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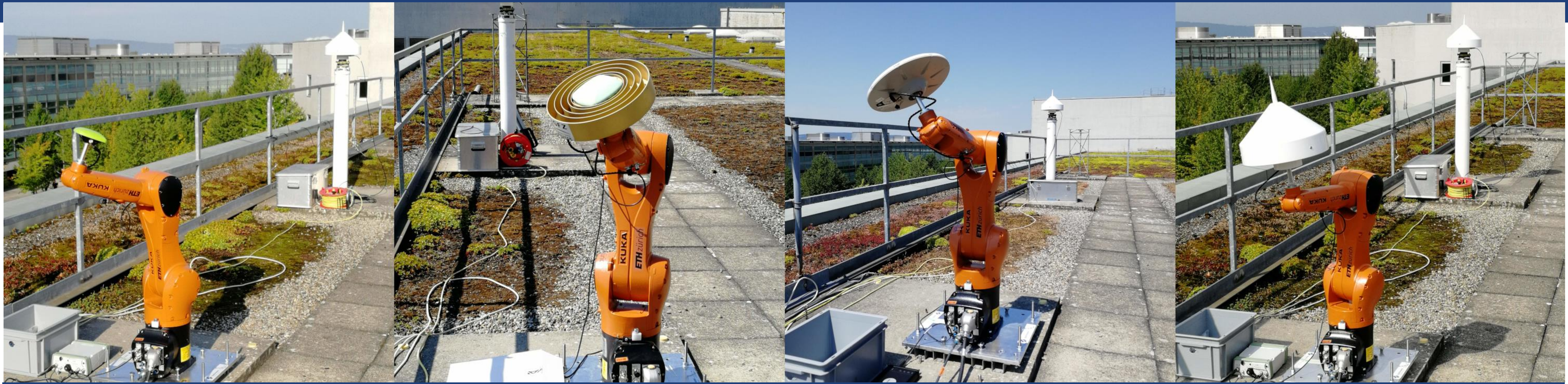

Multi-GNSS Absolute Antenna Field Calibration with a Robot at ETH Zurich

基于机器手臂的多模GNSS绝对天线校准

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Calibration of receiver antennas

State of the art

- Routinely performed nowadays
  - Geo++, NGS, University of Hannover, Geoscience Australia, Wuhan, University of Bonn, …
- GNSS modernization
  - Galileo E5a
  - GPS L5
  - Beidou B1, B2, B3
  - GLONASS 3rd frequency, GLONASS CDMA
- Consistency between methods
  - Sub-millimetre consistency not achieved yet (Wim and Moore, 2013)
  - Significant offsets found between different calibration institutes (Kallio et al. 2018)

Definitions

Phase Centre Correction (PCC)

- **Phase Centre Offset (PCO)**
  - Connection between the physical Antenna Reference Point (ARP) and the virtual / conventional Mean Phase Centre (MPC)
  - $\boldsymbol{X}_{\mathrm{MPC}} = \boldsymbol{X}_{\mathrm{ARP}} + \boldsymbol{PCO}$
- **Phase Centre Variations (PCV)**
  - Direction-dependent range correction function
  - $\Phi_A^i = \Phi_A\left(\alpha^i, z^i\right)$

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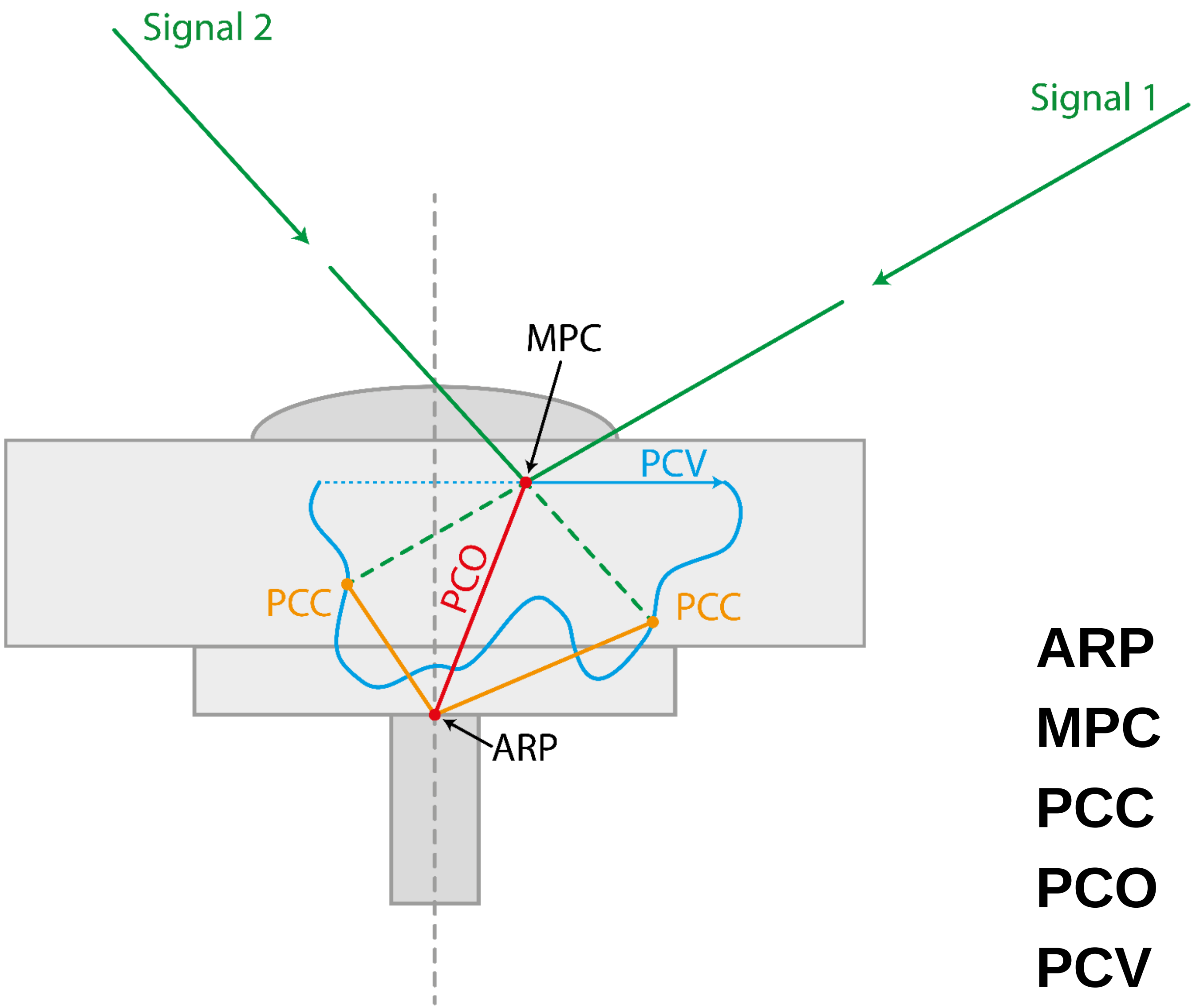


