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Absolute calibration of GPS antennas: laboratory results and comparison with field and robot techniques

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Abstract A critical assessment of the accuracy of GPS antenna calibration is most effectively done by comparison between different calibration methods. We present new chamber calibrations of five different GPS receiver antenna types in an anechoic chamber and a comparison of an individual antenna calibrated by the absolute field calibration technique with robot mount of IfE/GEO++. The accuracy is described using standard error parameters which allow the characterization of the quality of different antennas. The results validate the absolute calibration methods at the 1-mm level and confirm the presence of significant variations in quality between antennas of different design. For the antenna pattern we directly use the measured phase variations and do not have to fit any functions for the chamber calibrations. We include the results of an earlier test made with a set of identical antennas calibrated at five different institutions: two using the absolute field technique with robot mount and three others applying the standard field calibration with reference antenna.

Introduction

For precise geodetic and geophysical applications site positions should be known to the level of a few millimeters. To fulfill this requirement it is important to know the exact position of the phase center of the receiving GPS antenna because as in all geodetic satellite techniques the antenna stands for the actually estimated positions. Unfortunately, the theoretical concept of a mathematical point representing the intersection of all ranges measured from the satellites cannot be realized because the properties of the incoming signals are determined by the electric field, which is distorted by the environment of the antenna, the characteristics of the atmosphere and the antenna itself.

The calibration of geodetic GPS antennas has a topic of intensive research over the last years. One driver were the needs of RTK differential applications with mixed receiver and antenna types, e.g., in continuously operating reference station networks, see, e.g., (Schmitz et al. 2002; Mader 1999; Menge et al. 1998), where phase center variation modeling fosters a short time to fix the ambiguities. Another driver was the IGS permanent network, where the use of the Dorne Margolin antenna as reference without phase center variations (PCVs) was identified to cause a scale problem in the IGS coordinate solutions and systematic errors in the station heights, see (Rothacher 2001; Schmid and Rothacher 2003; Zhu et al. 2003).

In August 2002, we calibrated GPS receiver antennas in a large anechoic chamber of the Bundeswehr (Federal Armed Forces) in Greding/Germany. The aim of the new set of chamber measurements and comparisons is to gain a better insight into the performance of different calibration methods. The validation of an antenna calibration result is only possible by comparing the results of individual antennas calibrated by different organizations or different methods as done in the so-called German benchmark test. Up to that initiative most comparisons had been referred to antenna types but not to identical antennas. Hence, the reason for discrepancies between results of different measurements could not be correctly interpreted. The systematic difference between individual antennas of the same type adds to the difference caused by the calibration procedures themselves. Unfortunately at the time of the German benchmark test no calibration measurements were available to validate the absolute results of the robot system of IFE (University of Hannover)/GEO++ (Wübbena et al. 1997) by an independent technique for one and the same antenna. Therefore our intention was to fill this gap.

Antenna calibration model

The adopted antenna calibration model is based on the well-known antenna phase center variation correction equation (see, e.g., Geiger 1988) where the total phase center correction in the direction of the satellite consists of the absolute mean antenna phase center offset (PCO) with respect to the antenna reference point (ARP) **a** plus the elevation and azimuth dependent phase center variations (PCVs) $\mathrm{d}\varphi$, given in degrees (Fig. 1).

$$\mathrm{d}r(\alpha,\beta) = \mathbf{a}\cdot\mathbf{r}_0 + \lambda\cdot\mathrm{d}\varphi(\alpha,\beta) \tag{1a}$$

with PCO: $\mathbf{a}(\lambda) = (\mathrm{a}_x, \mathrm{a}_y, \mathrm{a}_z)$ where λ is the wavelength of carrier phase.

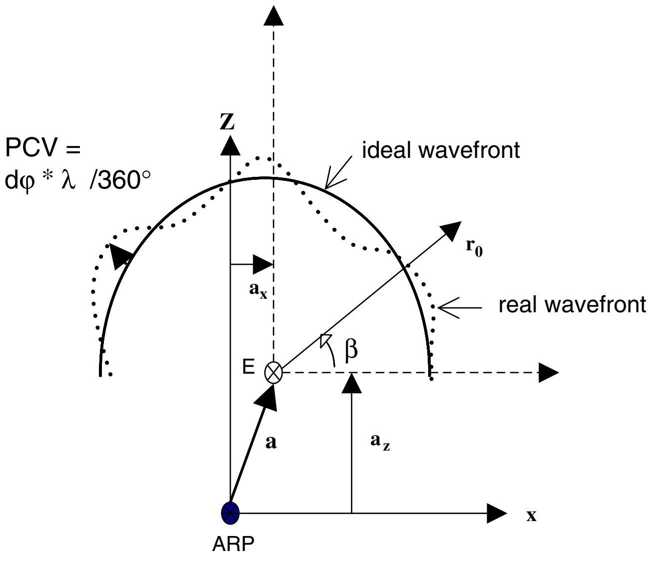


Fig. 1 Antenna calibration model

The estimation procedure according to this model is done in two steps due to practical aspects. The first step contains the estimation of the three components of the mean PCO with respect to the ARP:

$$\sum \mathrm{d}\varphi(\alpha,\beta)^2 = \mathrm{Min!} \tag{1b}$$

The ARP has been conventionally defined by the IGS as the intersection of the vertical antenna axis of symmetry with the bottom of the antenna. It is important to note that Eqs. 1a and b are necessary and sufficient to estimate the PCO for the chamber measurements. The phase pattern is in this case obtained directly as residuals from the adjustment of 1b. The measured values of the PCVs can be plotted to allow visual inspection of the phase pattern.

In a second step the pattern can be modeled using harmonic functions in order to obtain estimates of the measurement noise and the smoothness—or quality—of the phase pattern.

For our first setup we used the following two-dimensional functional model for the PCVs:

$$\begin{aligned}\mathrm{d}r(\beta) &= \sum (\mathrm{a}_k \cos\ \beta + \mathrm{b}_k \sin\beta),\\ k &= 0,\ldots,3 \text{ or } 5\end{aligned} \tag{2}$$

From the differences between modeled and measured data the RMS scatter is calculated to provide a measure of the scatter of the phase pattern.

The calibration procedures used can be found in Table 1.

For many years relative phase center corrections have been used by the GPS community that can be estimated from GPS measurements on a short baseline (Breuer et al. 1995). According to the IGS standard the relative phase center corrections are based on the absolute values for the PCO of the reference antenna (the Dorne Margolin T) estimated from chamber measurements and upon the arbitrary assumption that the PCVs of the reference antenna are zero. Relative antenna calibrations in the field do not permit a homogeneous distribution of observations with regard to the antenna hemisphere. In addition, they contain site-dependent effects.

Absolute corrections for the receiver antennas can be obtained from two independent methods: the measurements in an anechoic chamber (Schupler et al. 1991) and the field measurements on a short baseline using a robot mount (see chap. 2). In the chamber setup during our first test runs the receiving antenna is rotated through zenith angles from −90° to +90° (one meridian) for various azimuth values as well as rotated around the vertical axis through all azimuth angles for a fixed elevation. During these tests which were limited to 3 days we could not achieve a complete coverage of the hemisphere of the antenna.

Table 1 Methods available for GPS antenna calibration

	PCO (x, y)	PCO (height)	PCV
Field calibration without rotating the antenna	Relative	Relative	Relative, only elevation-dependent
Field calibration with rotation of the antenna	Absolute	Relative	Relative
Robot system	Absolute	Absolute	Absolute
Anechoic chamber	Absolute	Absolute	Absolute

The German bench mark test 2002

In early 2002 several institutions in Germany carried out the so-called "German benchmark test" initiated by the LGN Niedersachsen (State Survey and Geospatial Basic Information Lower Saxony) in order to study the performance of the different calibration methods (Rothacher et al. 2002). A selected set of five antennas (five different antenna types by three different companies, among them three reference station antennas and two rover antennas) was calibrated successively at five different institutions (Table 2).

Two institutions used an absolute field technique with a robot calibration system (Fig. 2). They carried out field measurements on a short baseline using a robot capable of tilting and rotating one of the antennas (Wübbena et al. 1997). Three other institutions employed standard field calibration in relative mode with a reference antenna. (LGN Hannover, TU Dresden, and our group University of Bonn). Unfortunately at that time it was not possible to have chamber calibrations involved in the test, the only alternative method to obtain absolute results. Therefore, recent new chamber tests will be presented in this paper.

The official comparisons of the benchmark test were carried by Schmid (TU München) and were presented at the 4th GPS Antenna Workshop in Hannover in May 2002. (Schmid et al. 2002). As an example we show the five individual calibration results for the elevation-dependent PCVs for one and the same Leica AT303 antenna (Fig. 3), for the L1 and the L2 carrier in the upper plots of Fig. 4. All results have been converted to the absolute level. The plots below show the variations against the mean.

