Results of Absolute Field Calibration of GPS Antenna PCV[1]

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BIOGRAPHY

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ABSTRACT

The electromagnetic behavior of antennas is not homogeneous. The so-called phase center variations (PCV) describe the signal reception of GPS antennas and have been an important field of interest for the GPS community during the last years and still are. It remains as a main goal to improve antenna calibration procedures and to evaluate their accuracy. The paper presents some results of an approach, which can determine azimuth- and elevation-dependent PCV of GPS antennas in an absolute sense through a field calibration. The PCV for different antenna types derived from absolute field calibrations are evaluated and remaining error sources are discussed. The impact of absolute PCV on regional/global networks using mixed or even identical antenna types is characterized.

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INTRODUCTION

The determination of PCV for GPS antennas and the introduction in the processing of operational field surveys is an important field of research these days. In order to reach the millimeter accuracy level in networks consisting of different antenna types, especially concerning the height component, the application of PCV is inevitable. Beside these engineering surveys the processing of larger networks is also problematic due to the estimation of a tropospheric scale factor, which is biased by the uncorrected phase pattern resulting in height errors (UNAVCO 1995, Rothacher et al. 1995a). The PCV effect is misinterpreted as tropospheric refraction and height. Furthermore, absolute PCV are requisite for large networks, even if using the same antenna type, because the directions of the simultaneously received signals are different on all sites and thus have to be corrected with different PCV values. This kind of application needs further investigation since the most often used PCV calibration sets (Rothacher et al. 1996, Mader 1998) are currently relative with respect to a reference antenna with a PCV pattern set to zero.

Beside these relative field calibrations, also absolute calibrations are possible. On the one hand, there is the calibration in anechoic chambers (e.g. Schupler 1994), which is using simulated GPS signals. On the other hand, there exists an absolute field calibration technique. The basic ideas and functionality of this procedure have already been successfully proven, showing the feasibility of a direct absolute calibration in the field and the treatment of multipath errors using sidereal day time differenced observations (Wübbena et al. 1997). Several aspects of the procedure are still evolving. Nonetheless, different absolute calibration sets have been determined, which now will be evaluated in an operational GPS application.

ABSOLUTE FIELD CALIBRATION - SUMMARY

The absolute field calibration of GPS antenna PCV is so far implemented in the GPS software package GEONAP (Wübbena 1989) using undifferenced observations. The idea for and the development of the procedure was mainly caused by the fact, that the existing field surveys are relative and are influenced by multipath (Rothacher et al. 1995a), since no observation site can be totally unaffected by this effect.

In order to avoid correlations of the estimated PCV with the calibration site, the basic idea of the procedure is the use of the repeated satellite constellation after one mean sidereal day. Thus, in case of unchanged multipath conditions on the site, the multipath effects repeat with the same periods. Forming the differences of the observations between two sidereal days, the multipath error term together with the phase center variations and the geometric information (since the design matrix is almost identical) is eliminated. Investigations concerning the exact period of the geometry repeatability (Seeber et al. 1997) revealed slightly different values (24 h - 240...254 s) for each satellite instead of the generally assumed number of 24 h - 236 s. A mean value for a calibration can be calculated from the actual observations. Nevertheless, the calibration is rather insensitive to differences of a few seconds. As already mentioned, the interesting PCV are also removed while forming the observation differences. But this information is re-obtained through rotations and tilts of the calibrated antenna on one of the two days using a calibrated antenna mount. This procedure additionally contributes to a good coverage with satellite observations over the whole antenna's hemisphere without a 'northern hole' and allows a determination of PCV down to zero degree elevation.

The observation equation for the mean sidereal day time difference δ^{SID} yields (multipath and geometric information eliminated; different d_{PCV} for the two days; remaining differences on a short baseline are very small for atmospheric errors d_{ION}/d_{TROP} or are correctly modeled; clock errors dt/dT):

$$\begin{aligned}\delta^{SID} l_{\Phi i}^{\,j} &= c_0 \cdot (\delta^{SID} dt_i - \delta^{SID} dT^j) - \lambda \cdot \delta^{SID} N_i^j \\ &\quad - \delta^{SID} d_{ION\,i}^{\;j} + \delta^{SID} d_{TROP\,i}^{\;j} \\ &\quad + d_{PCV\;\;i}^{(\alpha_0, z_0)\,j} - d_{PCV\;\;i}^{(\alpha_0+\Delta\alpha, z_0+\Delta z)\,j} + \delta^{SID} \varepsilon_\Phi .\end{aligned}$$

