Single-receiver ambiguity fixing for GPS-based precise orbit determination of low Earth orbiters

Using CODE's new clock and phase bias products

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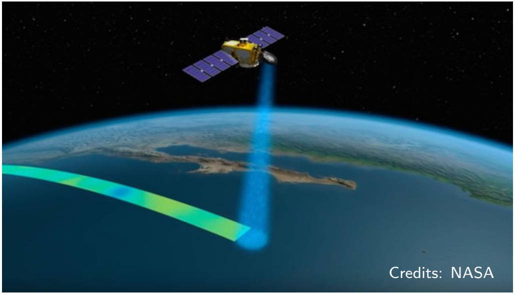
Motivation (1)

- GNSS-based Precise Orbit Determination (POD) of Low Earth Orbiters (LEOs) has become a standard application for high-quality GNSS products
- Processing of dual-frequency GNSS carrier phase data enables the abolute positioning of LEOs with (sub-)cm accuracy in post processing
  $\rightarrow$ crucial, e.g., for altimetry satellites



Motivation (2)

Code and phase observation eqs. for satellite s, receiver r, freq. i

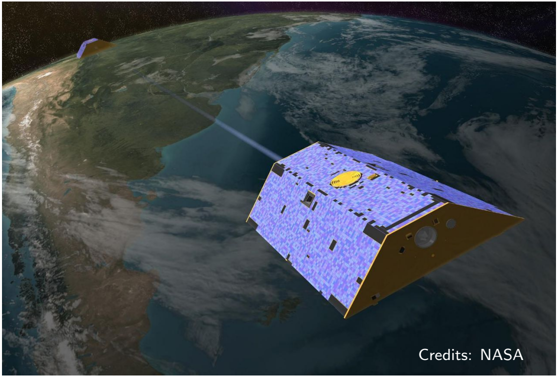
$$P^s_{r;i} = \rho^s_r + I^s_{r;i} + c(\delta t_r - \delta t^s) + c(d_{r;i} - d^s_i)$$
$$L^s_{r;i} = \rho^s_r - I^s_{r;i} + c(\delta t_r - \delta t^s) + c(\phi_{r;i} - \phi^s_i) + \lambda_i \omega^s_r + \lambda_i N^s_{r;i}$$

$P^s_{r;i}$	code observation
$L^s_{r;i}$	phase observation
ρ^s_r	geometric distance
$I^s_{r;i}$	ionospheric correction
δt_r	receiver clock correction
δt^s	satellite clock correction
$d_{r;i}, \phi_{r;i}$	receiver code/phase bias
d^s_i, ϕ^s_i	satellite code/phase bias
λ_i	carrier wavelength
ω^s_r	phase windup
$N^s_{r;i}$	integer phase ambiguity

- Fixing ambigities to their integer values stabilizes solution
- When not modeling phase biases, their effect will be absorbed by ambiguity parameters $\longrightarrow$ not integers anymore
- Classical ambiguity resolution approach: Form double differences

Motivation (3)

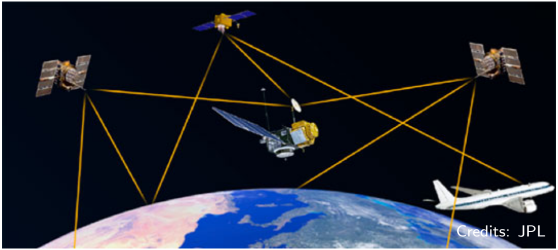
- Double-difference processing of space baselines has been proven successful and beneficial for relative POD of LEO constellations, e.g., GRACE



Credits: NASA

Motivation (3)

- Double-difference processing of space baselines has been proven successful and beneficial for relative POD of LEO constellations, e.g., GRACE
- Double-difference processing of space-ground baselines is very costly in computational terms if all correlations shall be modeled



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- Usual LEO POD is based on Precise Point Positioning (PPP), where GNSS satellite orbits and clock corrections from an external global solution are introduced

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- Usual LEO POD is based on Precise Point Positioning (PPP), where GNSS satellite orbits and clock corrections from an external global solution are introduced
- Undifferenced ambiguity resolution in PPP mode requires satellite phase biases as well

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New CODE clock and phase bias product

- Since GPS week 2009 (July 2018) CODE (Center for Orbit Determination in Europe) produces a high-quality signal-specific phase bias product

```
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
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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
...
```

