DETERMINATION OF ANTENNA PHASE CENTER VARIATIONS USING GPS DATA

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ABSTRACT

When processing GPS data without using a correction model for elevation-dependent *phase center variations (PCV)* of GPS antennas two error types have to be considered: (1) a bias in the (relative) station height (up to 10 cm) if different antenna types are mixed, (2) a scale factor in the baseline length (up to 0.015 ppm) which is essential on long baselines even if antennas of the same type are used.
Both effects are of importance in the context of the *International GPS Service for Geodynamics (IGS)* — for global solutions as well as for regional densification of the IGS network with a mixture of different receiver and antenna types. The elevation-dependent PCV also have an impact on the estimation of tropospheric zenith delays and ionosphere parameters (both effects relying on a correct mapping).
Two independent methods are available to obtain antenna phase center calibrations: the *anechoic chamber tests*, where the phase pattern of a single GPS antenna is measured, and the *estimation of phase center corrections from the GPS data* taken on short baselines. We focus on the parameterization and estimation of the PCV from GPS measurements. The consistency of the estimates of the coefficients of a spherical harmonics development is shown for two cases, elevation-dependent corrections only and for the azimuth- and elevation-dependent corrections. The solutions are compared to the results obtained from anechoic chamber tests.
There is hope that residual problems concerning the interpretation of *absolute* calibrations can be sorted out in the near future by a close and fruitful collaboration of the groups performing chamber tests and those deriving corrections from GPS data processing.

INTRODUCTION

In early tests and studies concerning the combination of different antenna types the emphasis was put on the calibration of the *vertical* and possibly *horizontal offsets* between the phase centers of various antennas. In preparation for the EUREF-89 Campaign (Seeger et al., 1992), one of the first major campaigns to involve most of the geodetic GPS receivers and antennas available at that time (Minimac 2816, TI-4100, Trimble 4000SLD, and WM-102), an antenna calibration campaign was organized at Wettzell to determine the relative phase

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center offsets. The analysis showed (Gurtner et al., 1989) that discrepancies up to about 4 cm could be detected between the nominal values published by the receiver manufacturers and the GPS estimates. At that time it was thought, that by using these calibration values the antenna combination errors could be reduced to below the 1 cm level. In these early studies only L1 and L2 solutions were checked, neither the use of the ionosphere-free linear combination (called L3 below) nor the estimation of troposphere parameters were considered for very short baselines. In 1992, few months after the start of the IGS Test Campaign (Beutler et al., 1994), we detected a bias of about 10 cm in height for Zimmerwald in our daily solutions with respect to the ITRF (i.e. SLR) results. The GPS results essentially stemmed from the baseline Wettzell – Zimmerwald, a mixed Rogue (Dorne Margolin B antenna) – Trimble 4000SSE (4000ST L1/L2 GEOD antenna) baseline. After checking the local ties between the SLR/VLBI and GPS points and after installing an Ashtech Z-12 next to the Trimble receiver in Zimmerwald it became clear that the 10 cm height error was due to the different antenna phase patterns of the Rogue and Trimble antennas. This observation was confirmed by (Rocken et al., 1992): if troposphere parameters were estimated in an L3 solution the elevation-dependence of the phase center was mis-interpreted by the parameter estimation program as tropospheric refraction creating the large bias in height.

Comparable to the effect of relative and absolute troposphere biases (Beutler et al., 1988) there are two major impacts of the elevation-dependent PCV on geodetic GPS results:

(i) If different antenna types with different elevation-dependences of the phase center location are mixed, mainly the relative station height is affected. As pointed out above this bias may reach values up to 10 cm — *independent* of the baseline length.

(ii) If only antennas of the same type are used, the main effect is a scale factor in the network of up to about 0.015 ppm due to the fact that for long distances the antennas "see" the same satellite under different elevation angles; an error pattern similar to a incorrect mapping function in the troposphere delay model is the result.

It is clear that azimuth-dependent variations may exist, too, which would cause biases in the horizontal position. In addition, there might be considerable differences between antenna units of the same type. VLBI, pointing its antennas towards the celestial radio sources, does not suffer from this type of PCV.

For the IGS as well as for many other GPS applications, these antenna phase center variations are one of the major error sources today. Already now the IGS global network is equipped with different receiver and antenna types. For the densification of the network the problem of receiver/antenna mixing will even become more pronounced. Any change of an antenna at one of the permanent IGS sites may cause an apparent jump in its coordinate time series and thus may affect the velocity estimates. *Unmodeled* PCV will also produce systematic biases in the determination of troposphere and ionosphere models, both IGS products to be established in the near future (see (Rocken et al., 1995) and (Schaer et al., 1995)). Even the change of the elevation cut-off angle (e.g. for the processing of AS data) may produce systematic changes in the GPS solutions.

To correct the biases caused by the PCV all GPS antennas used in a network have to be calibrated, i.e. elevation-dependent or elevation- and azimuth-dependent corrections have to be determined for each antenna type or even each individual antenna. The two methods available to determine such corrections are described in more details below.