Obviously, the difference between the PCV values of two days now leads to a value unequal zero. Hence, the observable for the estimation of the absolute PCV is a difference of two antenna orientations' PCV. However, it is still an absolute approach, because PCV for a single antenna are calculated independently from a reference antenna. A spherical harmonic function serves for the determination of elevation (and azimuth) dependent PCV (P_{nm} are the normalized associated Legendre functions):

$$d_{PCV}(\alpha, z) = \sum_{n=0}^{n_{\max}} \sum_{m=0}^{n} (A_{nm} \cos m\alpha + B_{nm} \sin m\alpha) P_{nm}(\cos z).$$

Thus, the PCV are estimated in one adjustment without separating phase offset and phase pattern and refer to that point of the antenna, which is adjusted to the point of intersection of the rotation axis of the antenna mount during the calibration procedure. The low order coefficients represent the offset to that reference point. Generally, an antenna is only completely described by the combination of offsets (or reference point) and associated PCV referring exactly to that point. Only in this case one can avoid systematic errors, because an offset represents a mean value derived from a special geometry (elevation mask dependent). More detailed descriptions of the absolute approach and the calibration procedure can be found in Wübbena et al. (1996, 1997). Several different antenna types have been calibrated (Ashtech Geodetic I, II, III, Marine and Choke Ring Dome; Trimble 4000ST L1/2 Geod and Choke Ring), but so far there are only several calibration sets for the Ashtech Geodetic II model.

APPLICATION IN MIXED BASELINES - EVALUATION

Some tests for the evaluation of several absolute calibrated antenna types were carried out on the roof of the Geodetic Institute at the Universität Hannover on two days (210, 211) in 1998. Five Ashtech antenna types were mounted on pillars (Table 1) with baseline lengths between 5 and 8 m.

Table 1 - Used antenna types

Pillar no.	Antenna type (ASHTECH)
8	Geodetic III, 700718.B
7	Geodetic II, 700228.D Rev. B
6	Geodetic I, 700228.A
5	Choke Ring Radome, 700936.E
4	Marine, 700700.B

All ambiguities were fixed during the processing of the two 24 h data sets. Several kinds of coordinate sets for different signals (original L1, L2, ionospheric corrected L0, Narrow-Lane LN) were generated using mean offsets, relative PCV (Mader 1998) and our absolute PCV. Additionally, solutions with different references (fixed coordinates) and 1 h and 0.5 h solutions were generated. As expected, the horizontal positions are not problematic, therefore the presented results will focus on the height component. In this way, the quality of the PCV corrections can be best evaluated. The results of a precise leveling for the pillar heights served as a reference.

Only some representative results from the multiple comparisons will be shown. First of all, in Figures 1-3 the differences between leveled heights and GPS derived heights are presented for the signals L1 (original signal, 3.0 mm noise), LN (combination of L1/L2, 2.4 mm lowest noise) and L0 (ionospheric corrected signal, 10.0 mm high noise) for both days with reference pillar 8 (Ashtech Geodetic III), elevation mask 15°. These three signals represent the results for both frequencies and furthermore different areas of applications, e.g. LN for small engineering networks and L0 for larger networks. Only the results concerning the introduced relative and absolute PCV are shown (remarks to offsets will follow later in this paragraph).

The figures of L1 and LN show, that with these lowest noise signals one can reach accuracies ≤ 5 mm with both used PCV sets.

