# GRACE-like orbit determination with multi-GNSS constellation: a simulation study

**Grzegorz Michalak and Karl-Hans Neumayer**

# Overview

Within the preparation for the GRACE FOLLOW-ON and other future satellite missions the GFZ's orbit determination software EPOS-OC was updated to enable fully multi-GNSS simulation and processing of both ground and space-borne data.

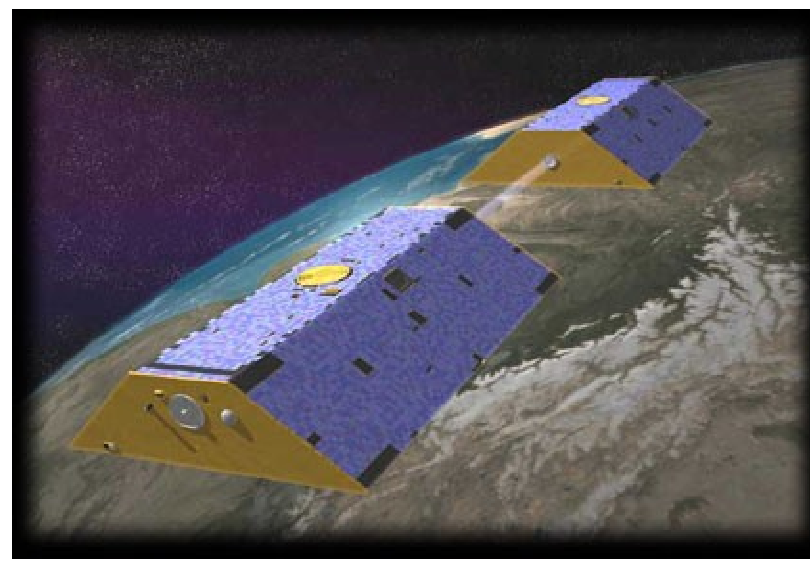
- Short overview of the GRACE mission
- Details of the simulations/recovery scenarios for GNSS (GPS+GAL+GLO) and GRACE data
- Some details about performance of cycle slip fixing method
- Comparison of dynamic orbit determination (recovery) for GPS-only and multi-GNSS case
- Conclusions

# GRACE mission

- Twin satellites flying in a formation with distance ~200 km
- For gravity field determination and radio occultations
- Microwave K-band ranging instrument (micrometer range accuracy, range biased)
- 3 channel accelerometer for measuring of the non-gravitational forces
- 2 frequency GPS receiver (BlackJack)
- Data used by GFZ for

  - Time variable and static gravity field determination

  - Atmospheric sounding



# GNSS Simulation/Recovery

**Day 2016-05-10**

- 124 real GPS stations, globally distributed
- 79 GNSS satellites: 30 GPS, 22 GLONASS and 27 GALILEO (9 actual, equally distributed in 3 orbital planes)
- Undifferenced ionosphere free combination($L_3$)
- $L_3$ data noise: 50 cm pseudo-range (code), 5 mm carrier phase, 30 s spacing
- Models and standards: Rapid Science Orbits

<u>Parametrization</u>

- Initial states of GNSS satellites
- Scaling factors of Solar Radiation Pressure model (ROCK4)
- Periodic empirical coefficients (SIN, COS,T,N) 4/day
- Station coordinates
- Tropospheric scaling factors (10/day) for each stations
- Ambiguities (~6000 GPS, ~15000 GNSS)
- IS/IF L3 code biases: GLONASS 1/station/frequency, GALILEO 1/station

<u>Recovery scenarios for GNSS orbits and clocks</u>

(1). **No model errors** → orbit accuracy 3 mm
(2). **Solar Radiation Pressure errors**: biases in Y and Z direction (Sun oriented system) → orbit accuracy ~4 cm
(3). **Earth Orientation Parameters (EOPs) errors** → orbit accuracy ~4 cm

# GRACE A+B Simulation/Recovery

**Day 2016-05-10**

- Simulated ‘true’ (error free) GNSS orbits used as reference
- $L_3$ data noise: 50 cm pseudo-range (code), 3 mm carrier phase, 10 s spacing
- K-band range (bias and noise free) for validation
- Models and standards: Rapid Science Orbits

Parametrization

- Initial states
- Scaling factor of Solar Radiation Pressure model
- Atmospheric drag scaling factors (5/day)
- Periodic empirical coefficients (SIN, COS, T, N, 1/rev and 2/rev) 248/day
- Ambiguities (700 per LEO)
- IS/IF biases: GLONASS 1/LEO/frequency channel, GALILEO 1/LEO

Recovery in the 2-step approach: GNSS orbits, clocks and EOPs from scenario 1, 2 and 3 are kept fixed.