ARP Antenna Reference Point

MPC Mean Phase Center

PCC Phase Centre Correction

PCO Phase Centre Offset

PCV Phase Centre Variation

Existing calibration methods

	Anechoic chamber	Relative field calibration	Absolute field calibrations
GNSS signal	No, artificial signal	Yes	Yes
Fast movement	Yes, robot or moving source	No, manual rotation every 24h	Yes, rotation by a robot
Infrastructure	Very demanding	Virtually none	Demanding

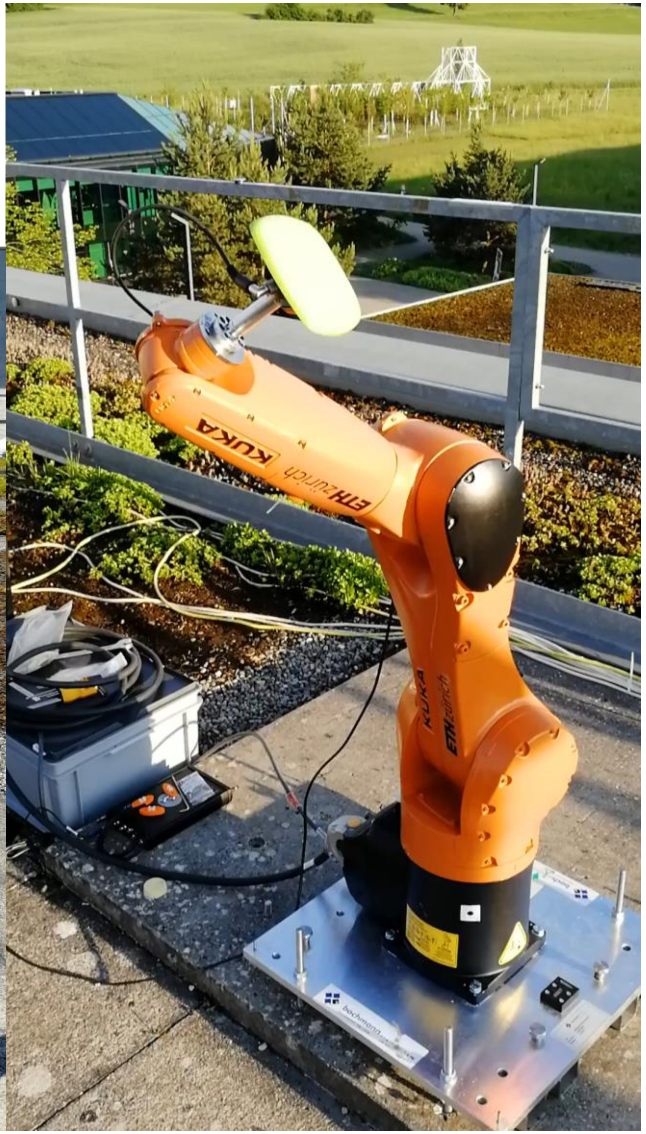
System components

Calibrated robot

Reference antenna

Robot controller
and software

GNSS receivers



Triple difference approach

1) Station differences

- satellite clocks, ionosphere, troposphere

2) Satellite differences

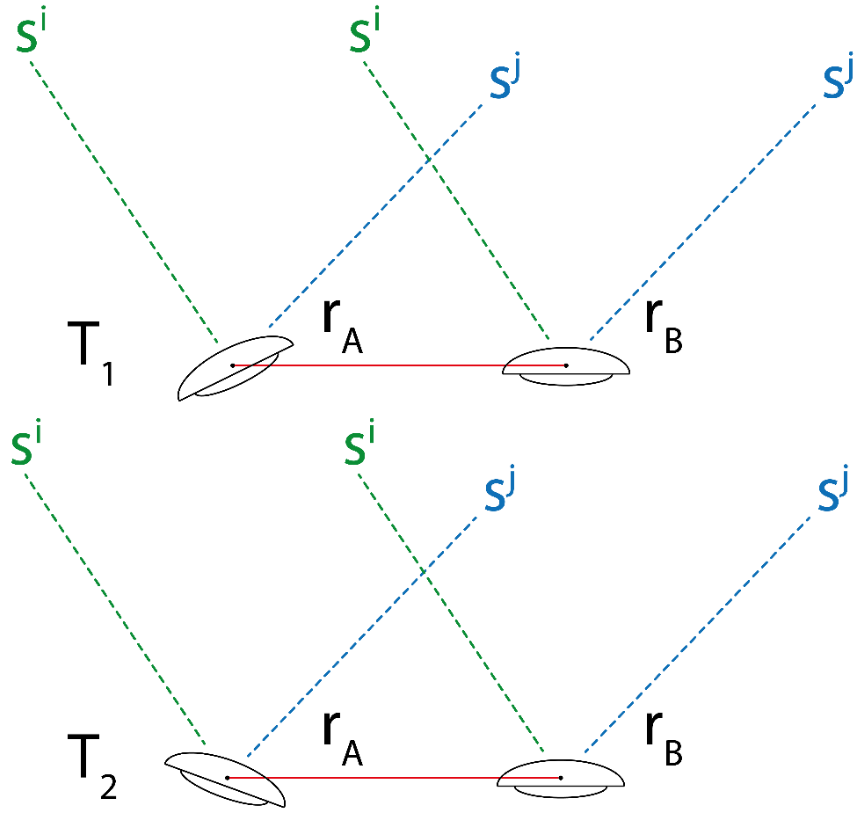
- receiver clocks

3) Time differences

- multipath, reference PCC, coordinate bias

Rotation sequence

- 1440 to 4320 orientations (40 min to 4 h)
- Randomization
- 20 Hz measurements
- 1 - 2 seconds travel time between orientations



$$P^{ij}_{AB,t_1t_2} = \left((P^j_B - P^j_A) - (P^i_B - P^i_A)\right)_{t_2} - \left((P^j_B - P^j_A) - (P^i_B - P^i_A)\right)_{t_1}$$