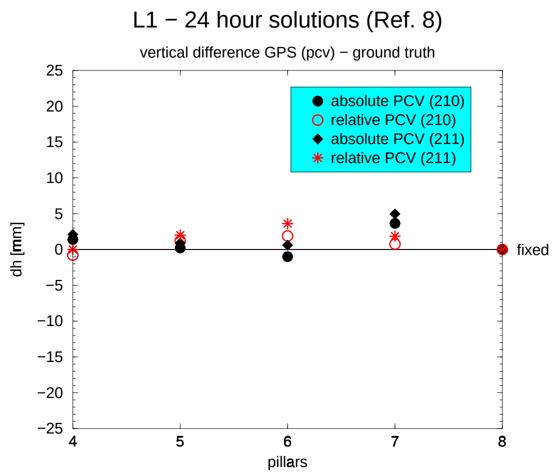

Fig. 1 - Height difference GPS-leveling, L1

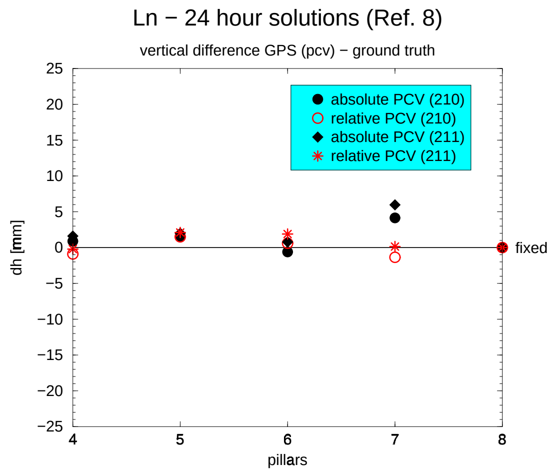

Fig. 2 - Height difference GPS-leveling, LN

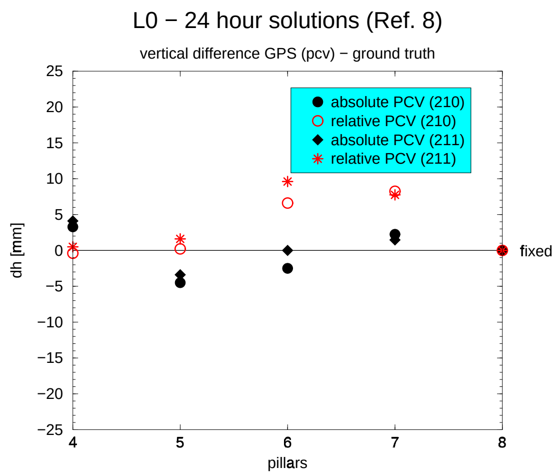

Fig. 3 - Height difference GPS-leveling, L0

Except for pillar 7, both PCV sets are at the same accuracy level. Considering the observation noise of the signals (2...3 mm), the significance of the differences is hardly to evaluate. The plot of the L0 results demonstrates, that also both PCV sets allow precise solutions for a small network in the $\leq$ 10 mm range. For these and the following results one has to keep in mind, that all solutions are a function of the fixed reference antenna and its associated PCV. A different reference antenna (e.g. pillar 7 fixed instead of pillar 8) produced a slightly different result depending on the quality of the PCV.

As an extension to the prior results, the L0 solutions for the relative and absolute PCV corrections with additionally estimated tropospheric parameters are depicted in Figure 4 (day 211, reference pillar 8). The plots show, that both PCV sets can already describe the real phase pattern quite well, valid for short baselines. An existence of remaining PCV errors is indicated by the degraded solutions with estimated trophospheric parameters. However, these errors of up to several cm also can be attributed to remaining multipath effects. Earlier investigations of the multipath environment at the test site revealed a high influence.

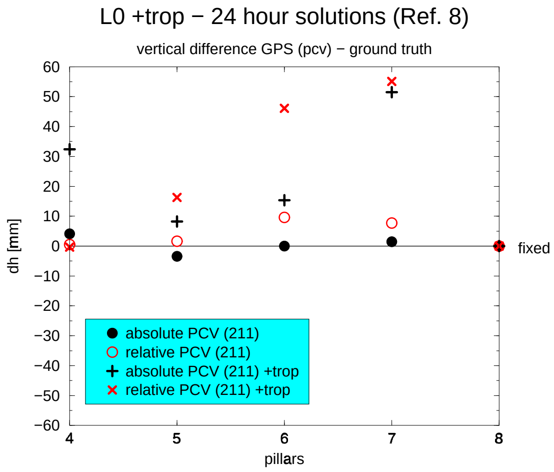

Fig. 4 - Height difference GPS-leveling, L0, +trop

As an example for short time observations, 1 h and also 0.5 h L1 results for one antenna (Geodetic I, reference pillar 4, Choke Ring) are presented in Figure 5 and 6. Also an 'offset only' correction using values from Mader (1998) is shown in order to explain the problem with just an offset correction in general. The precision of short time observations is a very important issue for economic operational GPS surveys. For these applications there is scarcely no averaging effect over the time - the PCV must be precisely known. Due to the multipath influence, no shorter data sets were selected for this example.

