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 precision modeling is the necessity to solve for a large number of LEO carrier phase ambiguities.

To reduce this number, we present here a new 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 number of 1 per LEO GPS satellite at the beginning of the orbit arc (approximately ~30 in total).

For validation, the method is applied to simulated GRACE orbit-boards GPS data in 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 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 (I) combinations of two frequency GPS data. The integer CS ($\Delta n_L$, $\Delta n_I$) on the $L_1$ and $L_2$ frequencies are computed from following equations:

\[
\Delta n_L = \frac{\lambda - \lambda_1}{f_2 - f_1} - \frac{\lambda - \lambda_2}{f_2 - f_3} = \Delta n_WL
\]

\[
\Delta n_I = \frac{\lambda_1 - \lambda_2}{f_2 - f_3} - \Delta n_WL = \Delta n_{WLI}
\]

where the wide-lane combination, $\Delta n_WL$, is computed as a difference of mean WL bias before and after the cycle slip, the CS in the ionospheric combination $\Delta n_{WLI}$ is computed with the help of an ionospheric extrapolation (polynomial) function. Due to the poorly predictable behaviour of the ionosphere, this approach can only be used to connect phase sessions separated by data gaps. To overcome this problem, the CS $\Delta n_{WLI}$ in the ionospheric combination $\Delta n_{WLI}$ is replaced by the CS in ionosphere-free geometry-combination $\Delta n_{LI}$.

The CS in this combination is computed as a difference of $L_1$ ambiguities obtained in the POD solution before and after the CS. Equation (2) can be replaced by

\[
\Delta n_{LI} = \frac{\lambda - \lambda_1}{f_2 - f_1} - \frac{\lambda_1 - \lambda_2}{f_2 - f_3} = \Delta n_{WLI} - \Delta n_{f} = \Delta n_L
\]

where $\lambda_1$ and $\lambda_2$ are the wavelengths, $f_1$ 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 iteration). The iterative CS fixing process is performed for phase gaps from 10 minutes and sequentially increased up to 330 minutes (all possible iteration).

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 ~0.5 - 8 cm. The radial component improves by 20% - 50%.
- The SLR residuals from the dynamic orbit solutions improve by ~15%, from ~1 cm to ~1 cm.
- DD ambiguity fixing does not improve 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.

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 GRACE R6.05 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 (sino/cos, transversal/normal direction, spaced every 1 h)
- 75 accelerometer biases (radial/transversal/normal directions, spaced every 1 h)
- 1 scaling factor for solar radiation pressure (SRP) modeling

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.

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