Recovery of the GRACE dynamic orbits and clocks with:

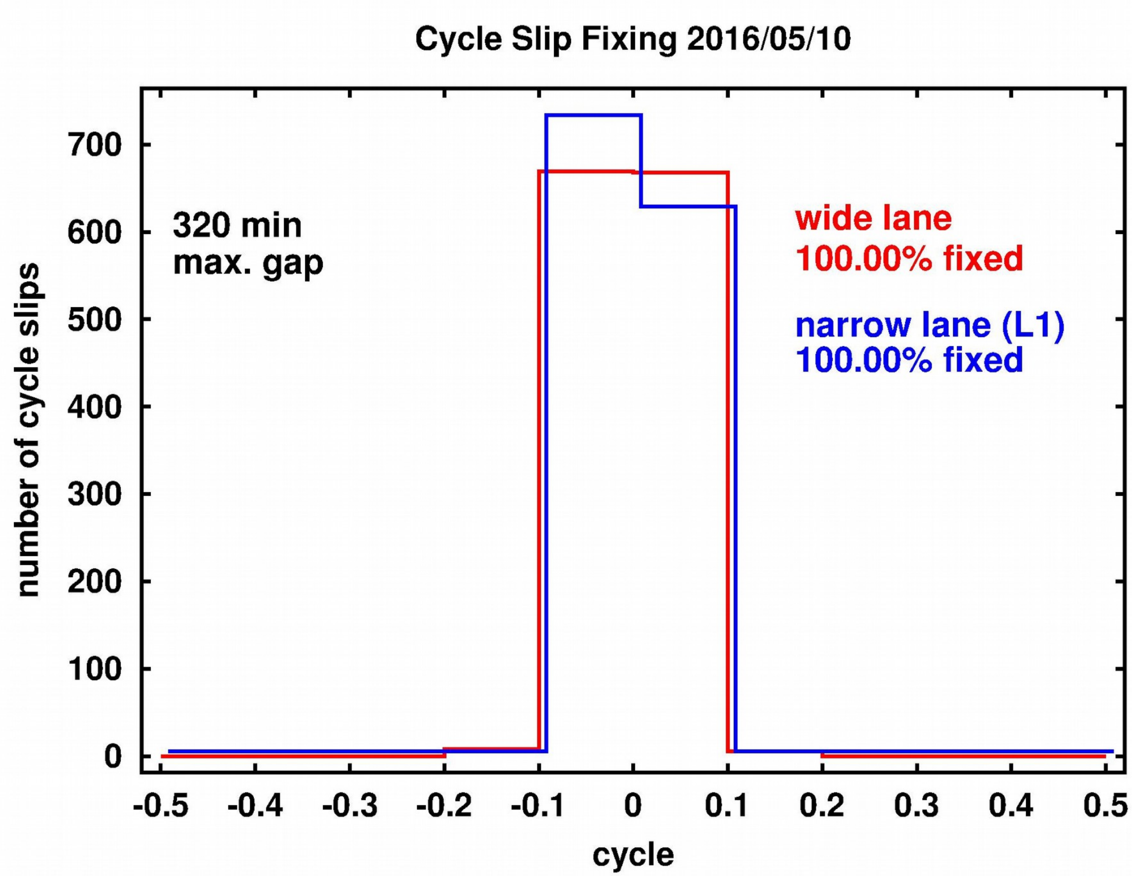
- **Float ambiguities**
- **Double difference ambiguity fixing** GPS, GAL (as constraints for combination of 4 undifferenced ambiguities)
- **Cycle slip fixing** → “ Satellite baseline determination with phase cycle slip fixing over long data gaps”