The 1 h results are almost in the same range than the previous long 24 h observations. The variations of the 0.5 h observation blocks are a little higher, but still on a sufficient level. The results show a systematic effect, if only offsets are used. This is especially valid for short time measurements. It also holds true for longer observation periods, because a mean phase center can never represent exactly the actually needed phase pattern for a satellite constellation.

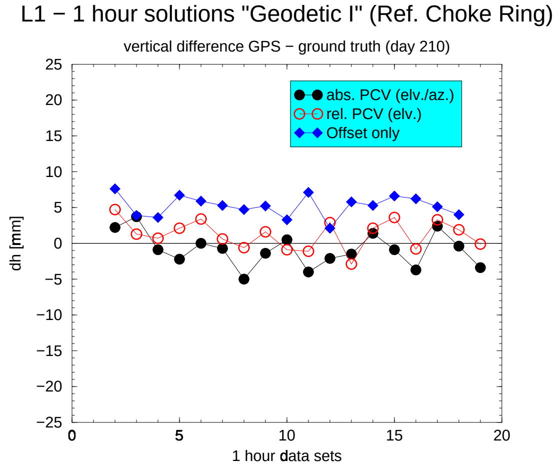

Fig. 5 - 1 h results Ashtech Geodetic I antenna, L1

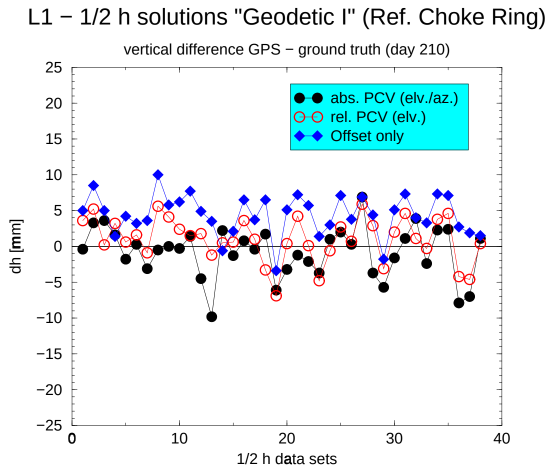

Fig. 6 - 0.5 h results Ashtech Geodetic I antenna, L1

The last plot for the mixed baseline calculations leads to a short discussion of remaining effects within the procedure of absolute field calibration. In Figure 7 the L1-24 h-results (day 210, reference pillar 7) with different PCV corrections and offsets introduced are shown. There seems to be a problem with the offset and not with the PCV corrections, derived from the absolute field calibration, especially on pillar 8 (Geodetic III). An assessment was carried out using calibration sets of the Geodetic II antenna. This type is the only model we calibrated 4 times up to now. Therefore we checked the different offset results. Again, inconsistencies in the range of several mm show up. The reason for this problem is due to the used model for the offset estimation within the spherical harmonic function. Since we work in an absolute sense, the adjustment model $\sum \underline{vv}_{phase} \Rightarrow$ min is not the exact representation for the pure offset estimation (degree m and order n = 1). A model $\sum \underline{vv}_{pcv} \Rightarrow$ min of the absolute PCV should improve the offset results in the future.

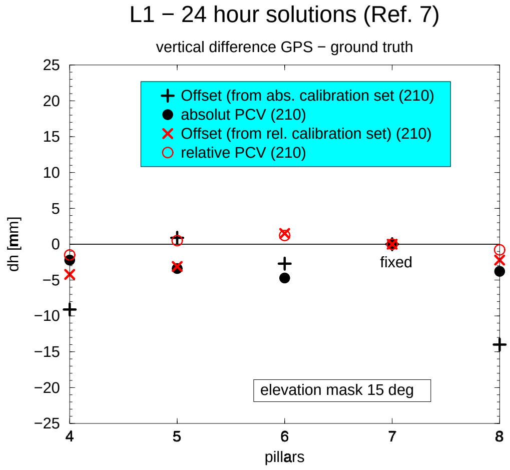

Fig. 7 - Height difference GPS-leveling, L0, Offsets

The other factors with remaining impacts on the absolute PCV approach are generally known and currently evaluated. The used antenna mount has some disadvantages, namely shading effects within the axis for the tilts (90°, 270°), the stability, the precision, and the complicated calibration for the mount. A second group of possible factors are concerned with remaining differential effects of the multipath and antenna gain. Changes of multipath effects due to the rotations/tilts and to different weather conditions (humidity of reflectors) are currently investigated.