TWO INDEPENDENT ANTENNA CALIBRATION METHODS

Two independent methods are in use today to determine the PCV of geodetic GPS antennas: the anechoic chamber measurements and the determination of phase center corrections from processing GPS data. It is important to have both methods available to detect problems in either of the two approaches. For comparisons and a clear understanding it is important to be aware of the degrees of freedom inherent in the two calibrations techniques.

Degrees of Freedom in the Calibration Values

Elevation- and azimuth-dependent calibration values determined by both methods have some inherent degrees of freedom one should be aware of to fully understand what chamber measurements are referring to and what parameters may be estimated from the GPS data. An original set of phase center corrections consisting of a phase center offset vector $\boldsymbol{r}_0$ (usually the "mean" phase center location) and an azimuth/zenith-dependent function $\Delta\phi(\alpha, z)$ may be transformed in the following way into a new set $\boldsymbol{r'}_0$ and $\Delta\phi'(\alpha, z)$ that will give exactly the same results as the original set when applied in GPS data processing:

$$\boldsymbol{r'}_0 = \boldsymbol{r}_0 + \boldsymbol{\Delta r} \tag{1a}$$

$$\Delta\phi'(\alpha, z) = \Delta\phi(\alpha, z) - \boldsymbol{\Delta r} \cdot \boldsymbol{e} + \Delta\phi_0 \tag{1b}$$

where $\Delta\phi_0$ and the offset vector $\boldsymbol{\Delta r}$ may be chosen arbitrarily, and $\boldsymbol{e}$ denotes the unit vector in the direction antenna – satellite defined by the zenith distance z and the azimuth α.

The constant $\Delta\phi_0$ is an arbitrary phase offset, constant for all directions, and $\boldsymbol{\Delta r}$ allows for an arbitrary location of the "mean" phase center in three dimensions (i.e. in vertical *and* horizontal direction).

As an example the elevation-dependent PCV transformed with $\boldsymbol{\Delta r} = (0, 0, \Delta h)$ and $\Delta\phi_0 = -\Delta h$ for four different values of Δh are shown in Figure 1. All these values give identical results when introduced into the GPS data processing together with the corresponding phase center offsets Δh in height.

The constant $\Delta\phi_0$ is often uniquely defined by asking for

$$\Delta\phi(\alpha, 0) = 0 \tag{2}$$

and the vector $\boldsymbol{r}_0$ may be defined as a "mean" phase center location over the zenith interval $[0, z_0]$ using e. g. the condition

$$\int_{\alpha=0}^{2\pi} \int_{z=0}^{z_0} \Delta\phi(\alpha, z) \sin z \, dz \, d\alpha = \text{min}. \tag{3}$$

It is obvious that this "mean" phase center $\boldsymbol{r}_0$ depends on the zenith angle cutoff z_0 and that the two components $\boldsymbol{r}_0$ and $\Delta\phi(\alpha, z)$ of a calibration set have to be consistent with each other.

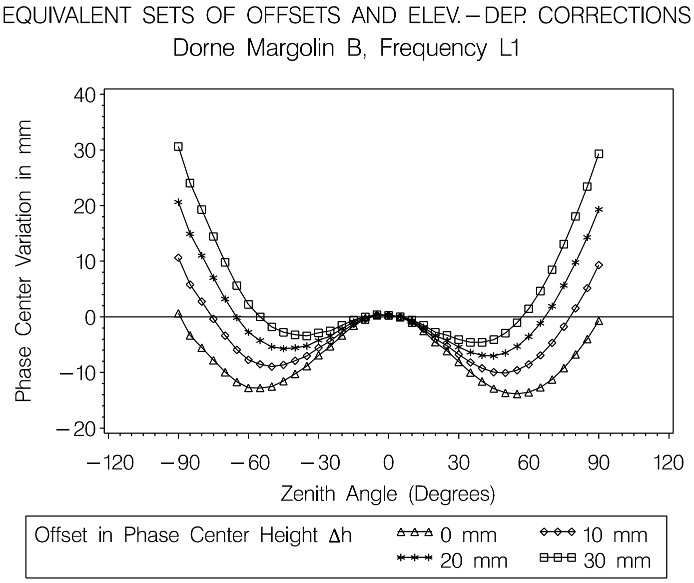

Figure 1. Elevation-Dependent PCV Transformed According to Eqns. (1a) and (1b) with $\boldsymbol{\Delta r} = (0, 0, \Delta h)$ and $c = -\Delta h$

Because GPS is an interferometric technique we have the additional problem that from data collected on short baselines only the *differences* between the PCV of the two antennas may be estimated.