Parametrisation of PCC

Spherical Harmonics expansion

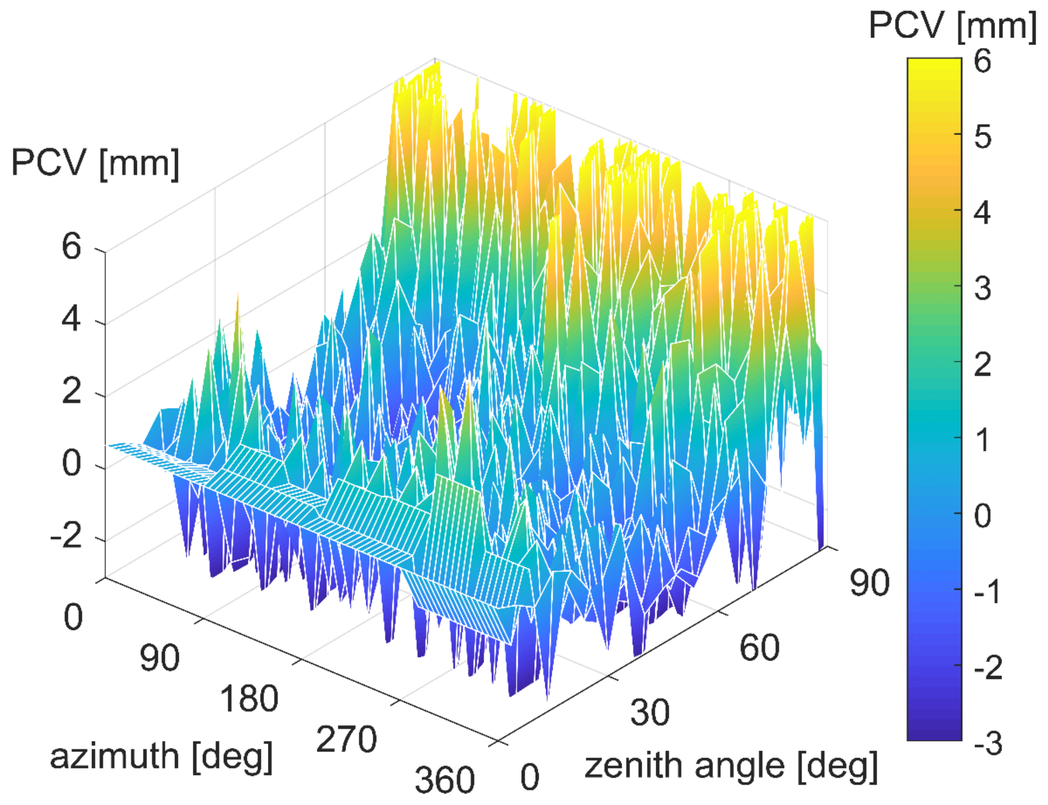
$$\Phi_A(\alpha^i, z^i) = \sum_{m=0}^{m_{\max}} \sum_{n=0}^{m} \tilde{P}_{mn}(\cos z^i)\left(a_{mn}\cos n\alpha^i + b_{mn}\sin n\alpha^i\right)$$

- PCO terms present in the series
- Various singularities
  - Absolute term
  - Anti-symmetrical terms

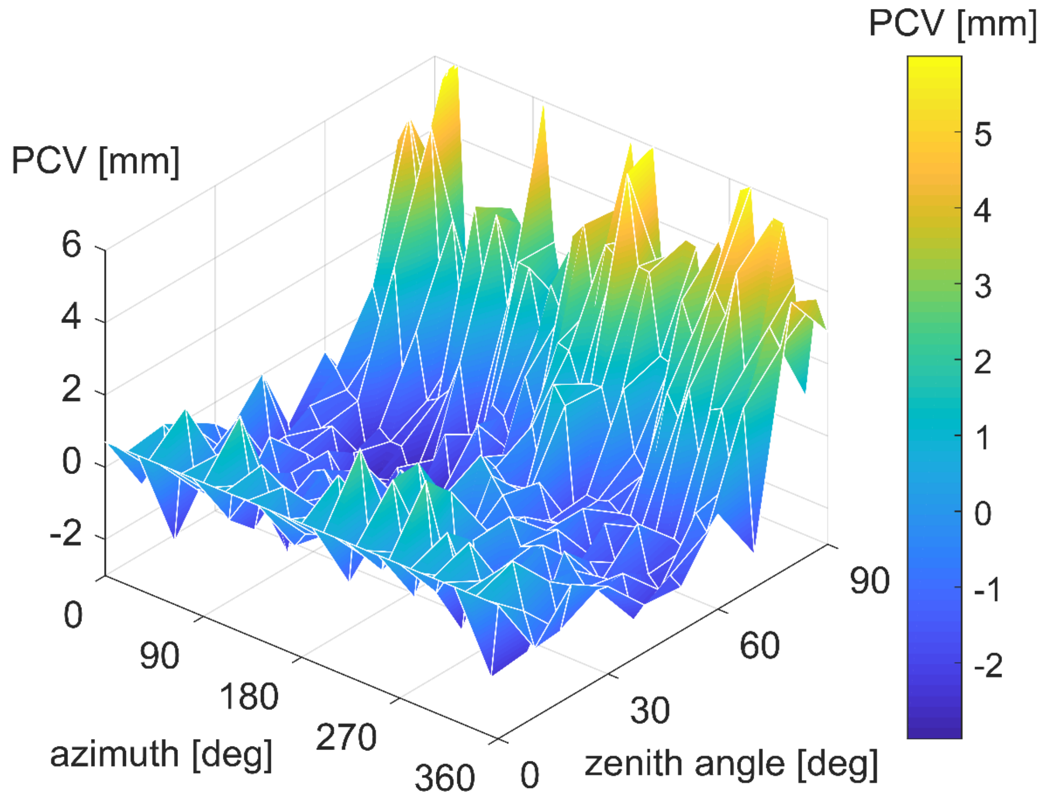
					a_{00}					
				b_{11}	a_{10}	a_{11}				
			b_{22}	b_{21}	a_{20}	a_{21}	a_{22}			
		b_{33}	b_{32}	b_{31}	a_{30}	a_{31}	a_{32}	a_{33}		
	b_{44}	b_{43}	b_{42}	b_{41}	a_{40}	a_{41}	a_{42}	a_{43}	a_{44}	
b_{55}	b_{54}	b_{53}	b_{52}	b_{51}	a_{50}	a_{51}	a_{52}	a_{53}	a_{54}	a_{55}

Grid parametrization

5 degree grid (1296 param.)