An example for the repeatability of absolute PCV determination is shown in Figure 8. The Ashtech Geodetic II antenna was calibrated two times (days 63/64 and 65/66 in 1997) under almost equal conditions (consistent weather conditions etc.). The differences are in the range of +/- 2 mm, whereas the absolute range is approximately 2 cm.

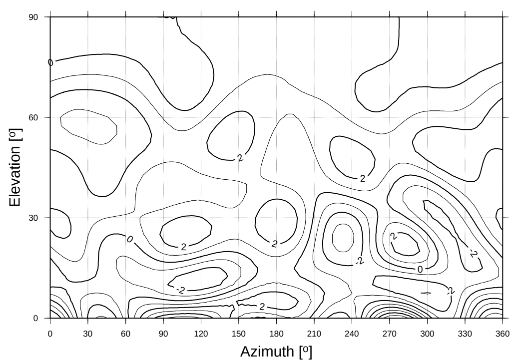

Fig. 8 - Repeatability Geodetic II calibration (L1) [mm]

A great step forward will be an automation of the procedure with a robot. Currently, the use of a robot and the resulting benefits are investigated in a research project (concerning the antenna calibration and the multipath issue).

ADVANTAGES OF ABSOLUTE PCV - DISCUSSION

At his point, the question of the advantages of absolute PCV compared to relative PCV arise, because of the considerable efforts for the absolute approach.

In brief, the advantages of an absolute field calibration are the following ones:

- calibration of a single antenna, independent from a reference antenna
- multipath elimination/reduction, independent of site
- no reference coordinates necessary
- calculated PCV refer to a well known antenna reference point, offset incorporated, no pre-determination of an offset necessary
- antenna covered well with correction values due to the rotations/tilts, possibly down to elevation zero

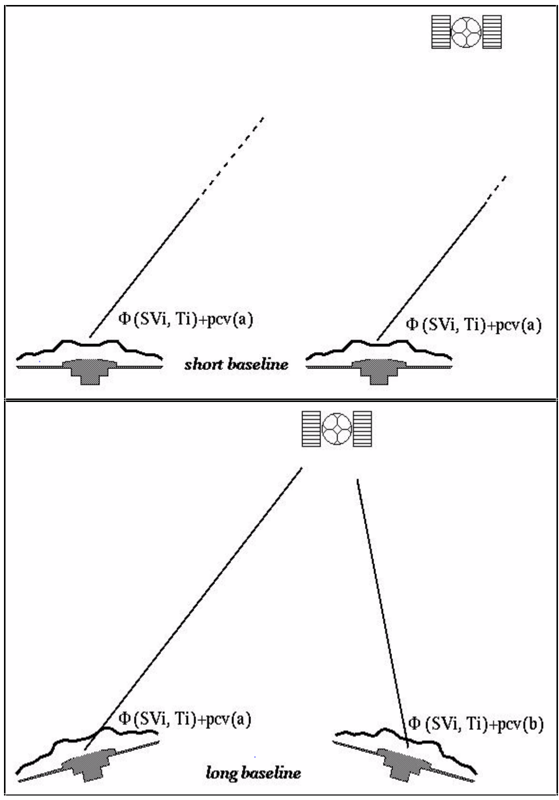

Fig. 9 - Directions of simultaneously received signals

The importance of the absoluteness itself should not be underestimated as the effects in large networks will show. Since relative calibrations only represent the difference of PCV to a reference antenna with a pattern set to zero (Rothacher, Mader 1996, Mader 1998), the reference antenna is not corrected. The relative PCV corrections with the widest distribution refer to the Dorne Margolin T choke ring antenna (DM-T), e.g. the mostly used type in the permanent network of the International GPS Service for Geodynamics (IGS). Beside the zero correction of this type, also the relative PCV for the other antenna types 'lack' in that particular absolute PCV range. The consequences can be explained with the help of the sketches in Figure 9. The satellite signals in a small network will be received under almost identical elevation and azimuth angles. Therefore a 'no correction' for the same antenna type does not effect the coordinate estimation, because it is the same error on each station. The direction of the simultaneously received signals will differ more and more with an increasing baseline length. Thus, the effect of the not considered PCV is also different on each station and does not cancel out. The effect increases while estimating tropospheric parameters.

