



Multi-facility GNSS antenna calibration

Final results of the IGS antenna ring campaign 2022–2025

Tobias Kersten^{1,2} · Johannes Kröger¹ · Steffen Schön^{1,3} · Andria Bilich⁴ · Igor Sutyagin⁵ · Martin Schmitz⁶ · Ansgar Dreier^{7,8} · Heiner Kuhlmann⁷ · Stefano Caizzone⁹ · Benedikt Soja¹⁰ · Andreas Brown¹⁰ · Gregor Möller^{10,11} · Guorong Hu¹² · Zhigang Hu¹³ · Arturo Villiger¹⁴

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Abstract

Accurate antenna calibrations are a cornerstone of high-quality global navigation satellite systems (GNSS) positioning, time and frequency transfer, precise orbits, and troposphere estimates. The international GNSS service (IGS) antenna committee maintains antenna phase center corrections in the ANTEX file relying on five calibration facilities. Since new calibration facilities have been set up and user demands have grown along with hardware and software updates of GNSS, we organized an international inter-comparison across nine facilities, using both anechoic chambers and field robots. Six antennas with different designs were calibrated by each facility and compared with the Geo++ robot solution (GPP4), a proxy for the IGS ANTEX. Where available, we also considered the IGS type means. We examined differences between the antenna patterns and subsequent differences in station coordinates. To this end, we used a standardized forward simulation as well as multi-GNSS PPP solutions using the GNSS toolbox developed at Leibniz University Hannover, Institut für Erdmessung (IfE). Our study yields several important results. We found that multi-GNSS antenna calibrations exhibit frequency- and elevation-dependent variations, with deviations of up to 3 mm to 4 mm at low elevations. We show that organizations like Topcon (TPS), national geodetic survey (NGS), and Wuhan GNSS Research Center (WHU) yield calibration results that are in very good agreement with those of IGS accepted facilities such as GPP, IfE, and to some extent geoscience Australia (GA). These differences result in position deviations of a few millimeters, with the Up component being the dominant contributor.

Keywords IGS ANTEX · Antenna calibration · Carrier phase variations (PV) · Carrier phase center offsets (PCO) · GNSS · Precise point positioning (PPP) · Calibration campaign

✉ Tobias Kersten
tobias.kersten@hs-anhalt.de

- ¹ Institut für Erdmessung (IfE), Leibniz University Hannover, Hannover, Germany
- ² Anhalt University of Applied Science, Dessau-Roßlau, Germany
- ³ Federal Agency for Cartography and Geodesy, Frankfurt/Main, Germany
- ⁴ National Geodetic Survey, NOAA/NGS, Seattle, WA, USA
- ⁵ Topcon Positioning Services (TPS), Livermore, CA, USA
- ⁶ Geo++ GmbH, Garbsen, Germany
- ⁷ University of Bonn, Bonn, Germany
- ⁸ AVT Airborne Sensing GmbH, Greven, Germany

1 Introduction

Receiver antennas are the first element in the reception chain of signals from global navigation satellite systems (GNSS). Their electromagnetic response is direction-, frequency-, and signal dependent. If unmodeled, these effects map into ele-

- ⁹ DLR Oberpfaffenhofen, Wessling, Germany
- ¹⁰ ETH Zurich, Zurich, Switzerland
- ¹¹ TU Vienna, Vienna, Austria
- ¹² GeoScience Australia, Canberra, Australia
- ¹³ GNSS Research Center, Wuhan University, Wuhan, China
- ¹⁴ Swisstopo, Wabern, Switzerland

vation and azimuth-dependent errors in code and carrier phase observations and propagate to key geodetic products, including station coordinates, precise orbits and clocks, tropospheric parameters as well as to geodetic time and frequency transfer.

To mitigate these effects, the International GNSS Service (IGS) distributes absolute receiver antenna phase center offsets (PCO) and carrier phase variations (PV) in the current Antenna Exchange format (ANTEX) in version 1.4 (Rothacher and Schmid 2010) and 2.0 (Montenbruck and Steigenberger 2026). Here, *absolute* means that the calibrations are not referenced to a particular *reference antenna* (as in former relative models) but are tied with respect to its antenna reference point (ARP). While phase corrections are routinely applied in high-precision GNSS processing, corresponding corrections for the code phase variations (GDV, group delay resp.) are still under investigation as shown by comprehensive works of Wübbena et al. (2006b); Kersten (2014); Wanninger et al. (2017); Caizzone et al. (2019); Beer et al. (2021); Brevi (2025).

Two main calibration methods are used to determine absolute antenna corrections. In field (robot) calibrations, the antenna under test (AUT) is rotated and tilted to cover the full upper hemisphere while tracking real GNSS signals. A nearby reference station and antenna—often in a common clock setup—allows separating the AUT pattern from environmental effects. This approach was initially presented by Wübbena et al. (1997), with the first results provided by Menge et al. (1998). The concept was further proven by Böder et al. (2001); Seeber and Böder (2002). In anechoic chamber calibrations, unmodulated synthetic waves are radiated in a controlled, reflection-free environment, and the phase pattern is derived from vector network analyzer measurements. Initial activities in the geodetic community are summarized in Campbell and Görres (1999), with results for chamber calibrations presented by Schupler and Clark (2001); Görres et al. (2006). A dedicated anechoic chamber optimized for GPS/GNSS antennas became operational in 2009 (Zeimet and Kuhlmann 2008; Zeimet 2010).

Field methods use real GNSS signals and enable testing of complete installations (radomes, mounts, cables). Chamber methods offer environmental control and wide frequency coverage, including bands not yet operational or from regional systems not visible at a field site. The two approaches are complementary, and in practice, both provide calibration data to the IGS ANTEX. Typically, millimeter-level agreement for PCO and PV over mid to upper elevation ranges can be achieved. Larger discrepancies are to be expected at low elevations and for certain radome–antenna combinations. GDV generally show larger scatter and are less mature than carrier phase patterns nowadays.

Numerous comparison studies, historically focused on GPS and GLONASS, have assessed the consistency of

calibrations across methods, laboratories, and installations, either in the pattern domain (PV and PCO as a function of elevation and azimuth) or in the parameter domain (position estimates). Early robot-based work demonstrated systematic, elevation-dependent PV/PCO deviations due to radomes and quantified their impact on long baselines (Seeber and Böder 2002), supported by large-scale analyses of absolute robot calibrations that documented repeatability and azimuthal structures (Wübbena et al. 2000b). Environmental and near-field effects were shown to be a significant driver of pattern differences and positioning impacts of several millimeters under common conditions and up to one centimeter in adverse setups (Dillssner et al. 2008). A metrology-focused analysis quantified calibration error sources and argued for in situ phase center corrections to capture site-specific effects, indicating overall uncertainties at the few-millimeter level with potentially larger effects in critical environments (Bergstrand et al. 2020). Network-level studies confirmed that the choice of antenna calibration model propagates into station coordinates, most notably in the vertical component, with typical horizontal differences of 1 mm to 5 mm and vertical differences of 5 mm to 10 mm depending on antenna type and model source (Baire et al. 2013; Araszkiewicz and Völkse 2016). Inter-comparisons across laboratories and methods generally indicate overall consistency, while revealing method-specific discrepancies of about 2 mm to 4 mm root-mean-square (RMS) at mid to high elevations and 5 mm to 10 mm at low elevations, and highlighting radome–antenna combinations that induce systematic offset in the Up component on the order of 5 mm to 12 mm and enhanced azimuthal terms (Kallio et al. 2018). Case studies also highlight measurable robot–chamber differences for specific antenna types and the implications for type means handling and uncertainty specification (Krzan et al. 2020). Various contributions by Geo++ from 2006 to 2010 further compared geodetic antennas with and without radomes and under different environmental conditions, and formulated recommendations for detailed ANTEX metadata and the use of uncertainty entries, as reported, e.g., by Wübbena et al. (2006a). Ring tests within the European Permanent Network (EPN) and IGS inter-laboratory studies confirm the overall consistency of absolute receiver antenna calibrations, while highlighting azimuthal pattern differences and radome-dependent offsets that require separate type-specific handling (Aerts et al. 2010, 2011; Moore et al. 2012; Schmid et al. 2005, 2007). However, during the first IGS ring calibration analysis at NGS in 2012 (Bilich et al. 2012), a different robot system was used than is employed today.

With the advent of multi-GNSS and new signals such as GPS L5, Galileo E1/E5/E6, and BeiDou, with the transition of the IGS ANTEX to multi-GNSS IGS20 (Wübbena et al. 2019) and with new calibration facilities becoming available that complement the established ones (Geo++, IfE,

Table 1 Calibration facilities participating in this campaign.