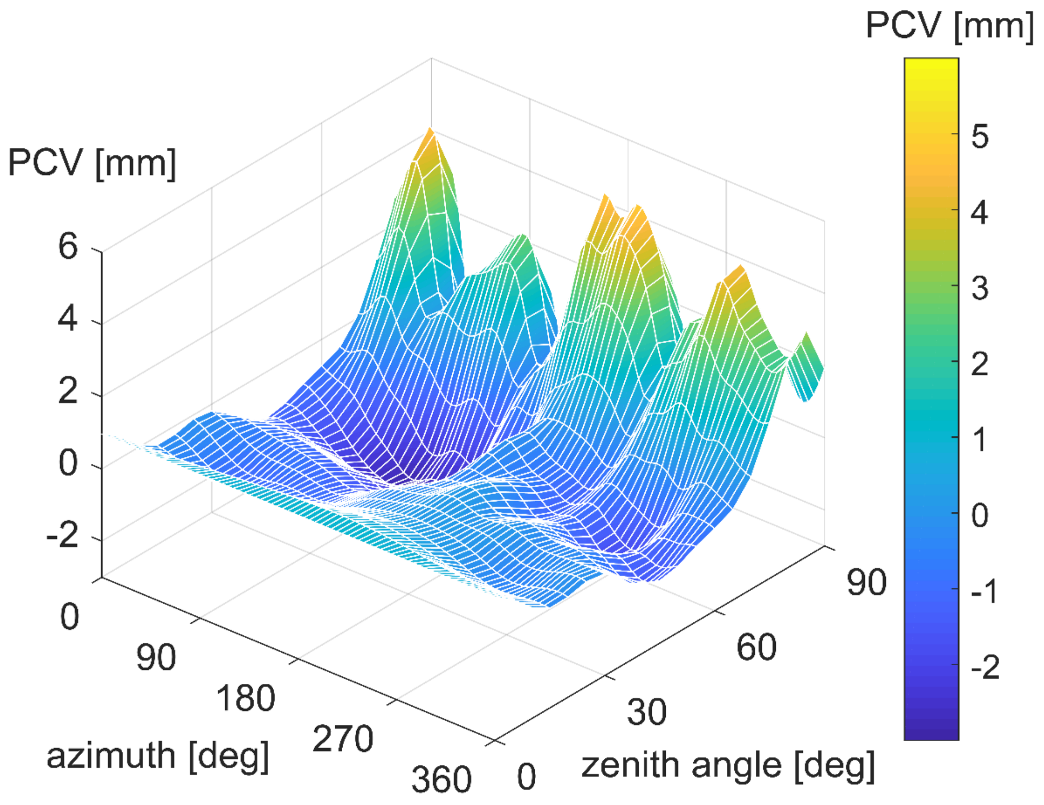


10 degree grid (324 param.)

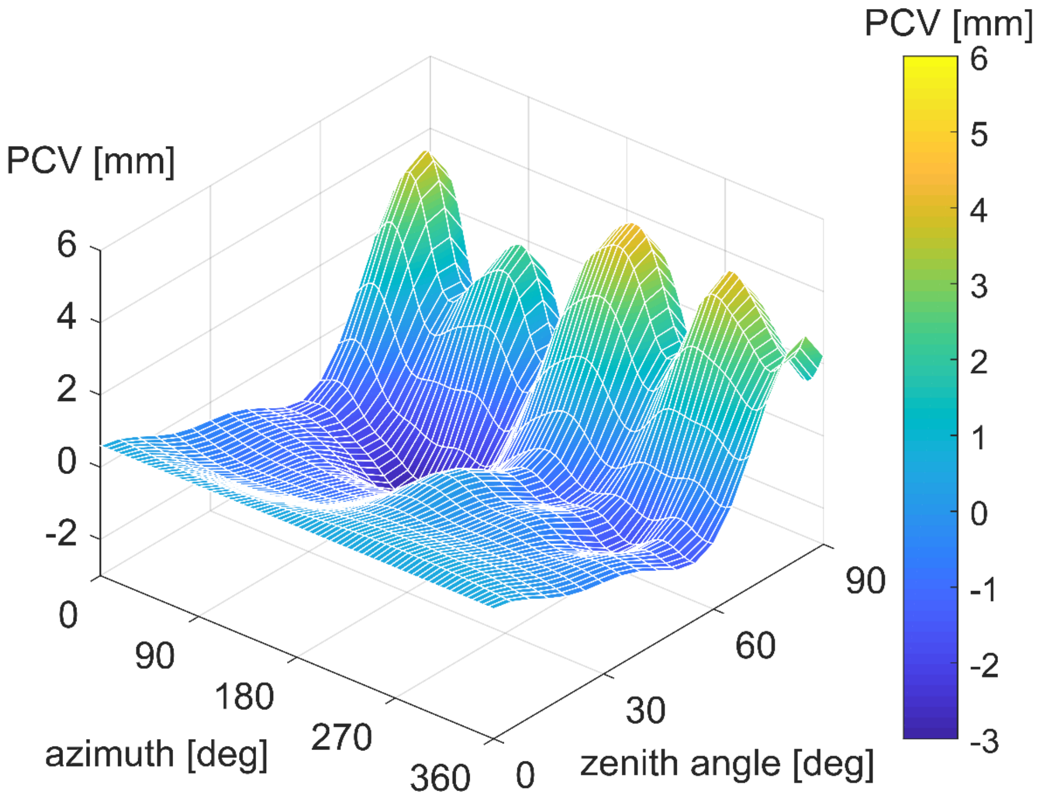


Spherical harmonics parametrization

Degree and order 12 (91 param.)



Degree and order 8 (45 param.)



