Undifference ambiguity resolution for GPS-based precise orbit determination of low Earth orbiters using the new CODE clock and phase bias products

IGSWS2018 – PS13
International GNSS Service
Workshop 2018 29 Oct.-02 Nov. 2018, Wuhan, China

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Introduction

- GNSS-based Precise Orbit Determination (POD) of Low Earth Orbiters (LEOs) has nowadays become a standard application for high-quality GNSS products as provided by the IGS, or its individual analysis centers. For many LEOs, e.g., for altimetry missions, the centimeter absolute orbit precision and accuracy achieved by **carrier phase-based GNSS positioning** is mandatory and could hardly be obtained by other tracking data.
- Resolving carrier phase ambiguities to their integer values has been known to inherently stabilize solutions for parameters since a long time and has been confirmed in many applications.
- E.g., double-difference (DD) processing of space or space-ground baselines for relative LEO POD allows for ambiguity resolution (AR) without any dedicated GNSS products in addition and is known to significantly enhance relative POD.
- In case of Precise Point Positioning, **undifferenced or zero-difference ambiguity resolution (ZD AR)** requires the knowledge of GNSS satellite phase biases which cancel out in forming baselines. Recently, the Center for Orbit Determination in Europe (CODE) IGS analysis center has established the generation of a **high-quality signal-specific phase bias product and a fully consistent ambiguity-fixed clock product** within its rapid and final IGS-related processing (more details in presentation Schaer et al. in session PY01).
- Using this new product, we demonstrate the benefit of ZD AR on the quality of LEO POD and compare its performance to results obtained in double-difference processing (including AR).

Methods

Reduced-dynamic and kinematic single-satellite orbits and baseline solutions are computed using the development version of the Bernese GNSS Software (Dach et al., 2015). The following parameters are estimated in a batch least-square adjustment:

- Reduced-dynamic POD: 6 initial conditions, 3 constant empirical accelerations in radial (R), along-track (T), and cross-track (N) direction, constrained 6-min. piecewise constant accelerations (PCAs) in R,T,N direction, epoch-wise receiver clock correction, carrier phase ambiguities.
- Kinematic POD: 3-dimensional position and receiver clock correction at every observation epoch, carrier phase ambiguities.
- For both the reduced-dynamic and kinematic baseline determination, the reduced-dynamic orbit of LEO A serves as reference orbit and relative parameters for LEO B are estimated. For the reduced-dynamic baseline determination the differential accelerations are relatively loosely constrained ($1 \cdot 10^{-8} \mathrm{m/s^2}$).

Satellite-specific phase center variation (PCV) maps are introduced (i.e., no relative PCV corrections). For the reduced-dynamic POD GOCO03S up to degree and order 120 is used for the Earth gravity field model and non-gravitational forces are not explicitly modeled.

AR strategy: For both ZD AR and DD AR in a first step, the Melbourne-Wuebbena linear combination of pseudo-range and carrier phase observations is processed to resolve the widelane ambiguities. In a second step, the ionosphere-free linear combination is processed to resolve the narrowlane ambiguities using the sigma strategy (Dach et al., 2015) and to solve for the parameters of the reduced-dynamic orbit. The same resolved ambiguities are then introduced in the subsequent kinematic POD.

Data used: For GRACE, GPS and attitude data of April 2007 are processed. Sentinel-3A and -B are in formation with nearly identical orbits and 30s separation since June 2018, thus allowing for double difference processing of baselines. Furthermore, the generation of Sentinel-3 carrier phase data has recently been refined to avoid half-cycle ambiguities (Montenbruck et al., 2018), allowing for proper integer AR. For this study, Sentinel-3 orbits and baselines are computed for the month September 2018. In all cases, data sampling is 10 s.

Ambiguity resolution

Figure 3 shows the percentage of successfully resolved narrowlane ambiguities for both the ZD AR and DD AR in the GRACE and Sentinel-3 processing. For GRACE, slightly less ambiguities are resolved in the DD processing compared to the ZD processing. In ZD AR more ambiguities are resolved for GRACE-B (99.1%) than for GRACE-A (97.1%). The AR success rate for Sentinel-3 is in all cases close to 100%.