Fig. 2 Robot calibration system (IfE/GEO++) (from Wübbena et al. 2003)

Here, the comparisons of the different calibration methods for one and the same antenna show an excellent agreement between the two different calibrations with the two robots at the 1-mm level for all elevations with a quite smooth behavior off the PCV, whereas the standard field calibrations display larger variations of 2 mm at L1 resp. 4 mm at L2 to the

Table 2 Calibrations done in the first German benchmark test 2002

Institution	Calibration method	Used software
University of Hannover (IfE)	Robot–absolute	GNPCV
Geo + + Garbsen	Robot–absolute	GNPCV
State Survey… Lower Saxony (LGN)	Relative field calibration	WaSoft/Kalib
University of Dresden (TUD)	Relative field calibration	WaSoft/Kalib
University of Bonn (GIB)	Relative field calibration	Bernese GPS Software
University of Bonn	Chamber test	Not available in spring 2002

Fig. 3 LEIAT303 LEIC

mean. The well-known problems for the highest and lowest elevations can be seen, caused by the small number of observations near the zenith as well as the systematic effects near the horizon (multipath, troposphere, etc.), and of course the effect of the reference antenna. If we express the results in RMS differences over all elevations (Fig. 5), it can clearly be seen that absolute PCVs derived from relative field calibrations are a factor of two worse than those from robot calibrations.

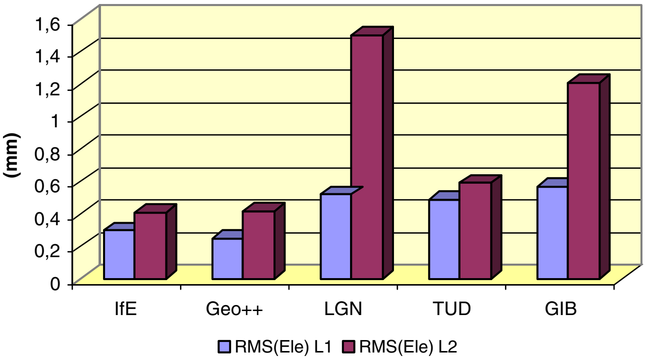


Fig. 5 RMS differences over all elevations of the German benchmark test for the Leica AT303 with radom

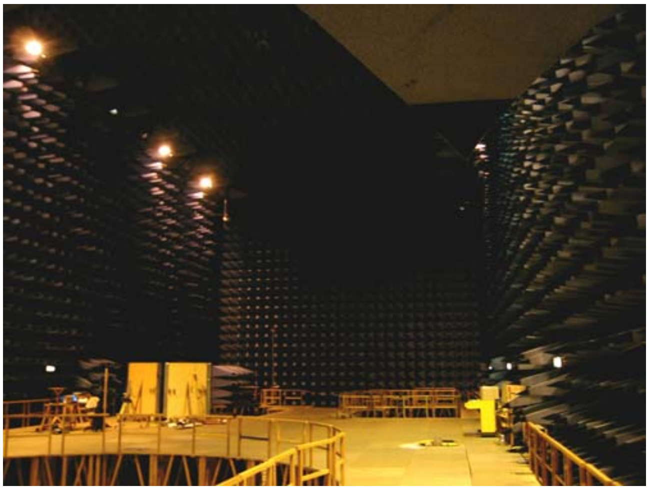
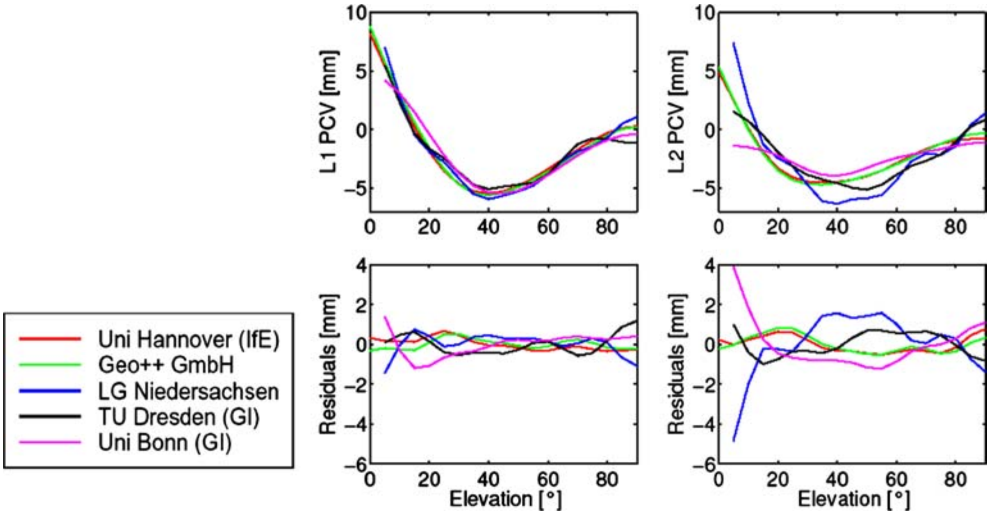


Fig. 6 Anechoic test chamber in Greding/Germany

Fig. 4 Results of the German benchmark test for the Leica AT303 with radom (from Schmid et al. 2002)



Antenna calibration in the anechoic chamber in Greding

The anechoic test chamber of the "Technical Center for Information Technology and Electronics" in Greding/Germany is the largest anechoic chambers in Europe with a size of 41 m in length and 16 m in width and 14 m height (Fig. 6). The absorbing material is designed for frequencies from 0.5 GHz upwards. So it is well suited for the GPS frequencies L1 and L2. We used a transmitting antenna from the Max-Planck-Institute for Radio Astronomy in Bonn which is able to produce right hand circular polarized radiation.