Results

- Repeatability
- Comparison with Geo++ calibrations
- Small network validation

JAV_GRANT-G3T NONE
SEPCHOKE_B3E6 SPKE

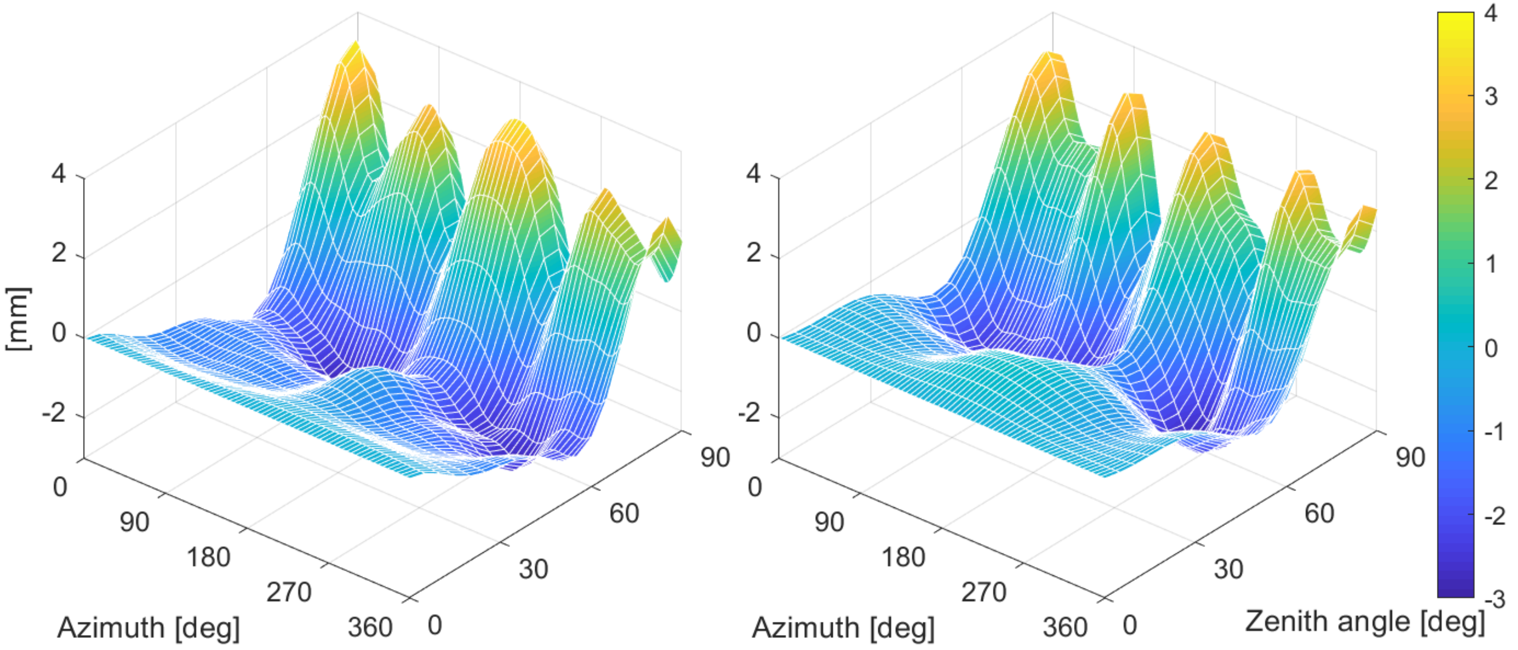
Type-mean Geo++ calibration

TRM57971.00 NONE
TRM57971.00 NONE

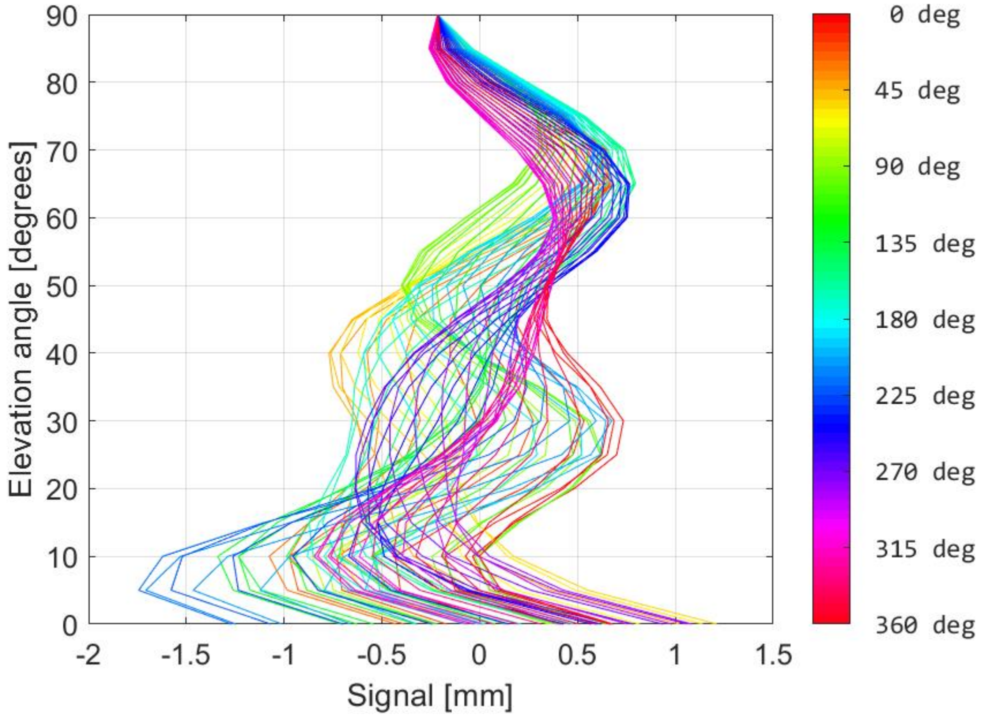
Individual Geo++ calibration

JAV_GRANT-G3T Repeatability (GPS L1)