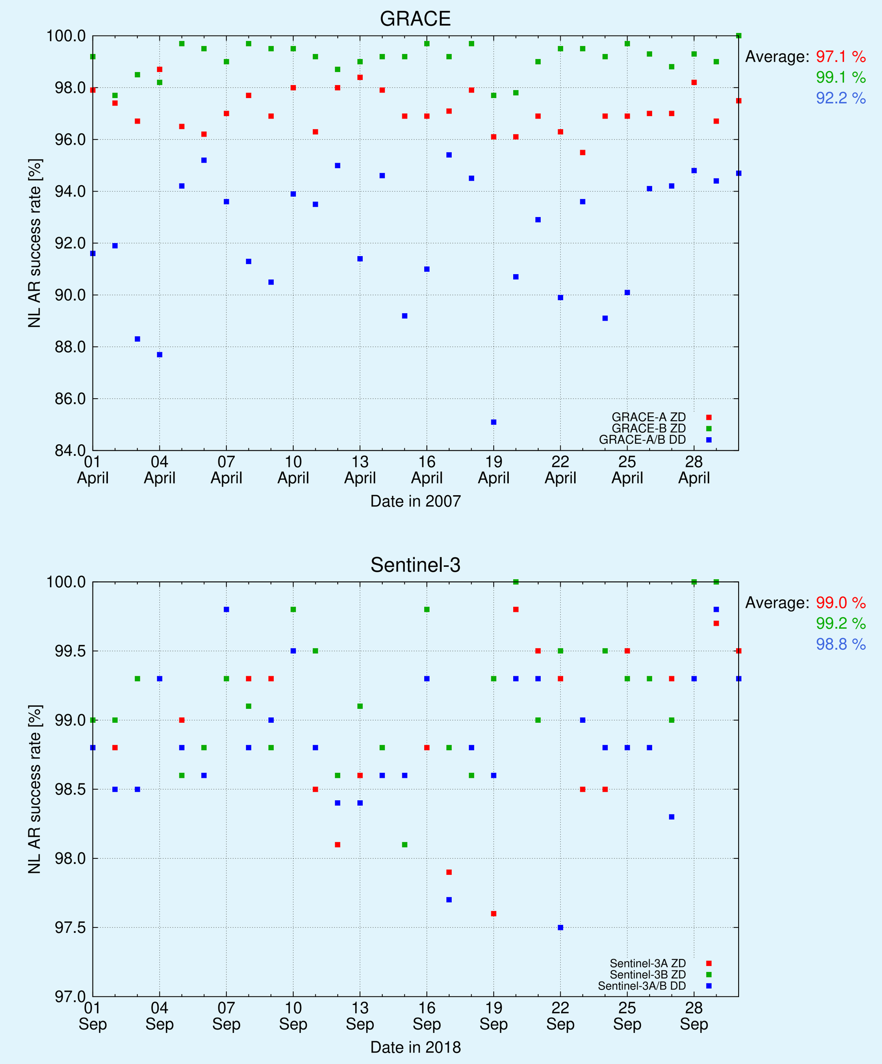


Figure 3: Percentage of resolved narrowlane ambiguities for GRACE (top) and Sentinel-3 (bottom). Red: ZD AR for LEO A. Green: ZD AR for LEO B. Blue: DD AR for baseline.

K-Band validation

GRACE offers the possibility to validate computed orbits, in particular the along-track component, with the ultra-precise inter-satellite K-band measurements. Figure 4 shows the K-band range (KBR) residuals of reduced-dynamic ambiguity-float and ambiguity-fixed GRACE orbits for one day, as well as the spectral analysis of the residuals. Both the ZD and the DD AR lead to a significant reduction of KBR residuals, especially regarding longer periods. Figure 5 shows the daily RMS values of K-band residuals for the entire month for both reduced-dynamic and kinematic orbit and baseline solutions. For the reduced-dynamic and kinematic solutions ZD AR and DD AR implies a reduction of the KBR residuals by about a factor of 3-4 and 3-5, respectively.