In the measurement setup during the test run (see Fig. 7) the transmitting antenna was kept fixed and the receiving antenna, which is to be tested, was mounted on a positioner that rotates the antenna around two independent axes and can be shifted in three directions. The distance between both antennas was about 18 m. The transmitted and received GPS carrier waves were compared in a network analyzer. Recordings of phase delay and signal-to-noise ratio were performed for both the L1 and L2 frequencies. In addition to the phase recordings the location of the center of rotation of the test antenna has to be determined with high accuracy with respect to a physical point on the test antenna, e.g., the ARP.

In August 2002 we tested five different antennas from two manufacturers (see Table 3 and Fig. 8). Three antennas are made by Trimble, two 10-years old (geodetic and compact) and one new Zephyr geodetic antenna with ground plane, as well as two antennas with choke ring manufactured by Leica. We calibrated the Leica AT 504 which is designed after the Dorne Margolin T and the Leica AT 303 with different choke rings and a radome.

Fig. 7 Measurement setup in the anechoic test chamber

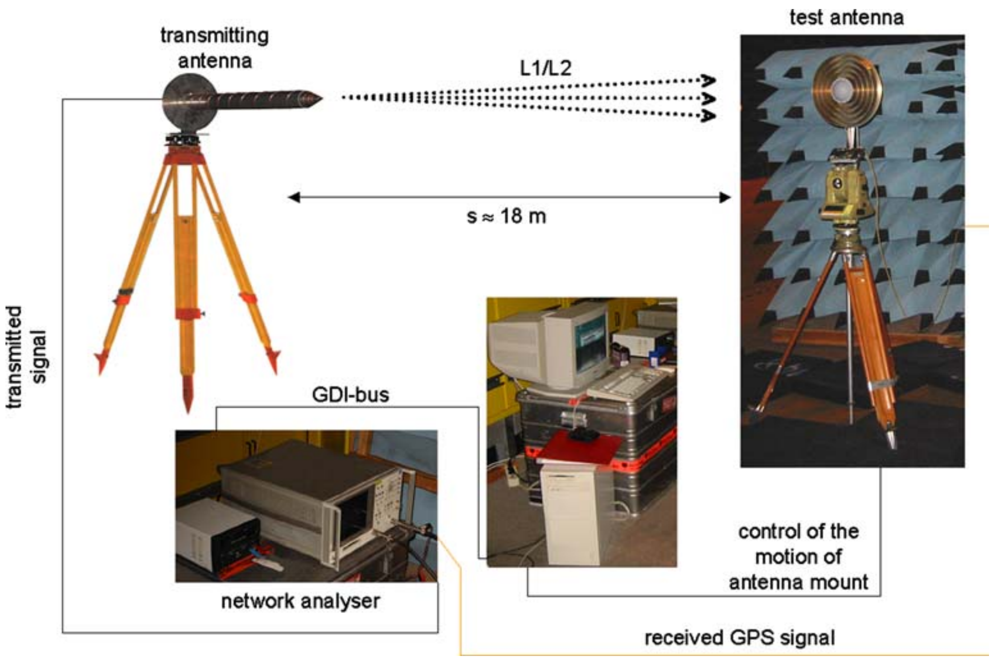


Table 3 Antennas tested in the anechoic chamber in 2002

Antenna Type	IGS-Code	
Trimble compact	TRM22020.00 + GP	With groundplane
Trimble Zephyr geodetic	TRM41249.00	Stealth groundplane (anti-reflex)
Trimble geodetic	TRM14532.00	
Leica AT 504	LEIAT504	Dorne Margolin Antenna with choke rings (designed after D/M T)
Leica AT303	LEIAT303_LEIC	Micropulse antenna with choke rings (identical to AT503)

Results of the chamber measurements

The measurements of the elevation-dependent PCVs show very smooth patterns for all five tested antennas (Fig. 9). The measured values are shown as recorded, no fitting functions were applied. The resolution of the phase measurements is about 0.1 mm.

For the L1 results two types of typical patterns may be distinguished: the patterns with two maxima common to most antennas and the patterns with three maxima of the "old" Trimble antennas. For the L2 plot all antennas behave in a similar mode. We found distinct asymmetric patterns for the older Trimbles, which we had already noticed in earlier chamber tests (Breuer et al. 1995) in a small antenna laboratory in Bonn (Max-Planck-Institute for Radioastronomie).

