Satellite baseline determination

with

phase cycle slip fixing over long data gaps

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Overview

- The cycle slip fixing methode
- 3 solutions
  - Float ambiguities
  - Ambiguities fixed on double-difference level
  - Cycle slip fixing
- Tests with 1 month of **real** GRACE A/B and TerraSAR-X/TanDEM-X data
  - Examples of performance of the method
  - Validation statistics
    - Number of ambiguities
    - Carrier phase residuals
    - Satellite Laser Ranging data
    - with K-band range data (GRACE)
    - Precise baseline (TSX/TDX)
- Conclusions

Carrier phase cycle slip fixing

Classical approach: $(\Delta n_{1,} \Delta n_2)$: cycle slips on the 2 frequencies

$\Delta n_1 - \Delta n_2 = \Delta WL$ (cycle slip in wide-lane phase combination)

$\lambda_1 \Delta n_1 - \lambda_2 \Delta n_2 = \Delta LI$ (cycle slip in ionospheric phase combination)

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Approach using L_3 ambiguities : second equation can be replaced by

$$\frac{cf_1 \Delta n_1 - cf_2 \Delta n_2}{f_1^2 - f_2^2} = \Delta L_3$$ (cycle slip in L_3 phase combination = difference between neighboring L_3 ambiguities)

Advantage: no dependence on ionospheric delay,
cycle slips over long data gaps can be fixed

Requirement: L_3 ambiguities estimated with 1-2 cm accuracy
uncalibrated phase delays stable over the arc

GRACE mission

Data

- 1 month (June 2008) GPS Level 1B data (clock offsets, phase ambiguities and cycle slips reduced to small values)
- Undifferenced GPS L_3 ionsphere-free combination of code and carrier phase
- 1 day arcs, 10 s spacing
- Accelerometer, attitude data and phase center variation mask
- K-band ranging data (for validation)
- SLR data (for validation)

Processig and Parametrization

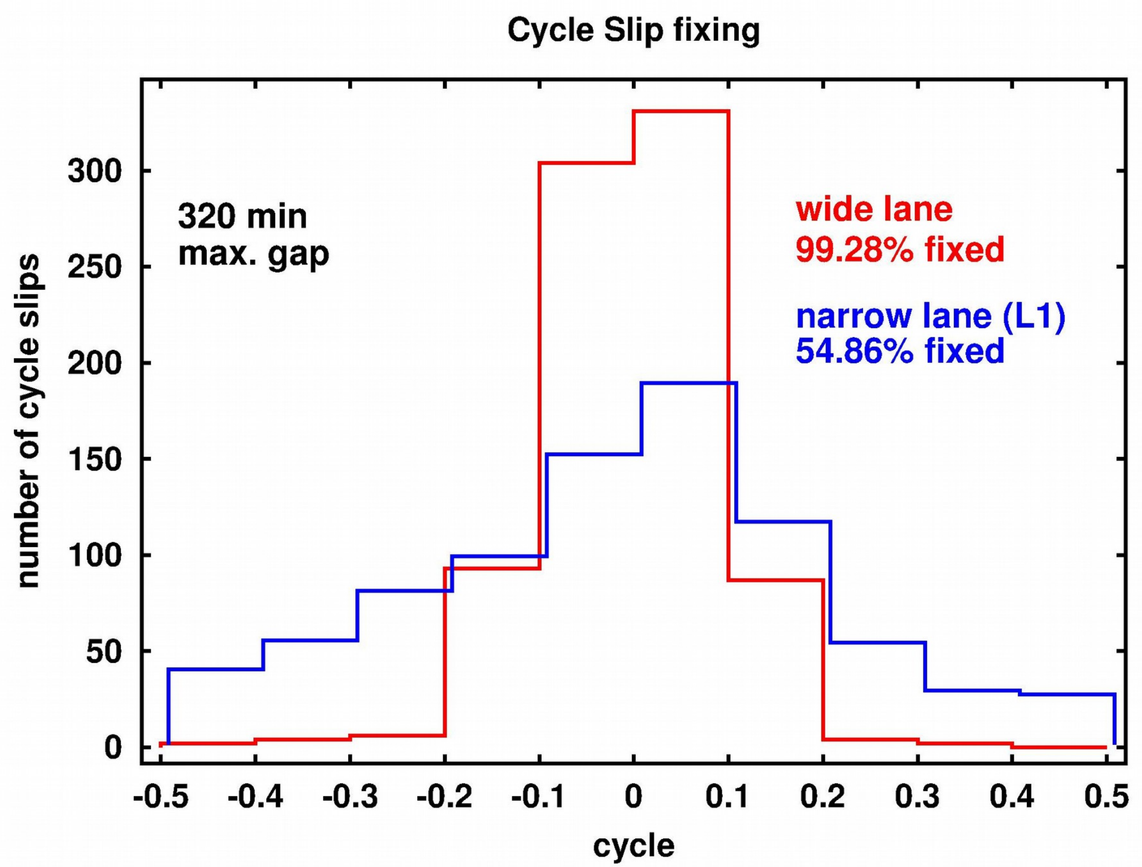
- Dynamic orbits in a two-step approach (GPS constellation and clocks offsets fixed)
- Reference: 1 day GPS Post-processed Science Orbits and clocks, 30 s spacing (3D accuracy ~3-4 cm) used for the gravity field processing
- No cycle slip fixing in the preprocessing
- Initial state vectors
- Empirical periodic accelerations in transversal and normal directions (20/day)
- Accelerometer biases in R,T,N directions, 1/hour (75/day)
- K-band ranging bias (1, in few exceptions 2)
- L_3 float ambiguities and epoch-wise LEO clock offsets