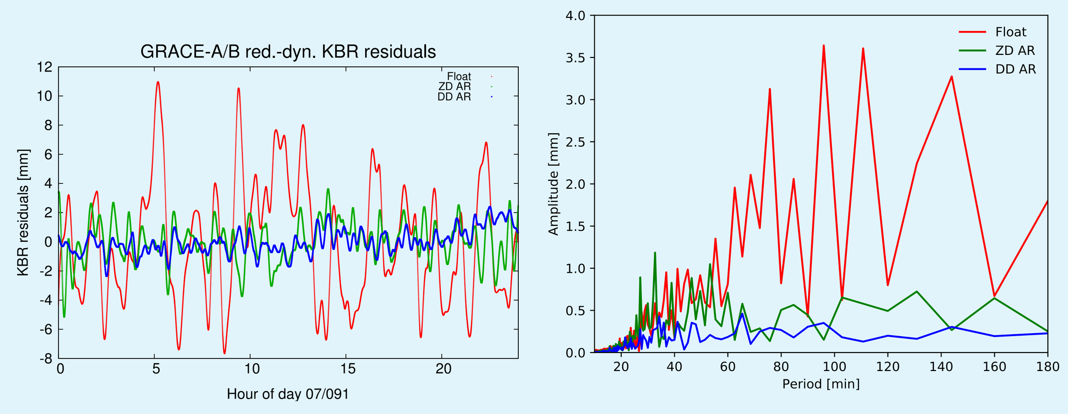


Figure 4: K-band range residuals for reduced-dynamic orbits and baseline solutions, as well as their spectral analysis for April 1, 2007.

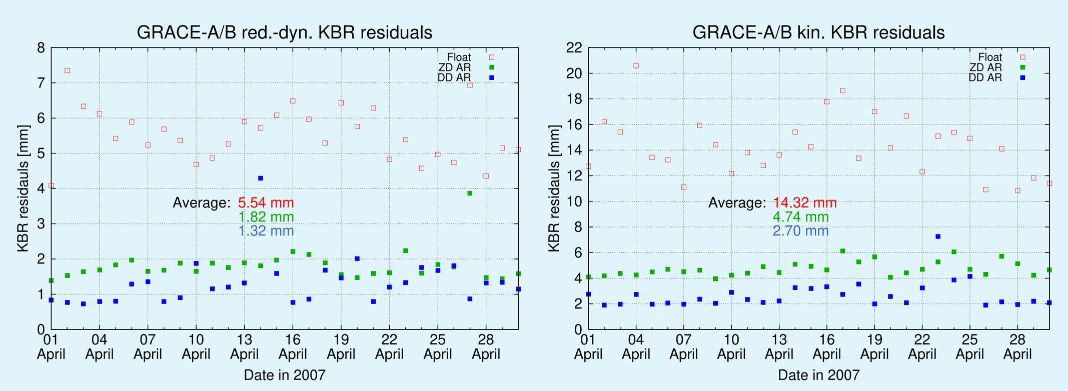
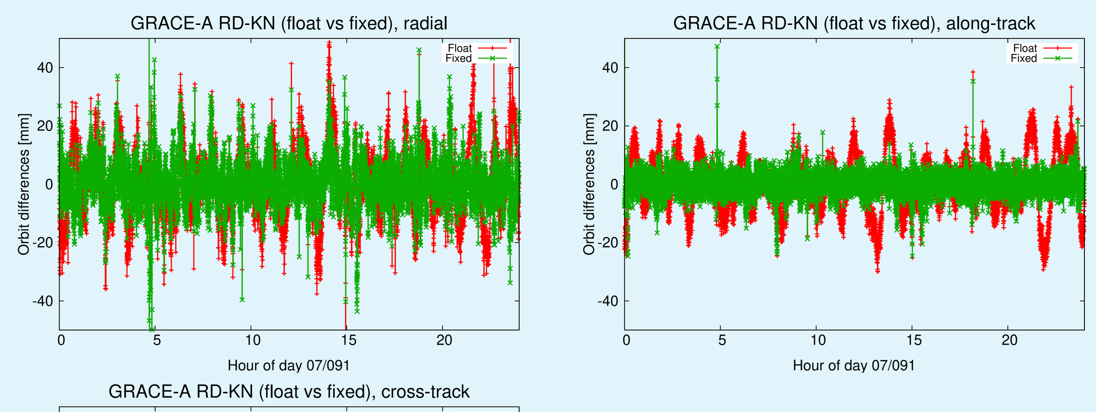