Test 1 / Test 2

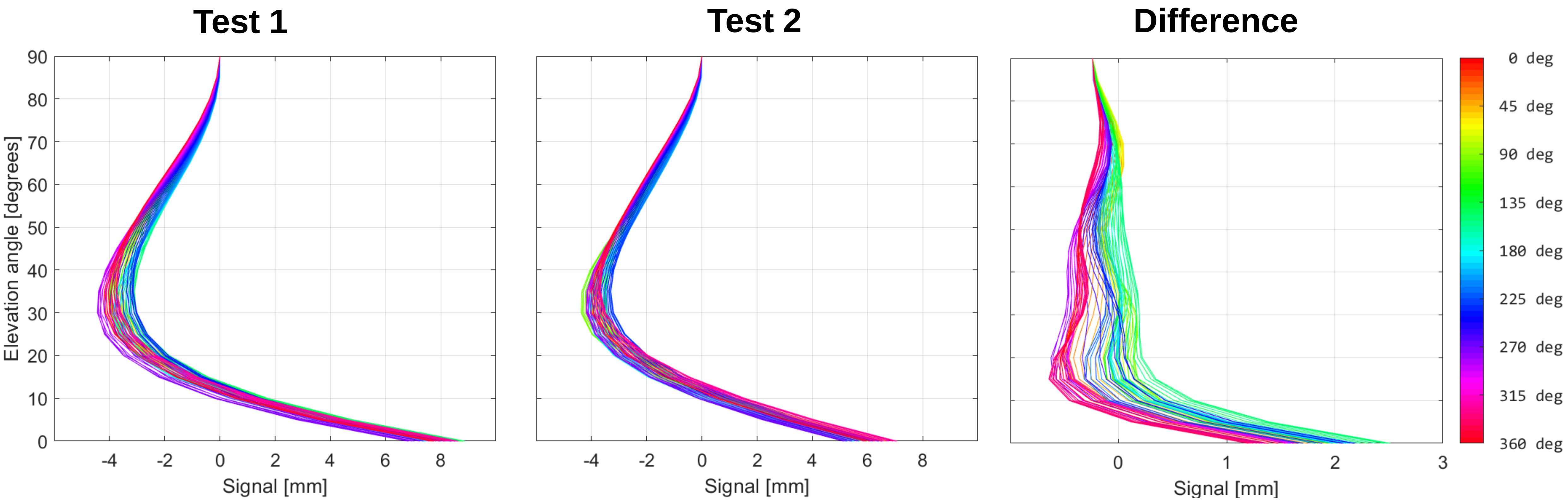


Difference



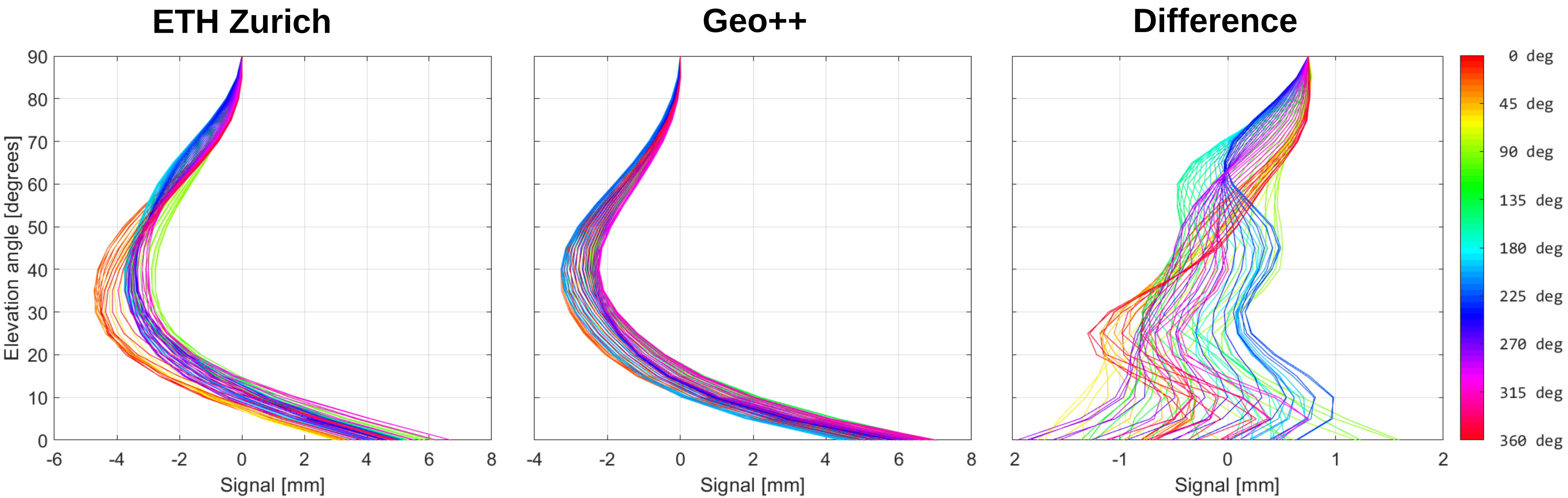
	RMS [mm]	MIN [mm]	MAX [mm]
0 deg mask	0.44	-1.74	1.21
10 deg mask	0.41	-1.62	0.80

SEPCHOKE_B3E6 SPKE Repeatability (GPS L1)



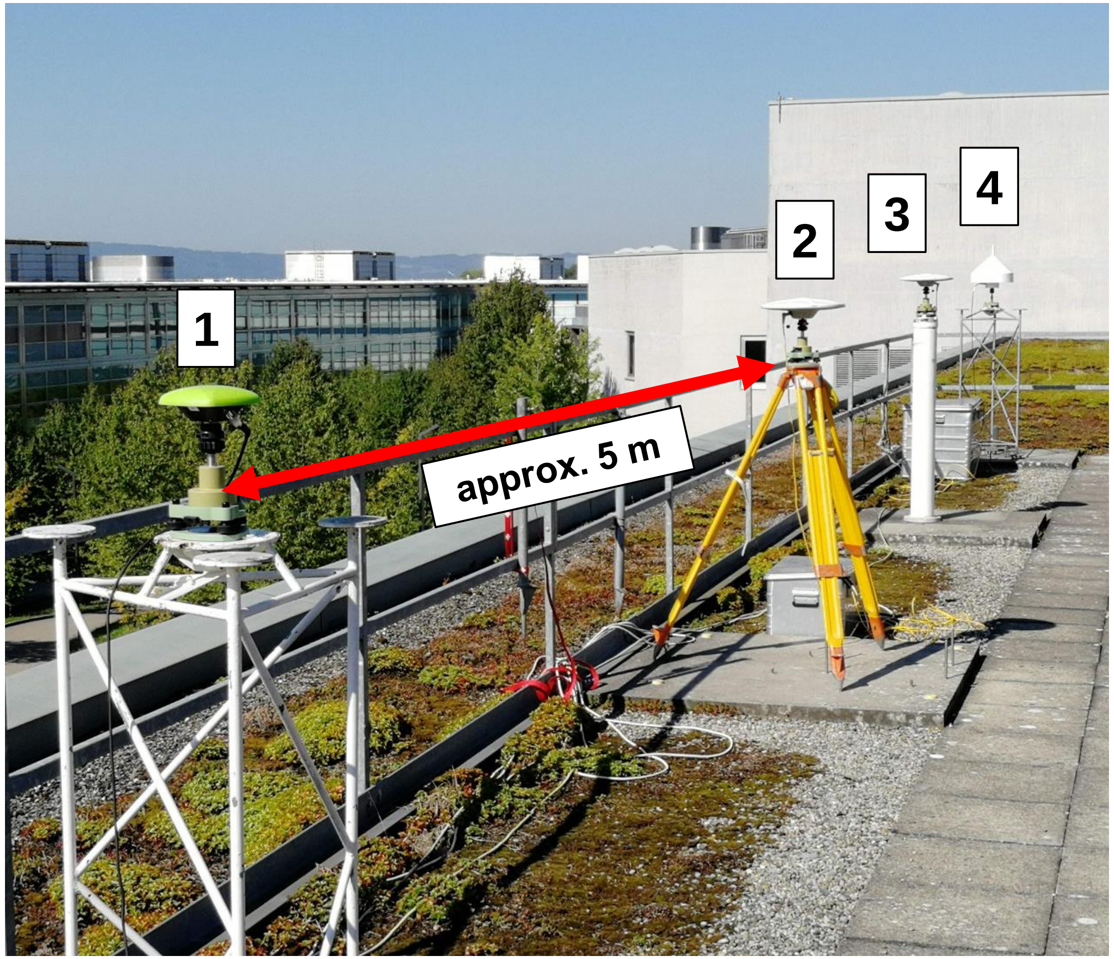
	RMS [mm]	MIN [mm]	MAX [mm]
0 deg mask	0.51	-0.64	2.51
10 deg mask	0.24	-0.64	0.70