GRACE mission

Cycle slip fixing performance

Example: Day 2008/06/01

Wide-lane and L1 cycle slip distribution around nearest integer



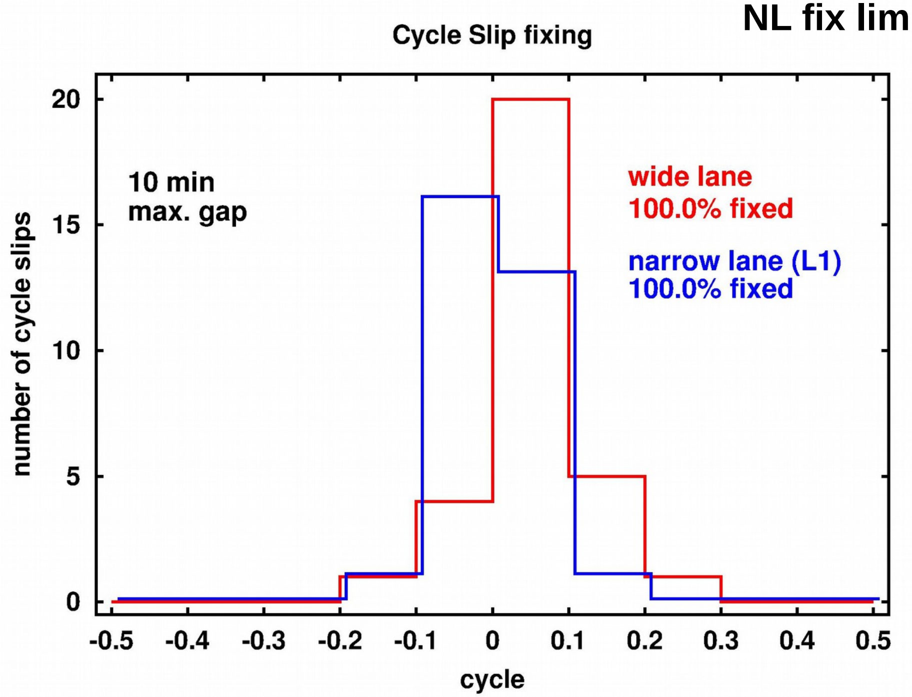
GRACE mission

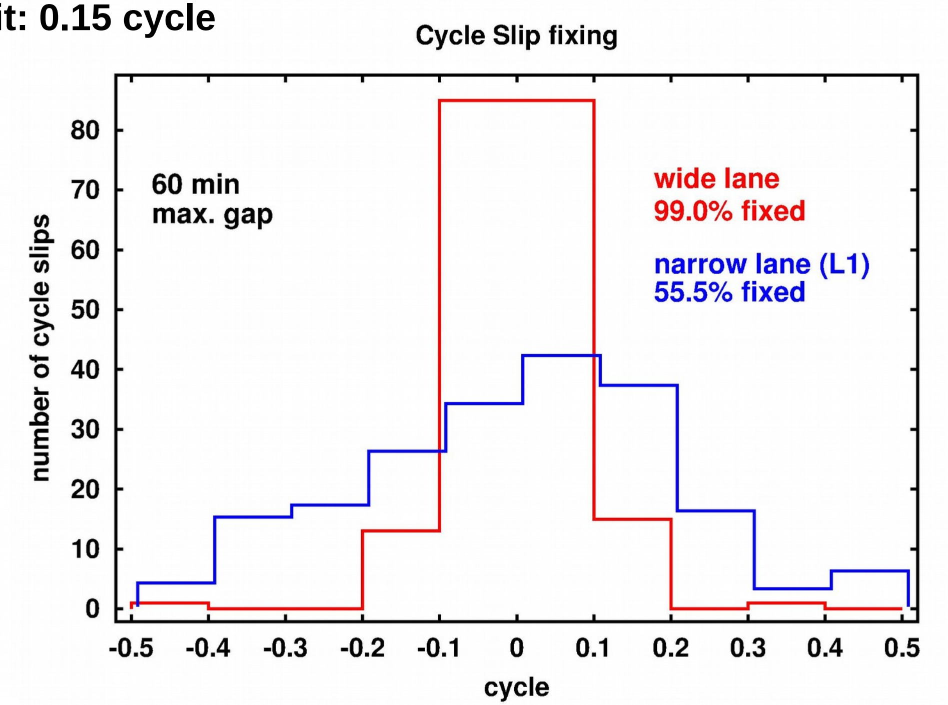
Example: Day 2008/06/01

Iterative cycle slip fixing over data gaps

Wide-lane and L1 cycle slip distribution around nearest integer

NL fix limit: 0.15 cycle





GRACE mission

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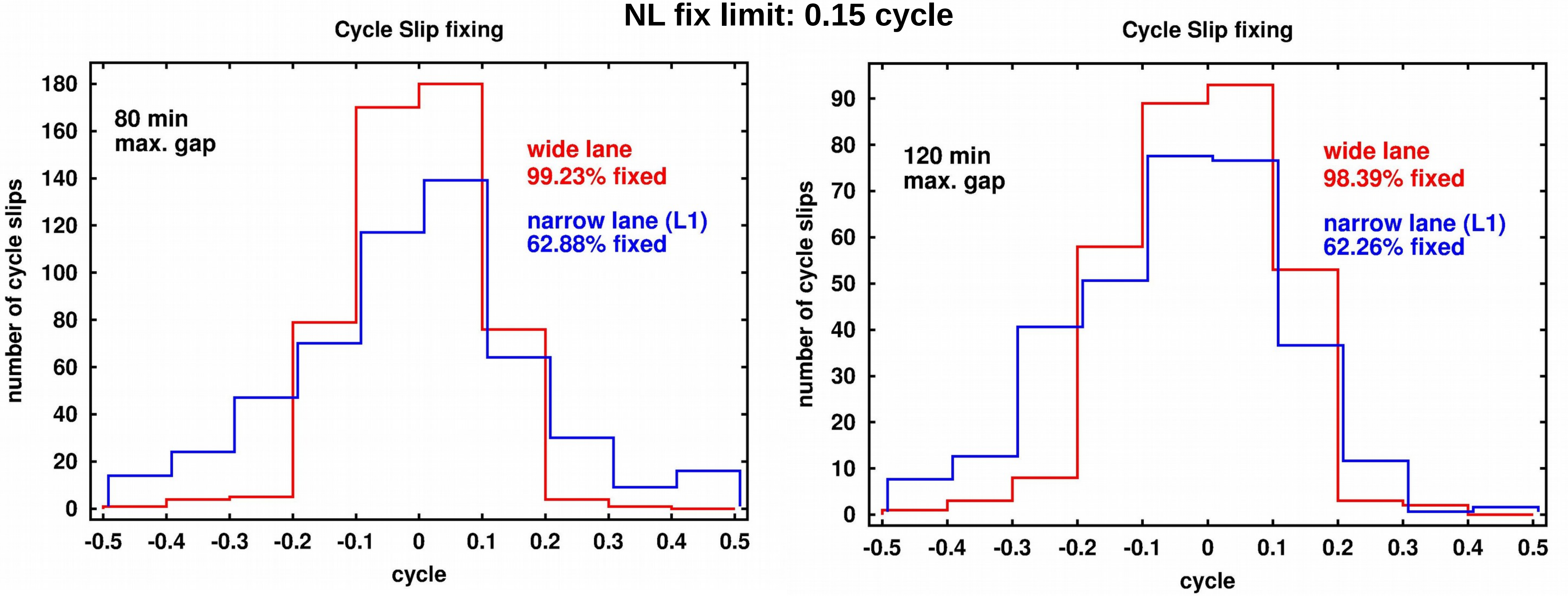