Fig. 8 Antennas tested in the anechoic chamber in 2002

Due to the limitations of the experimental setup azimuth-dependent PCVs were recorded only at a fixed elevation of 12.5° (Fig. 10). The observed amplitudes are smaller than those of the elevation-dependent patterns with peak-to-peak variations of −2.5 to 2.5 mm for the Leica AT303 (only L2) and Trimble geodetic antennas.

The smallest azimuthal variations are typical of the Leica AT504 choke ring and Trimble Zephyr geodetic antennas. The latter were designed to emulate the symmetric choke ring pattern (optimized rotational symmetry).

It is interesting to note that both the Leica AT303 in L2 and the Trimble geodetic in L1 show a large azimuthal oscillation with 180°-period.

The RMS scatter of the elevation- as well as azimuth-dependent PCVs is given in Fig. 11. The two groups of antennas can be clearly distinguished again: the older ones with a large scatter contrasting the modern ones with distinctly smoother patterns.

Comparison of chamber measurements with robot technique

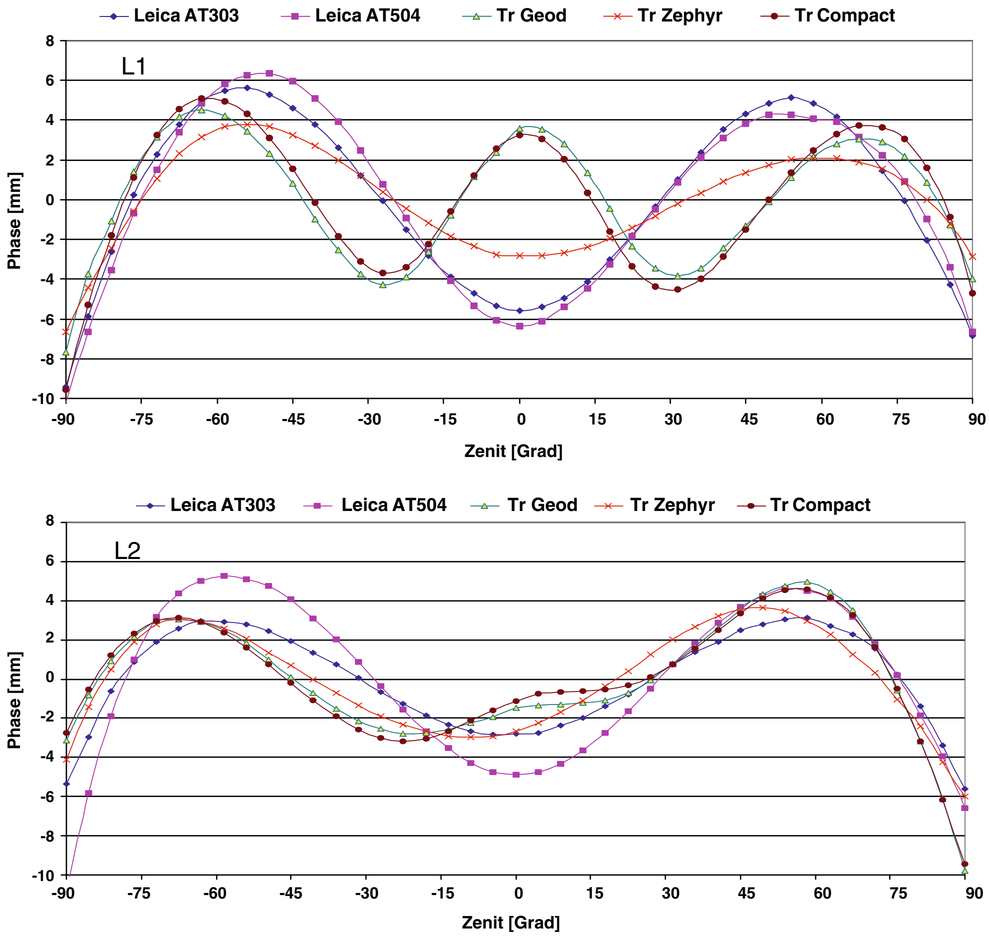
Because a critical assessment of the obtained accuracy of antenna calibration is most effectively made by comparison between different calibration methods, an individual Leica AT303 antenna of our test sample was also calibrated using the absolute field calibration technique with robot mount of IfE/GEO++ as well. Absolute corrections for the receiver antennas can be obtained from these two independent methods only. The receiver antenna corrections stemming from robot measurements were kindly made available by the company Geo++.

