Kersten T., Schön S. (2016) Receiver Antenna Phase Center Models and Their Impact on Geodetic Parameters. In: Freymueller J.T., Sánchez L. (eds) International Symposium on Earth and Environmental Sciences for Future Generations. International Association of Geodesy Symposia, vol 147. Springer, Cham
Manuscript Version of Original Article

Receiver Antenna Phase Center Models and Their Impact on Geodetic Parameters

Tobias Kersten*, Steffen Schön

Abstract
Evaluating the impact of receiver antenna phase centre corrections (PCCs) in geodetic positioning and timing applications in a general way is quite challenging, because several estimation concepts, implementation philosophies as well as different sets of PCCs exist and interact with each other and their contributions are not identifiable.
In this paper, the authors present a methodology, based on investigations of Geiger (1988) and Santerre (1991), to classify PCCs and forecast their impact on all geodetic parameters, i.e. not only the position but also the receiver clock and troposphere parameter in a phase based precise point positioning (PPP) approach. In a first step, we introduce the mathematical model and generic PCC patterns. In the second step, simulation studies are carried out. Findings are evaluated by empirical studies using differences of PPP results to isolate the impact of different patterns. In parallel, the software impact is analysed since every software handles the observation modelling and parameter estimation differently, e.g., Kalman filter versus least squares approach. We show that all geodetic parameters are affected by PCC and that the impact on the parameters can be even amplified compared to the magnitude of the generic patterns.

Keywords
GNSS — Carrier Phase Centre Variation (PCV) — GNSS antennas — generic patterns

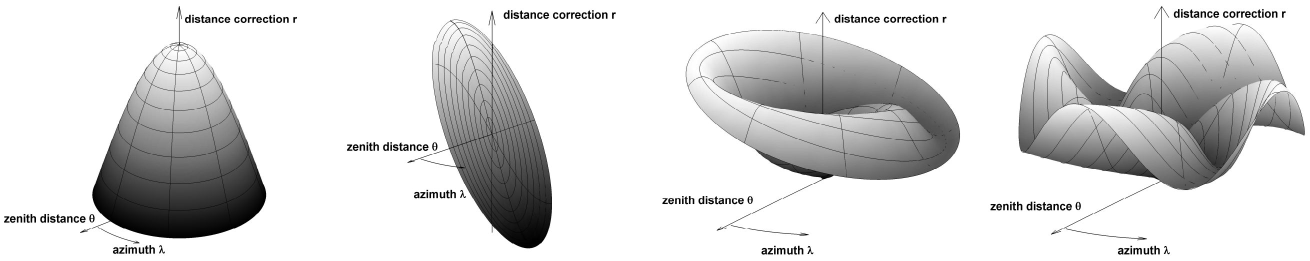
Institut für Erdmessung, Leibniz University Hannover, Lower Saxony, Germany
***Corresponding author**: kersten@ife.uni-hannover.de

Contents

1. Introduction

The comparability of phase centre corrections (PCC) obtained from different calibration institutions (Bilich and Mader, 2012; Moore and Ridell, 2016; Seeber et al., 1997; Wübbena et al., 1996; Zeimetz and Kuhlmann, 2008), where some institutions using independent calibration strategies, is still an issue in the International GNSS Service (IGS). Becker et al. (2010) showed that for several antennas PCC obtained from chamber and robot antenna calibrations agree below 1 mm. However, challenges exist as shown by Aerts (2011); Aerts and Moore (2013) for other individual calibration sets with variations up to 6-8 mm. Discrepancies between individual and type mean calibrations of up to 4 mm could be verified. Furthermore, differences of individual and type mean PCC values are reported in regional and global networks, (Sidorov and Teferle, 2012; Steigenberger et al., 2013). Differences of individual and type mean calibration values introduce systematic discrepancies of up to 10 mm in the up component and up to 4 mm in the horizontal component in European Permanent Network (EPN), (Baire et al., 2014). Therefore, generic patterns are used as a method to analyse the difference of PCC patterns and to study their impact on geodetic parameter estimation, consequently.