Anechoic Chamber Tests

The measurements are performed in an anechoic test chamber where one specific antenna is mounted on a positioner, that may rotate the antenna around two independent axes and shift it in three directions. The transmitting antenna is kept fixed while the receiving antenna (to be tested) is rotated through zenith angles from -90 to $+90$ degrees for various azimuth values. To rotate the test antenna as precisely as possible around the "mean" phase center for the actual measurements, the antenna is first shifted with respect to the center of rotation until the phase center variations with elevation are minimal and as symmetrical as possible for zenith angles corresponding to $-z$ and $+z$ degrees. Apart from the recording of the antenna phase values using a stripchart recorder, the signal amplitude and axial ratio pattern are common measurements in chamber tests. These recordings have to be performed for both GPS carrier frequencies. Finally the location of the center of rotation with respect to a physical point on the test antenna, e.g. the *antenna reference points (ARP)* as defined by the IGS, has to be determined. For more details on chamber measurements we refer to (Schupler et al., 1991), (Schupler et al., 1994), and (Wohlleben et al., 1988).

As an example Figures 2 shows the elevation-dependent PCV in L1 for some geodetic GPS antennas as measured and made available by Schupler (downloaded by anonymous ftp in May 1995).

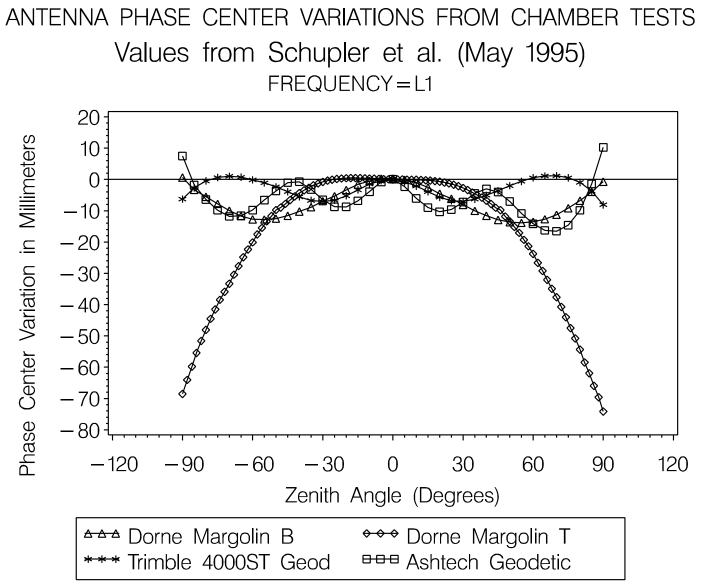

Figure 2. Elevation-Dependent PCV in L1 from Chamber Measurements

From Figure 2 we clearly see the various degrees of freedom as discussed in the previous section:

(i) Only the *change* in the phase with elevation can be measured, i.e. an unknown (and irrelevant) phase offset remains undetermined (constant $\Delta\phi_0$ in eqn. (1b)). In the case considered here the phase values were set to zero for zenith angle $z = 0$ according to eqn. (2).

(ii) In principle the center of rotation for the antenna tests may be arbitrarily chosen corresponding to the vectors $\boldsymbol{r}_0$ or $\boldsymbol{r'}_0$ in eqns. (1a) and (1b). Obviously the phase pattern of most of the antennas in Figure 2 was minimized using a condition similar to that in eqn. (3). For the Dorne Margolin T antenna, however, no such minimization was performed.

It is one of the advantages of chamber measurements that a single antenna may be calibrated. To collect the chamber measurements, however, a considerable effort is required as compared to the setup of a GPS calibration campaign.

Phase Center Estimation from GPS Data

The first phase center corrections obtained from GPS were simple vertical (and horizontal) offsets between different antennas determined on short baselines with known point coordinates (see e.g. (Gurtner et al., 1989), (Mireault et al., 1993), and many others). We mention in particular the GPS group at UNAVCO which periodically performed receiver and antenna tests for receiver evaluations (Braun et al., 1994).

In 1994 a few groups started estimating elevation-dependent correction models from GPS data, among them (Mader et al., 1994), who determined elevation-dependent corrections from the GPS post-fit residuals and (Breuer et al., 1995) setting up the coefficients of low-degree polynomials as parameters.

We at AIUB modified the Bernese GPS Software (Rothacher et al., 1993) in order to be able to estimate the parameters of two different models for elevation- or elevation- and azimuth-dependent PCV:

(i) Coefficients of piece-wise linear functions in elevation (and azimuth): polygonal approach.

(ii) Coefficients of a series of spherical harmonic functions of maximum degree $n_{\max}$ and maximum order $m_{\max} \leq n_{\max}$:

$$\Delta\phi(\alpha, z) = \sum_{n=0}^{n_{\max}} \sum_{m=0}^{n} \widetilde{P}_{nm}(\cos 2z) \cdot (a_{nm} \cos m\alpha + b_{nm} \sin m\alpha) \tag{4}$$

where $\Delta\phi(\alpha, z)$ is the phase center correction (or range correction) in the direction with zenith angle z and azimuth α. $\widetilde{P}_{nm}$ are *normalized* associated Legendre polynomials of degree n and order m; a_{nm} and b_{nm} are the unknown coefficients to be estimated. The normalization used is given in (Schaer et al., 1995), eqn. (6).