After correct conversion of the offsets, the elevation-dependent calibration results for this particular antenna agree at the level of 1 mm (Fig. 12), even though we are comparing the raw sample of the chamber results and a harmonic function of the robot results.

In the comparison of the azimuth dependence (Fig. 13), a small phase shift can be seen, perhaps due to an uncertainty of the antenna orientation in the chamber setup.

In those cases where we did not have an identical antenna calibrated by the different methods the agreement is less good for most of the antenna types. Due to the fact that for the comparison we have to consider the disagreement in offsets and the agreement in the shape of the pattern, we made an additional adjustment and estimated residual offset differences (height component) between the patterns of the chamber and the robot measurements (see Fig. 14). In the case of the Leica AT504 and the Trimble antennas with asymmetric shape

Fig. 9 Elevation-dependent phase pattern from chamber tests



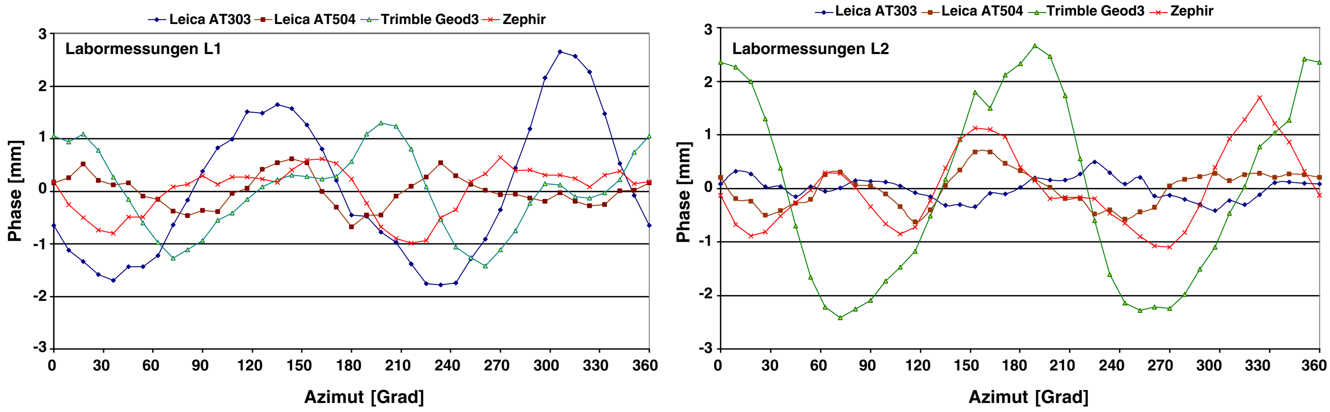


Fig. 10 Azimuth-dependent phase pattern from chamber tests (Elevation 12.5°)

of the pattern the offsets increased to 4 and 5 mm respectively, but were nearly zero for the Leica AT303 and the Trimble Zephyr geodetic antenna.

The reason for these differences with systematic tendency can be explained by the improvised measurement of the mechanical center of rotation relative to the ARP in the earlier experimental setup. Another shortcoming of the comparison is that we only measured one meridian and one parallel circle and not the complete hemispherical pattern. Finally