Figure 5: Daily RMS values of K-band residuals for reduced-dynamic (left) and kinematic (right) orbit and baseline solutions. For the kinematic solution statistics an outlier threshold of 10 cm was applied.

Reduced-dynamic vs. kinematic solutions

Figure 6 shows for GRACE-A the differences between the reduced-dynamic and kinematic single-satellite solutions for one day. It can be observed that especially in along-track and cross-track direction the long-periodic differences are significantly reduced by the ZD AR. Figure 7 shows the daily RMS values of orbit differences for April 2007. Figure 8 shows the corresponding statistics for Sentinel-3 for September 2018. In all cases a pronounced reduction can be observed in the ambiguity-fixed orbits.



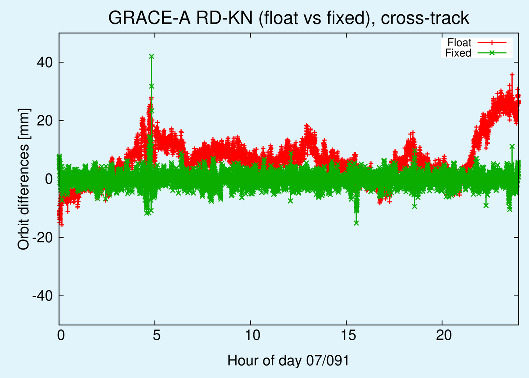
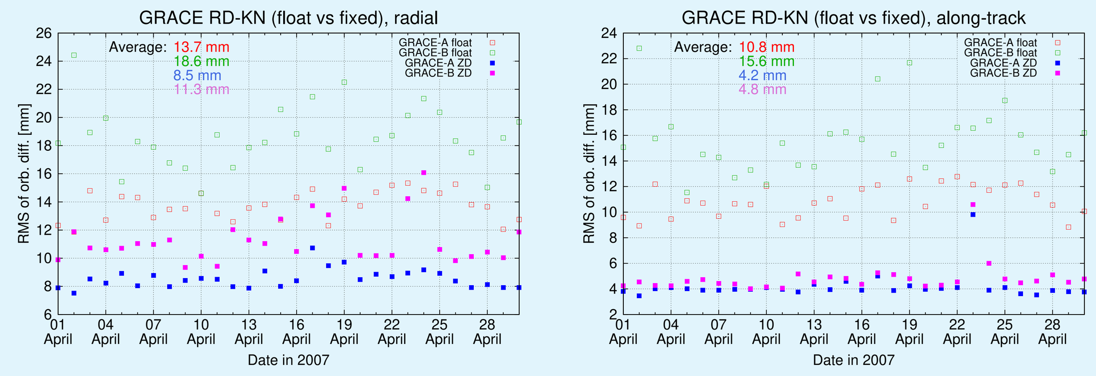


Figure 6: Differences between reduced-dynamic and kinematic GRACE-A orbit for April 1, 2007 in radial (top left), along-track (top right), and cross-track (bottom) direction for the ambiguity-float (red) and the ZD ambiguity-fixed (green) solution.