New CODE clock and phase bias product

- Since GPS week 2009 (July 2018) CODE (Center for Orbit Determination in Europe) produces a high-quality signal-specific phase bias product
- The Bernese GNSS Software has been extended to introduce these biases, and the new CODE rapid, final, and MGEX clock corrections are based on a fully consistent ambiguity-fixed processing (ambiguity-float clocks $\rightarrow$ extract phase biases $\rightarrow$ fix ambiguities and re-estimate clocks)

```
Bias SVN   PRN  Station name    Obs   yyyy mm dd hh mm ss  yyyy mm dd hh mm ss  Value (ns)     RMS (ns)
***  ****  ***  *************   ***   *******************  *******************  ***********  ***********
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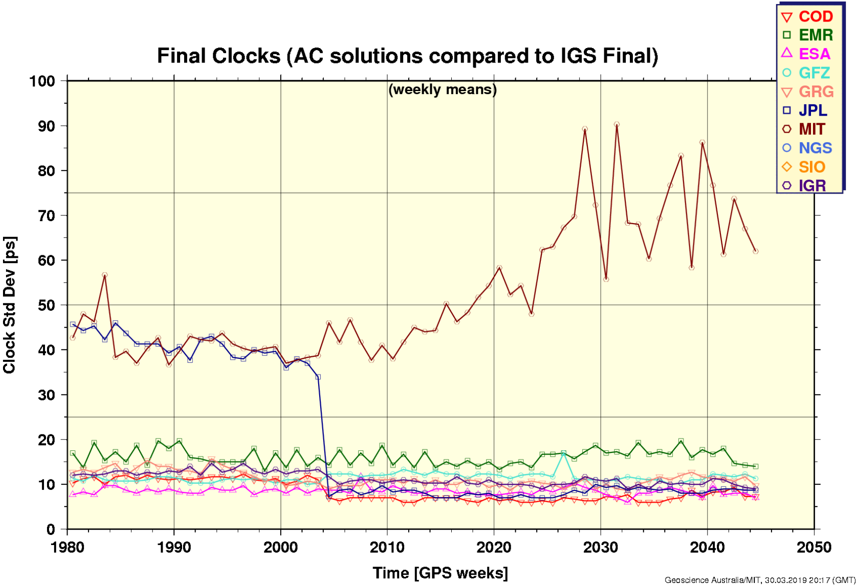
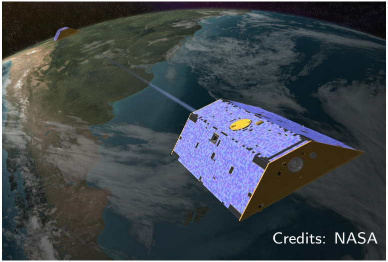


Test scenario

Using the new CODE products, we

- test undifferenced ambiguity resolution (AR) for POD of
  - GRACE-A/B, April 2007
  - Sentinel-3A/B, September 2018
- compare its performance to double-difference processing, including AR



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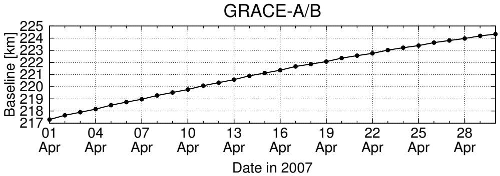