To prevent the normal equation system from becoming singular a loose a priori constraint has to be put on each parameter in case (i) because of the arbitrary constant $\Delta\phi_0$ in eqn. (1b) whereas in case (ii) the zero-degree coefficient a_{00} cannot be estimated. The results from case (i) may be introduced more easily into other software packages (linear interpolation between tabular values) whereas the representation (ii) is physically more meaningful, in particular for the azimuth-dependent variations.

It is also clear from eqns. (1a) and (1b) that the station heights have to be fixed on known ground truth values, if elevation-dependent corrections are estimated and that all three components of the station coordinates have to be fixed if elevation- and azimuth-dependent variations are determined. This requirement is not necessary if the antennas were rotated during the test campaign. When estimating the PCV, one and the same set of coefficients may be estimated from several antennas of the same type (grouping of antennas).

The advantage of the "GPS approach" compared to chamber tests is certainly the smaller effort needed to obtain calibrations for a large number of antennas in a short time period. A small network with known point coordinates within 1 mm (at least the heights of the points) has to be available, however. Unfortunately, as mentioned in the introduction, only the differences between the PCV of different antennas may be obtained with GPS and, therefore, the PCV from chamber measurements for at least one reference antenna have to be introduced as known.

ANTENNA CALIBRATION CAMPAIGNS

GPS data from three campaigns were used to estimate PCV and to check these estimates.

Thun 1994 Antenna Calibration Campaign

In this campaign taking place on a test range of the Swiss Federal Office of Topography in Thun, Switzerland, two sessions (days 248 and 249 of year 1994) of 24 hours each were measured with (for antenna names and antenna sketches see the files `ANTENNA.GRA` and `RCVR_ANT.TAB` at the IGS Central Bureau Information System described in (Gurtner et al., 1995)):

- 2 Ashtech Z-12 with GEODETIC L1/L2 P antennas
- 2 Leica SR299E with EXTERNAL antennas, with and without groundplane
- 2 Trimble 4000SSE with 4000ST L1/L2 GEOD antennas
- 2 Trimble 4000SSE with TR GEOD L1/L2 antennas, with and without groundplane
- 2 Turborogues with Dorne Margolin T antennas

The 10 monuments of the test network in Thun are separated by about 10 m; the ground truth is known to within 1 mm. Between the sessions the antennas were exchanged.

The institutions involved were:

- Federal Office of Topography, Wabern, Switzerland (Organization; Trimble receivers)
- Institut Géographique National, Paris, France (Ashtech receivers)
- Institut für Angewandte Geodäsie, Wettzell, Germany (Operator)
- Technical University, Munich, Germany (Turborogue)
- Bavarian Academy of Sciences, Munich, Germany (Turborogue)

Observations from Graz

A few days of data from August 1994 and November 1994 were also available from Peter Pesec at the Graz Observatory, Austria, including Rogue, Turborogue and Trimble receivers on baselines of a few meters. This data was mainly included in this study to detect any significant biases between Dorne Margolin B and T antennas.

Baseline Onsala–Zimmerwald from IGS

The long mixed baseline Onsala – Zimmerwald of about 1200 km with a Rogue (Dorne Margolin B) and a Trimble 4000SSE (4000ST L1/L2 GEOD) receiver was processed for 46 days (DOY 070 – 115, 1995) to test the various PCV available from chamber tests and from the estimation from GPS data.

RESULTS

Antenna Offsets

Before starting to estimate any PCV the coordinates of the points were estimated to obtain the "mean" phase center offsets for the various antenna types involved in the campaign of Thun by comparing the results to the ground truth. An elevation cutoff angle of 20 degrees was used. The resulting phase center offsets are summarized in Table 1.

Day	Receiver	Antenna Type	No.	L1 Offset (mm)			L2 Offset (mm)		
				N	E	U	N	E	U
248	TRIMBLE	TR GEOD L1/L2 W/O	1	2.7	–4.6	15.1	4.5	–0.1	13.1
249	TRIMBLE	TR GEOD L1/L2 W/O	1	2.7	–4.7	15.1	5.4	0.5	14.6
248	TRIMBLE	TR GEOD L1/L2 W/O	2	2.8	–5.5	13.6	5.9	0.1	10.4
249	TRIMBLE	TR GEOD L1/L2 GP	2	2.7	–5.3	–0.6	3.8	0.1	–3.5
248	TRIMBLE	4000ST L1/L2 GEOD	1	0.0	0.2	1.3	0.3	0.1	1.7
249	TRIMBLE	4000ST L1/L2 GEOD	1	–0.1	0.1	0.9	–0.2	0.1	1.0
248	TRIMBLE	4000ST L1/L2 GEOD	2	0.0	–0.2	–1.3	–0.3	–0.1	–1.7
249	TRIMBLE	4000ST L1/L2 GEOD	2	0.1	–0.1	–0.9	0.2	–0.1	–1.0
248	ASHTECH	GEODETIC L1/L2 P	1	–2.2	–2.3	2.2	–1.1	–3.6	5.0
249	ASHTECH	GEODETIC L1/L2 P	1	–1.7	–1.4	5.0	–0.9	–3.5	7.5
248	ASHTECH	GEODETIC L1/L2 P	2	4.8	–5.7	4.8	7.9	0.1	7.6
249	ASHTECH	GEODETIC L1/L2 P	2	4.5	–6.8	0.2	7.2	–0.7	3.7
248	SR299E	EXTERNAL WITHOUT	1	2.2	–2.7	20.5	3.0	0.6	9.9
249	SR299E	EXTERNAL WITH	1	4.7	–4.2	–2.5	6.8	3.2	–5.1
248	SR299E	EXTERNAL WITHOUT	2	1.6	–2.7	22.4	4.9	1.2	9.9
249	SR299E	EXTERNAL WITH	2	5.0	–4.7	–0.6	6.3	2.7	–1.9
249	TURBOR.	DORNE MARGOLIN T		0.0	–2.7	–14.7	3.6	–2.0	–8.4