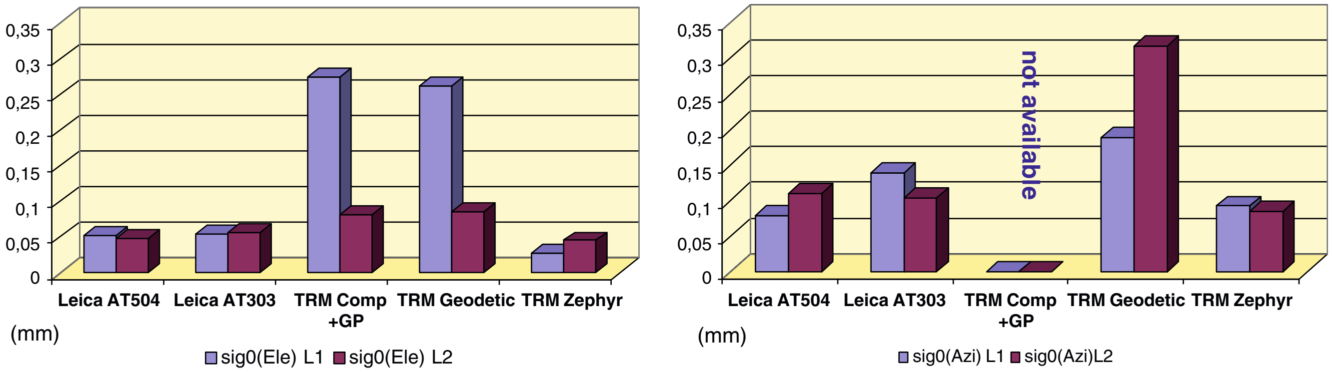


Fig. 11 RMS scatter for elevation- and azimuth-dependent PCV

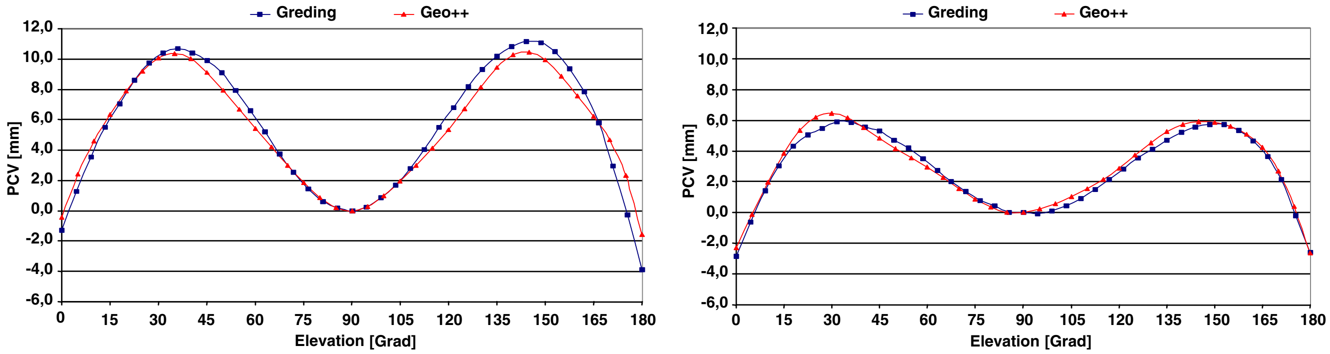


Fig. 12 Comparison of elevation-dependent phase pattern from chamber and robot calibration for the Leica AT 303 for L1 and L2 (identical antenna)

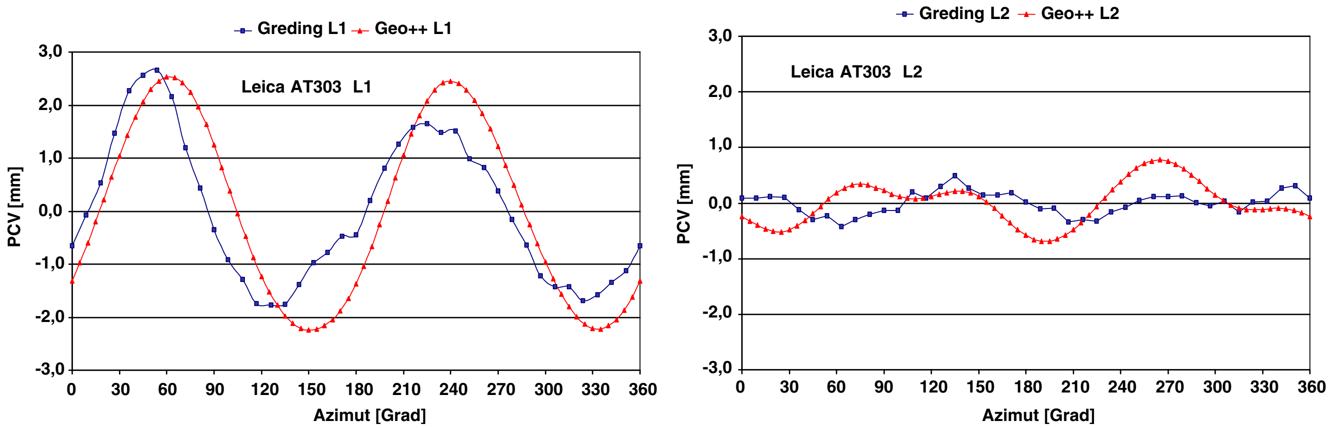


Fig. 13 Comparison of azimuth-dependent phase pattern (elevation 12.5°) of chamber and robot calibration for the Leica AT 303 (identical antenna)

there obviously exist variations among the patterns of individual antennas of the same type (Wübbena et al. 2003). Depending on the type of antenna (groundplane, choke rings, etc.) differences of up to 8 mm in the ionospheric free linear combination were demonstrated, which come up to deviations to the type mean of 4 mm for the Dorne Margolin type antennas.