# Performance of the cycle slip fixing

**GNSS orbits scenario 1: no model errors → orbit accuracy 3 mm**

**Wide-lane and L1 cycle slip distribution around nearest integer**

NL fixing limit:
0.15 cycle



# Performance of the cycle slip fixing

**GNSS orbits scenario 2: SRP model errors → orbit accuracy 4 cm**

**Wide-lane and L1 cycle slip distribution around nearest integer**

NL fixing limit:
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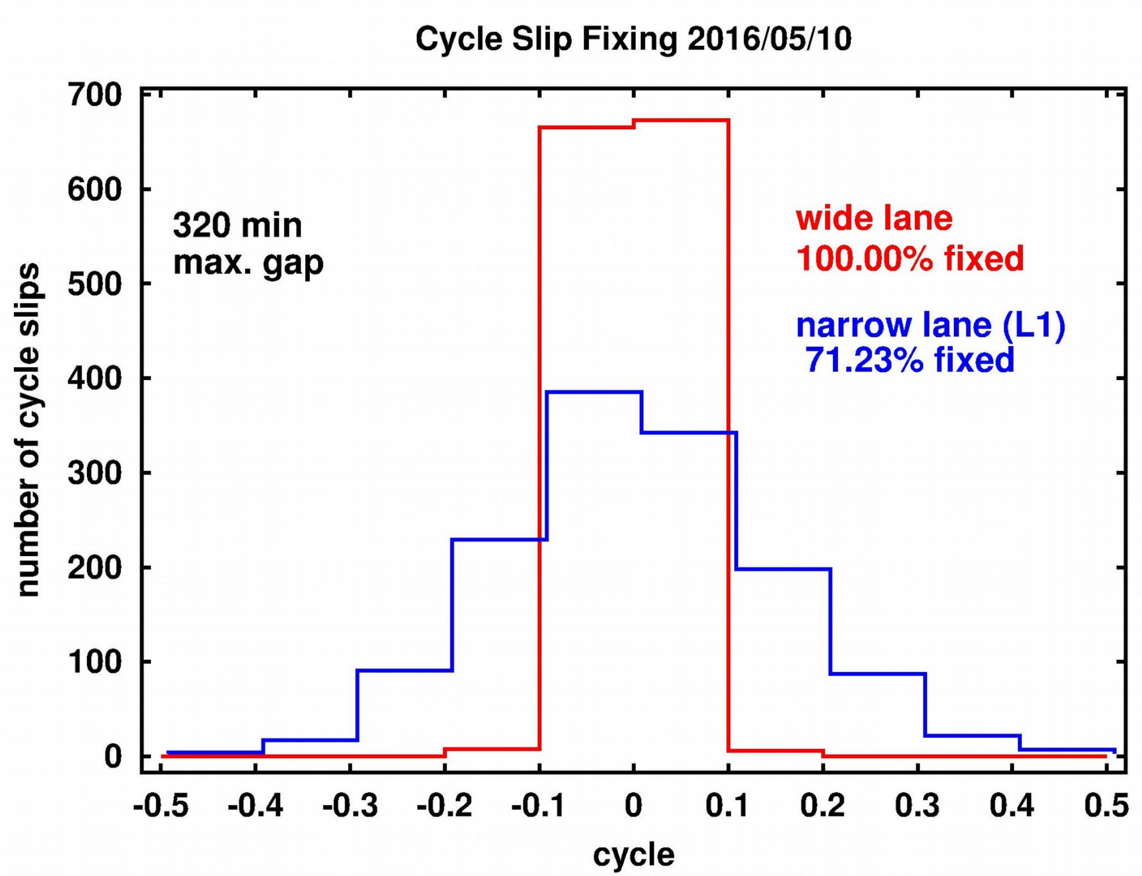