Table 1. Phase Center Offset Differences with Respect to the IGS Values. Mean Offset of the 4000ST L1/L2 GEOD Antennas was set to the IGS Value. Antenna Types Containing "W/O" and "WITHOUT" Were Used *Without* Groundplane (GP)

All phase center offsets in Table 1 are corrections to the IGS values available at the IGS Central Bureau Information System (CBIS, see (Gurtner et al., 1995), file `RCVR_ANT.TAB`) and were computed fixing the *mean* offset of the two 4000ST L1/L2 GEOD antennas to the IGS value. Table 1 shows that the horizontal offsets are of the order of a few millimeters, in some cases even between two antennas of the same type. In general the vertical offsets are not larger, but the use of an antenna *without groundplane* systematically changes the vertical offset by about 1 to 2 cm. This effect will even be more pronounced when using a lower elevation cut-off angle. The Dorne Margolin T antenna has an offset of about 1.5 cm when compared to most other antennas.

Elevation-Dependent Corrections from GPS

Both estimation models, the piece-wise linear and the spherical harmonics functions, were tested and revealed no significant differences. Therefore only the spherical harmonics results will be presented here. A maximum degree of $n_{max} = 10$ and an order of $m_{max} = 0$ (elevation-dependence only) were used (see eqn. (4)). All the PCV were computed relative to the Trimble 4000ST L1/L2 GEOD antenna no. 1. The IGS offset values were introduced as "mean" phase center offsets for all antenna types.

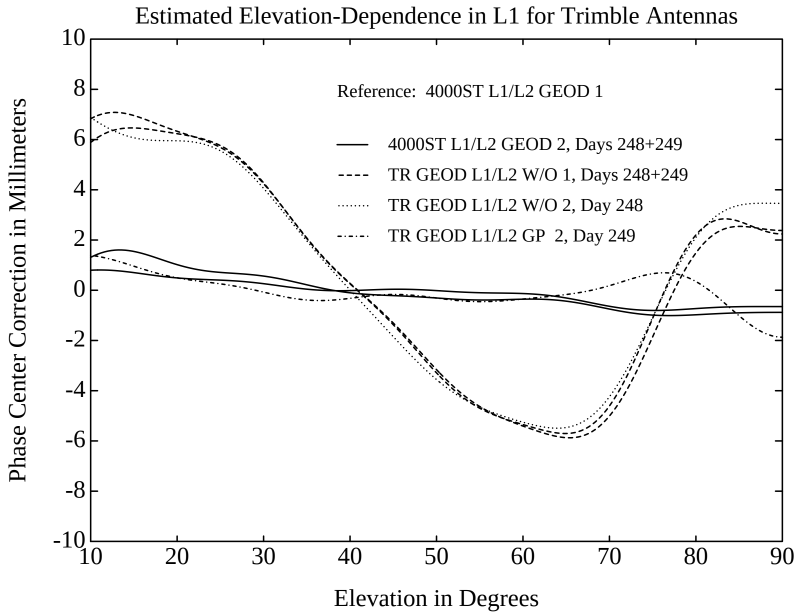

Figure 3. Trimble Antennas: Spherical Harmonics Development of Degree 10 Estimated from GPS Data

Figure 3 shows the results for the two Trimble antenna types for both 24-hour sessions (days 248 and 249, see also Table 1) in Thun:

- The estimates for the same antenna are very similar for both sessions
- The estimates for different antennas of the same type are also very consistent.
- The compact Trimble antenna TR GEOD L1/L2 W/O GP (without groundplane) exhibits a very different behaviour with elevation. If the groundplane is attached to this antenna, however, it behaves almost like a 4000ST L1/L2 GEOD antenna. The groundplane changes the phase pattern of the antenna significantly. The same effect shows up for the SR299 EXTERNAL antenna (see Table 1).

In Figure 4 the PCV for the Ashtech antennas are plotted. Again the antenna pattern is repeatable within 1 to 2 mm, except for the low elevations (< 15 degrees), where multipath is most probably the critical influence.