PCC can be compared directly (cf. IGS comparison strategy as shown in Bilich et al. (2012); Kersten and Schön (2013); Schmid et al. (2015)). However, even more important seems the impact on the estimated parameters, like e.g. coordinates, tropospheric delays as well as clock parameters or ambiguities. This impact depends on the geometric shape of the PCC difference, the processing strategy of positioning applied as well as the geographic location. The authors propose to categorize the pattern of PCC differences and subsequently their impact on all geodetic parameters in precise point positioning (PPP) by generic patterns and simulation



(a) turnstile (b) micro-strip (c) 1-wire helix (d) 4-wire helix

Figure 1. Generic patterns to analyse the impact of different PCC patterns, (a) turnstile, (b) micro-strip, (c) 1-wire helix and (d) 4-wire helix.

studies. The method is based on investigations initially introduced by Geiger (1988) and Santerre (1991).

The paper is organized as follows: In the first part several generic antenna patterns are presented. Next, the obtained simulation results are compared with those from different PPP software packages. There, the influence of different processing strategies (Kalman filter versus common least squares approach) is studied that propagates generic PCC patterns differently to the estimated parameters (position, receiver clock and troposphere). To this end, generic patterns are added to real, absolutely and individual calibrated PCCs.

2. Simulation Strategy

The relationship between PCC as well as differences of PCCs and estimated geodetic parameters is given by the least-squares solution

$$\Delta\mathbf{x} = (\mathbf{A^T P A})^{-1}\mathbf{A^T P r}(\theta,\lambda) \tag{1}$$

with the unknown vector $\Delta\mathbf{x}$ containing the estimated parameters, the Jacobi- or Designmatrix $\mathbf{A}$, the weight matrix $\mathbf{P}$, the generic patterns (or PCCs), $\mathbf{r}(\theta,\lambda)$ along the line-of-sight (LOS) to the satellite with zenith distance θ and azimuth angle λ in the antennas body-frame. In this contribution, the vector

$$\Delta\mathbf{x} = \begin{bmatrix}\Delta N & \Delta E & \Delta U & \delta_{rec} & \delta_{trop}\end{bmatrix}^T \tag{2}$$

contains the horizontal components ΔN, ΔE, and the vertical component ΔU of the estimated position as well as the troposphere delay δ_{trop}, and the receiver clock parameters δ_{rec}.

To qualify the impact of the receiver antenna PCCs on the estimates, different sets of generic patterns are used to characterize different kind of PCC patterns or differences of PCCs. The simulation strategy proposed by Geiger (1988) and Santerre (1991) was used, assuming continuous satellite sky distribution and expressing all terms in Eq. 1 by integrals. The initial formulas by Geiger and Santerre were extended to improve on the one hand the approximation of the northern hole in the sky distribution and on the other hand to take into account different observation weighting models like identical-, $\cos\theta$ and $\cos^2\theta$.

3. Generic Patterns

Generic PCC patterns, that are described as error functions in Geiger (1988), are adequate to analyse and get access to the impact of PCC on geodetic parameters. In Fig. 1 four different generic patterns are shown, that can be interpreted as a component on the real receiver antenna PCC pattern.

A typical turnstile (cross dipole) pattern is described by

$$\mathbf{r}(\theta,\lambda) = A\cdot\cos(\theta) \tag{3}$$

with the amplitude A and the zenith distance θ. Fig. 1(a) indicates that this generic pattern is completely independent from the azimuth angle and depends on the amplitude and zenith distance only. Because of the pure zenith angle dependency, inaccurate antenna orientations does not matter.

Modelling the error function of a micro-strip antenna as shown in Figure 1(b) yields

$$\mathbf{r}(\theta,\lambda) = A\cdot\sin(\theta)\cdot\cos(\lambda - a_0) \tag{4}$$

where the orientation of the antenna is modelled by a_0 and the azimuth angle by λ.