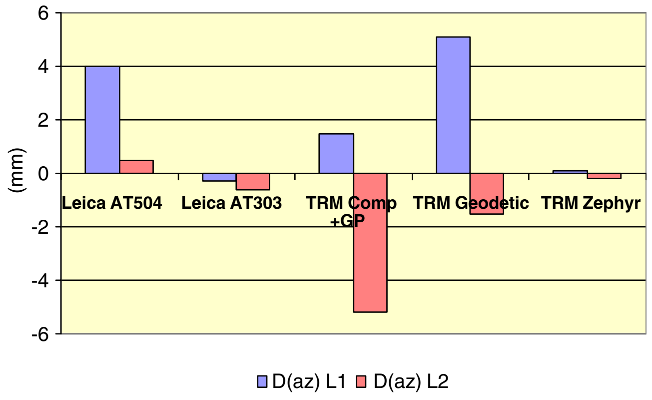


Fig. 14 Residual-offsets from best fit between chamber (Greding) and robot (GEO++)

The total precision of the calibration σ_{antcal} is composed of the accuracy of the PCO from the adjustment σ_{PCO} and the error of the mechanical measurement of the point of rotation σ_{D}. This holds for all calibration methods.

$$\sigma_{\text{antcal}}^2 = \sigma_{\text{PCO}}^2 + \sigma_{\text{D}}^2$$

The quality of the agreement of the shape of the PCV pattern after the additional fit described above can be seen in terms of RMS difference in Fig. 15.

The plots show that both the methods agree at the 1-mm level or even better, if an identical antenna is calibrated (Leica AT303). For that antenna the PCO as well as the PCV values are in perfect agreement. The results for the comparison of the Trimble Zephyr Geodetic have a similar quality although not an identical antenna but one of the same types could be compared. The relatively high noise to be seen for the Trimble geodetic and Trimble compact antennas may have been be caused by the asymmetries in the phase pattern we have seen above.

This adds to the noise to be expected due to the deviations from the type mean as described above.

Conclusions

The results of calibrations of GPS antennas presented in this paper show a great potential for antenna calibrations in anechoic chambers. The results validate the absolute calibration methods of chamber measurements and robot by agreement of the estimated parameters at the 1-mm level if this comparison is made for identical antennas.

In contrast to the relative field calibrations, the chamber test and the robot permit homogenous distribution of observations with regard to the antenna hemisphere and the estimation of PCV for low elevations with the same high quality.

Since we directly use the sampled PCV values (no fitting function is used!) the chamber has the potential to study the characteristics of the patterns of the PCVs in greater detail at a high level of precision. The results confirm the presence of significant variations as well in both the magnitude and the pattern of PCV corrections as in quality between antennas of different design.

Further measurements in the anechoic chamber with an improved antenna mount which allows the automated measuring of the entire hemisphere of the antenna under test were conducted in 2004 and are currently under evaluation.

Acknowledgements We are grateful for the occasion to use the anechoic test chamber of the “Technical Center for Information Technology and Electronics” in Greding/Germany (WTD81 of the FAF) and for providing the Leica AT303 antenna by the Bavarian State Survey Department, Munich. The robot data were kindly made available by the company Geo++.

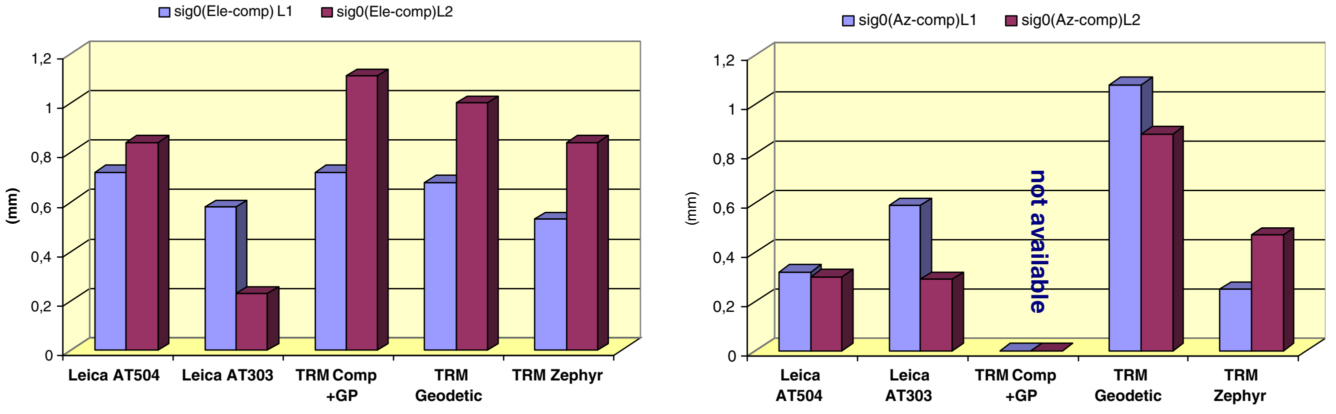


Fig. 15 Scatter between PCV patterns from chamber and robot measurement: elevation-dependent after best fit on the left and azimuth-dependent on the right

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