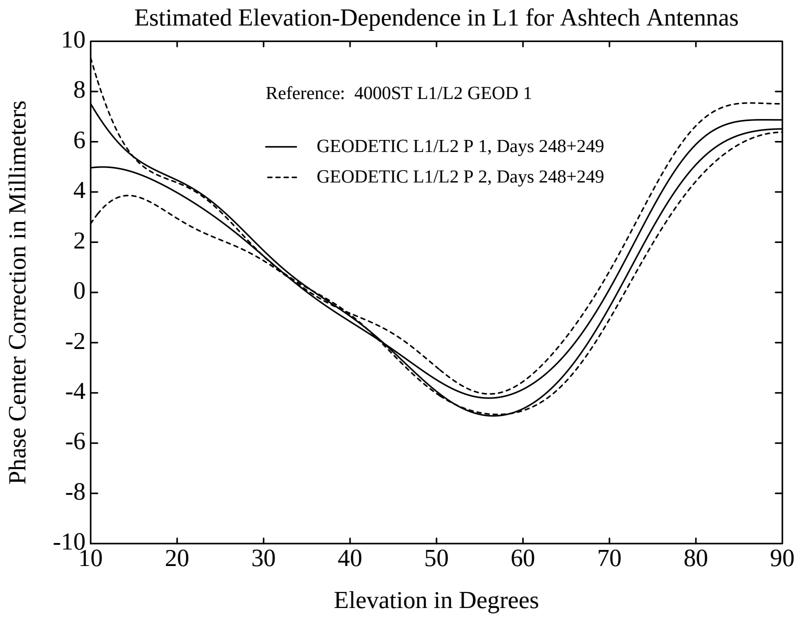

Figure 4. Ashtech Antennas: Spherical Harmonics Development of Degree 10 Estimated from GPS Data

The reason for the large bias of about 10 cm in the height for a mixed Rogue – Trimble baseline when using the ionosphere-free linear combination L3 (and estimating troposphere delays) becomes apparent in Figure 5.

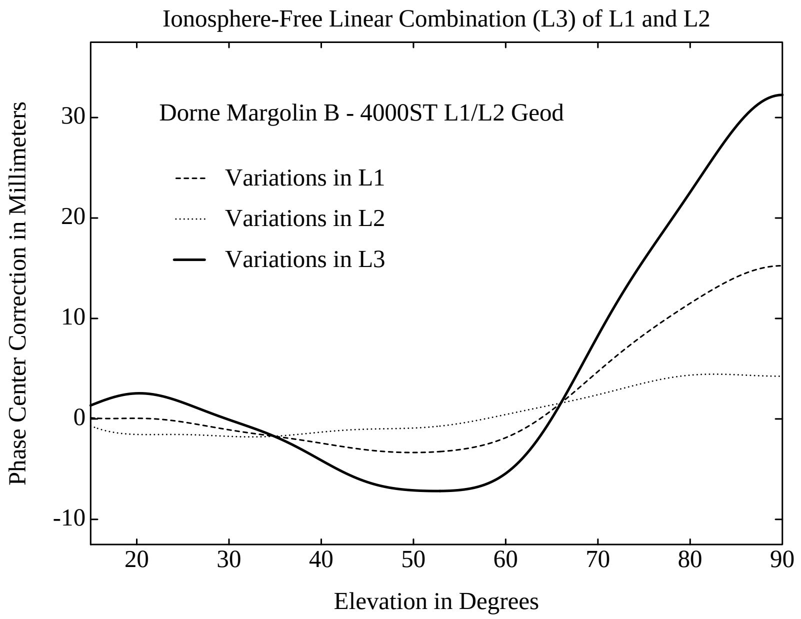

Figure 5. Magnification Effect of the Phase Center Variations in the Ionosphere-Free Linear Combination. Spherical Harmonics Development of Degree 10 for the Dorne Margolin B Estimated from GPS Data

The variations in L3 are much larger than those in L1 and L2. The results in Figure 5 were computed using the Graz GPS data.

Azimuth-Dependent Correction from GPS

As an example for the estimation of azimuth-dependent PCV Figures 6 and 7 depict the differences between the phase patterns of the Dorne Margolin B and the Trimble 4000ST L1/L2 GEOD antenna for the L1 and the L2 frequency. The Graz data set was used for the estimation. The two areas inside the dashed lines enclose the region — we call it the "northern hole" — where no GPS satellites are ever visible and therefore no corrections can be estimated. This hole in the data might be removed by rotating the antennas systematically (by e.g. 180 degrees for a second session).

The consistency of the estimated azimuth-dependent variations from day to day and between antennas of the same type is similar to the consistency of the elevation-dependent variations given in the last section.

The PCV of the Dorne Margolin B (Rogue) and Dorne Margolin T (Turborogue) antennas are almost identical (within about 2 mm over all the azimuth and elevation angles down to 15 degrees).