Furthermore, an 1-wire ($n = 1$, Fig. 1(c)) or a 4-wire ($n = 4$, Fig. 1(d)) helix antenna is described by

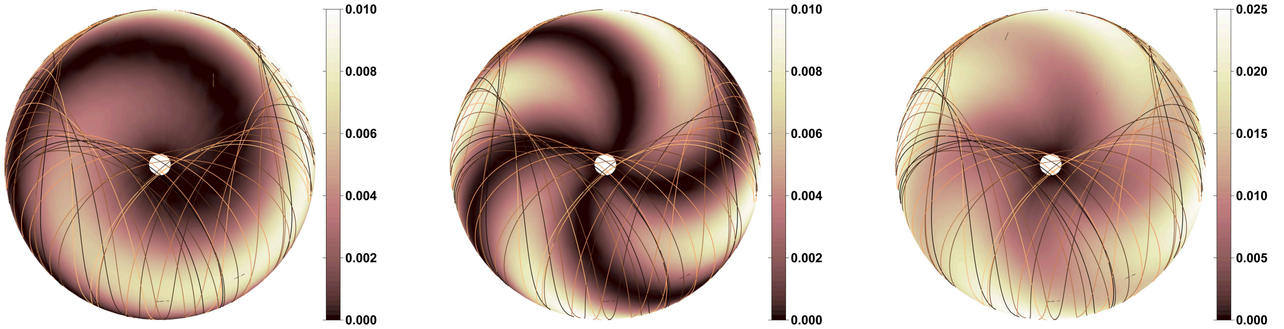
$$\mathbf{r}(\theta,\lambda) = A\cdot\sin(\theta) + D\cdot\cos(\theta)\cdot\cos(n\cdot\lambda - 4\theta - n\cdot a_0) \tag{5}$$

with an additional amplitude D.

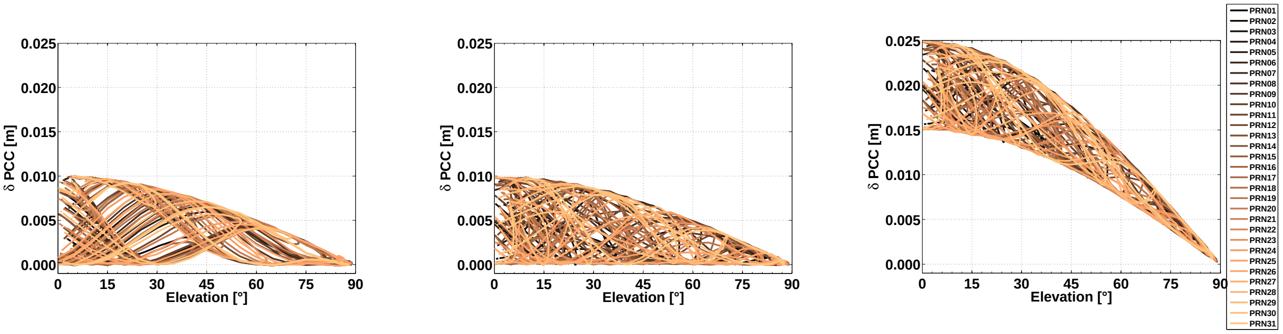
Table 1 summarizes the most prominent patterns and parameter values used in this study to describe differences in the PCC of ionosphere free linear combination (L3). The patterns are part of actual PCC patterns as determined from receiver antenna PCC comparisons at the Institut für Erdmessung (IfE). The considered magnitudes and shapes for L3 PCC are also reported in other studies (Aerts, 2011; Aerts and Moore, 2013) where similar differences between chamber and robot calibrations are obtained for different sets of receiver antenna models. Differences in the up-component of the phase centre offset (PCO) values result in differential PCC patterns similar to the generic pattern of Fig. 1(a), differences in the horizontal PCO to those of Fig. 1(b). If variations in azimuth are taken into account, generic patterns like the 1-wire helix and 4-wire helix (cf. Fig **??**) are adequate as first approximation.

Table 1. Configurations of generic patterns used in the study to analyze the impact on geodetic parameters.