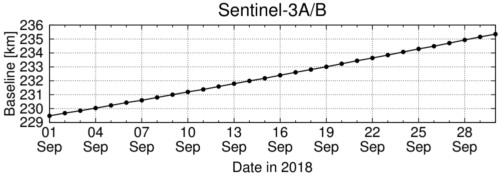

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- test undifferenced ambiguity resolution (AR) for POD of
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- compare its performance to double-difference processing, including AR
- demonstrate benefit of undifferenced AR for Swarm POD for June 2018 to March 2019

Methods (1)

Computation of reduced-dynamic and kinematic orbits using Bernese GNSS Software v5.3

- Reduced-dynamic orbit:
  - 6 initial conditions
  - constant accelerations in radial (R), along-track (T) and cross-track (N) direction
  - 6-min piecewise constant accelerations (constrained) in R,T,N
  - no explicit non-gravitational force modeling

- Kinematic orbit: epoch-wise 3-dimensional position (+ clocks)

- Double-difference processing:
  - reduced-dynamic orbit of GRACE-A / Sentinel-3A is reference
  - relative orbit parameters for GRACE-B / Sentinel-3B estimated
  - relative empirical accelerations are only rather loosely constrained ($1 \cdot 10^{-8}$ m/s^2)

Methods (2)

Melbourne-Wubbena linear combination of code and phase observations, fix wide-lane ambiguities

↓

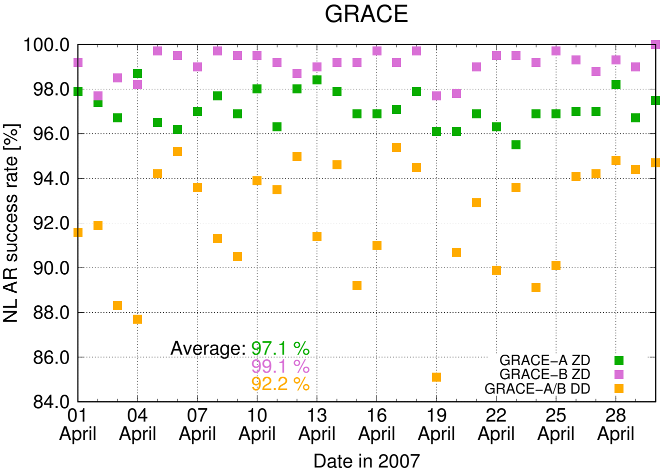