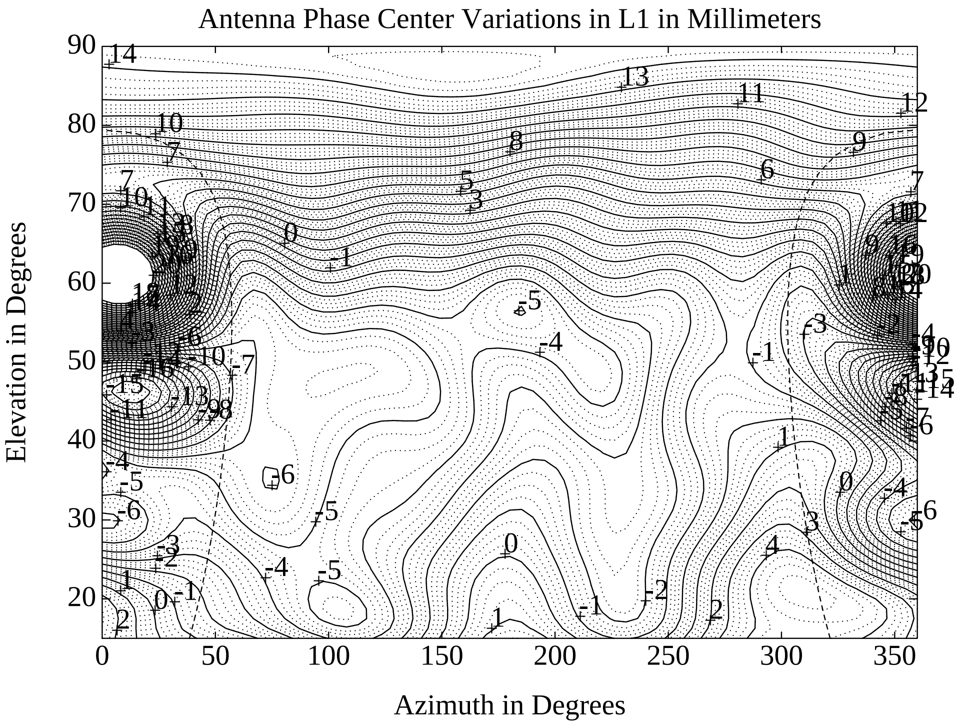

Figure 6. Spherical Harmonics Development of Degree 10 and Order 5 Estimated for the Difference Between Dorne Margolin B and 4000ST L1/L2 GEOD Antenna

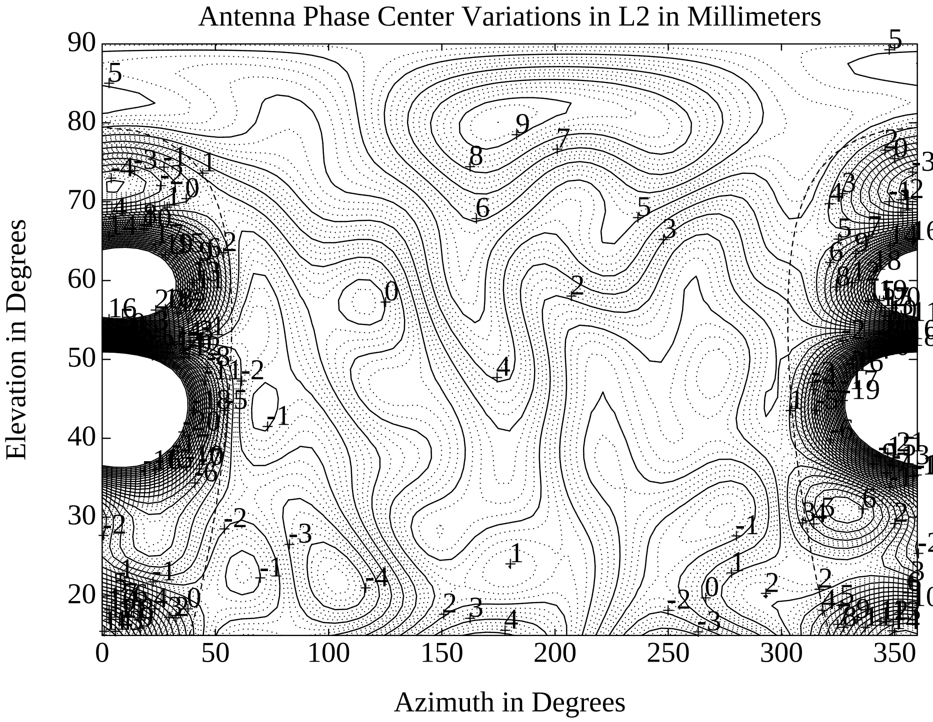

Figure 7. Spherical Harmonics Development of Degree 10 and Order 5 Estimated for the Difference Between Dorne Margolin B and 4000ST L1/L2 GEOD Antenna

Multipath effects are clearly visible in the azimuth-dependent phase corrections for elevation angles below 20 degrees. They limit the applicability of corrections determined at one location to another location with a different multipath environment. This an important issue to be studied in future.