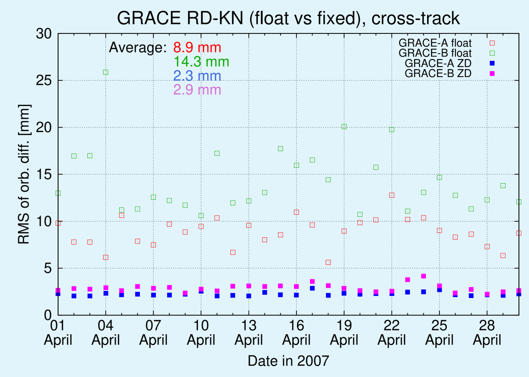
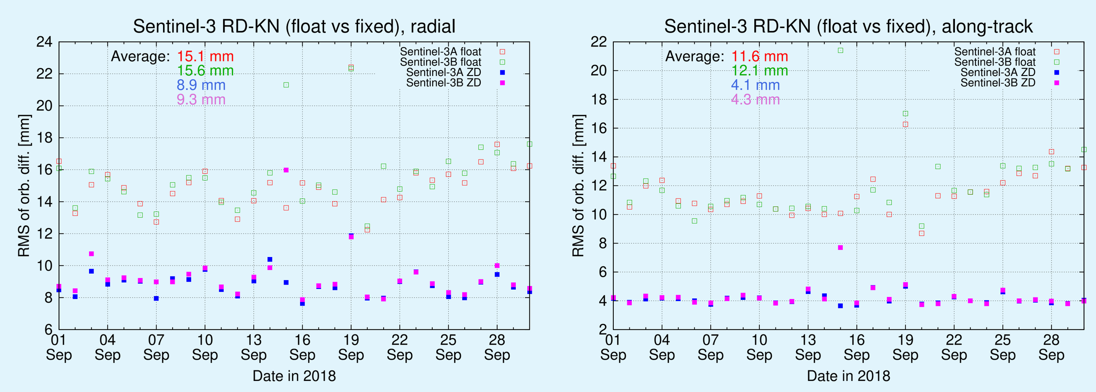


Figure 7: Daily RMS values of differences between reduced-dynamic and kinematic orbit solutions for April 2007 in radial (top left), along-track (top right), and cross-track (bottom) direction for GRACE-A and -B.



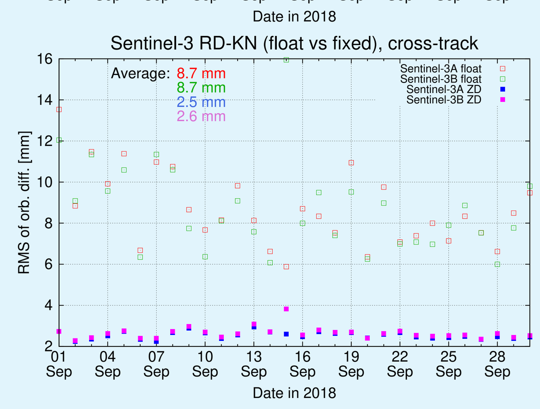


Figure 8: Daily RMS values of differences between reduced-dynamic and kinematic orbit solutions for September 2018 in radial (top left), along-track (top right), and cross-track (bottom) direction for Sentinel-3A and -3B.

SLR validation

Satellite Laser Ranging (SLR) normal points from 12 laser stations were used for orbit validation, residuals larger than 20 cm have been rejected and an elevation cutoff of 10° applied. No parameters were estimated. Table 1 shows the mean values and standard deviations of SLR residuals, confirming the positive impact of ZD AR on the orbit quality.

	Float		ZD AR	
Orbits	red.-dyn.	kin.	red.-dyn.	kin.
GRACE-A	+0.5/15.5	+1.5/16.6	+2.5/12.4	+2.6/12.0
GRACE-B	+0.9/12.1	-0.5/16.9	+3.8/8.5	+3.7/9.6
Sentinel-3A	-6.0/11.5	-6.5/14.7	-5.7/10.7	-5.4/11.9
Sentinel-3B	-2.9/12.4	-4.3/15.2	-3.5/10.4	-3.3/11.1

Table 1: Mean values and standard deviations in mm of SLR residuals over April 2007 (GRACE) and September 2018 (Sentinel-3), respectively.