Study Abbreviation	IGS ANTEX Abbreviation	Institution	Calibration	References
IGS		<i>published IGS type mean</i>	mixed	IGS (2023a, b)
DLR		German Aerospace center	CHAMBER	
ETH		Inst. of Communications and Navigation		Caizzzone et al. (2019)
GPP4		ETH Zurich	ROBOT	Willi (2019); Willi and Guillaume (2019)
GPP8		Geo++ GmbH	ROBOT	Wübbena et al. (2000a)
GA		Geoscience Australia		
IFE		Leibniz University Hannover	ROBOT	Riddell et al. (2015)
		Inst. für Erdmessung (IfE)	ROBOT	Menge et al. (1998)
IGG		University of Bonn	CHAMBER	Seeber and Böder (2002)
		Inst. of Geodesy and Geoinformation		Zeimetz (2010)
NGS		National Geodetic Survey/NOAA		
	NGS		ROBOT	Bilich and Mader (2010)
TPS		TOPCON Agriculture S.R.L.		
WHU		GNSS Research Center of Wuhan University	ROBOT	Bilich et al. (2018)
			ROBOT	Sutyagin and Tatarnikov (2020)
				Zhou et al. (2022, 2023)

The column labeled *Study Abbreviations* is used throughout this paper to identify each participant. The *IGS ANTEX Abbreviations* column is reserved for facilities that contributed to IGS ANTEX prior to this study

University of Bonn, GeoScience Australia), the IGS Antenna Committee initiated an inter-laboratory antenna calibration campaign from 2022 to 2025 to strengthen the foundation of multi-frequency, multi-GNSS antenna models. The campaign, coordinated by IFE, involved nine laboratories employing field robot and anechoic chamber methods: German Aerospace Center–Institute of Communication and Navigation (DLR), ETH Zürich (ETH), Geo++ GmbH (GPP), Geoscience Australia (GA), Leibniz University Hannover (IFE), University of Bonn (IGG), National Geodetic Survey (NGS), Topcon Positioning Systems (TPS), and Wuhan GNSS Research Centre (WHU). For Geo++, two calibration sets are considered: one derived from manipulator 4 (MP4, commonly referred to as *GPP4*), which represents a large fraction of the IGS ANTEX type means. The abbreviation MP4 is the internal designation of the fourth robot arm (manipulator) in the Geo++ calibration facility. The second robot arm at Geo++ is called manipulator 8 (MP8) which is commonly referred in this article as *GPP8*.

Six GNSS receiver antennas of designs commonly used at reference stations were circulated as test samples: two 3D choke ring antennas (Harxon 601 A, and Leica AR25 rev. 3), two 2D choke ring antennas (Javad RingAnt with Dorne–Margolin element, Topcon CR-G5C), and two compact designs with integrated ground plane (Topcon G5_A1, Trimble Zephyr Geodetic II) to cover multiple constellations and frequencies. By collecting multiple independent individual calibrations per antenna, the campaign enables a direct assessment of inter-laboratory consistency, installation effects, and laboratory-specific solution comparisons. In addition, we evaluate the impact of the obtained patterns relative to the current IGS type means, which historically relied to a large extent on Geo++ calibrations.

The remainder of the paper is organized as follows. Section 2 summarizes the campaign design, participating facilities, antenna samples, and metadata standards. Section 3 describes the modeling, comparison metrics, and uncertainty estimation, and outlines the PPP experiment design. Section 4 presents inter-laboratory consistency, installation effects, and solution impacts. Section 5 discusses geodetic relevance, likely causes, and implications for IGS antenna models. Section 6 concludes and outlines future work.

2 Calibration facilities, infrastructure, and procedures

2.1 Calibration facilities

The participating facilities are listed alphabetically in Table 1 and photographs of the infrastructure are shown in Fig. 1. Seven facilities operate field robot systems in outdoor envi-

ronments, while two facilities use anechoic chambers (cf. Fig. 1).

Robot-based facilities share core concepts (rotation/tilt coverage of the upper hemisphere, often in a common clock setup, nearby reference antenna) but differ in the aforementioned implementation details (cf. Table 2).

The two chamber facilities differ in chamber dimensions, quiet zone characteristics, and vector network analyzer settings. While IGG operates a far-field anechoic chamber, DLR uses a MVG StarLab multi-probe spherical near-field system (Caizzzone et al. 2019). Where degrees of freedom (DOF) are reported, we distinguish between actuated scan DOF and mounting/alignment DOF: StarLab measurements employ one actuated scan axis (rotation) for directional sampling, while the fixture typically provides three to five alignment DOF for centering and bore sight.

Facility-related parameters are documented where available and are considered in the harmonization and uncertainty assessment (cf. Sect. 3 and 4). It is noteworthy that GPP, GA, and IFE utilize the same type of Schunk robots, and in this campaign the calibration software provided by Geo++. These three facilities are permitted to provide calibrations to the IGS routinely due to the standardized equipment. However, differences among these facilities exist, including variations in the analysis software (as seen with IFE), the GNSS receivers used, and the respective field environments.

2.2 Facility-related parameters

For robot calibrations, parameters influencing the resulting patterns include: receiver brand/firmware type, bandwidth and tracking loop settings, masking angles, sampling and dwell times per pose, rotation/tilt step size and sequence, reference antenna model and common clock realization, local multi-path environment, and applied smoothing and/or regularization. For chamber calibrations, key parameters include: chamber size and absorber layout, quiet zone extent and field uniformity, far-field distance, turntable angular resolution, transmit antenna and polarization purity, feed network linearity, and network vector analyzer (NVA) settings (IF bandwidth, averaging, power levels). Notably, the synchronization methodology varies among facilities, with some using a common clock with external oscillator, a common clock based on a single receiver, while others employ individual internal receiver oscillators or network vector analyzers (cf. Table 2 for a detailed overview of the synchronization methods used by each facility). A concise per-facility overview is provided in Table 2, and a methodological handling in the comparison is outlined in Sect. 3.

Table 2 System configuration of participating calibration facilities

Method	Institution	NA/NVA or GNSS receiver	Bandwidth PLL	C/A L1 [MHz] CLL/DLL	MP	System	DOF	Synchronization
Chamber	DLR	MVG StarLab multi-probe spherical near-field	n/a	n/a	n/a	Near-field chamber	1, 3–5	NVA
Chamber	IGG	NVA Agilent ENA E5062A	n/a	n/a	n/a	Far-field chamber	2	NVA
Robot	ETH	LEICA GR10	n/a	n/a	off	KUKA Agilus KR6	6	TD
Robot	GA	JAVAD TRE_3 DELTA	n/a	n/a	off	SCHUNK	5	IO
Robot	GPP	JAVAD TRE_3 DELTA	n/a	n/a	off	SCHUNK	5	IO
Robot	IFE	JAVAD TRE_3S DELTA	25	3.00	off	SCHUNK	5	CC
Robot	NGS	SEPT POLARX5	15	0.25	on	KUKA KR60 HA	6	CC
Robot	TPS	TPS NET-G5	25	0.80	n/a	Stäubli TX90	6	RO
Robot	WHU	NET10 PLUS GNSS	n/a	n/a	n/a	Fanuc	6	CC

NVA: Network vector analyzer; IF BW: intermediate-frequency bandwidth; PLL: phase-locked loop; DLL: delay-locked loop; CLL: code-locked loop; MP: multi-path reduction. DOF: degree of freedom; IO: internal oscillators; RO: reference oscillator (common clock setup based on the reference receiver); TD: triple differences; CC: common clock (external oscillator); please note that the abbreviations DLL is a synonym for CLL (Javad 2025)



Fig. 1 Robot systems and site photos for each campaign participant, see Table 1

2.3 Antenna samples

Six antenna samples were analyzed (cf. Table 3 and Fig. 2). The selection represents models commonly installed in the IGS network and EPN and spans different designs and manufacturers to reflect the current network infrastructure (as of GPS week 2378). Choke ring antennas dominate, accounting for 84 % of IGS and 82 % of EPN stations. Within this class, 3D choke ring antennas represent 64 % of IGS and 37 % of EPN, while 2D choke ring antennas account for 20 % and 45 %, respectively. Antennas with integrated ground plane make up the remaining 16 % of IGS and 18 % of EPN.

In order to simplify logistics and remove a potential source of inconsistency, all antennas in this campaign were calibrated without radomes, even if a radome variant is widely deployed in the IGS network. All facilities that provided antenna test samples agreed to store the antennas and retain them for future use.

2.4 Calibration data and file format

Each facility performed individual calibrations using its own equipment and software. The resulting multi-GNSS phase calibrations are stored and exchanged in IGS ANTEX 1.4 format (Rothacher and Schmid 2010) as well as related metadata (antenna model/serial number, method, laboratory identifier, calibration period, frequency tags, and uncertainty entries where available).

2.5 Signal and frequency handling

Differences in receiver equipment and estimation concepts leads to the situation that not all nominal signals (cf. Fig. 3) listed in RINEX convention are uniformly used or delivered by all facilities. Practically, three variants occur (cf. Fig. 4):

1. Per-signal calibrations (e.g., distinct values for GPS L1 vs. Galileo E1);
2. Per-band calibrations (common values for all signals within a nominal band, e.g., L1=E1=B1); and
3. Copied values for unmeasured signals within the same band (assumed identity).

It should be noted that frequency-specific entries in Fig. 4 are not duplicates of a single frequency but combined PCC estimates from all GNSS signals operating in the same frequency band. All tracked constellations contribute to the PCC estimate for that band.

For cross-laboratory comparison and application experiments, we adopt the following rules:

- Group by nominal frequency bands as depicted in Fig. 3 (L1/E1/B1, E5b/B2b, E5a+b/B2a+b, L5/E5a/B2a), unless a per-signal analysis is explicitly required.
- Prefer per-signal patterns where available; otherwise, use the delivered per-band pattern; if only copied entries exist, retain them but flag as “copied” in the metadata.