Reduced-dynamic POD: ionosphere-free linear combination of phase observations, introduce fixed wide-lane ambiguities, fix narrow-lane ambiguities

↓

Kinematic POD: introduce fixed ambiguities

AR success rate

Percentage of fixed narrow-lane ambiguities for zero-difference (ZD) and double-difference (DD) processing:



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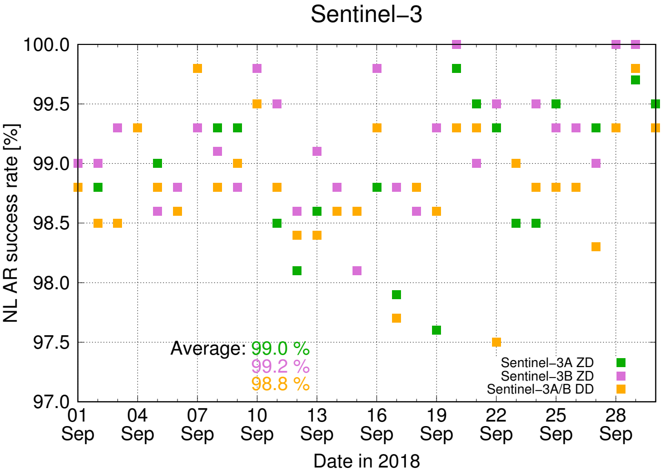
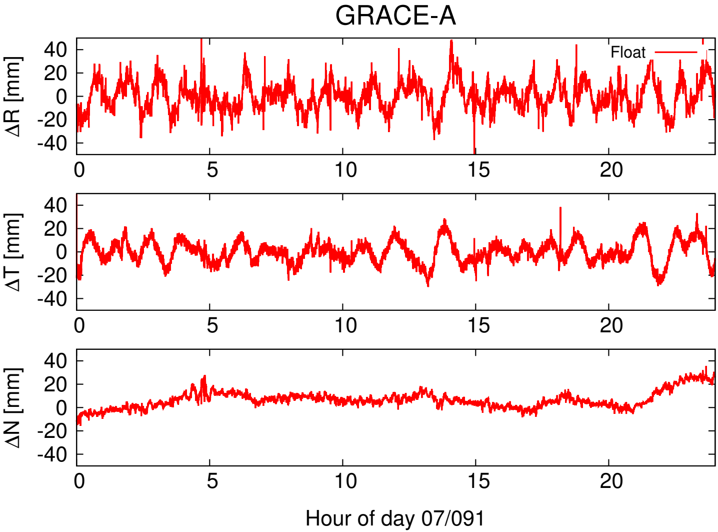


Internal orbit consistency

Differences between reduced-dynamic and kinematic orbits:



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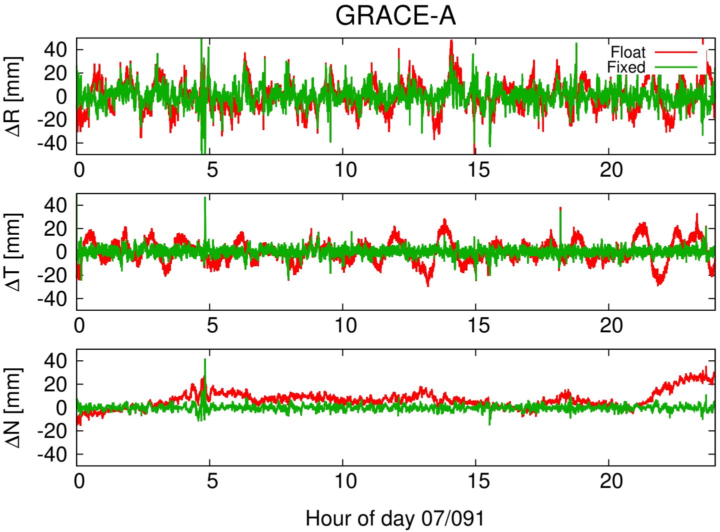

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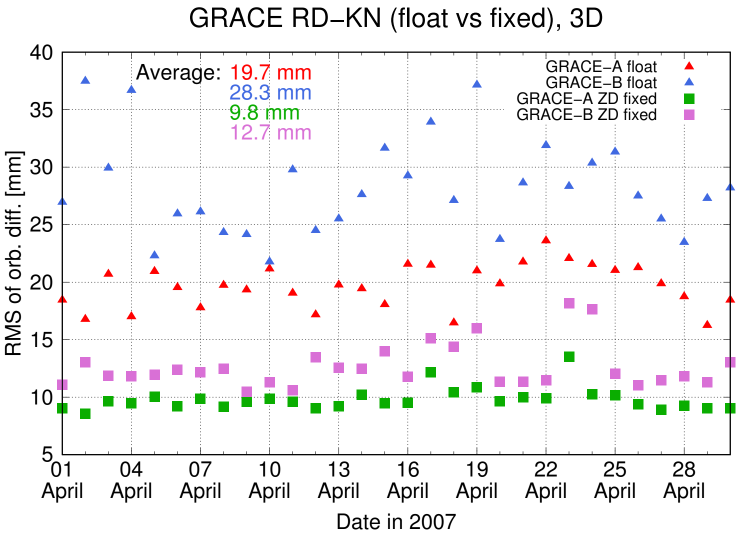

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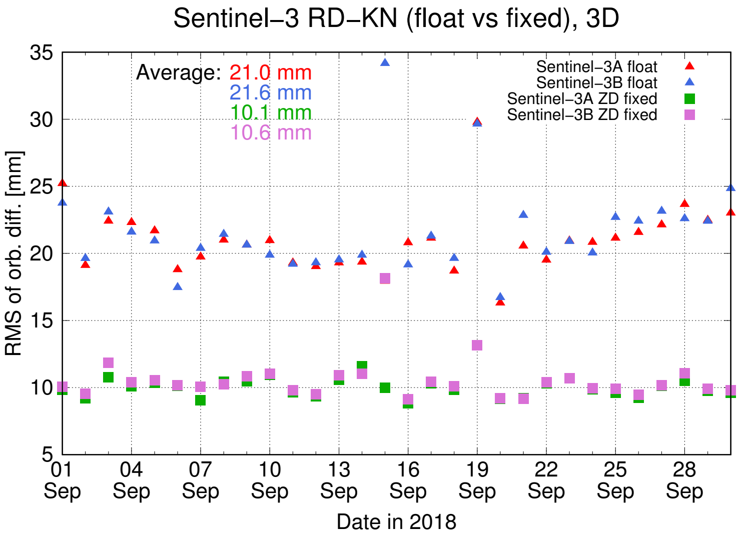
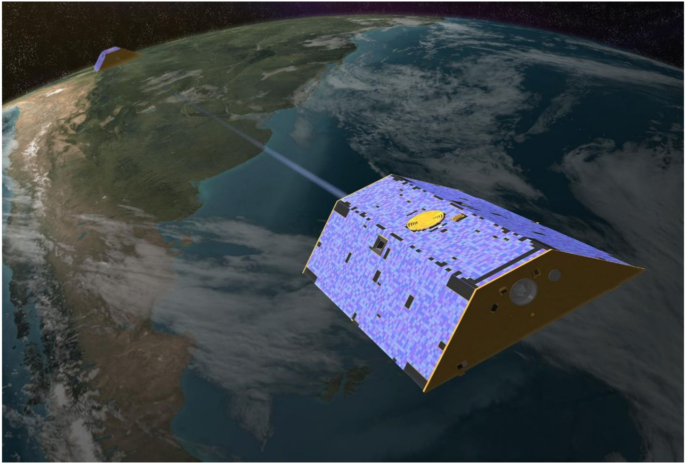


K-band validation

K-band residual = difference between computed range and range derived from ultra-precise inter-satellite K-band measurement.

External orbit validation!



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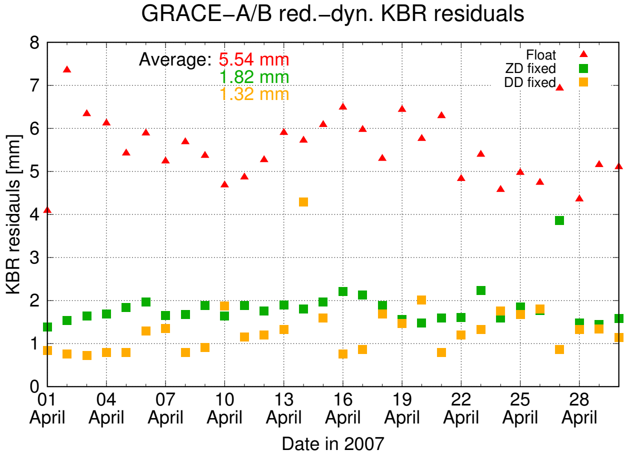

SLR validation