USING IDENTICAL ANTENNAS - EXPERIMENTS WITH ABSOLUTE PCV

In order to evaluate the influence of absolute PCV in a network consisting of the same antenna type, the following experiments have been carried out:

- processing of a short baseline
- processing of a simulated zero-baseline
- processing of a large network

Only DM-T antennas participated in these tests. This antenna was chosen, because it is the mainly used type within the permanent network of the IGS and also serves as the reference model (pattern set to zero) in various relative calibrations. Since a DM-T antenna was not accessible for an absolute field calibration, we used the absolute PCV of an Ashtech Choke Ring antenna, which has a very similar phase pattern (Mader 1998).

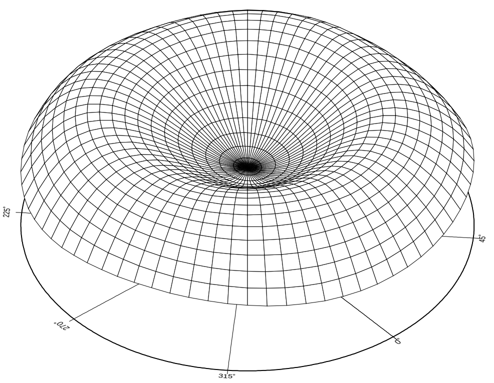

Fig. 10 **-** Phase pattern (qualitative) L1 Choke Ring

The absolute PCV were transformed to the generally used offset for the DM-T (L1 and L2 $[n,e,h]_m$ = 0.0,0.0,0.110 / 0.0,0.0,0.128). A total uniformity to the real DM-T phase pattern is not important for the experiments, since all antennas are corrected equally with the same values. The used absolute PCV for L1 are shown in Figure 10. There are almost no azimuth dependencies. The variations span a range of approximately 1.5 cm and are quite similar to other absolute chamber calibrations (Schupler 1994, 1995, UNAVCO 1995). The variation range for L2 is a little bit smaller.

Every analysis was carried out with GEONAP. First of all, a short baseline (length 65 m) was processed. We used a 24 h data set from the Wettzell 1995 calibration campaign (Rothacher et al. 1995b), with a baseline of two DM-T antennas. The height components of four different baseline solutions (always elevation mask 15°, ionospheric corrected linear combination L0) were compared (see Table 2).

Table 2 **-** Short DM-T baseline comparisons

Options A		Options B		Δ dh
Point 1	Point 2	Point 1	Point 2	[cm]
-pcv	-pcv	+pcv	+pcv	0.0
-pcv+t	-pcv+t	+pcv+t	+pcv+t	0.0
+pcv	+pcv	+pcv+t	+pcv+t	1.2

(-/+ pcv = no PCV/absolute PCV, +t = trop. parameter estimated)

The comparisons show the expected results for a short baseline with always identical conditions for both points (atmosphere, multipath, satellite directions). There is no difference between the coordinate solution without and with absolute PCV introduced. There is also no difference between these two solutions when tropospheric parameters are estimated. These expected results verify the later results in the large network. The difference between the estimated coordinates without and with tropospheric parameters results from multipath effects, which are misinterpreted by the tropospheric parameters as tropospheric changes (e.g. UNAVCO 1995).

The next experiment was the processing of a simulated zero-baseline. The goal was to 'extract' the total effect of the absolute PCV when the ionospheric corrected signal L0 is used and tropospheric parameters are estimated. Therefore the observation file of one station of the previous test data was duplicated. Only one file was updated with absolute PCV. Afterwards the solution for the zero-baseline was calculated, hence, the deviations from zero show the absolute effect due to these PCV corrections while using L0 and adjusting a tropospheric scale factor. An effect appears almost only for the height component, as expected, because of the dominant elevation dependent corrections and the horizontal satellite symmetry for 24 h observations. The height component for the zero-baseline is 8.1 cm (2.2 cm without tropospheric estimation). The exact values are of course only valid for this special observation data and the used PCV, but gives a good impression about the total effect of absolute PCV for this kind of coordinate estimation.