GRACE mission

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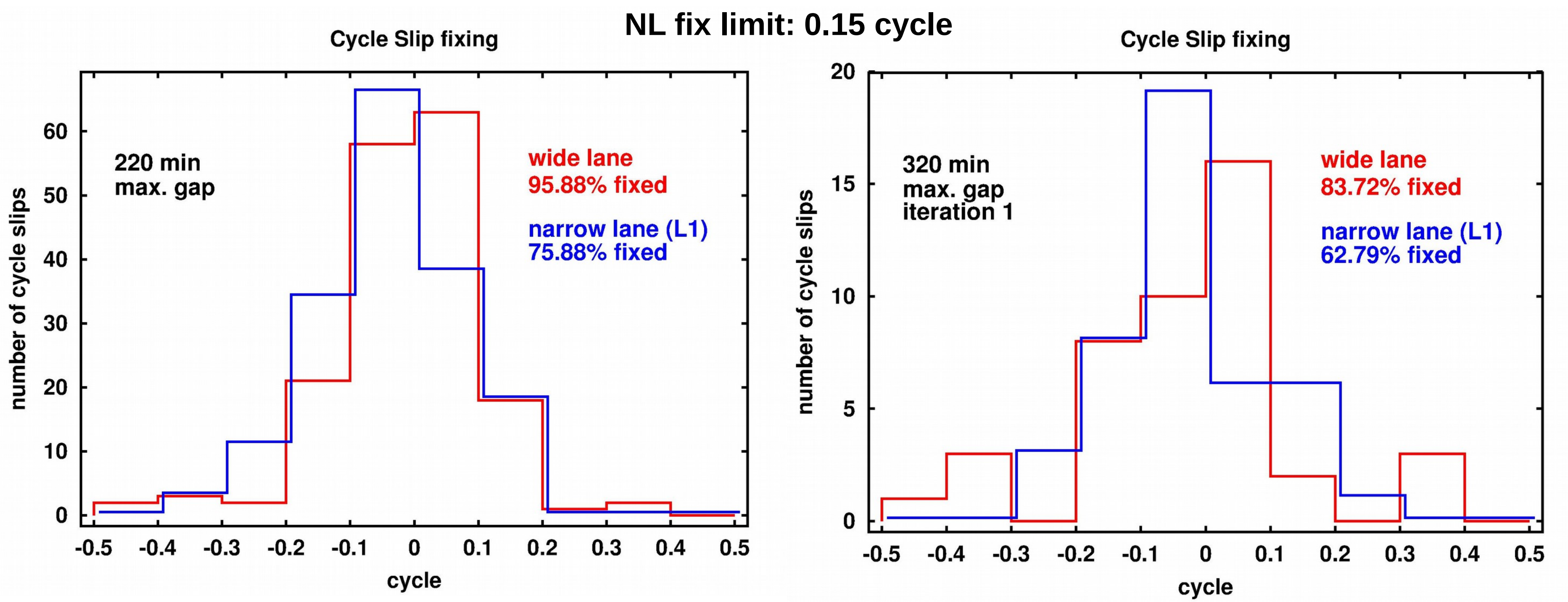
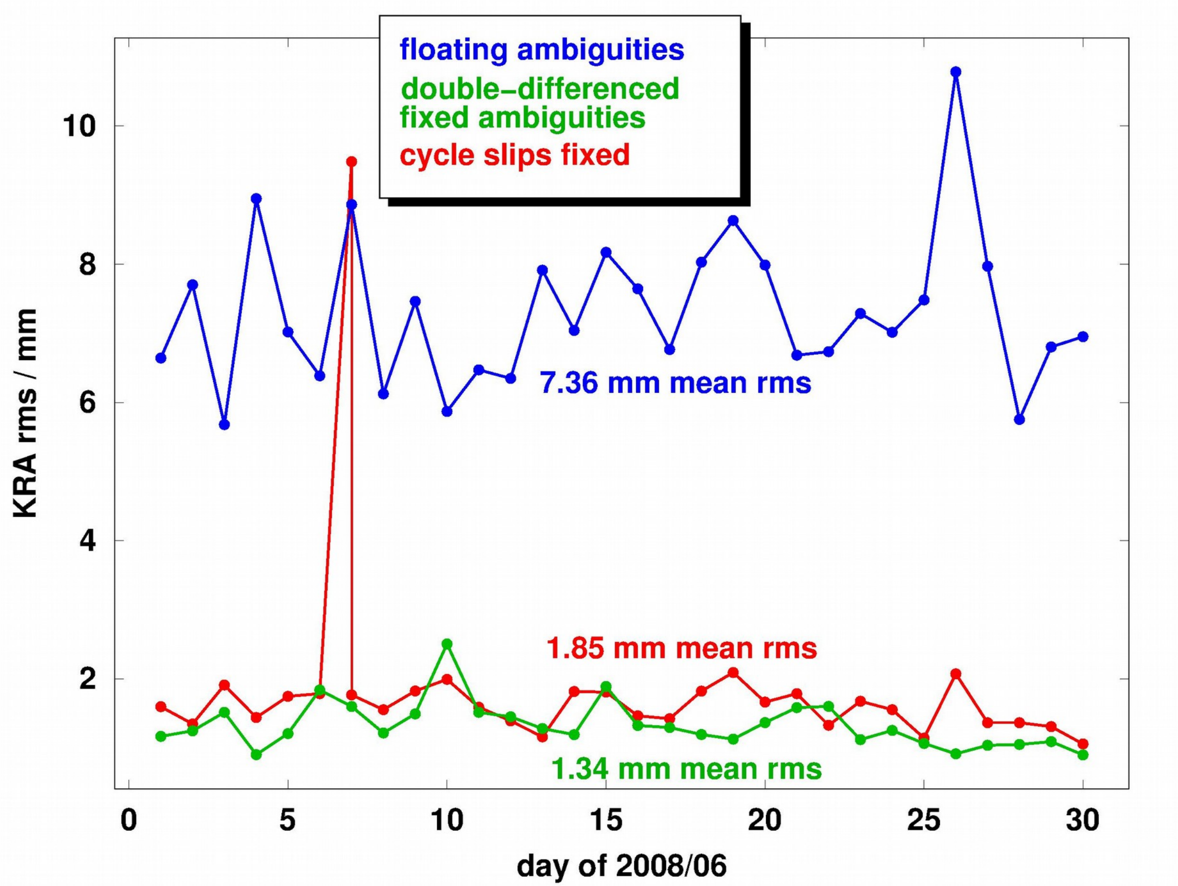