How to use CODE's new clock and phase bias products

Since GPS week 2009 (July 2018) CODE produces a high-quality signal-specific phase bias product (the products for April 2007 have been generated for this study), see Fig. 1 . The corresponding OSB files can straightforwardly be introduced into GPSEST, the main parameter estimation program of the Bernese GNSS Software, which has been extended to allow for zero-difference ambiguity resolution, see Fig. 2. **The new CODE rapid, final, and MGEX clock corrections are based on a fully consistent ambiguity fixing processing.**

```
Bias SVN  PRN  Station name   Obs   yyyy mm dd hh mm ss  yyyy mm dd hh mm ss  Value (ns)     RMS (ns)
*** **** ***  ************* ***   ******************* ******************* ***********  ***********
OSB G032  G01                 C1C   2007 04 01 00 00 00  2007 04 02 00 00 00      0.52254      0.00610
OSB G032  G01                 C1W   2007 04 01 00 00 00  2007 04 02 00 00 00     -0.00000      0.00025
OSB G032  G01                 C2W   2007 04 01 00 00 00  2007 04 02 00 00 00     -0.00000      0.00025
...
OSB G032  G01                 L1C   2007 04 01 00 00 00  2007 04 02 00 00 00      0.16431      0.00000
OSB G032  G01                 L1W   2007 04 01 00 00 00  2007 04 02 00 00 00      0.16431      0.00000
OSB G032  G01                 L2C   2007 04 01 00 00 00  2007 04 02 00 00 00      0.24524      0.00000
OSB G032  G01                 L2W   2007 04 01 00 00 00  2007 04 02 00 00 00      0.24524      0.00000
OSB G032  G01                 L2X   2007 04 01 00 00 00  2007 04 02 00 00 00      0.24524      0.00000
...
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Figure 1: Observation-specific bias (OSB) files generated by CODE, containing pseudo-range and phase biases for Integer-PPP (IPPP).

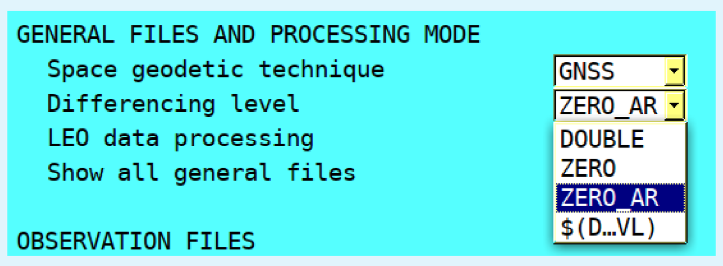

Figure 2: GPSEST, the main parameter estimation program of the Bernese GNSS Software, now allows for zero-difference ambiguity resolution.

Conclusions

Using CODE's new observation-specific phase bias product, a consistent ambiguity-fixed clock product and extensions of the Bernese GNSS Software, zero-difference ambiguity resolution was applied to the GPS-based POD of the GRACE and Sentinel-3 satellites. Ambiguity fixing is shown to significantly improve the orbit quality in terms of the independent validation measures K-band and SLR, as well as in terms of the internal consistency between the reduced-dynamic and kinematic orbit solutions. The achievable relative orbit quality is comparable to what can be obtained from a double-difference processing of space baselines employing ambiguity fixing. **All results confirm a high quality of the CODE clock and phase bias product.**

References

R. Dach, S. Lutz, P. Walser, and P. Fridez, editors. *Bernese GNSS Software, Version 5.2*. Astronomical Institute, University of Bern, Bern, Switzerland, November 2015. ISBN 978-3-906813-05-9. doi: 10.7892/boris.72297. User manual.

O. Montenbruck, S. Hackel, and A. Jäggi. Precise orbit determination of the Sentinel-3A altimetry satellite using ambiguity-fixed GPS carrier phase observations. *Journal of geodesy*, 92(7):711–726, 2018.

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