Identifer	Name	Generic Pattern	Parameter Values
P1	turnstile	$\mathbf{r}(\theta,\lambda) = A \cdot \cos(\theta)$	A=1cm
P2	micro-strip	$\mathbf{r}(\theta,\lambda) = A \cdot \sin(\theta) \cdot \cos(\lambda - a_0)$	A=1 cm
P3	1-wire helix	$\mathbf{r}(\theta,\lambda) = A \cdot \sin(\theta) + D \cdot \cos(\theta) \cdot \cos(\lambda - 4\theta - 1a_0)$	A=D=0.5 cm
P{4/5}	4-wire helix	$\mathbf{r}(\theta,\lambda) = A \cdot \sin(\theta) + D \cdot \cos(\theta) \cdot \cos(4\lambda - 4\theta - 4a_0)$	A={0.5 cm/2 cm}, D=0.5 cm



(a) 1-wire helix (A=D=5 mm) (b) 4-wire helix (A=5 mm, D=5 mm) (c) 4-wire helix (A=20 mm, D=5 mm)



(d) 1-wire helix (A=D=5 mm) (e) 4-wire helix (A=5 mm, D=5 mm) (f) 4-wire helix (A=20 mm, D=5 mm)

Figure 2. Sampling of PCC pattern by a real satellite sky distribution. Identical skyplot traces in (a-c) lead to different PCC representations in the observation domain versus elevation as shown in (d-f).

4. Evaluation and Comparison with PPP

4.1 Methodology

The simulation strategy is evaluated by taking the difference of two PPP runs (performed in static mode with 24 hour sessions), where the reference solution is determined without and the second run with additional generic patterns (cf. Tab 1). Results obtained from different software packages are compared to the simulation strategy (model) in Fig. 3.

Setup The first PPP solution is based on a 24 hour data set with an 30 sec data sampling and a cut-off angle of 3°. The data was recorded on DOY339, in 2011 with a Leica AR25.R3 antenna and a Javad TRE_G3T receiver on the laboratory network of the IfE located at a mean latitude of 54°. The solutions for DOY339 are confirmed by repeatability checks of consecutive days (DOY340 and DOY341). The Leica antenna is individually and absolutely calibrated by IfE by using the Hannover Concept of antenna calibration, developed by IfE and Geo++® during joint research projects, (Seeber et al., 1997; Wübbena et al., 1996, 2000, 1997). This calibration facility is accepted in the IGS (Dow et al., 2009) and provides PCC patterns with azimuth and elevation dependent values independently from any reference antenna or place and time of calibration.

Parameters For the second PPP processing, the original azimuth and elevation dependent PCC pattern was manipulated with sets of generic patterns (cf. Tab. 1). For seek of simplicity, since we are interested in the ionosphere-free linear combination (L3), both L1 and L2 patterns are manipulated here with the same generic pattern, so that also for L3 the same generic pattern is used. The troposphere was corrected using the Hopfield model and zenith path delay (ZPD) parameters are estimated as piece-wise linear function with parameter spacing of 2 hours. No gradients were estimated.

The obtained PPP solutions are subtracted from the reference solution. They show only the impact of generic patterns on coordinates, receiver clock and tropospheric delay, respectively. This is true, since the same observation data is used and the impact of the observation noise is eliminated by subtraction. Additionally, first studies show, that the float ambiguity parameters are affected additionally.

The obtained results for the first five parameters (position, receiver clock, troposphere) are summarised in Fig. 3 for the different software packages.

Software Several software packages were used to obtain the different PPP solutions and access the effect of PCC patterns due to different implementation strategies or processing schemes. In this contribution, results using the Bernese 5.2 Software (Dach et al., 2015), CSRS-PPP from Natural Resources Canada's CSRS (Canadian Spatial Reference System) (MacLeod and Tetreault, 2014) and GPS-Toolkit (GPSTk) (Conn et al., 2012) are compared in Fig. 3 with each other.

In addition, a second Bernese analysis was processed using (1) different observation weightings ($\cos z$ vs. equal weighting) as well as (2) different tropospheric mapping functions (global mapping function (GMT) vs. Niell model (Saastamoinen zenith path delay (ZPD) with Niell mapping function)), (Boehm et al., 2006; Niell, 1996). These results are summarised in Fig. 4.

4.2 Impact of Simple Generic Patterns

As expected, the turnstile generic pattern only affects the height component, indicated by the first bar in Fig. 3(a)-3(e). In Fig. 3 the bars (2-5) show the typical behaviour, expected for the generic pattern of a micro-strip model, where only the horizontal component is affected by the introduced generic pattern. The orientation a_0 is varied from 0° to 35° (5) in 10° steps.