But the starting point for the tests was the possible influence of absolute PCV in a large network with identical antennas, where the directions of the simultaneous tracked satellites differ. The general assumption is 'no correction' of absolute PCV for an identical antenna type. Therefore the data of one day of several IGS stations with DM-T antennas were selected (Figure 11), namely the stations WTZR, MADR, MATE, ANKR, ZWEN with baseline lengths between 1000 and 2000 km. Additionally stations for an even more extended DM-T network were taken, REYK, ALGO, KOUR, ASC1, resulting in distances of more than 8600 km. The experiment was quite simple. Only the difference between two solutions was compared. Thus, there are no dependencies to reference coordinates (and their calculation) and to the quality of the processed network. The first coordinate set was derived from a L0-solution with tropospheric parameters estimated, an elevation mask of 10°, precise ephemeris (IGS combined orbits), the coordinates of one fixed point (WTZR) and no PCV corrections introduced - a normal procedure for the processing of a large network. The second coordinate set was calculated exactly the same way (identical data and options), except for the correction of all stations with the same absolute PCV. The comparison of the two solutions revealed amazing differences. Within the smaller, regional network WTZR, ANKR, MATE, ZWEN, elevation and azimuth of simultaneously received satellites can differ more than 20°, individual components show differences up to 3.5 cm. There are differences in the horizontal and vertical components, mainly because of the fixing of the base-coordinate (WTZR). Therefore, the residual vectors are within the direction of the baseline from this fixed point. The comparison of the two solutions for the global network show even larger differences, e.g. up to more than 7 cm for one individual component (Figure 11).

Transformations between the two solutions for the smaller and the larger network always comprise a scale factor of more than $1.2 \cdot 10^{-8}$, a value that already appeared in connection with comparisons with absolute PCV from chamber calibrations (Rothacher et al. 1995a). But in our example, the absolute PCV are evaluated (see other paragraphs) referring to an exactly known reference and thus, the great influence is simply due to the correct inclusion of absolute PCV. The bias can be clearly seen in the increase of all baseline lengths for the case of introduced absolute PCV. A mean bias for the baseline was calculated to 0.0138 ppm (Figure 12). The 'no correction' of absolute PCV in large networks leads to a great systematic error, mainly to a scale in the baseline length, because the tropospheric parameters also mis-model the uncorrected phase pattern differently for all stations due to the different satellite directions. This is underlined by the result of a comparison of two solutions without troposphere estimation, where the differences are much smaller. Still, the effect of 'no correction' of absolute PCV clearly shows up, even for identical antennas.

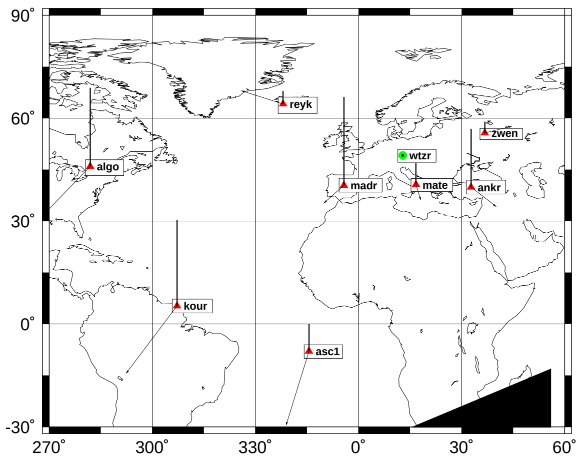

Fig. 11 - Test network, residuals +/- absolute PCV

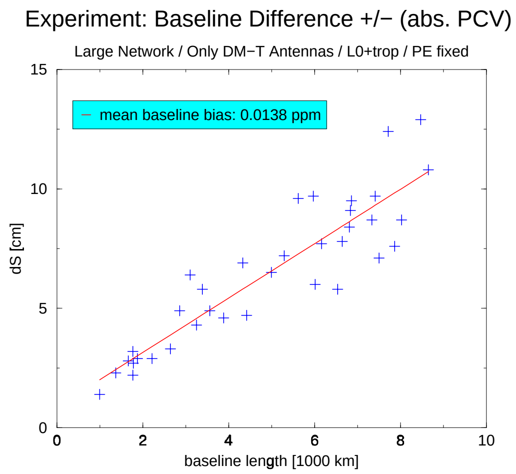

Fig. 12 - Baseline differences +/- absolute PCV

One conclusion of this experiment is the necessity of absolute PCV in order to reach an accuracy level of 1 cm/1000 km for the absolute positioning and scale of a network and avoid this systematic error. Again, the exact values of the effect are only valid for the data and options of this special experiment, but clearly show a great effect and should encourage the GPS community to be aware of this influence on network processing.