TRM57971.00 comparison with Geo++ (GPS L1)



	RMS [mm]	MIN [mm]	MAX [mm]
0 deg mask	0.56	-1.95	1.59

High precision network for validation

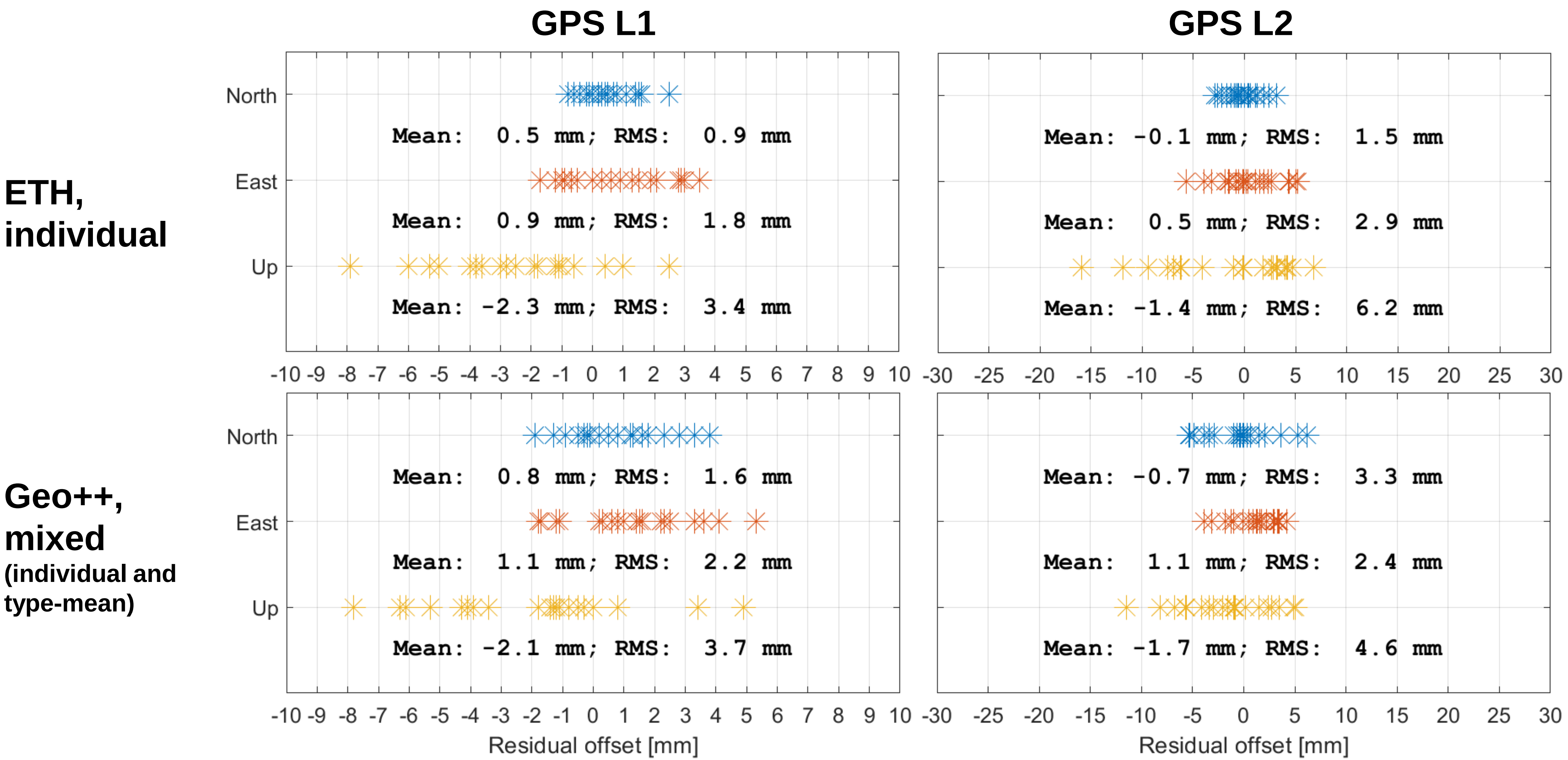


Campaign
- 4 GNSS session / 48 h each
- Permutation and rotations
- 4 stations, 5 m distance

Ground truth
- Optical triangulation
- 0.2 mm standard deviation of final coordinates

Processing
- Bernese GNSS Software V5.2
- Unity weighting
- 10 degree elevation cut-off