In both cases (turnstile and micro-strip) the magnitude in position domain (10 mm) equals the amplitude in the observation domain (10 mm). Thus, neither an amplification nor a reduction of possible discrepancies in PCC pattern of these types occur when analysing the parameters.

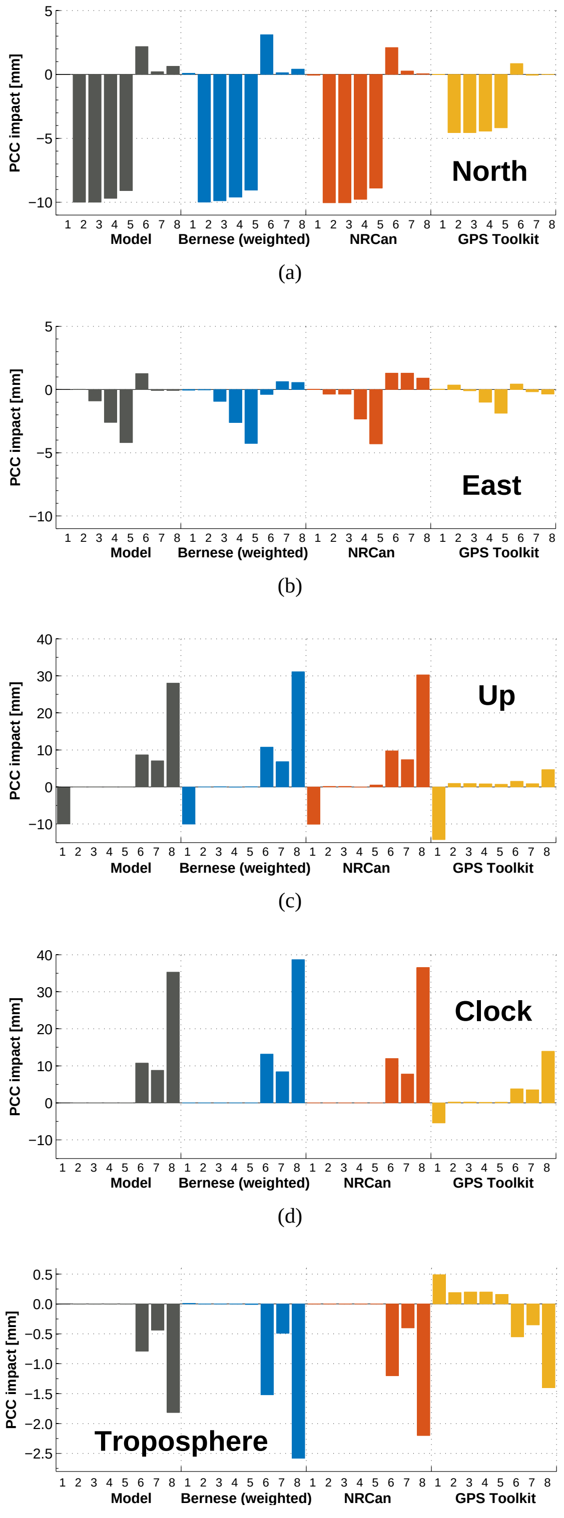
The Fig. 3 also indicates, that all software packages (expect GPS Toolkit) agree at the sub-millimetre level with respect to the values from simulations (model). In the case of GPSTk, the studies shown that exact the half of the amplitude in the observation domain is transferred to the horizontal position domain. From Fig. 3 it can be noted additionally, that GPSTk show differences between the expected model values for receiver clock and troposphere parameter.

Additionally, further studies (Hiemer et al., 2015) showed that the observation weighting has no significant impact on this comparison for turnstile and micro-strip antennas as depicted in Fig. 3.