GRACE mission

2008/06/01 - 2008/06/30

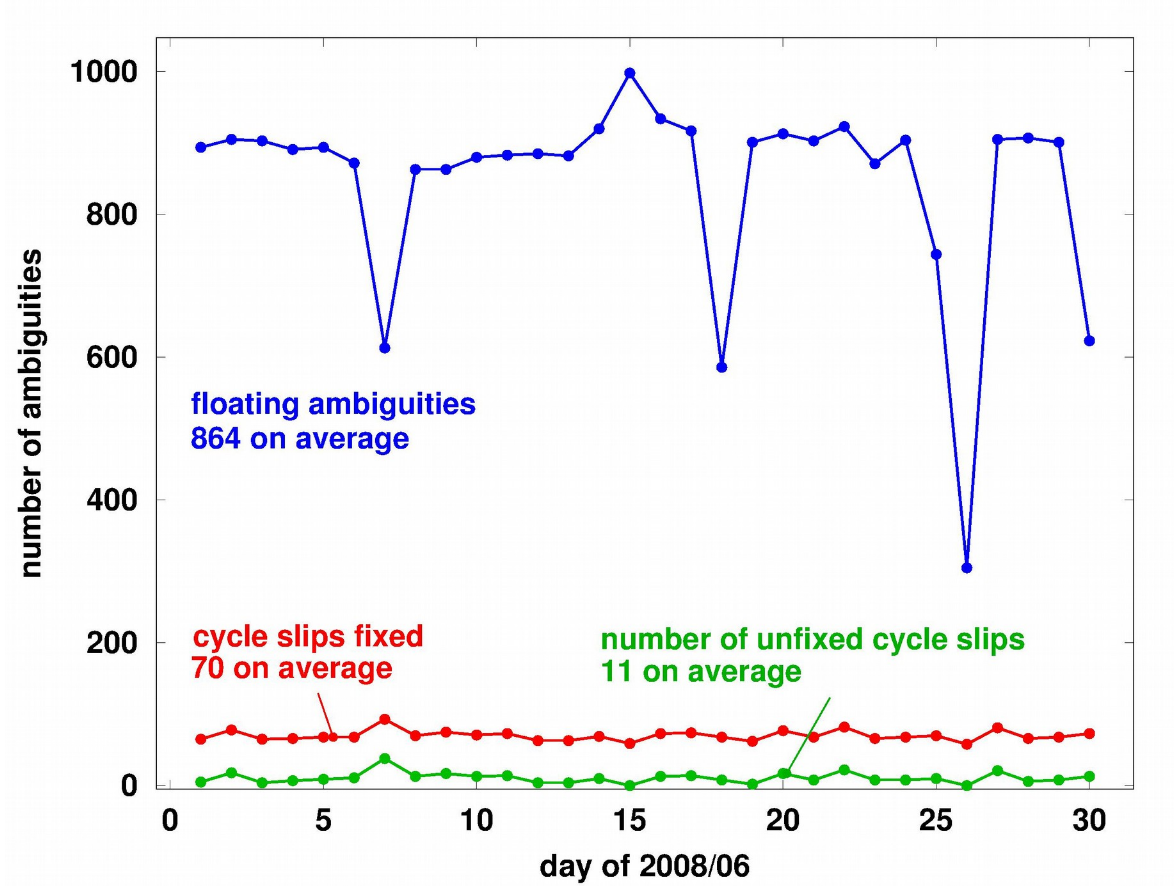
K-Band Range



GRACE mission

2008/06/01 - 2008/06/30

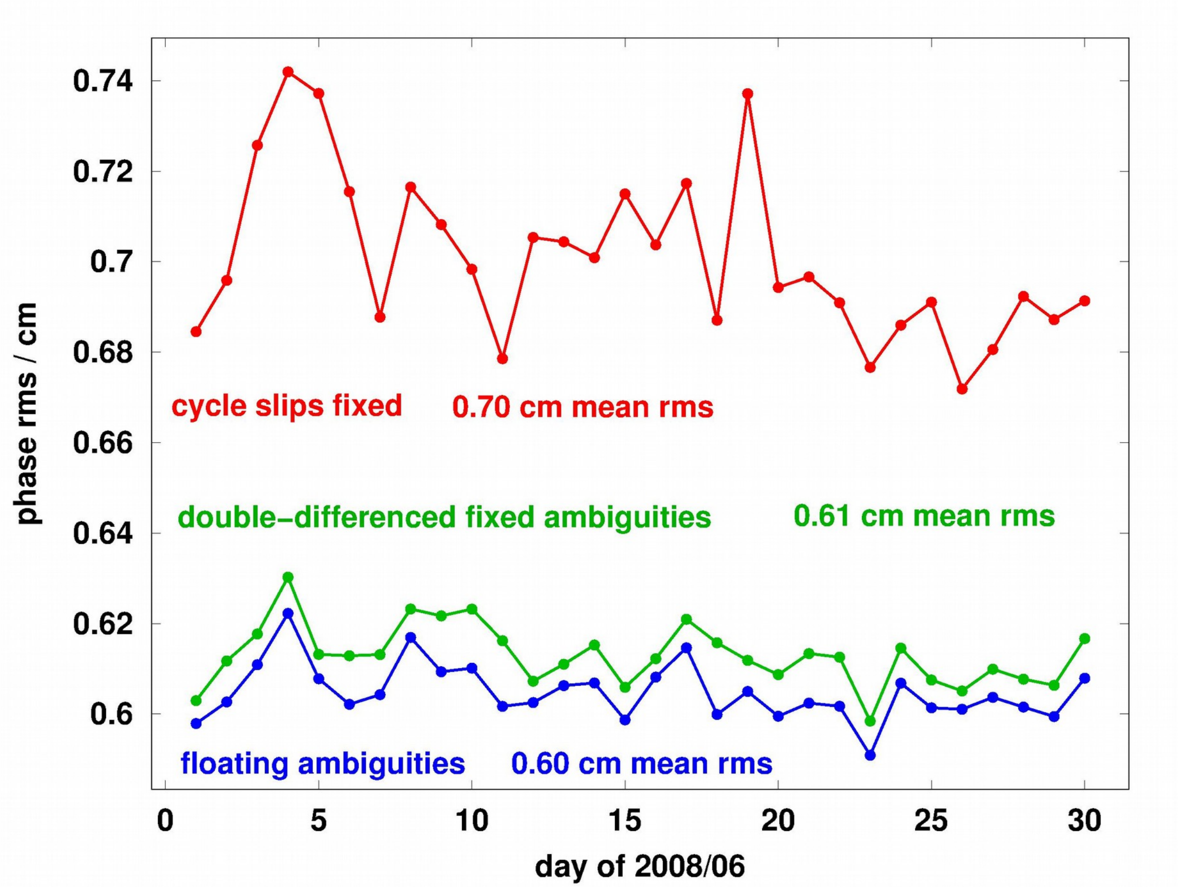
Number of ambiguities and unfixed cycle slips



GRACE mission

2008/06/01 - 2008/06/30

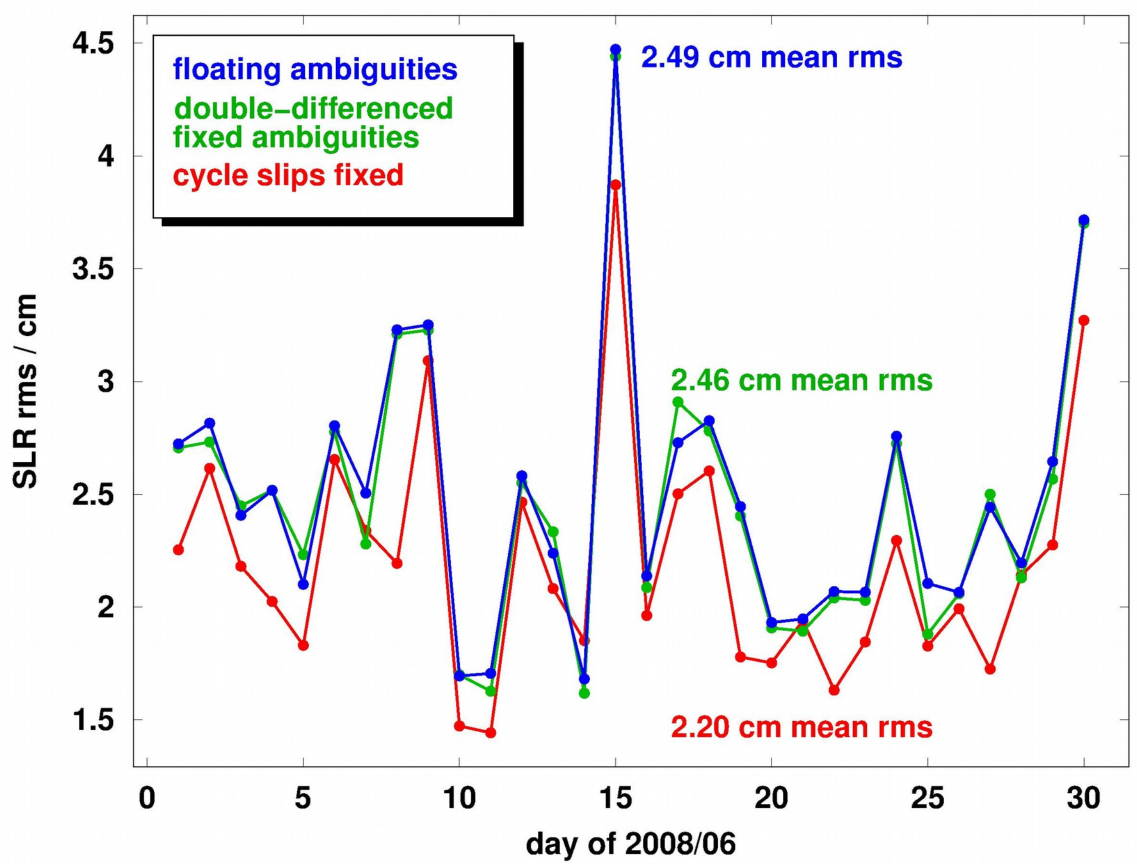
Carrier phase



GRACE mission

2008/06/01 - 2008/06/30