Table 3 Details of the antennas used in the campaign and validation PPP data windows and corresponding IGS ANTEX type means for receiver antennas (IGS 2023a, b)

IGS antenna/radome name	Serial number	Provider	PPP Processing			IGS type mean	
			YEAR	DOY	# of days	GPS week	
HGCCGX601A NONE	C2203001817	GNSS Research Center of Wuhan University	2023	357–361	5	–	
LEIAR25.R3 NONE	08360013	Leibniz University Hannover, IfE	2025	232–237	5	2290	
JAVRINGANT_DM NONE	2099	Geoscience Australia	2024	005–008	4	2290	
TPSCR.G5C NONE	1364-10003	TOPCON Agriculture S.R.L	2022	242–244	3	2233	
TPSG5_A1 NONE	1327-10001	TOPCON Agriculture S.R.L	2022	239–240	2	2290	
TRM57971.00 NONE	144111204	Geoscience Australia	2023	363–365	3	2290	
			2024	001–003	3		



Fig. 2 GNSS antenna designs used in the campaign, such as 3D choke ring design (a–b), 2D choke ring (c–d), and integrated ground plane (e and f)

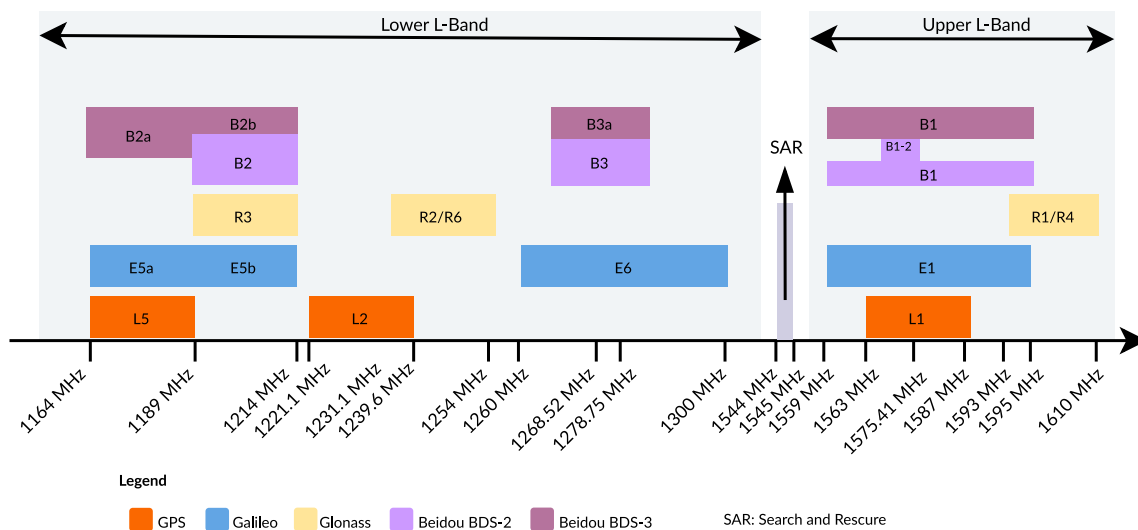


Fig. 3 Overview of frequency bands for major GNSS constellations

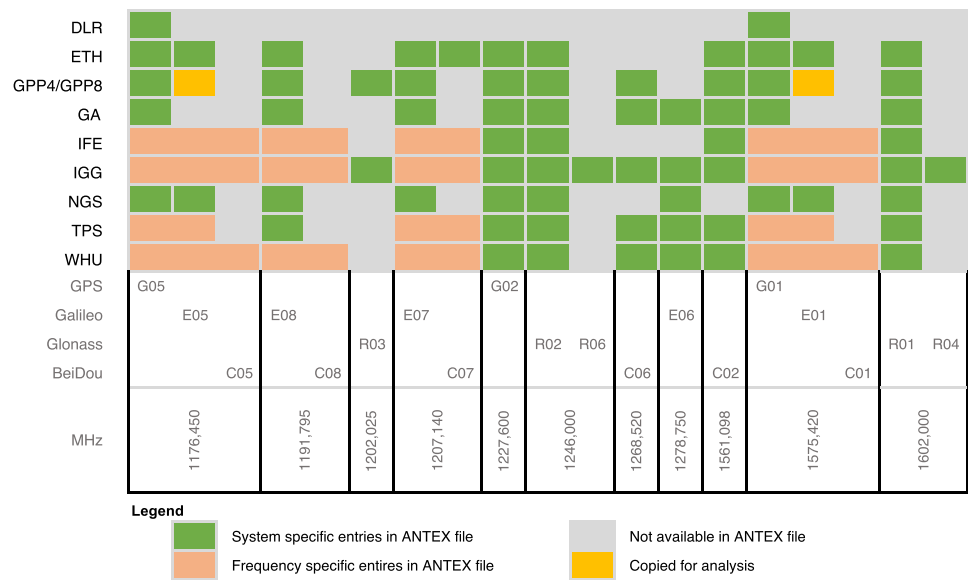
2.6 Observation data for PPP analysis of PCC impact on positioning

For a PPP-based assessment of the impact of different PCC sets on positioning, each AUT was installed on a pillar at IfE with well-known coordinates for multiple days (cf. Table 3). The receivers used in the validation are identical to those used in the calibration at IfE. The dataset is published in Kersten (2025). The campaign report (Kersten et al. n.d.) summa-

rizes processing variants and analysis specifics applied to the datasets. For further details on the analysis and processing of the datasets, please refer to Sect. 3.5.

Compared with a CORS network solution, PPP evaluates the effect at a single site and does not capture inter-station correlations. In network adjustments, correlations among stations and, in particular, among antenna types can amplify differences when antenna correction models from different calibration procedures are mixed (Kersten et al. 2022). Con-

Fig. 4 Comparison of calibration results for AUTs from contributing facilities across GNSS frequency bands, identified by ANTEX frequency identifiers



sequently, discrepancies in a CORS network may be larger than those suggested by single-station PPP tests.

3 Data and analysis concept

3.1 Modeling convention

We analyze the consistency of absolute receiver antenna calibrations in two domains: (i) in the pattern domain by direct comparison of ANTEX entries and (ii) in the parameter/position domain by ionosphere-free combinations and PPP experiments. For each antenna, we compare all submitted calibrations against GPP4, which represents a large fraction of the IGS ANTEX type means. If available, the current IGS type mean for the respective antenna model is also considered in this comparison, abbreviated as *IGS*. The ANTEX files used in this study are archived (Kersten et al. 2025).

3.2 Definitions, conventions, and standards

We adopt an antenna reference frame (ARF, cf. Fig. 5) and decompose the phase-center correction (PCC) into offsets and variations (e.g., Schmid et al., 2007; Kersten et al., 2022; Kröger, 2025). We use a local, right-handed ENU frame with x = East (E), y = North (N), and z = Up (U), where the y -axis aligned with the antenna North marker (a dedicated structural element at the antenna). The phase-center offsets are denoted $\text{PCO} = (E, N, U)$ relative to the ARP. The phase variations are $\text{PV}(\alpha, e)$, where azimuth α is measured clockwise from North (0° at the North marker), and elevation e is measured from the local horizon to zenith (0° to 90°). For clarity, we do not adopt the Up–East–North (UEN) axis

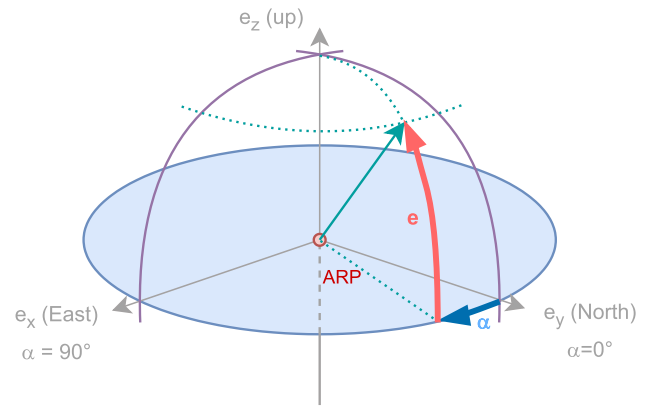


Fig. 5 Definition of the body-fixed antenna reference frame (ARF)

ordering used in some ANTEX 1.x contexts for static reference sites; instead, all quantities are defined in the antenna body-fixed ARF and are therefore independent of the mounting orientation and any antenna motion during testing. This definition is consistent with Montenbruck and Steigenberger (2026). We describe the line-of-sight unit vector (LOS) as

$$\vec{s}(\alpha, e) = (\sin \alpha \cos e, \cos \alpha \cos e, \sin e) \quad (1)$$

Theoretically, the phase center corrections can be represented as:

$$\text{PCC}(\alpha, e) = -\tilde{\text{PCO}} \cdot \vec{s}(\alpha, e) + \tilde{\text{PV}}(\alpha, e) + r. \quad (2)$$

Rothacher et al. (1995) showed that a direction-independent phase offset r is not estimable, so that only the relative form of the correction is obtained. In terms of spherical harmonics, this corresponds to the term of degree and order zero. This ambiguity arises as neither the anechoic

chamber method nor the field robot method provide absolute distance measures, but only relative phase patterns (Kersten et al. 2022). Consequently, the IGS conventions (cf. Fig. 6) state the following representation:

$$PCC(\alpha, e) = -PCO \cdot \vec{s}(\alpha, e) + PV(\alpha, e). \quad (3)$$

We use calibrations *as delivered*, which means that no re-centering the PVs in zenith to zero is applied. For diagnostics of differences of PCC patterns, we follow the methodology described by Kersten et al. (2022).

3.3 Pattern differences and azimuth-averaged representation

Given two calibrations for the same antenna, we define

$$\Delta PCO = PCO_B - PCO_A \quad \text{and} \quad (4)$$

$$\Delta PV(\alpha, e) = PV_B(\alpha, e) - PV_A(\alpha, e) \quad (5)$$

representing the full pattern difference as

$$\begin{aligned} \Delta PCC(\alpha, e) &= PCC_B - PCC_A \\ &= -\Delta PCO \cdot \vec{s}(\alpha, e) + \Delta PV(\alpha, e). \end{aligned} \quad (6)$$

For the pure elevation-dependent, i.e., azimuth-averaged plots (cf. Figs. 7 and 8), we use mean values $\overline{\Delta PCC}(e)$ per elevation bins of the differential pattern in the standard sampling of IGS ANTEX files, i.e., 5° . We show for the azimuth-averaged plots:

1. The mean values $\overline{\Delta PCC}(e)$,
2. The minimum and maximum values of ΔPCC over the azimuth α per elevation bin, and
3. The minimum constraint solution with a shift c so, that deviations are minimized over an elevation range of 15° to 90° resulting to an individual PCO correction.