SLR residual = difference between computed range and range derived from Satellite Laser Ranging (SLR) measurement.

External orbit validation!

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External orbit validation!

	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

Mean values and standard deviations in mm of SLR residuals over April 2007 (GRACE) and September 2018 (Sentinel-3), respectively. No parameters estimated, station coordinates according to SLRF2008 (GRACE) and SLRF2014 (Sentinel-3) introduced. SLR data of 12 stations used. 20 cm outlier threshold, 10° elevation cutoff.

Swarm POD (1)

- Initially, Swarm GPS data were affected by *half-cycle ambiguities*, hindering successfull AR
- Fixed for the reprocessed level-1 Swarm GPS data (Montenbruck et al., 2017)

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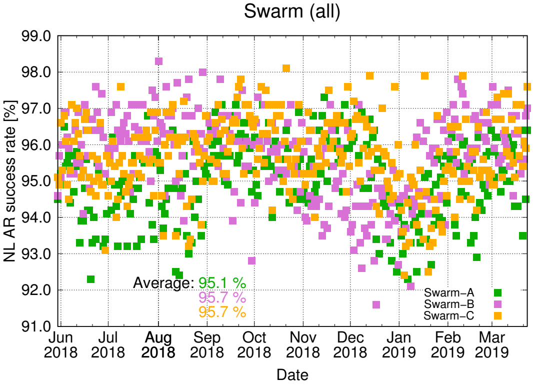

Counting all NLs

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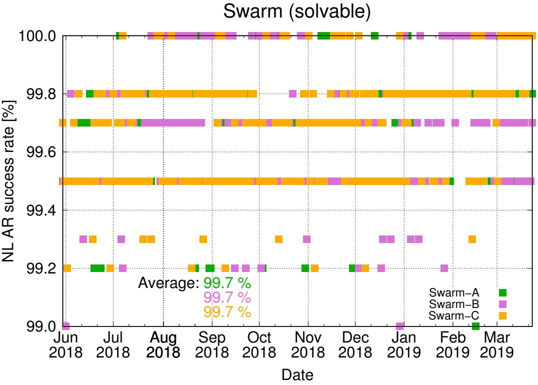
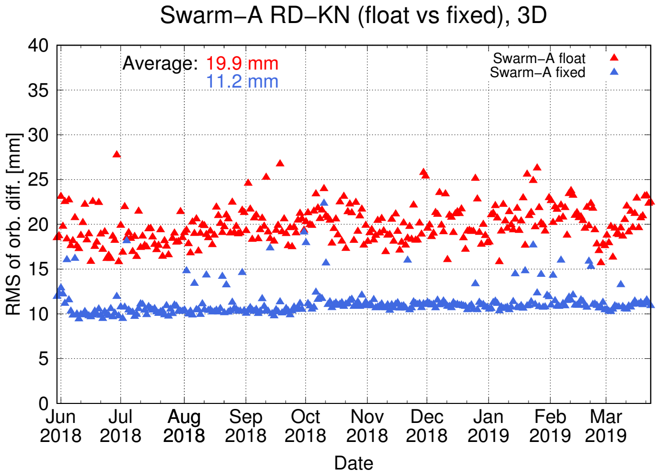


Counting only those NLs where the WLs could be resolved

Swarm POD (2)

Internal orbit consistency:



Swarm POD (3)