Satellite Laser Range



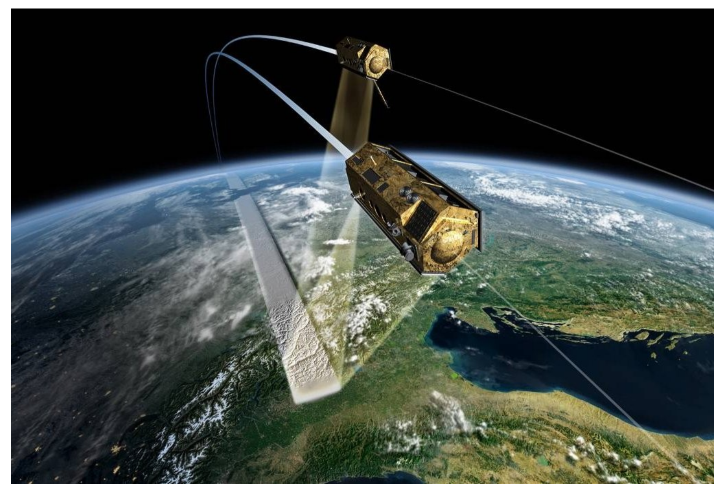
TerraSAR-X – TanDEM-X mission

- Two radar satellites flying in a close formation with baseline of 800 m (05/2016)
- Synthetic Aperture Radar (SAR) for precise topographic maps
- Radio occultations
- For SAR the baseline accuracy requirement : < 1 mm in radial and crosstrack
- Precise baseline generated by:

  - GFZ with EPOS and Bernese software

  - GSOC with GHOST software

  using reduced dynamic approach



TerraSAR-X – TanDEM-X mission

Data

- 1 month (May 2016), undifferenced GPS ionsphere-free combination of code and carrier phase
- 14 h arcs, 30 s spacing, arcs without maneuvers
- Attitude and phase center variation mask
- SLR data for validation

Procesing and parametrization

- Reduced dynamic orbits in a two-step approach (GPS constellation and clocks offsets fixed)
- Reference: 1 day GPS Rapid Science Orbits and Clocks, 30 s spacing (3-5 cm accuracy)
- Processing standards and parametrization exactly the same as for precise baseline determination
- Some cycle slips fixed in the preprocessing
- Initial state vectors
- 1 scaling factor for the Solar Radiation Pressure model
- 6 min spaced empirical accelerations in RTN directions, modeled as polygon (429/arc)
- Ionospheric free L3 ambiguities (~300/arc) (float, fixed on double-difference level, CS over data gaps 13, 63, 83, 123 223, 323 min. iteratively fixed)
- Empirical accelerations tightly constrained to be the same for both satellites

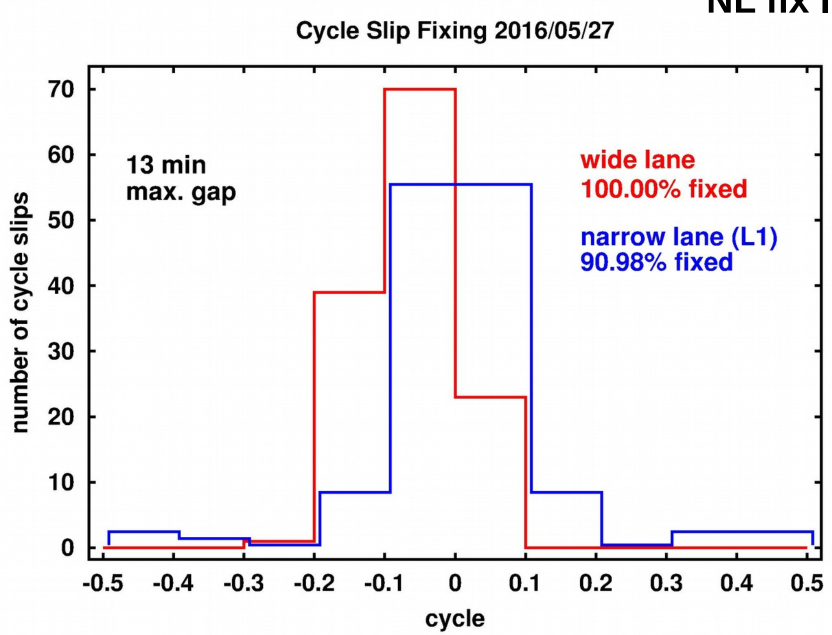
TerraSAR-X – TanDEM-X mission

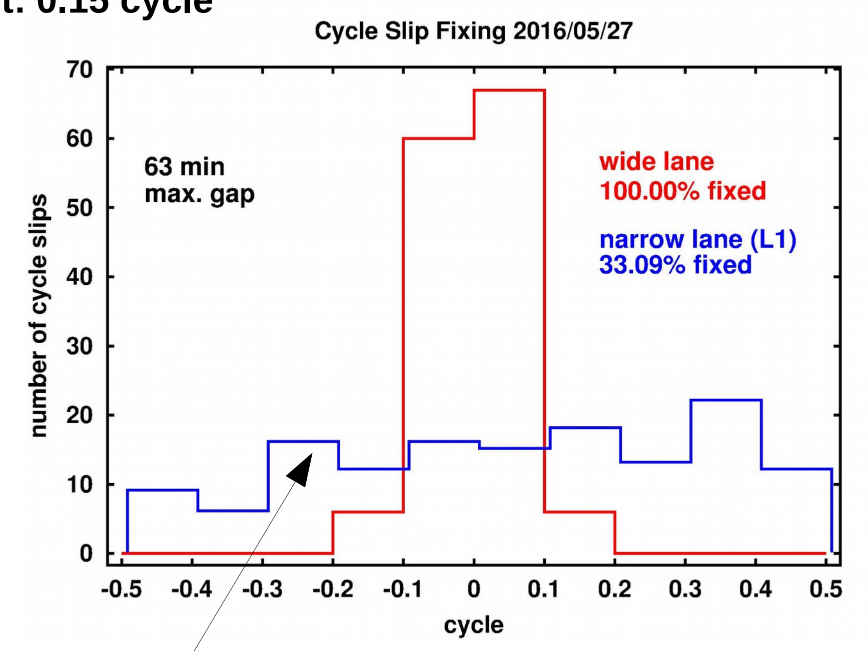
Example 1 : Day 2016/05/27

Iterative cycle slip fixing over data gaps

Wide-lane and L1 cycle slip distribution around nearest integer

NL fix limit: 0.15 cycle





Problem: flat NL distribution

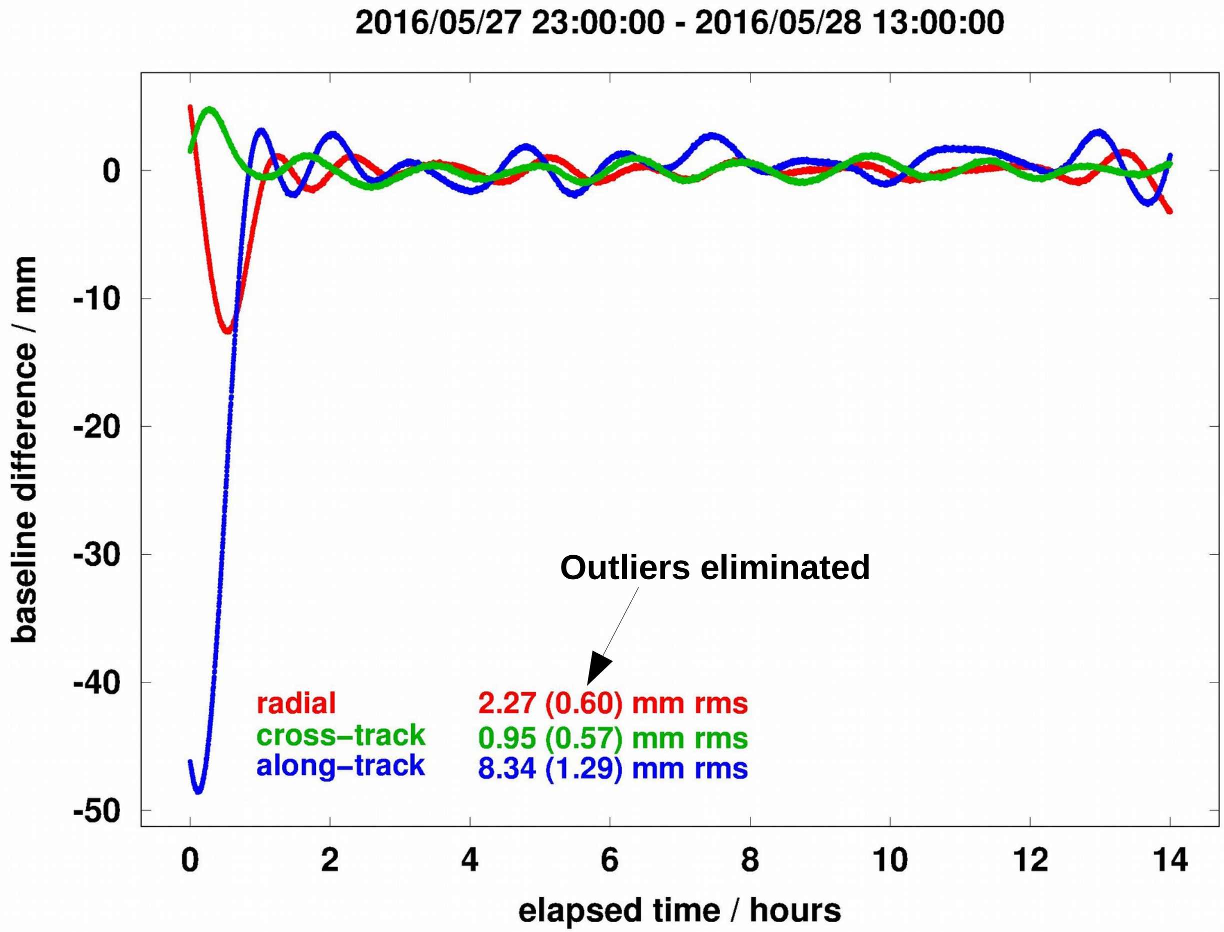
TerraSAR-X – TanDEM-X mission

Example 1 : Day 2016/05/27

Baseline difference to the GFZ's precise baseline

Number of ambiguities:

- initial: 588
- final: 89 (85% reduction)
- unfixed CS: 30



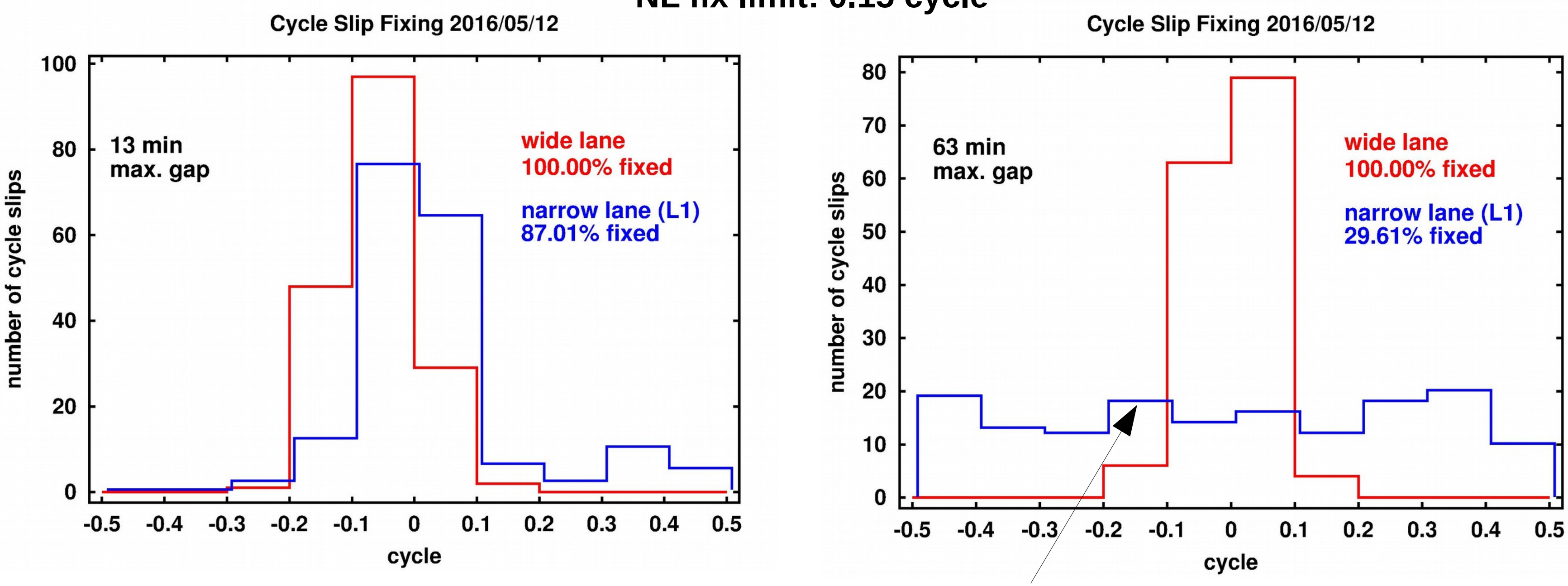
TerraSAR-X – TanDEM-X mission

Example 2 (good): Day 2016/05/12

Iterative cycle slip fixing over data gaps

Wide-lane and L1 cycle slip distribution around nearest integer

NL fix limit: 0.15 cycle



Problem: flat NL distribution

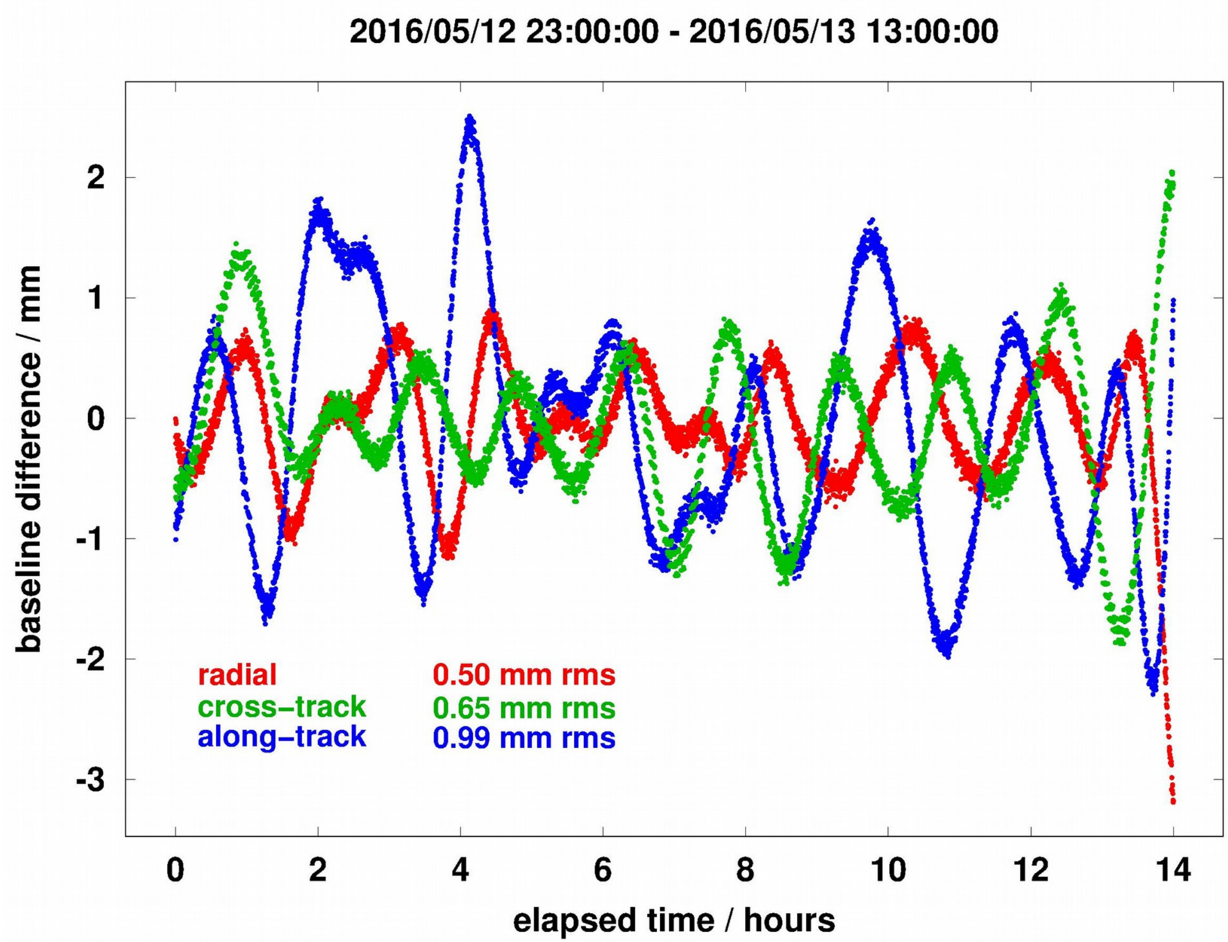
TerraSAR-X – TanDEM-X mission

Example 2 (good): Day 2016/05/12

Baseline difference to the GFZ's precise baseline

Number of ambiguities:

- initial: 654
- final: 66 (90% reduction)
- unfixed CS: 5



TerraSAR-X – TanDEM-X mission

Baseline determination summary for May, 2016 (30 arcs)

Average values, differences to GFZ's precise baselines

Solution	**Phase** RMS [cm]	**SLR** RMS [cm]	**Radial** STD [mm]	**Normal** STD [mm]	**Transversal** STD [mm]	**N amb**	**Unfixed CS**
Float	0.43	3.13	4.40	2.41	8.43	625	-
DD fix	0.46	3.08	0.38	0.33	0.77	625	-
CS fix (Elim)	0.71	3.45	3.84 (2.13)	2.20 (1.71)	3.86 (2.63)	98	37

(Elim) with 2.5 σ iterative outlier elimination
N amb number of ambiguities in the solution
Unfixed CS number of CS remained

Conclusions

- Cycle slip (CS) fixing for single station over long data gaps is possible
- Significant reduction of number of phase ambiguities (~90%)
- Baselines accuracy can reach the level of double-difference ambiguity fixing
- The absolute orbit accuracy improves if most CS fixed (GRACE SLR validation, simulation)
- Orbit errors of reference GPS constellation visible in phase residuals
- Reliable CS fixing requires NL CS distribution concentrated around integers
- Efficient CS fixing over small gaps up to 15 min (not possible with classical approach)

GRACE

- WL and NL CS distribution concentrated around integers
- K-band range RMS 1.85 mm is close to 1.34 mm from DD ambiguity fixing solution
- SLR RMS improves from 2.49 cm (DD ambiguity fixing) to 2.20 cm
- Average number of ambiguities reduced from 864 to 70 (92%) with 11 CS unfixed on average

TerraSAR-X/TanDEM-X

- Flat NL CS distributions prevent from reliable CS fixing: problem with data (?), orbit modeling (?), needs further investigations
- With outlier elimination the baseline (1.7-2.6 mm) improves by 50-70% in comparison to the float solution
- An example of successful CS fixing (5 unfixed) shows baseline accuracy < 1 mm

Thank you for your attention!