For orientation, azimuth-averaged plots of original frequencies contain additionally a dashed horizontal line indicating the ± 1 mm level. Important remarks here are that (i) results are presented without centering the ANTEX values at zenith to zero, and (ii) no further centering was applied after converting the PCCs to a common PCO per frequency. A transformation to a common offset per frequency is conducted to analyze offset differences.

Comparisons are provided per nominal frequency band (cf. Fig. 3) using per-signal patterns where available.

We compute and report ΔPCC here with respect to solutions of GPP4

$$\Delta(\cdot) = (\cdot)_{\text{facility}} - (\cdot)_{\text{GPP4}}. \quad (7)$$

All values are reported in millimeters. We use a consistent color scheme per facility in all the plots.

3.4 Ionosphere-free (IF) combination of patterns

Typical GNSS positioning uses dual-frequency data combinations to mitigate ionospheric effects. Accordingly, we analyze PCC differences with dual-frequency combinations. For the dual-frequency ionosphere-free (IF) linear combination, we define

$$\alpha = \frac{f_1^2}{f_1^2 - f_2^2}, \quad \text{and} \quad \beta = \frac{-f_2^2}{f_1^2 - f_2^2}$$

with the effective linear correction in the frequency bands

$$PCC_{IF}(\alpha, e) = \alpha \cdot PCC_1(\alpha, e) + \beta \cdot PCC_2(\alpha, e). \quad (8)$$

Correspondingly, we derive the differences

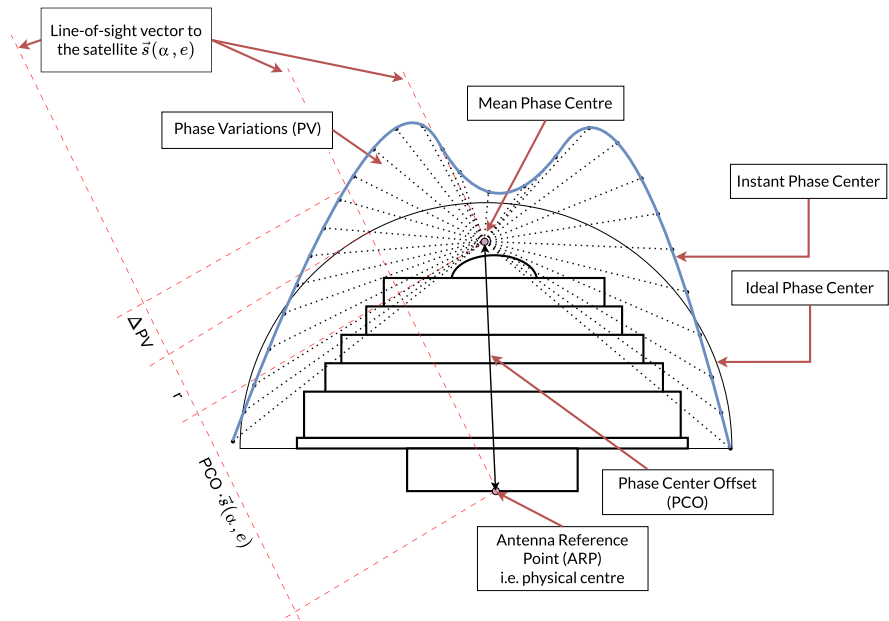
$$\Delta PCC_{IF} = \alpha \cdot \Delta PCC_1 + \beta \cdot \Delta PCC_2. \quad (9)$$

3.5 Position domain—PPP experiment design

Real GNSS observations per each AUT were collected on the GNSS laboratory roof of IfE, Leibniz University Hannover, when installed on a standard geodetic monument with precisely known coordinates (cf. Table 3). We processed the validation data sets using the precise point positioning approach (PPP, (Zumberge et al. 1997)) with identical model settings and vary only the antenna calibration sets. PPP processing was performed with the IfE GNSS Toolbox v6.1, which is validated against the Bernese GNSS Software Version 5.4. Our PPP module uses a sequential Kalman filter with elevation-dependent weighting. Observations were processed in daily batches at a 30 s sampling interval. Consistent products and models were used: precise multi-GNSS orbits and clocks from the Center for Orbit Determination in Europe (CODE; (Dach et al. 2024)), the IGS20 realization of the International Terrestrial Reference Frame (ITRF2020), and the corresponding igs20.atx satellite antenna model file. For periods before 2022-11-27 (reference frame switch), we used the IGS14 / ITRF2014 frame together with the igs14.atx antenna file. The troposphere was modeled by estimating the zenith total delay (ZTD) as a stochastic parameter and applying VMF3 mapping functions; ocean tide loading and solid Earth tides followed the IERS Conventions. Processing settings included an elevation cutoff of 10° , the ionosphere-free (IF) dual-frequency combination, and a PPP float solution. We applied the following IF combinations and ANTEX observation identifiers (in brackets):

- GPS: L1 and L2 (G01, G02),

Fig. 6 Definition and conventions of GNSS receiver antenna patterns



- GLONASS: GLO L1 and GLO L2 (R01 and R02),
- Galileo: E1 and E5a (E01 and E05), and
- BeiDou B1-2 and B3 (C02 and C06)

The DLR calibration values could not be used for PPP processing due to the limited availability of frequencies, hence we show no results for this facility.

The metrics we analyze are daily topocentric coordinate differences (North, East, Up) between calibration sets, and the effects on the daily differential receiver clock estimates and ZTD differences. We relate these effects to the pattern-domain metrics from Sects. 3.3 and 3.4.

4 Results

4.1 Pattern-domain analysis

Figure 7 shows the azimuth-averaged results for four AUTs (rows; selected to represent the principal antenna designs) and three frequencies (columns) for the facilities and, where available, the corresponding IGS ANTEX type means (with GPS week identifier; cf. Table 3). All panels share identical axes and consistent color scheme for each facility. Analyses for DLR were performed but are currently available for internal use only, which does not affect the comparative conclusions for the remaining data sets. Dash-dotted lines indicate the maximum value over azimuths, dashed lines the minimum for each frequency.

The notable differences between ETH and the calibrations of GPP/IFE can be explained by signal tracking issues at the ETH facility. During the campaign, we identified the irre-

versible issue on the provided data for some antennas which does appear just on the frequency GPS L2. However, we used the data as provided for this campaign. The causes of the deviations at GA for antennas TRM57971 and TPSG5.A1 (see Figs. 7 and 8) are not yet known and are subject to ongoing analysis of the team at the facility.

Overall, the azimuth-averaged ΔPCC relative to GPP4 depends on both frequency band and antenna type. Details for all analyzed AUT and all frequencies are available in the comprehensive report by Kersten et al. (n.d.).

All individual calibrations show a good comparability with respect to GPP4. As depicted in Fig. 7 (and Fig. 12), the mean azimuth-averaged curves agree well for the frequency 1575.41 MHz (L1, E1, B1), 1227.6 MHz (L2, R2) and 1176.45 MHz (L5/E5a/B2a). For most of the facilities, the mean azimuth-averaged ($\overline{\Delta PCC}(e)$) coincides for the frequency band 1555 MHz to 1610 MHz (L1, E1, R1/R4, B1) within ± 1 mm over elevation ranges 20° to 90° .

For frequency band 1221 MHz to 1254 MHz (L2, R2), agreement remains better than 1 mm above roughly 30° elevation, while systematic divergences appear below 30° with mean azimuth-averaged values of ± 3 mm to 4 mm. Azimuthal deviations are present and show values of ± 2.5 mm (cf. Fig. 7h) although the mean azimuth-averaged values are still below a 1 mm threshold. The GA calibrations exhibit an apparent offset of approximately 5 mm.

For the frequency band 1164 MHz to 1214 MHz (L5, E5a, B2a, B2, R3) we observe a similar pattern; an overall agreement within ± 1 mm with small azimuthal variations below 1 mm.