# Recovery results

## Dynamic orbits

| | Float ambiguities | | | DD ambiguity fixing | | | Cycle slip fixing (100% fixed) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Orbit 3D RMS [mm] | K-Band RMS [mm] | Phase RMS [mm] | Orbit 3D RMS [mm] | K-band RMS [mm] | Phase RMS [mm] | Orbit 3D RMS [mm] | K-band RMS [mm] | Phase RMS [mm] |
| | **GNSS orbits scenario 1 : no model errors → orbit accuracy 3 mm** | | | | | | | | |
| **GPS-only** | 1.49 | 1.37 | 3.05 | 1.24 | 0.43 | 3.07 | 0.85 | 0.45 | 3.23 |
| **Multi-GNSS** | 1.46 | **0.75** | 3.14 | 1.40 | **0.25** | 3.16 | 0.74 | **0.24** | 3.31 |
| | **GNSS orbits scenario 2: Solar Radiation Pressure errors → orbit accuracy 4 cm** | | | | | | | | |
| **GPS-only** | 9.55 | 2.57 | 4.40 | 11.81 | 0.48 | 4.71 | 6.05 | 0.49 | 9.58 |
| **Multi-GNSS** | **4.93** | **1.54** | 4.31 | **5.37** | **0.30** | 4.51 | **3.75** | **0.30** | 9.03 |
| | **GNSS orbits scenario 3: EOPs errors → orbit accuracy 4 cm, frame rotated** | | | | | | | | |
| **GPS-only** | 10.53 | 1.45 | 3.13 | 10.85 | 0.43 | 3.18 | 11.19 | 0.45 | 4.34 |
| **Multi-GNSS** | 11.11 | **0.80** | 3.17 | 11.29 | **0.26** | 3.19 | 11.58 | **0.25** | 3.73 |

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DD ambiguity fixing does not improve LEO absolute orbits

# Recovery results

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CS fixing improves the absolute orbits

# Recovery results

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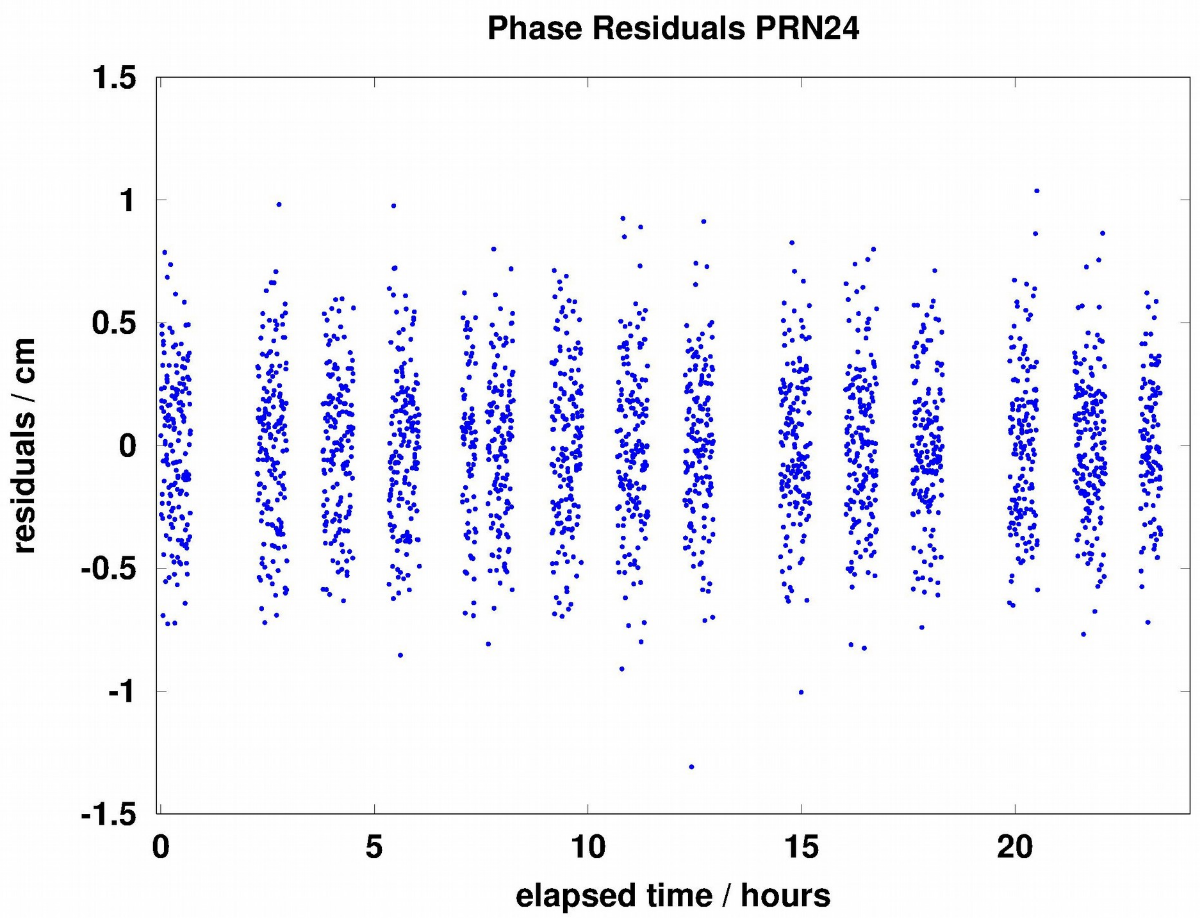
Significantly increased phase RMS