Single frequency residuals

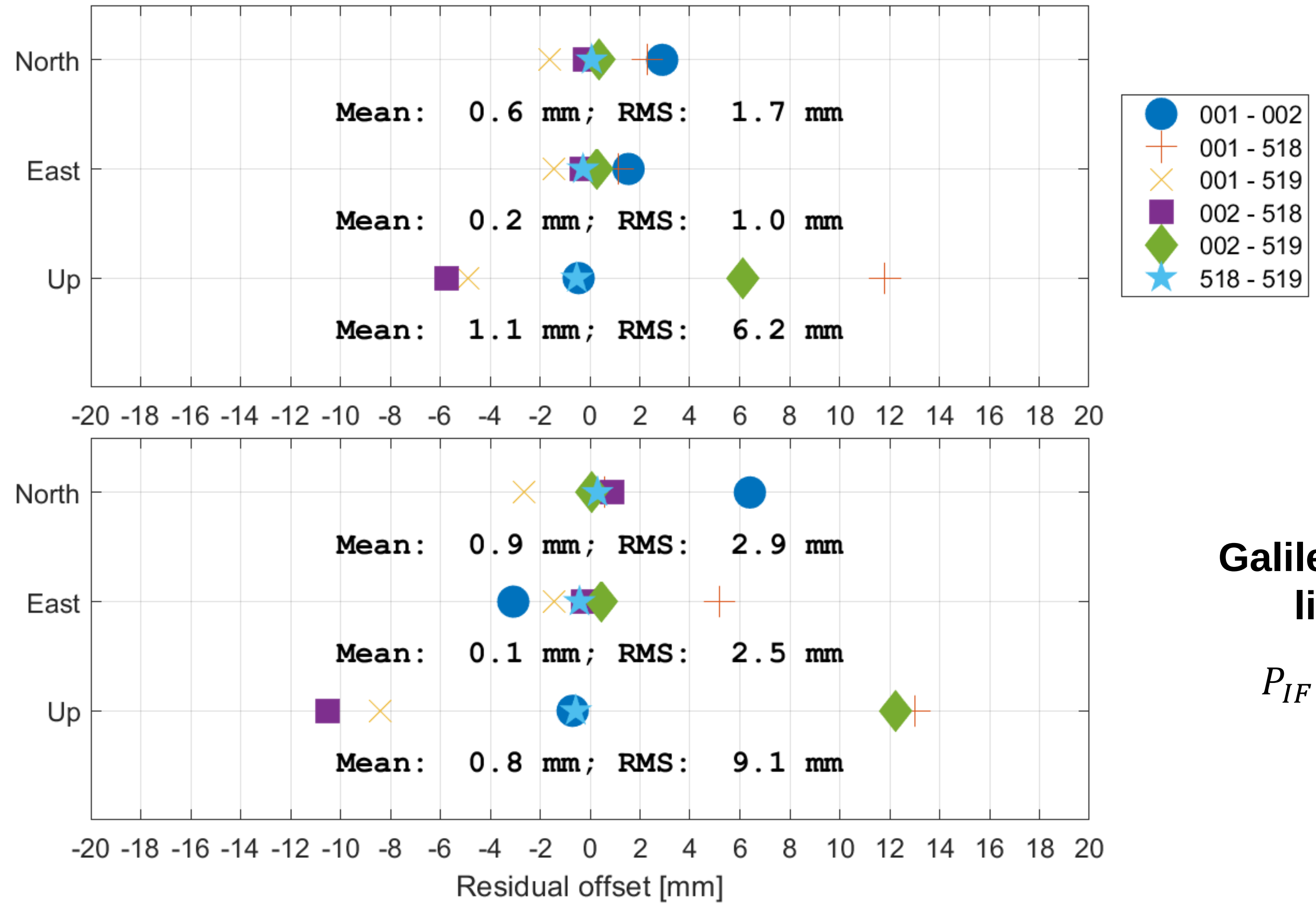


Ionosphere free residuals

Galileo IF + troposphere, E1 / E5a

ETH, individual

Geo++, mixed
(individual type-mean)



001 **002**

518 **519**

Galileo ionosphere-free (IF) linear combination:

$$P_{IF} = 2.26\, P_{E1} + 1.26\, P_{E5}$$

Conclusions

- Prototype operational
  - Interface (receiver, robot steering)
  - Triple-difference PCC estimation
  - Potentially all CDMA-signals (tested for GPS and Galileo)
- Repeatability below millimetre level
  - Very good for all elevations > 10 degree
- Plausibility proved by comparison with de facto standard (Geo++)
- Accuracy in the coordinate domain significantly improved with respect to type-mean calibrations
- Outlook: extended calibration campaign

Acknowledgement

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- Deutsches GeoForschungsZentrum GFZ
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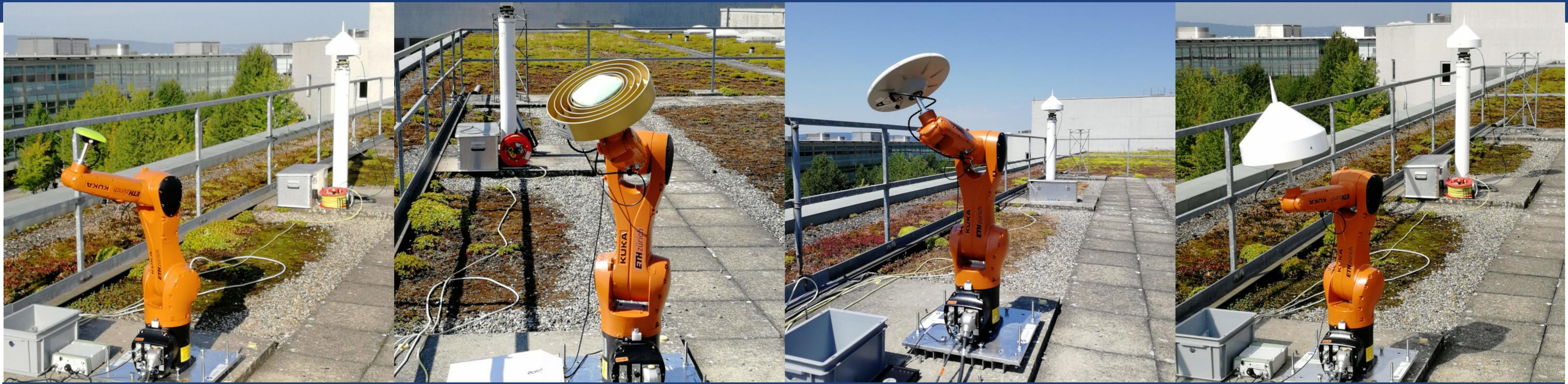

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