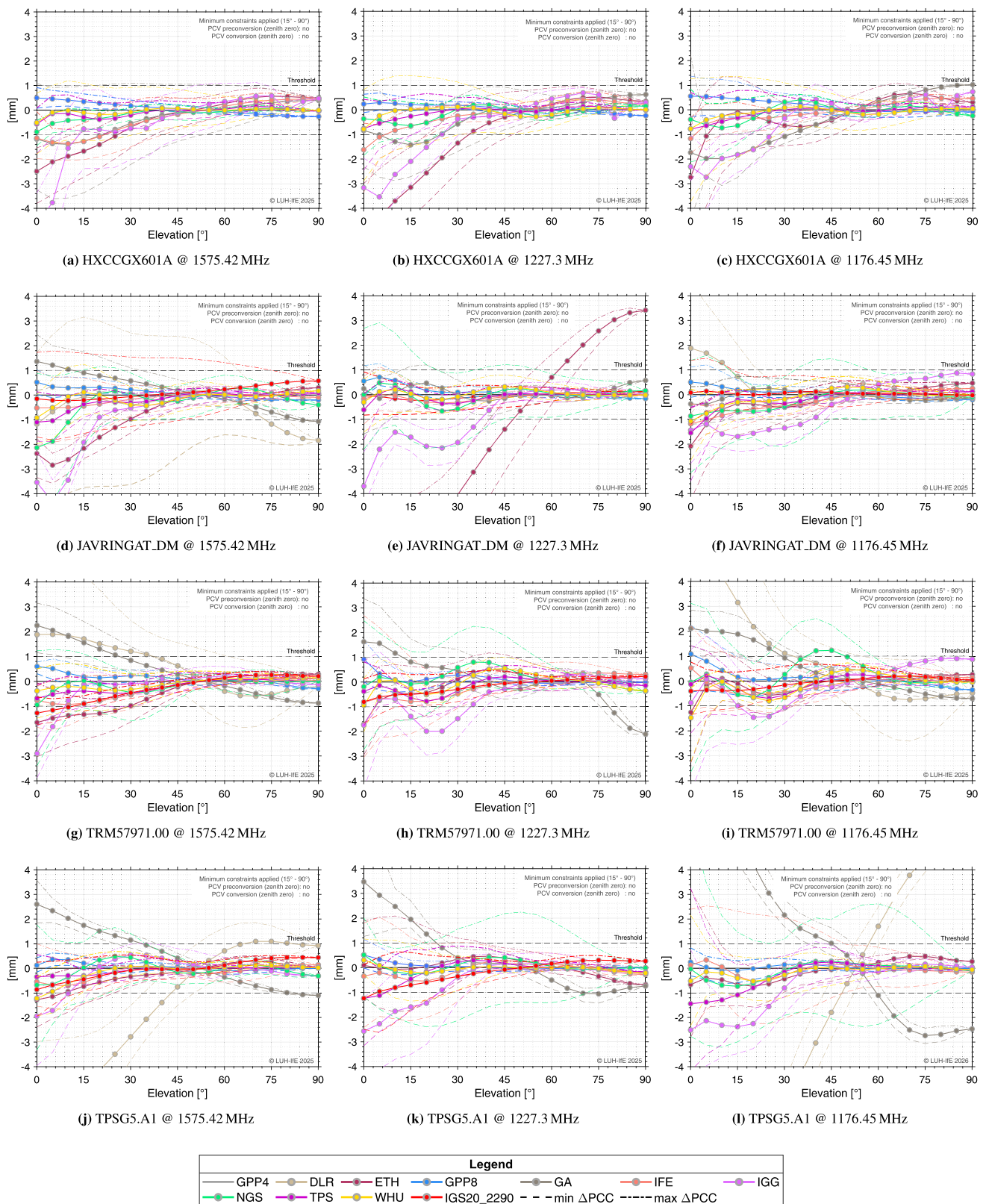


Fig. 7 Class-specific results of PCC differences w.r.t. GPP4 for various frequency bands, i.e., 1555 MHz to 1610 MHz (L1, E1, B1, GLO L1), 1221 MHz to 1254 MHz (L2, GLO L2), and 1164 MHz to 1214 MHz (L5/E5a/B2a, E5a+b/B2a+b, GLO L3, E5b/B2b)

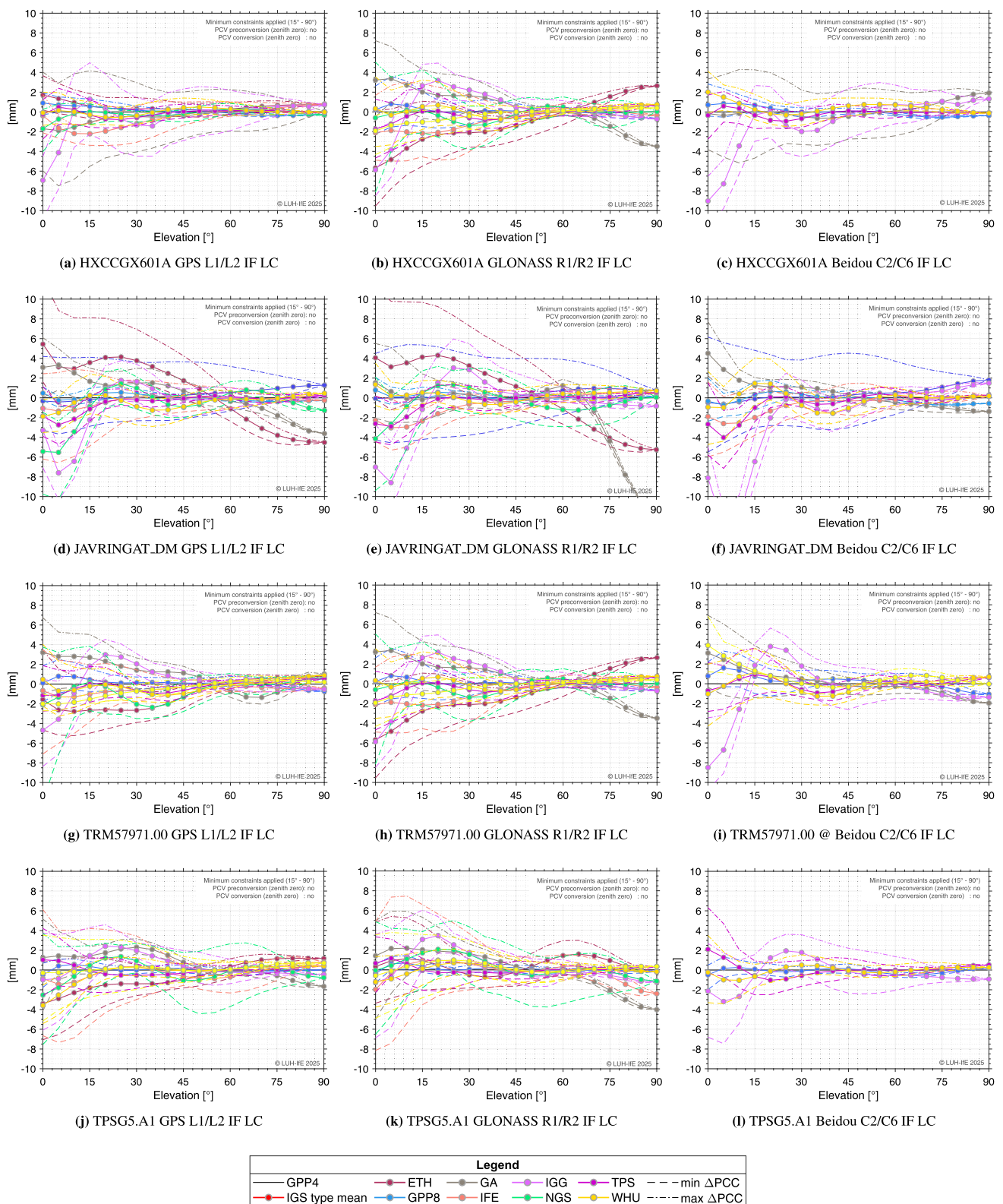


Fig. 8 Class-specific results of Δ PCC ionosphere-free linear combination (IF-LC) relative to GPP4

A PCO height offset is detectable for the IGG and GA calibrations, which is visible by the $\sin(e)$ -dependent azimuth-averaged contribution.

For the Topcon G5_A1 antenna (integrated ground plane), the pattern comparability degrades and azimuthal deviations

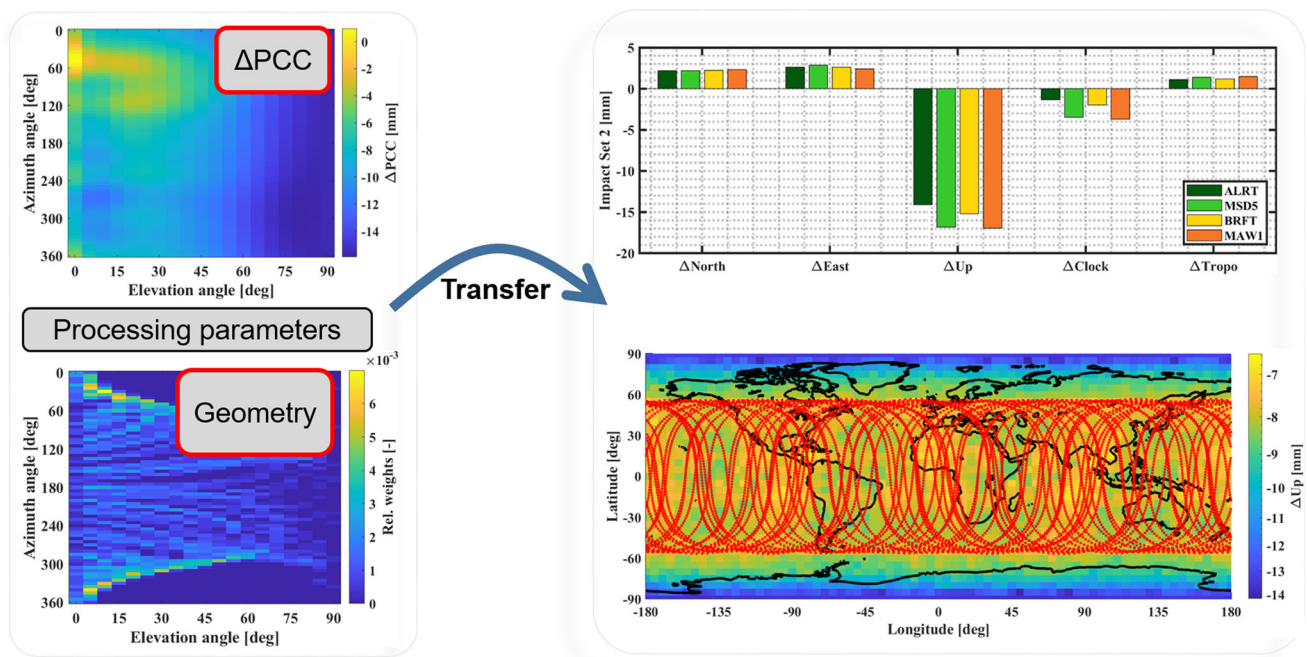


Fig. 9 Conceptional setting of the simulation environment used to assess the impact of PCC differences in the position domain (Kröger et al. 2025)

are larger with pronounced height offsets for GA and exhibit azimuthal deviations for NGS exceeding 2 mm (cf. Fig. 7i).

Modest systematic differences between robot- and chamber-based calibrations are apparent at elevation angles below 20°.

In addition to the individual results, the campaign enables an assessment of the reproducibility of repeated calibrations of the same AUT on the same facility at different epochs. We found that for all AUTs the results between GPP4 and GPP8 are closely comparable, with differences of 0.4 mm for most of the elevation range, and only marginal azimuthal divergences at lower elevations specifically below 10°. However, it is worth noting that no historical data on antenna calibrations of the same antenna at the same facility are available, and therefore, the campaign cannot provide insights into potential long-term changes or drifts in the antenna's calibration.