SLR residuals (mean and standard deviation) in mm (statistics computed as for GRACE and Sentinel-3):

	Float		ZD AR	
Orbits	red.-dyn.	kin.	red.-dyn.	kin.
Swarm-A	+6.4/12.2	+5.2/16.2	+4.6/10.1	+3.4/10.3
Swarm-B	+4.6/12.8	+3.8/16.9	+2.3/9.6	+1.3/10.1
Swarm-C	+4.9/12.2	+4.1/15.8	+3.0/9.8	+2.1/10.6

Summary and conclusion

- CODE operationally produces an observation-specific phase bias product
- The new CODE rapid, final, and MGEX clock corrections are based on ambiguity-fixed processing
- Tested undifferenced ambiguity fixing for LEO POD of GRACE, Sentinel-3 and Swarm. Beneficial for internal orbit consistency, as well as for absolute orbit quality (K-band and SLR residuals)
- A test data set including phase biases for GPS week 2026 (4-10 November 2018) will be provided to interested users. Please write an email to

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Thank you very much!

Ambiguity resolution strategy (1)

1. Form Melbourne-Wubbena linear combination of pseudo-range $P^s_{r;i}$ and carrier phase $L^s_{r;i}$ observations:

$$\mathsf{MW}(L^s_{r;i}, P^s_{r;i}) \doteq \frac{f_1 L^s_{r;1} - f_2 L^s_{r;2}}{f_1 - f_2} - \frac{f_1 P^s_{r;1} + f_2 P^s_{r;2}}{f_1 + f_2}$$
