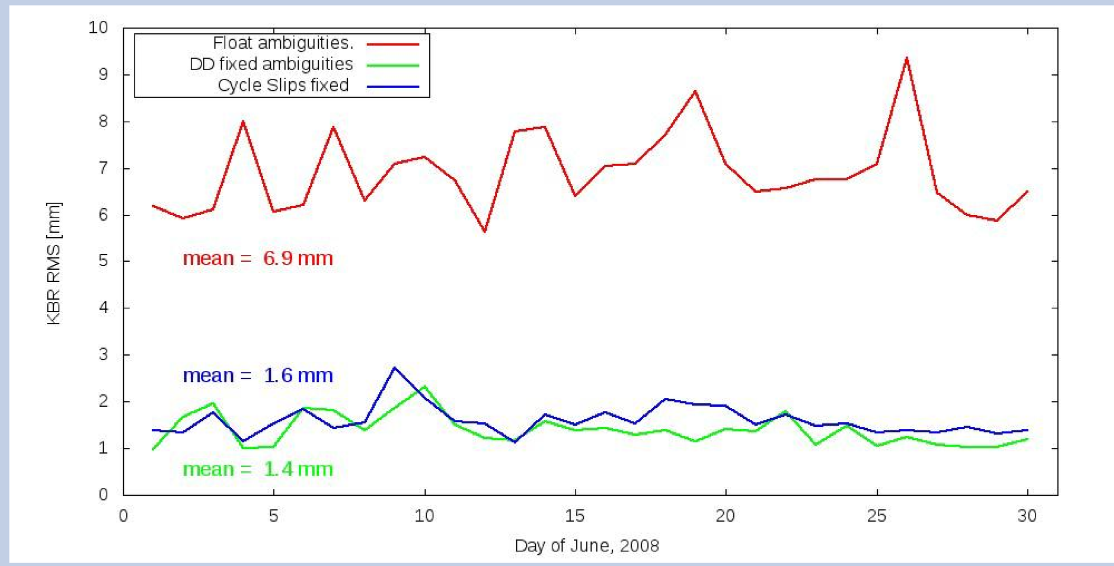

Fig. 7. Validation of the baseline with K-band ranging data

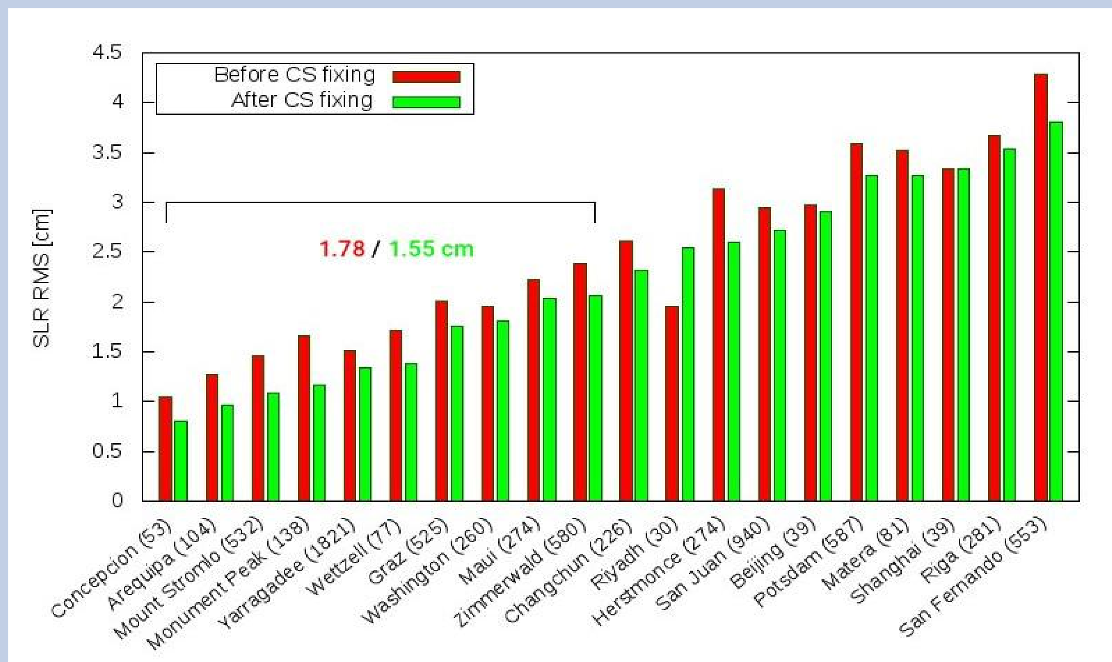

Fig 8. GRACE-A/+B SLR statistics for June, 2008. Number of obs. is given in (). Average values are computed from indicated subset of stations.

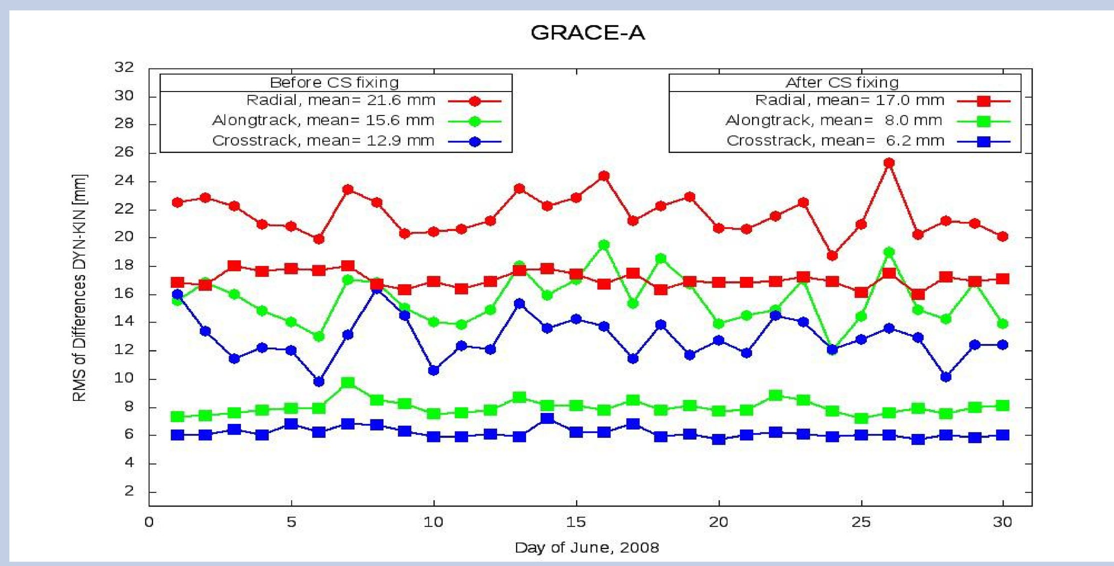

Fig 9. GRACE-A differences between dynamic and kinematic orbits before and after CS fixing. Improvement are mostly pronounced in along- and cross-track direction.

Conclusions

The carrier phase cycle slip fixing over data gaps of any length for LEO satellites is possible and leads to a significant reduction of the number of ambiguities. In most of the cases the number of ambiguities is close to the minimum from this method which is the total number of GPS satellites tracked (~30). In consequence both dynamic and kinematic LEO orbits are improved. In particular:

- Using simulated data the presented CS fixing method (single LEO mode) can produce baselines with accuracy close to those obtained using DD ambiguity fixing. This is also confirmed using real GRACE K-band ranging data, the results are however very sensitive to GPS data quality.
- Processing of both simulated and real data show a significant improvement in consistency between dynamic and kinematic solutions. In along- and cross-track direction the consistency is improved from 1.5 – 6 cm to 5 – 8 mm. The radial component improves by 20% – 50%
- The SLR residuals from the dynamic orbit solutions improve by ~15%, from ~1.8 cm to ~1.5 cm.
- DD ambiguity fixing does not improves the orbits in the two-step approach, however it is most accurate and stable for baseline determination.
- Most accurate dynamic and kinematic absolute orbits can be obtained with CS fixing over long data gaps. The method is demanding with respect to data screening and precise orbit modeling.