4.3 Impact of Complex Patterns

Comparison for several software packages: Contrary to the previous results, patterns of 1-wire and 4-wire helix affect all geodetic parameters cf. Fig. 3, bars 6-8. Due to high correlations between up component, clock and troposphere parameters, they are most sensitive for elevation dependent patterns. Different software solutions show similar qualitative pattern but vary about few millimetre, except for GPSTk where the variations are more important. It is very important to note that the impact of generic patterns on the up component (ΔU) and clock parameter (δ_{rec}) can reach values of approx 40 mm, much larger than the pattern itself (25 mm), compare Fig. 3 bar 6 and 7 (magnitude of 10 mm for 1-wire and 4-wire helix) with bar 8 where a magnitude of 25 mm for the 4-wire helix occurs. Thus, an amplification of PCC differences of this type are obtained.

Comparison for different processing strategies: In Fig. 4 the findings for complex patterns with two different processing strategies are summarised. The simulation of complex patterns for 4-wire helix antenna (II, III) with amplitudes of $A = D = 5$ mm agrees very well with the results from Bernese for all components. However, differences occur for



(a)

(b)

(c)

(d)

(e)

Figure 3. Differences between solutions obtained with different software packages, (1) turnstile, (2-5) micro-strip with orientations a_0 from 0° to 30°, (6) 1-wire helix, (7) 4-wire helix and (8) 4-wire helix with higher amplitude. Bernese results are obtained using $\cos z$ weighting, while the model and the other products run with equal weighted observation weighting.

different amplitudes, e.g. in the case of 4-wire (III) with $A = 20\,\text{mm}$ and $D = 5\,\text{mm}$, differences of 3-5 mm in the up component and receiver clock parameter are clearly detectable, cf. Fig. 4(c,d). The troposphere parameter is challenging since the discrepancies differ between 1 mm and 4 mm depending on the chosen amplitude (A versus D), cf. Fig. 4(e). Furthermore, the agreement between data and simulation of 4-wire helix antenna is better than for the 1-wire model. This is mostly depending on the non-symmetrical distribution of the 1-wire helix generic pattern, cf. Fig. 2(a) vs. Fig. 2(c). This emphasizes that the parametrization of the satellite sky distribution has an important impact on this simulation strategy and has to be modelled as precisely as possible. Therefore, an adequate distribution function to parametrise the satellite sky distribution for different geographic latitudes has to be improved.

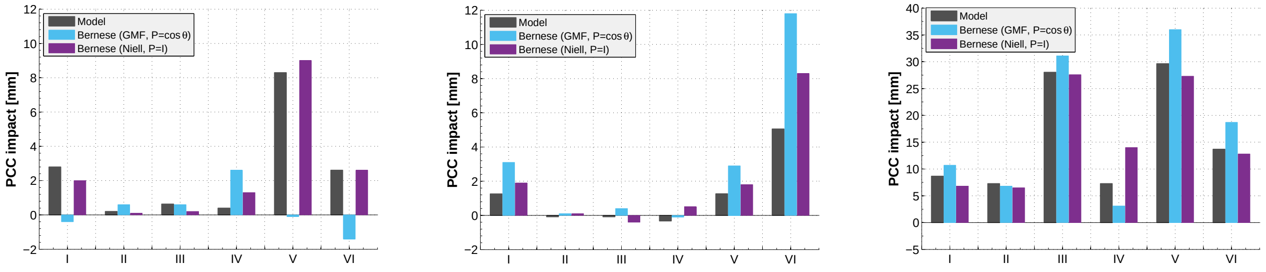
5. Conclusions

The analysis shows, that the improved theoretical model of generic PCC patterns gives valuable and qualitative information on the impact of variations of the PCC patterns on the estimated geodetic parameters. It should be stressed, that all geodetic parameters should be analysed including e.g. clock parameters and tropospheric delays as well as ambiguities, since besides positioning also time and frequency transfers as well as meteorological studies are important fields of GNSS. The values obtained from the simulations are generally smaller than those obtained from software packages.

The analysis showed that not only the magnitude of a PCC pattern but especially its shape is critical for a classification of the impact on geodetic parameters. Patterns $A\cos\theta$ and $A\sin\theta\cos(\lambda - a_0)$ are 1:1 transferred to the vertical and horizontal coordinates, respectively. The user should be aware that more complex pattern, like e.g., n-wire helix affect all parameters and the magnitude in the parameter domain can be amplified by up to 68% compared to that of the pattern. This can be the case, when type mean values are used instead of individual PCCs.