$$= \lambda_{\mathsf{wl}} N^s_{r;\mathsf{wl}} + c\mathsf{MW}(\phi_{r;i}, d_{r;i}) - c\mathsf{MW}(\phi^s_i, d^s_i)\,,$$

   where $\lambda_{\mathsf{wl}} = c/(f_1 - f_2) \approx 86$ cm and $N^s_{r;\mathsf{wl}} = N^s_{r;1} - N^s_{r;2}$.

2. Form satellite differences

$$\mathsf{MW}(L^{s1}_{r;i}, P^{s1}_{r;i}) - \mathsf{MW}(L^{s2}_{r;i}, P^{s2}_{r;i}) =$$
$$\lambda_{\mathsf{wl}}(N^{s1}_{r;\mathsf{wl}} - N^{s2}_{r;\mathsf{wl}}) - c\left[\mathsf{MW}(\phi^{s1}_i, d^{s1}_i) - \mathsf{MW}(\phi^{s2}_i, d^{s2}_i)\right]\,,$$

   introduce satellite code and phase biases and resolve wide-lane ambiguity differences, no fixing for reference satellite

Ambiguity resolution strategy (2)

3. Process ionosphere-free linear combination of phase observations,

$$
\begin{aligned}
L^s_{r;\mathsf{if}} &\doteq \frac{f_1^2 L^s_{r;1} - f_2^2 L^s_{r;2}}{f_1^2 - f_2^2} \\
&= \rho^s_r + c(\delta t_r - \delta t^s) + c(\phi_{r;\mathsf{if}} - \phi^s_{\mathsf{if}}) \\
&+ \lambda_{\mathsf{nl}} \left(N^s_{r;1} + \frac{\lambda_{\mathsf{wl}}}{\lambda_2} N^s_{r;\mathsf{wl}} \right) + \lambda_{\mathsf{nl}} \omega^s_r \,,
\end{aligned}
$$

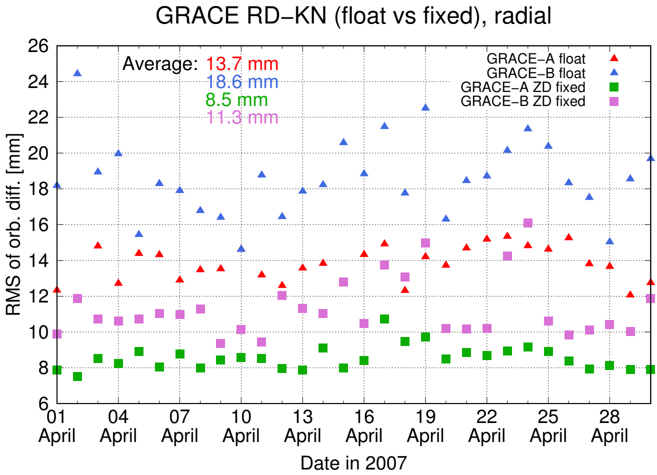