Figure 13 summarizes the root-mean-square errors (RMSE) of ΔPCC relative to GPP4 for the AUTs, subdivided by facility and frequency. The full azimuthal pattern is considered. In most cases, the RMSE over the full grid remains below 1.8 mm with few exceptions. For the majority of facilities, the RMSE is below 1 mm. The best agreement is consistently obtained on the L1/E1/B1 band at 1575.42 MHz. Larger deviations are observed on L2 signals (e.g., GPS L2 at 1227.6 MHz), reflecting known challenges in signal tracking and calibration on this frequency. By contrast, the L5/E5a/B2a band at 1176.45 MHz shows small differences, typically below 1 mm.

We conclude that the deviations are frequency- and elevation-dependent. They generally remain below 1 mm

above an elevation of 20° but increase to 3 mm to 4 mm below 20°. The observed differences can be attributed to various factors, including the use of different algorithms, synchronization approaches (cf. Table 2), receiver types, and software products. Additionally, the structural characteristics of the underlying base, such as the adaptation of robots and institutional variations, may contribute to the deviations at low elevations. The type of robot used also plays a role. However, in general, the robots show a good agreement, with only few frequency-specific individual deviations. These findings highlight the importance of considering the specific characteristics of each facility and robot when interpreting the results.

One would expect the type mean and individual calibrations of GPP4 and GPP8 to align, as the type mean is derived from a weighted average by calibration facilities and/or manufacturers. However, our analysis reveals discrepancies between the type mean and individual calibrations of GPP4 and GPP8, which, although not significant in magnitude, indicate a need for greater transparency in how changes to individual antennas are incorporated into the type mean to ensure traceability.

4.2 Position-domain analysis with simulated data

To quantify the impact of different PCC sets (ΔPCC) in the parameter domain, we apply a standardized forward simulation developed at IfE (Kröger et al. 2022, ?; Kröger 2025; Kröger et al. 2026). The approach evaluates the propagation of ΔPCC on topocentric coordinate differences (ΔEast ,

ΔNorth , and ΔUp), differential receiver clock error (Δt_{rx}), and tropospheric parameters (ΔZTD). The simulated PPP results are fully consistent with the real-data PPP results, using the same processing standards (e.g., elevation mask, weighting, etc.) and covering the identical time span to account for the varying orientation of GNSS orbital planes and the associated visibility geometry.

A conceptional overview is summarized in Fig. 9, while details are provided in Kröger (2025); Kröger et al. (2026). A set of PCC differences serves as input and is weighted by the actual satellite visibility for a specified geographic location and time span. The weighting is carried out on the azimuth elevation grid used in ANTEX format to store PCCs. We perform an element-wise multiplication of the gridded ΔPCC with weights derived from the number of available satellite observations in 5° elevation and azimuth bins. Component-wise design matrices are set up in a local ENU frame, and the resulting normal equation matrices are accumulated over the time interval of interest (24 h). The elevation cutoff angle, observation weighting scheme, tropospheric model, and the sampling rate are user-defined. The simulation supports multi-GNSS, multi-frequency PCC sets. The impact can be assessed for specific geographic locations or globally on a regular grid (Kröger et al. 2026).

In this analysis, we use the settings and observation periods as in Sect. 3.5 to ensure a fair comparison. For each AUT, differences with respect to Geo++ individual calibration GPP4 are formed, and the impact is evaluated for the dates listed in Table 3.

Figure 10 illustrates results for two representative antennas, calculated at the same latitude as the IfE data analyzed in the next section. Note that results for DLR are not included, as they are currently available for internal use only. Bars show mean daily 3D topocentric position offsets (magnitude) over all processed days and the black whiskers indicate the corresponding day-to-day standard deviations.

Overall, most 3D offsets lie between 2 mm to 5 mm, with larger values observed for ETH and IGG. Day-to-day standard deviations over the daily means are small, typically below 1 mm, primarily because 24 h solutions average out azimuthal and geometry-driven effects. As shown by Kröger et al. (2025, 2026), shorter solution intervals (e.g., 3 h) exhibit more pronounced variability of the ΔPCC impact due to stronger sensitivity to time-varying satellite geometry and azimuthal sampling.

The simulation approach enables global, design stage assessment of the impact of various ΔPCC sets on geodetic parameters without conducting or having access to real measurements. Comparisons with analyses based on real data show good overall agreement between the two approaches (Kröger 2025; Kersten et al. n.d.; Kröger et al. 2026). Thus, the simulation environment is a powerful tool for anticipating the effects of different PCC sets on GNSS-based positioning.

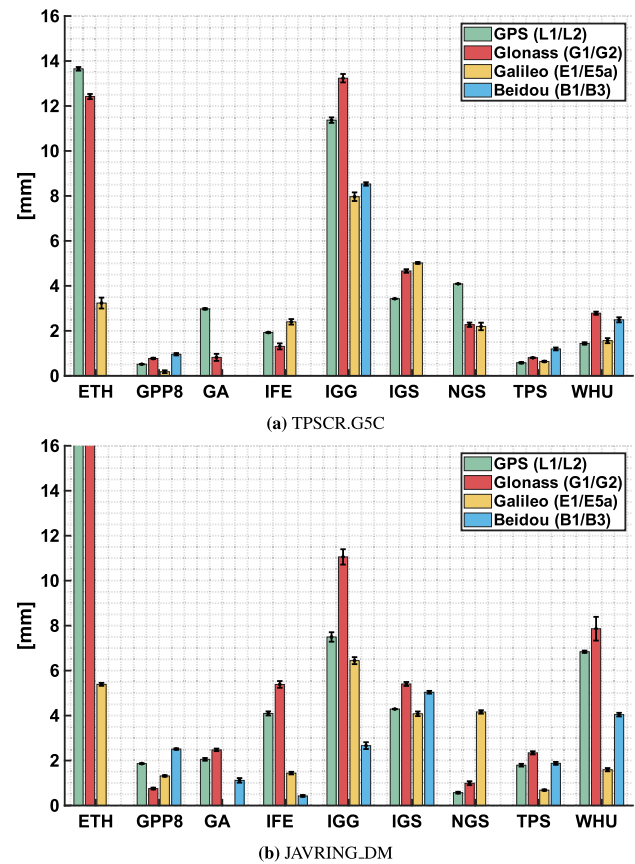
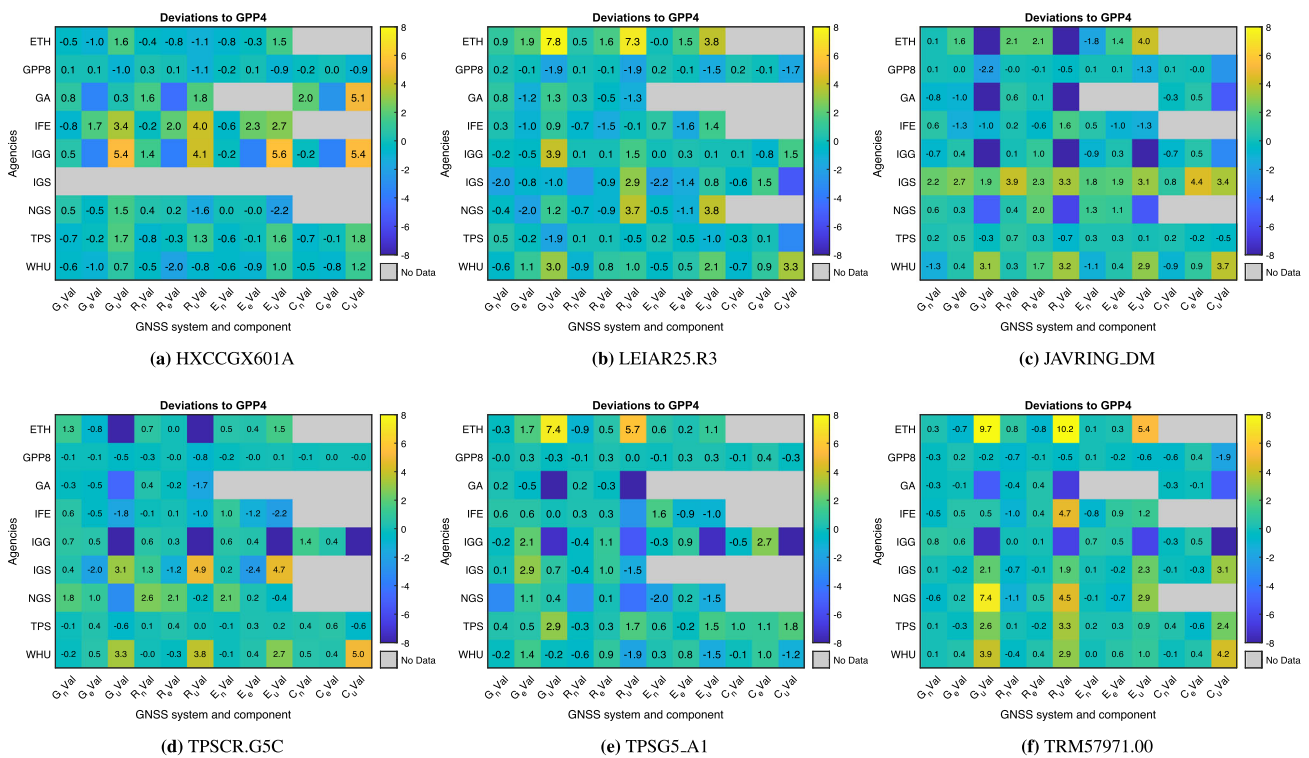


Fig. 10 Mean daily 3D topocentric position deviations for a mid-latitude site at 52° (northern latitude), obtained from the simulation and expressed relative to the solution of Geo++ MP4 (GPP4) individual calibration. Results for DLR are not available due to the limited number of provided frequencies (no GPS L2 available). Black whiskers denote the day-to-day standard deviations

4.3 PPP-based position-domain analysis with real data

Having real GNSS data from the AUTs at hand, we evaluate the impact of using different PCC in a PPP-based analysis (cf. Sect. 3.5). Daily RINEX files have a sampling interval of 30 s. We applied each facility's individual calibration in a PPP solution. The processing parameters (observation weighting, sampling, elevation mask, etc.) are fully consistent with the simulation presented in the previous section. We then subtracted the PPP estimates from those related to GPP4 and analyzed the resulting offsets (ΔNorth , ΔEast , and ΔUp), the receiver clock estimates (Δt_{rx}) and the tropospheric delay (ΔZTD). All results, including those obtained with different software packages, are provided in Kersten et al. (n.d.).