Acknowledgement

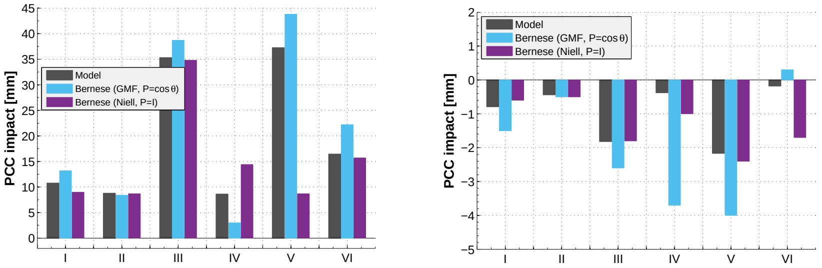
The authors acknowledge Leonard Hiemer, who processed and prepared parts of this work during his master thesis and beyond that. Furthermore, we thank Julia Leute from the Physikalische Bundesanstalt Braunschweig (PTB) for processing the generic patterns with the CSRS-PPP (NRCan). The comments of the three anonymous reviewers helped to improve the manuscript.



(a) north component

(b) east component

(c) up component



(d) receiver clock parameter

(e) tropospheric parameter

Note	Model	A [mm]	D [mm]
I	1-wire	5	5
II	4-wire	5	5
III	4-wire	20	5
IV	1-wire	20	20
V	1-wire	20	5
VI	1-wire	5	20

Figure 4. Additional studies with Bernese using 1-wire and 4-wire generic patterns with GMF-Model and elevation weighted (P=cos θ) as well as unweighted (P=I) observations with Niell.

References

Aerts, W. (2011). Comparison of UniBonn and Geo++® Calibration for LEIAR25.R3 antenna 09300021. Technical report, Royal Observatory of Belgium.

Aerts, W. and Moore, M. (2013). Comparison of UniBonn and IGS08 Antenna Type Means. White paper, International GNSS Service - Antenna Working Group IGS-AWG. EMail: IGS-AWG-393.

Baire, Q., Legrand, C. B. B., Pottiaux, E., Aerts, W., Defraigne, P., Bergeot, N., and Chevalier, J. M. (2014). Influence of Different GPS receiver antenna Calibration models on geodetic positioning. *GPS Solutions*, 18(4):529–539.

Becker, M., Zeimetz, P., and Schönemann, E. (2010). Anechoic Chamber calibrations of phase center variations for new and existing GNSS signals and potential impacts in IGS processing. In *IGS Workshop 2010 and Vertical Rates Symposium, June 28 - July 2, Newcastle upon Tyne, United Kingdom of Great Britain*.

Bilich, A. and Mader, G. (2012). GNSS Absolute Antenna Calibration at the National Geodetic Survey. In *IGS Workshop 2012, University of Warmia and Mazury, July 23-27, Olsztyn, Poland*. Poster.

Bilich, A., Schmitz, M., Görres, B., Zeimetz, P., Mader, G., and Wübbena, G. (2012). Three-Method Absolute Antenna Calibration Comparison. In *IGS Workshop 2012, University of Warmia and Mazury, July 23-27, Olsztyn, Poland*.

Boehm, J., Niell, A. E., Tregoning, P., and Schuh, H. (2006). Global mapping function (gmf): A new empirical mapping function based on numerical weather model data. *Geophysical Research Letters*, 33(7):4.

Conn, T., Gaussiran, T., Harris, R. B., Mach, J. L. R., Munton, D., Renfro, B., Tolman, B., Craddock, T., and Vermeer, M. (2012). *The GPS Toolkit - A User's Guide for Scientists, Engineers and Students*. The University of Texas at Austin. GPSTk Revision 1038.

Dach, R., Lutz, S., Walser, P., and Fridez, P., editors (2015). *Bernese GNSS Software Version 5.2*. Astronomical Institute, Universtiy of Bern, Bern Open Publishing. DOI: 10.7892/boris.72297.