# Phase residuals

**GPS orbits scenario 1: no model errors → orbit accuracy 3 mm**

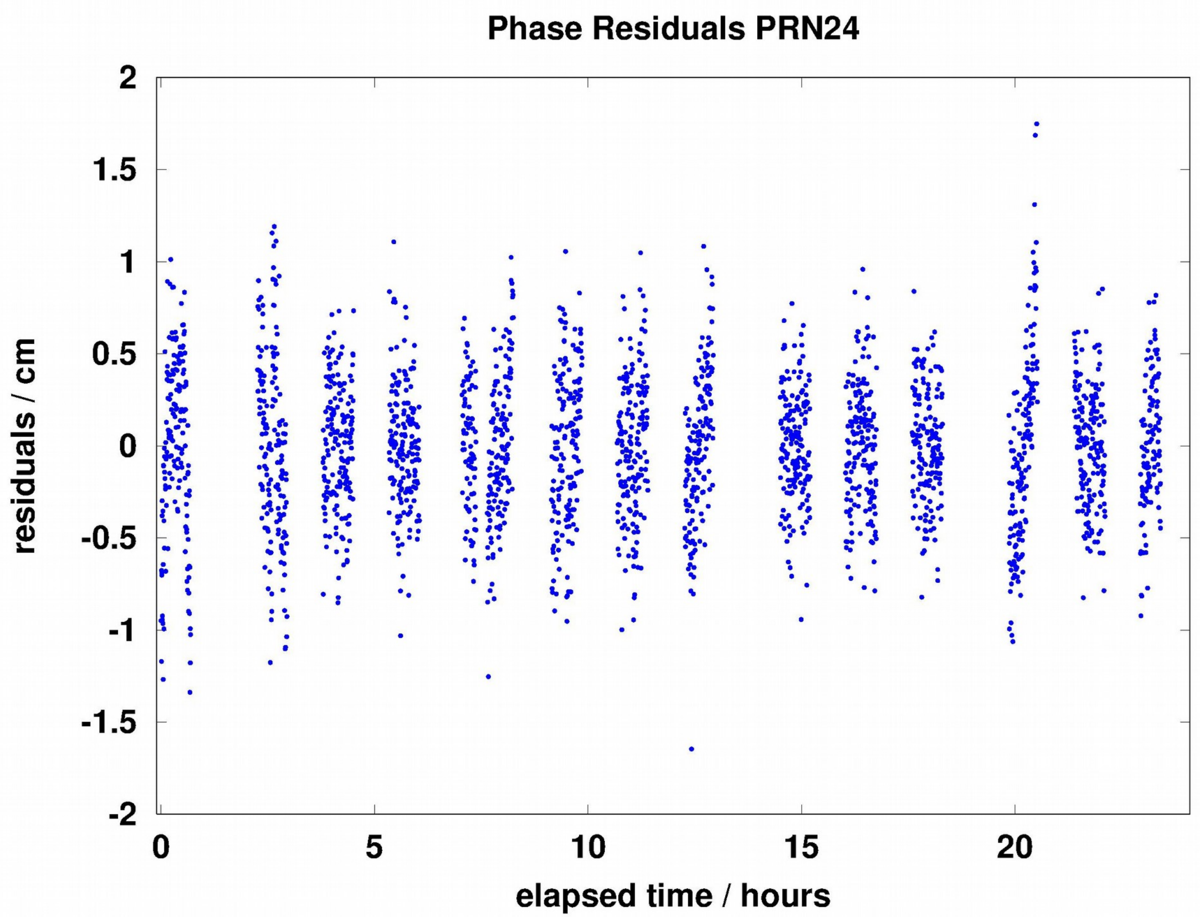
**Float ambiguity solution**



# Phase residuals

**GPS orbits scenario 2: SRP model errors → orbit accuracy 4 cm**

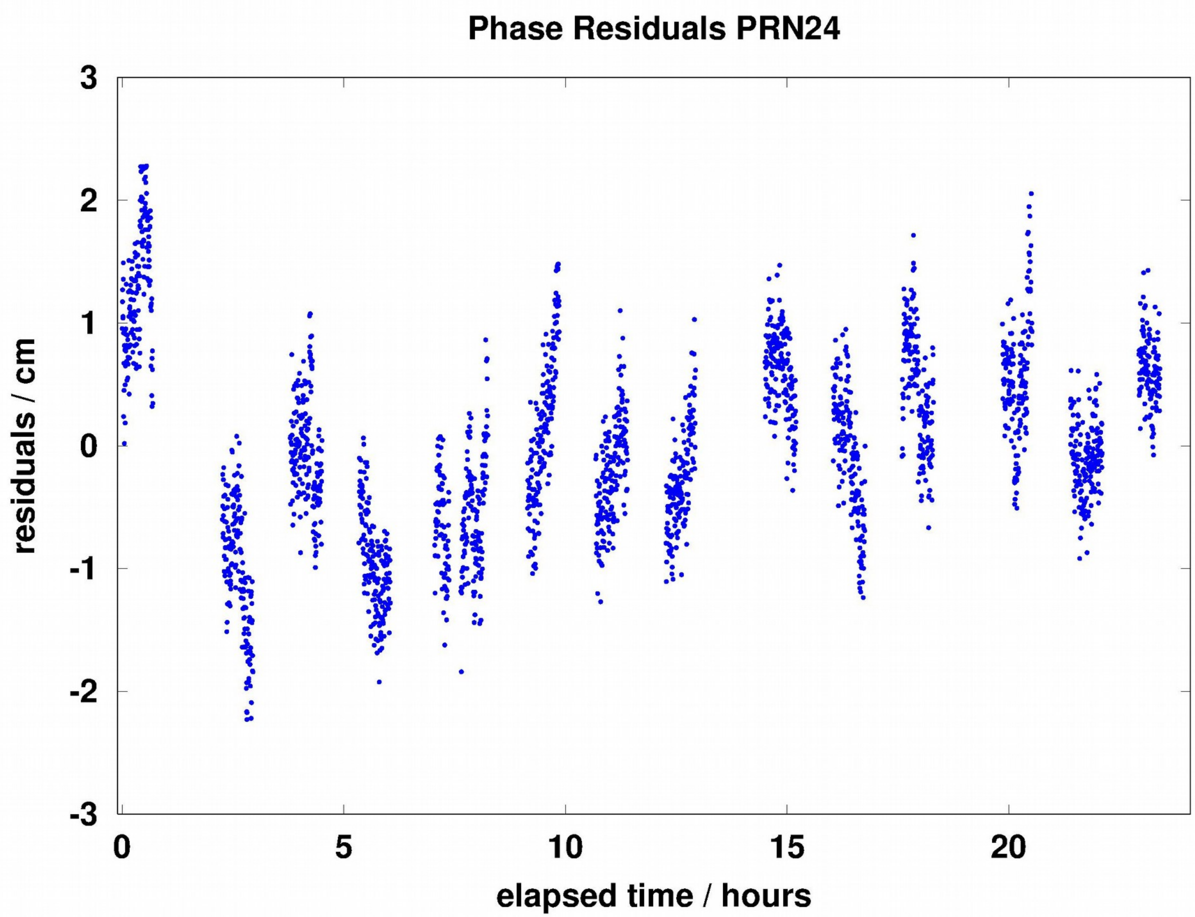
**Float ambiguity solution**



# Phase residuals

**GPS orbits scenario 2: SRP model errors → orbit accuracy 4 cm**

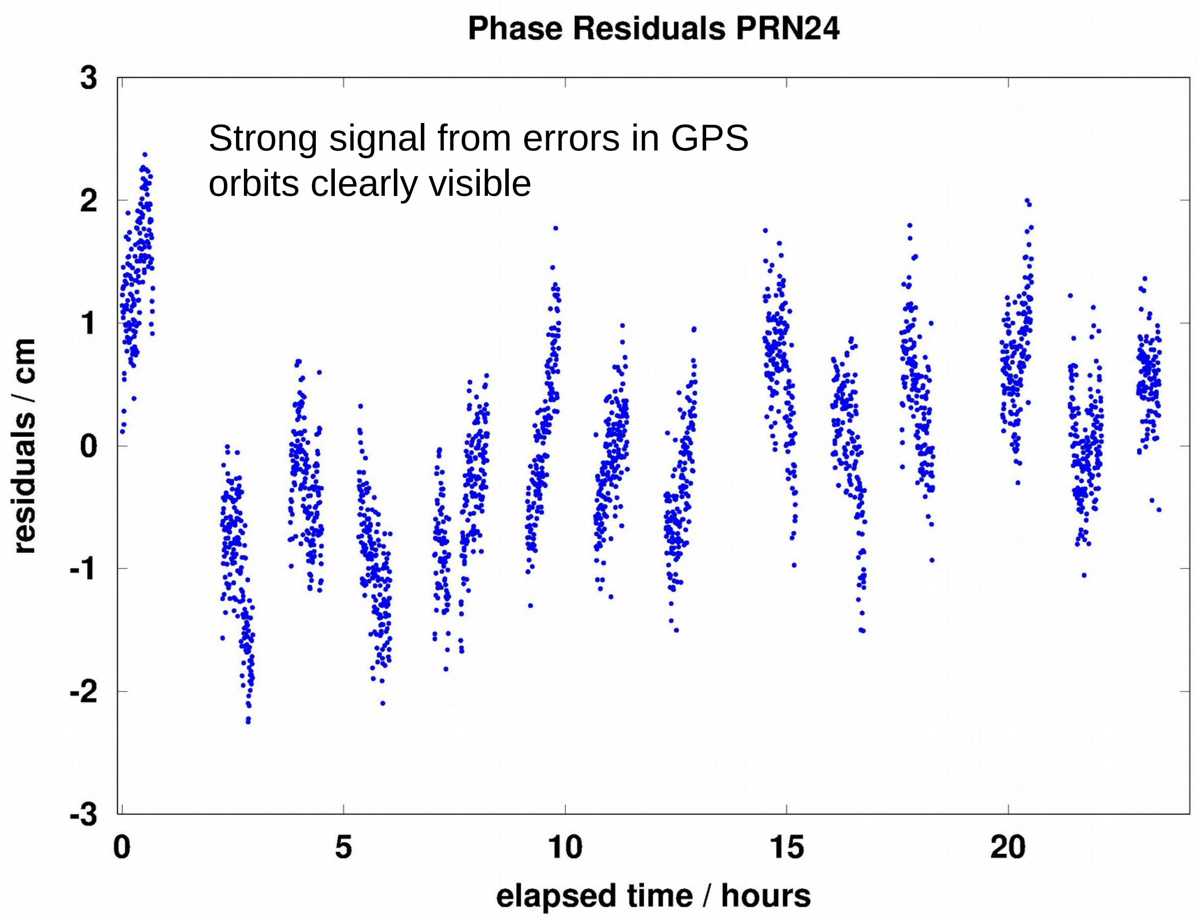
**100% cycle slips fixed**



# Phase residuals

**GPS orbits scenario 2: SRP model errors → orbit accuracy 4 cm**

**No cycle slips simulated**



# Conclusions

Comparison of multi-GNSS (GPS+GAL+GLO) to GPS-only solution:

- **Model error-free case**: does not improve of the GRACE orbits, the baseline improves by factor of ~1.8
- **SRP model errors case (4 cm):** improve the GRACE orbits by factor of ~2, the baseline improves by factor of ~1.6
- **EOP errors (4 cm)**: similar to ‘model error-free case’, systematic rotation of the reference frame

Remarks on the methods

- **LEO DD ambiguity fixing:** does not improve the GRACE orbits, baseline improves by the factor of ~3. Not sensitive to GNSS modeling errors
- **Cycle slip fixing:** improves the orbits by factor ~1.5, baselines are the same as with DD ambiguity fixing. GNSS orbit errors visible in phase residuals → useful for more precise modeling and estimation of geodetic parameters
- The simulation/recovery results are an example for certain error scenarios and application (GFZ’s dynamic Rapid Science Orbits generation), may depend on parametrization, can be repeated for other applications
- These conclusions are valid only for dynamic LEO orbits and the **two-step** approach

# Thank you for your attention!