Figure 11 summarizes the position-domain results as a heatmap. Where available, PPP position differences from the corresponding IGS ANTEX type means is shown alongside the facility solutions. For each AUT, heatmap entries give the mean daily offset relative to GPP4, indexed by topocentric



Abbreviations: G: GPS, R: GLONASS, E: Galileo, C: BeiDou, n: North component, e: East component, and u: Up component

Fig. 11 Heatmaps for individual facilities and antennas showing the differences (relative to Geo++ MP4 (GPP4)) in PPP processing. Results of DLR are not shown as the limited number of available frequencies.

component (n, e, u) and GNSS (G = GPS, R = GLONASS, E = Galileo, C = BeiDou). Colors code the magnitude (and sign) according to a uniformed color scale.

Across antennas and frequencies, the PPP results are in agreement with the simulation: Offsets are predominantly vertical; horizontal components are smaller, with the North component generally the smallest. As shown in Kersten et al. (n.d.), most 3D offsets are on the order of a few millimeters, with larger deviations for some facilities (notably ETH and IGG). This is consistent with findings in Sects. 4.1 and 4.2, where the pattern differences increased at low elevations, mirroring the frequency- and elevation-dependent discrepancies in the pattern domain.

Remaining discrepancies between both evaluation methods can be attributed to different C/N_0 -based cutoffs used in PPP processing, real-world azimuth-dependent obstructions not modeled in the simulation, and PPP ambiguity handling, which can introduce correlations between the ΔUp component, the tropospheric parameters (e.g., ΔZTD), and the receiver clock estimates.

In summary, the real-data PPP results confirm the conclusions drawn from the simulation-based analysis: pattern-domain differences, particularly low-elevation and azimuthal

G: GPS, R: GLONASS, E: Galileo, C: BeiDou, n: North component, e: East component, and u: Up component

effects resulting from the ionosphere-free linear combination, as well as occasional height offsets, translate into small but systematic position-domain impacts, predominantly in the vertical direction, with magnitudes at the few-millimeter level. However, the differences between the IGS type means and the GPP4/GPP8 calibrations are related to the differences in the corresponding individual pattern differences. The exact cause of these discrepancies between the GPP4 and GPP8 patterns and the IGS type mean remains unclear and warrants further investigation.

5 Discussion and findings

The pattern-domain deviations (ΔPCC as azimuth-averaged values) are consistent with the position-domain effects observed in both simulation and PPP, in that sense that strong deviations in the pattern domain also translates into the coordinate domain: The vertical (Up component) dominates, and the North component is smallest. Frequency dependence is verified: L1 is most consistent, L2 shows larger azimuthal variability for selected facilities, and L5/E5a is generally stable with antenna-specific exceptions (e.g., small inte-

grated ground plane antennas). Facility-specific signatures were identified in the pattern domain, e.g., GA height offset, stronger azimuthal variability at NGS or small robot chamber differences below 20° , propagate into millimeter-level 3D offsets in the position domain.

A desired outcome of this study was to assess what constitutes a reasonable level of agreement between calibration facilities, and recommend targets. Pattern-domain targets of azimuth-averaged ΔPCC over $e \geq 20^\circ$ are: mean $|\Delta\text{PCC}| \leq 1$ mm relative to GPP4, azimuthal anisotropy (max/min at fixed elevation) ≤ 2 mm for L1/L5 and ≤ 2 mm for L2, and a height offset ≤ 2 mm. Deviations of 3 mm to 4 mm confined to 10° to 20° may be tolerated if flagged. Position-domain targets for 24 h IF-LC PPP at mid-latitudes are: median $|\Delta\text{U}| \leq 3$ mm, $|\Delta\text{E}|$ and $|\Delta\text{N}| \leq 2$ mm, a mean 3D magnitude of ≤ 5 mm, and day-to-day standard deviations of daily means ≤ 1 mm. These values reflect the campaign statistics and provide operational thresholds. Please note that the limited availability of frequencies for the DLR facility means that no PPP position results are available. The practical relevance is twofold. Operators can use the thresholds to accept or reject calibrations prior to deployment, prioritizing Up component and low-elevation behavior. Analysis centers can combine coverage-weighted pattern metrics with scenario-based simulations (site latitude, elevation cutoff, GNSS constellation mixture) to predict PPP effects. Manufacturers are encouraged to supply uncertainty budgets and evidence of stability across frequencies and radomes.

The present campaign has demonstrated a high degree of consistency with previous inter-comparison studies, which is encouraging. However, when considering the improvement in inter-facility consistency over time, it is essential to acknowledge the complexities involved. The growing number of participants and the increasing diversity of calibration methods have enhanced the overall reliability of the measurements, but the consistency of the results across facilities has not shown a significant improvement. This may be attributed, in part, to the limited publicly available documentation of certain facilities, which may have introduced some variability in the results. This highlights the need for continued efforts to standardize and refine the calibration process, as well as to improve the documentation and transparency of the facilities involved.

The comparison between the calibrations of GPP4 and GPP8 reveals that there are differences between the two solutions, particularly on the individual frequencies (see Fig. 7). However, these differences are generally within an uncertainty of 0.5 mm and can be explained by a small PCO offset of 0.5 mm due to the antenna construction, mounting on individual robots and antenna mounts. In the IF-LC results (see Fig. 8), very small differences are observed, indicating that the calibrations of GPP4 and GPP8 are largely consistent. The observed differences can be attributed to different robot

generations and/or site conditions. It is possible that the use of different robot generations or changes in the site conditions led to small changes in the measurement setup, resulting in the observed differences. These results emphasize the importance of careful calibration and precise documentation of measurement conditions to ensure high consistency and accuracy of the calibrations.

The observed deviations in calibration results of different facilities suggest that various factors contribute to these differences, including the use of different software packages for data processing and analysis (1), variations in synchronization between facilities and systems (2), lack of documentation and unknown maintenance intervals of individual facilities (3), impact of robotic systems and near-field effects (4), and differences in receiver types and tracking issues (5).

Our results show that calibrations at different institutions (NGS, WHU, TPS) are in good agreement with those of GPP4/GPP8 and IFE, despite using different robots, suggesting that robot-related effects may be negligible when individually modeled accurately. However, individual differences can contribute to systematic PPP height differences in selected cases of up to 22 mm (Fig. 11) and highlight the need for further research and improvement in antenna calibration methods. Furthermore, the use of different adapters and mounts at various facilities may also introduce additional variability, emphasizing the importance of standardized calibration procedures and equipment to minimize potential errors and ensure accurate results.

For sustainability, we recommend routine inter-facility quality assessment (QA) using coverage-weighted WRMS, 95th percentiles, and correlation r against a stable reference (e.g., GPP4 or IGS). Periodic inter-comparisons on a standard set of AUT should be conducted under harmonized metadata. Position-domain validation via the standardized simulation should be complemented by spot-check PPP runs. Traceability requires versioned ANTEX files (including GPS week and software version), archived results of chamber and robot facilities, and documented uncertainty components. For onboarding of new facilities, we suggest an entry criterion of a coverage-weighted mean $|\Delta\text{PCC}|$ of below 1 mm ($e \leq 20^\circ$) performed with a standardized set of AUT, an evidence package with raw and processed ANTEX data files for reproducibility checks, and passing a PPP impact check (24 h with 3D deviations below 5 mm).

Limitations of our presented analysis include the reliance on GPP4 and/or IGS (IGS type means) as the numerical comparison basis and simulation simplifications (e.g., no ambiguity modeling, no site-specific obstruction masks).

6 Conclusion

We conducted an international antenna calibration campaign, coordinated by the IGS Antenna Committee, to investigate the consistency and comparability of calibrations across various facilities. A key aim was to support the development of a robust and accurate International Terrestrial Reference Frame (ITRF).

Frequency and elevation significantly influence calibration differences, which are generally small. At elevations above 20°, the azimuth-averaged Δ PCC values agree within approximately 1 mm, while the deviations increase to 3 mm to 4 mm at elevations below 20°. In particular, our results show that institutions such as TPS (Topcon), NGS, and WHU provide calibration results that are in high agreement with those from GPP, IFE, and, in some cases, GA. Institution-specific characteristics, such as elevation offsets in selected GA calibrations and greater azimuthal variability in NGS, are consistent across all antennas and frequency bands.

The results show a considerable difference between the type mean and the individual calibrations for GPP4 and GPP8. This discrepancy highlights the need for further investigations to improve the accuracy and reliability of the type mean, in order to reduce the gap between the mean and the individual calibrations. A transparent and traceable provision of the type mean, including covariance information, would be an important step in this direction.

Due to a lack of historical data, it is not yet possible to assess long-term calibration stability or any changes within the scope of this campaign. However, it lays the groundwork for future research by documenting the antennas used and making them available for ongoing testing, thereby enabling long-term monitoring and analysis to gain a better understanding of antenna performance over time.

The campaign highlighted the importance of considering the diversity of calibration methods and facilities, as the results showed that different methods and facilities can introduce variations in the antenna calibrations. The use of different calibration techniques, such as robot and chamber calibrations, and the varying degrees of automation and manual processing, contributed to the observed differences in the antenna calibrations.