Dow, J. M., Neilan, R., and Rizos, C. (2009). The International GNSS Service in a changing Landscape of Global Navigation Satellite Systems. *J Geod*, 83(3-4):191–198. DOI: 10.1007/s00190-008-0300-3.

Geiger, A. (1988). Modeling of Phase Centre Variation and its Influence on GPS-Positioning. In *GPS-Techniques Applied to Geodesy and Surveying*, volume 19 of *Lecture Notes in Earth Sciences*, pages 210–222. Springer.

Hiemer, L., Kersten, T., and Schön, S. (2015). On the Impact of GPS Phase Center Corrections on Geodetic Parameters:

Analytical Formulation and Empirical Evaluation by PPP. In *Geophysical Research Abstracts*, *EGU General Assembly 2015*, *Vienna*, *Austria*, volume 17.

Kersten, T. and Schön, S. (2013). On Adequate Comparison of Antenna Phase Center Variations. In *AGU Fall Meeting*, *December 09.-13.*, *San Francisco*, *California*. Abstract #G13B-0950.

MacLeod, K. and Tetreault, P. (2014). NRCan Precise Point Positioning (PPP) Service. In *Civil GPS Service Interface Committee, Tampa Convention Center, September 8*.

Moore, M. and Ridell, A. (2016). Geoscience Australia Antenna Calibration Facility. In *Internatinal GNSS Service (IGS) Workshop, February 08.-12.*, *Sydney, NSW, Australia*.

Niell, A. E. (1996). Global mapping functions for the atmosphere delay at radio wavelengths. *Journal of Geophysical Research*, 101(b2):3227–3246.

Santerre, R. (1991). Impact of GPS satellite sky distribution. *Manuscripta Geodaetica*, 16:28–53.

Schmid, R., Dach, R., Collilieux, X., Jäggi, A., Schmitz, M., and Dilssner, F. (2015). Absolute igs antenna phase center model igs08.atx: status and potential improvements. *Journal of Geodesy*, 90(4):343–364.

Seeber, G., Menge, F., Völksen, C., Wübbena, G., and Schmitz, M. (1997). *Advances in Positioning and Reference Frames*, volume 118 of *International Association of Geodesy Symposia*, chapter Precise GPS Positioning Improvements by Reducing Antenna and Site Dependent Effects, pages 237–244. Springer Berlin Heidelberg.

Sidorov, D. and Teferle, F. (2012). Antenna phase center calibration effects on sub-daily and daily position estimates. In *IGS Workshop 2012, University of Warmia and Mazury, July 23-27, Olsztyn, Poland*.

Steigenberger, P., Hugentobler, U., Schmid, R., Hessels, U., Klügel, T., and Seitz, M. (2013). GPS-Specific Local Effects at the Geodetic Observatory Wettzell. In *Reference Frames for Applications in Geosciences*, volume 138 of *International Association of Geodesy Symposia*, pages 125–130. Springer Berlin Heidelberg. DOI: 10.1007/978-3-642-32998-2_20.

Wübbena, G., Menge, F., Schmitz, M., Seeber, G., and Völksen, C. (1996). A new approach for field calibration of absolute antenna phase center variations. In *The Institute of Navigation (ION GPS 1996), September 17 - 20, Kansas City, MO*, pages 1205 – 1214.

Wübbena, G., Schmitz, M., Menge, F., Böder, V., and Seeber, G. (2000). Automated Absolute Field Calibration of GPS Antennas in Real-Time. In *The Institute of Navigation (ION GPS 2000), September 19 - 22.*, *Salt Lake City, UT, USA*, pages 2512–2522. Institute of Navigation (ION).

Wübbena, G., Schmitz, M., Menge, F., Seeber, G., and Völksen, C. (1997). A New Approach for Field Calibration of Absolute Antenna Phase Center Variations. *Navigation*, 44(2):247–256.

Zeimetz, P. and Kuhlmann, H. (2008). On the Accuracy of Absolute GNSS Antenna Calibration and the Conception of a New Anechoic Chamber. In *Proceedings of the FIG Working Week 2008 - Integrating Generations, June 14-19*, *Stockholm*, *Sweden*, page 16.