SUMMARY AND CONCLUSIONS

The results from field calibrations of absolute phase center variations for several antenna types have been evaluated in different operational GPS applications. A network of 5 antenna types was processed using absolute PCV values and compared with ground truth heights derived from a highly precise leveling. The absolute PCV show their effectiveness. Good results can be achieved, also in comparison with other sets of PCV calibrations (relative PCV). With a combination of different antenna types, accuracies below 5 mm for the estimated height component in a small engineering network are possible. Nonetheless, the estimation of a tropospheric scale factor leads to height errors in the cm-range. This emphasizes the fact, that a serious problem is the impact of multipath, which will be a more and more important field of research for the GPS community, especially concerning the operation of permanent reference stations.

Still, the efforts for a more precise determination of antenna PCV and their application in GPS field measurements have not reached the 1 mm border for mixed baselines, which the GPS community is striving for. Remaining factors to be investigated more deeply for our approach of absolute field calibration are the currently used antenna mount (precision, calibration, shading effects) and remaining differential multipath effects caused by the rotations/tilts of the mount and changing weather conditions. The limiting factors in using the absolute PCV approach for operational calibrations are the technical constraints and the considerable efforts during the field procedure. Therefore, a future goal is an automation. Currently, the use of a robot is in an initial stage.

The advantages of the absolute approach (namely the possibility to calibrate a single antenna, the independence from a reference antenna and reference coordinates, the multipath reduction) are predominant. Moreover, relative calibration values give only the difference of PCV to a reference antenna. In an experiment, 'no correction' compared to 'absolute correction' of this particular reference antenna type in a large network shows a relevant influence. Thus, for the network scale it is necessary to correct the absolute PCV within regional and global networks, even if they use the same antenna type. Otherwise, mainly caused by the estimation of tropospheric parameters, systematic errors can reach up to several cm or bias the baseline length in some parts of 10^{-8}, respectively.

ACKNOWLEDGMENTS

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REFERENCES

Mader, G. (1998). *Calibration of GPS Antennas*. NOAA, NOS, NGS, GRD, WWW-Server: http:// www.grdl.noaa.gov/GRD/GPS/Projects/ ANTCAL.

Rothacher, M., G. Mader (1996). *Combination of Antenna Phase Center Offsets and Variations*. Antenna calibration set: IGS_01, International GPS Service for Geodynamics (IGS).

Rothacher, M., S. Schaer, L. Mervart, G. Beutler (1995a). *Determination of Antenna Phase Center Variations Using GPS Data*. Paper presented at the 1995 IGS Workshop, May 15-17, 1995, Potsdam, Germany.

Rothacher, M., W. Gurtner, S. Schaer, R. Weber (1995b). *Azimuth- and Elevation-Dependent Phase Center Corrections for Geodetic GPS Antennas Estimated from GPS Calibration Campaigns*. Paper presented at the IUGG XXI. General Assembly, July 2-14, 1995, Boulder, Colorado, USA.

Rothacher, M., G. Mader (1996). *Combination of Antenna Phase Center Offsets and Variations.* Antenna calibration set: IGS_01, International GPS Service for Geodynamics (IGS), 1996.

Schupler, B.R. (1994). *Signal Characteristics of GPS User Antennas*. NAVIGATION: Journal of The Institut of Navigation, Vol. 41, No. 3, Fall 1994, USA.

Schupler, B.R., T.A. Clark, R.L. Allshouse (1995). *Characterizations of GPS User Antennas: Reanalysis and New Results*. In: Beutler, G. et al. (Eds.). GPS Trends in Precise Terrestrial, Airborne, and Spaceborne Applications. IAG Symposium, No. 113, July 3-4, 1995, Boulder, Colorado, USA.

Seeber, G., F. Menge, C. Völksen, G. Wübbena, M. Schmitz (1997). *Precise GPS Positioning Improvements by Reducing Antenna and Site Dependent Effects*. Paper presented at the Scientific Assembly of the International Association of Geodesy IAG97, September 3-9, 1997, Rio de Janeiro, Brasil.

UNAVCO (1995). *Receiver and Antenna Test Report*. University Navstar Consortium (UNAVCO) Academic Research Infrastructure (ARI), Boulder, Colorado.

Wübbena, G. (1989). *The GPS Adjustment Software Package -GEONAP- Concepts and Models*. Proceedings of the Fifth International Symposium on Satellite Positioning, Las Cruces, New Mexico, 452-461.

Wübbena, G., M. Schmitz, F. Menge, G. Seeber, C. Völksen (1997). *A New Approach for Field Calibration of Absolute GPS Antenna Phase Center Variations.* NAVIGATION: Journal of The Institut of Navigation, Vol. 44, No. 2, Summer 1997, USA.