In the positioning domain, both simulation and PPP results show few-millimeter impacts, dominated by the Up component, with day-to-day variability of daily means typically below 1 mm. The close agreement between simulation and PPP supports the use of the forward propagation approach for design stage sensitivity analyses.

Based on the analysis of these results, we conclude that establishing threshold values for antenna calibration is essential to ensure the quality of calibrations and to support the maintenance and improvement of the IGS ANTEX format and the ITRF. Standardized calibration processes and equipment, including standardized adapters and mounts, will ensure accurate and consistent results, facilitating the seamless integration of new facilities and antennas into the IGS network, and contributing to the long-term stability, consistency, and accuracy of the ITRF.

To improve the accuracy and stability of the ITRF, we propose the introduction of an independent process for combining type means, which would provide a more robust and reliable basis for the reliability and stability of IGS type mean calibrations.

Appendix

See Figs. 12 and 13.

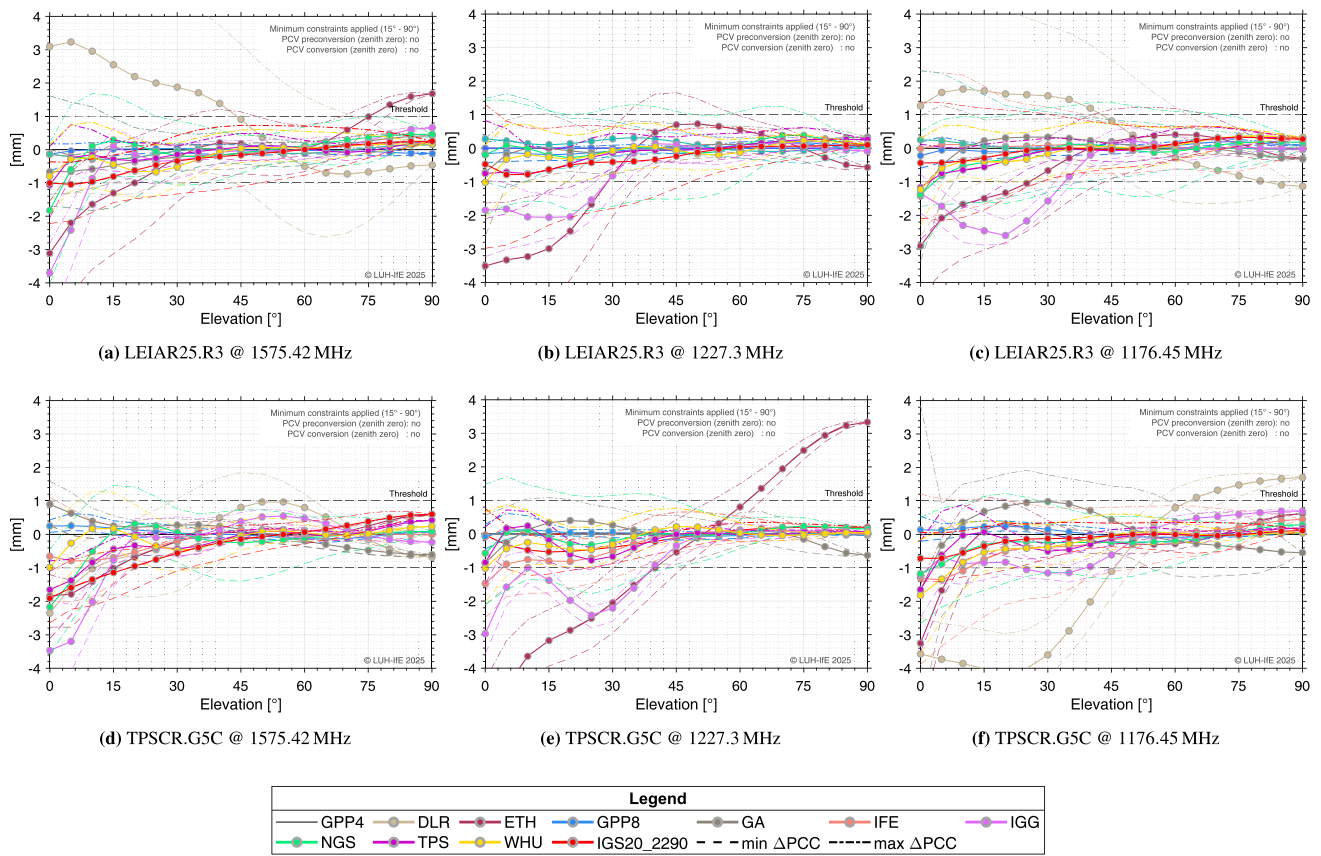


Fig. 12 Class-specific results of PCC differences w.r.t. GPP4 for various frequency bands, i.e., 1555 MHz to 1610 MHz (L1, E1, B1, GLO L1), 1221 MHz to 1254 MHz (L2, GLO L2), and 1164 MHz to 1214 MHz (L5/E5a/B2a, E5a+b/B2a+b, GLO L3, E5b/B2b)

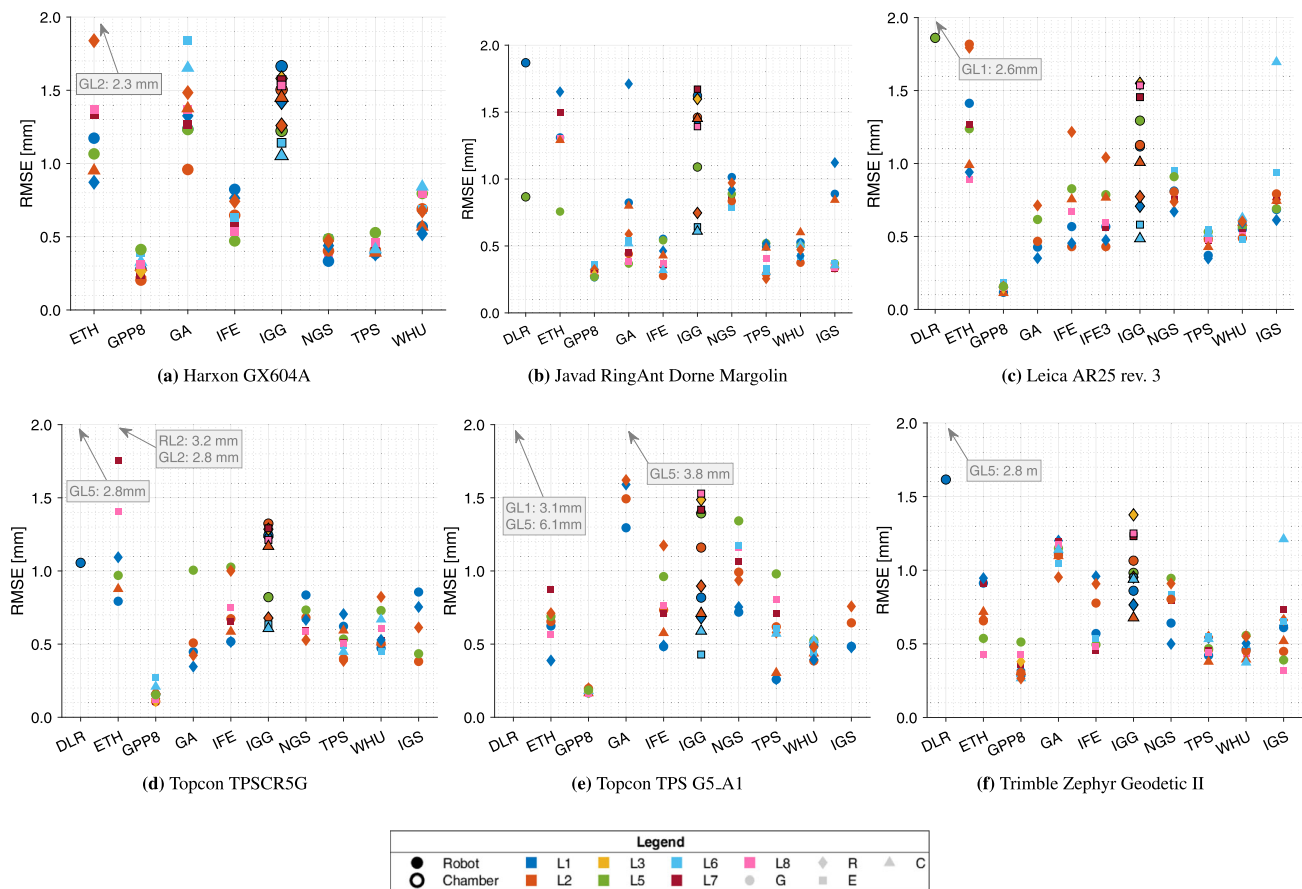


Fig. 13 Values of individual root-mean-square error (RMSE) of Δ PCC relative to GPP4 per facility, frequency, and AUT sample

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Author contributions Tobias Kersten set up the calibrations and experiments at IFE, performed the comparisons in the pattern and position domains (including PPP with real data), and led the writing of the manuscript including conception, methodology software writing. Johannes Kröger developed the simulation framework and wrote the corresponding section. Tobias Kersten, Johannes Kröger, and Steffen Schön co-authored the manuscript. Tobias Kersten, Andria Bilich, and Igor Sutyagin coordinated the IGS Antenna Ring calibration campaign and contributed to the evaluation of the results, including cross-check of data with independent software packages and data curation. All authors provided data from their facilities, contributed to the interpretation, and reviewed and approved the final manuscript.

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Data availability The ANTEX data is published by Kersten et al. (2025). The GNSS dataset with static observation data in RINEX 3.05 format is provided in compressed Hatanaka format with a resolution of 30 s (Kersten 2025). The simulation software used in Sect. 4.2 is publicly available for download at <https://doi.org/10.5281/zenodo.18618172>.

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