   where $\lambda_{\mathsf{nl}} = c/(f_1 + f_2) \approx 11$ cm.

4. Form satellite differences, introduce satellite phase biases, wide-lane ambiguities $N^s_{r;\mathsf{wl}}$ and resolve narrow-lane ambiguities $N^s_{r;1}$

CODE observation-specific biases

- CODE follows a so-called CC-OSB (common clocks and observable-specific signal biases) approach
- OSB values are provided in Bias-SINEX V1.00
- Easy to use and applicable for all applications

GRACE & Sentinel-3: Internal orbit consistency



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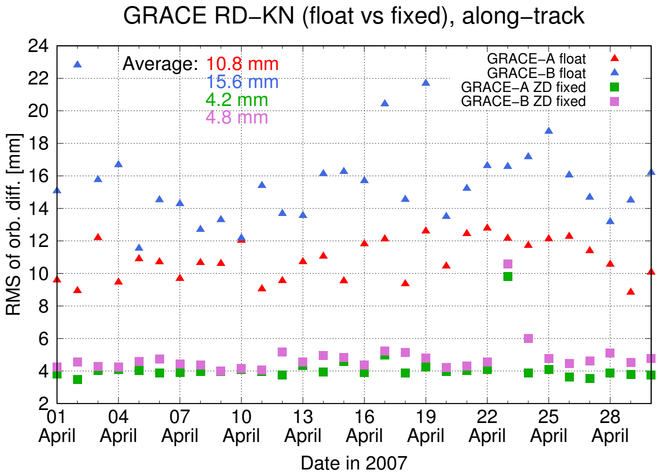

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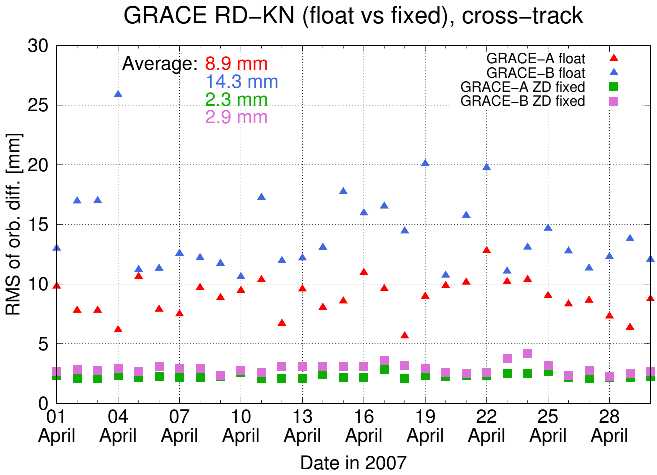

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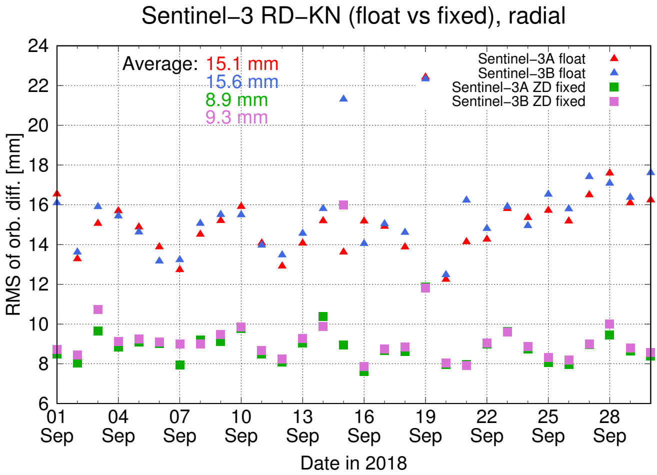

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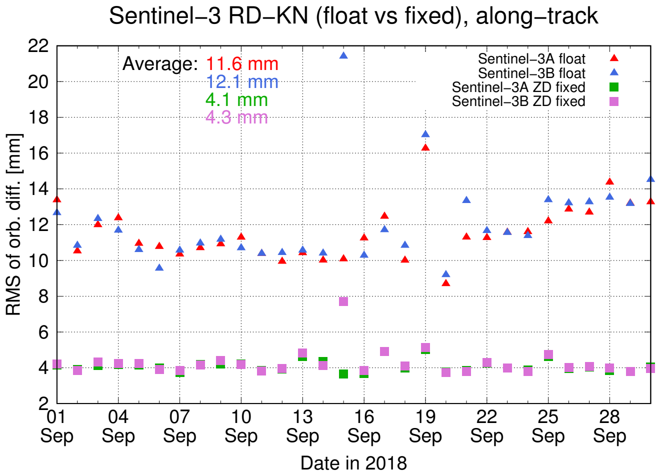

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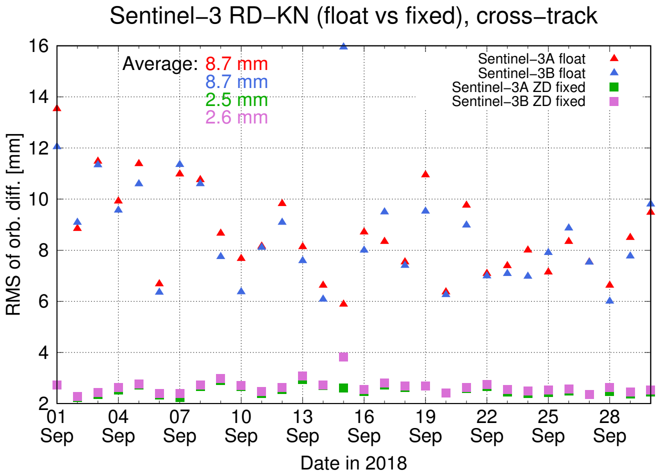
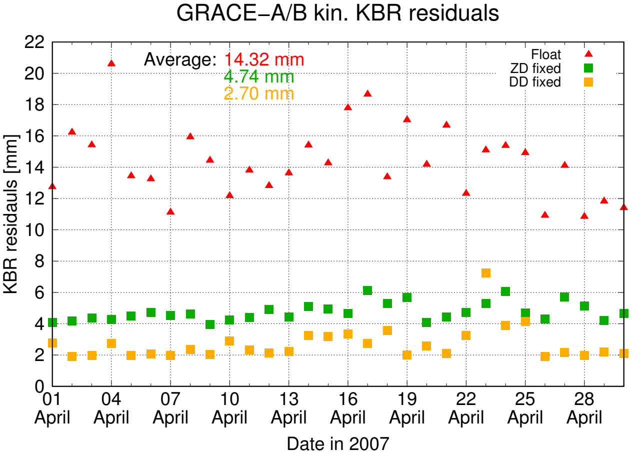
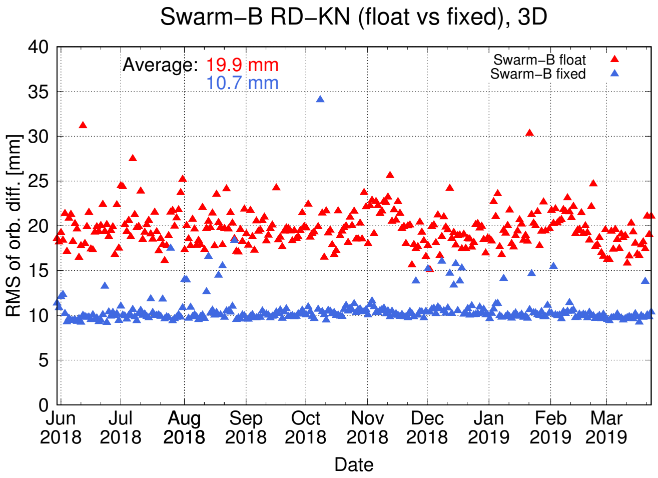


GRACE: K-band validation



Swarm: Internal orbit consistency



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