Comparison with Chamber Test Results

The elevation-dependent variations established with GPS were compared to the chamber test results in the case of the Dorne Margolin B and 4000ST L1/L2 GEOD antenna (i.e. only the difference can be compared). The good agreement between the two independent methods may be seen from Figures 8 and 9 for L1 and L2 respectively. The plots also indicate that there is *no* significant difference between the Dorne Margolin B and T antennas. The comparison has to be interpreted with care, because it only shows that the *difference* between the antenna types are reasonably consistent and that obviously the difference of the adopted "mean" phase centers was about the same. The consistency of offsets and elevation-dependent variations requested in eqns. (1a) and (1b) could not be safely established for the chamber measurements and there might still be problems in the absolute calibrations (see next section).

No attempt was made so far to compare the azimuth-dependence of the phase patterns.

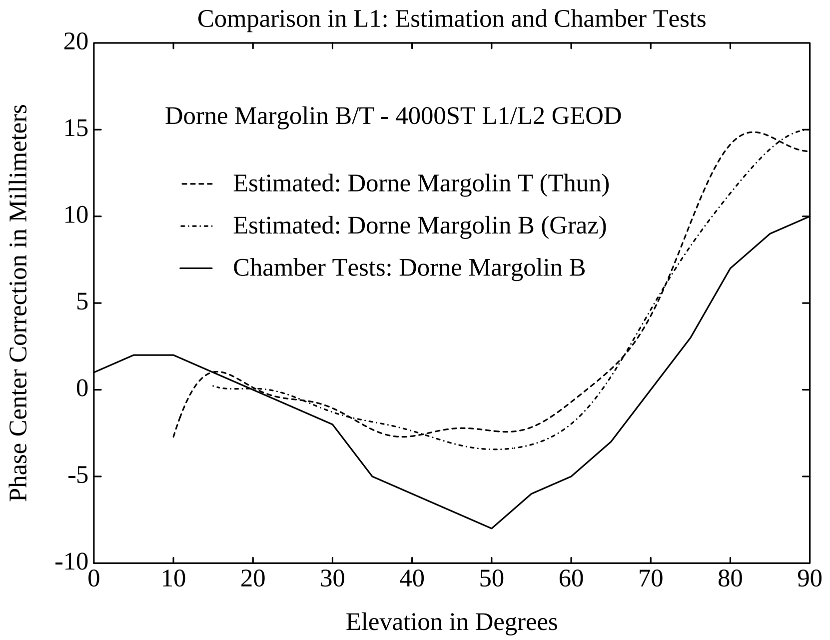

Figure 8. Comparsion Between Chamber Measurements from Schupler (May 1995) and Values Estimated from GPS Data

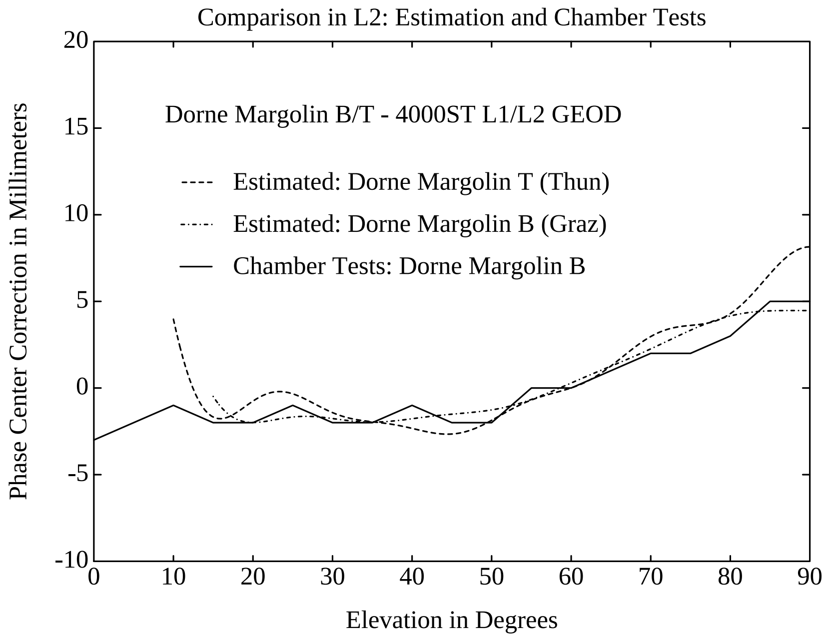

Figure 9. Comparsion Between Chamber Measurements from Schupler (May 1995) and Values Estimated from GPS Data

Checking of Phase Center Corrections on a Long Baseline

The long mixed baseline Onsala – Zimmerwald (baseline length 1200 km) was used to check the relative and in particular the *absolute* values of the antenna calibrations. Only chamber measurements can provide the *absolute* phase center corrections. The baseline components and the baseline length were compared to ITRF93 values (from SLR and GPS, see (Boucher et al., 1994)) for 46 days using different sets of antenna phase center corrections. The results of the daily ionosphere-free (L3) solutions with troposphere estimation are given in Figure 10.

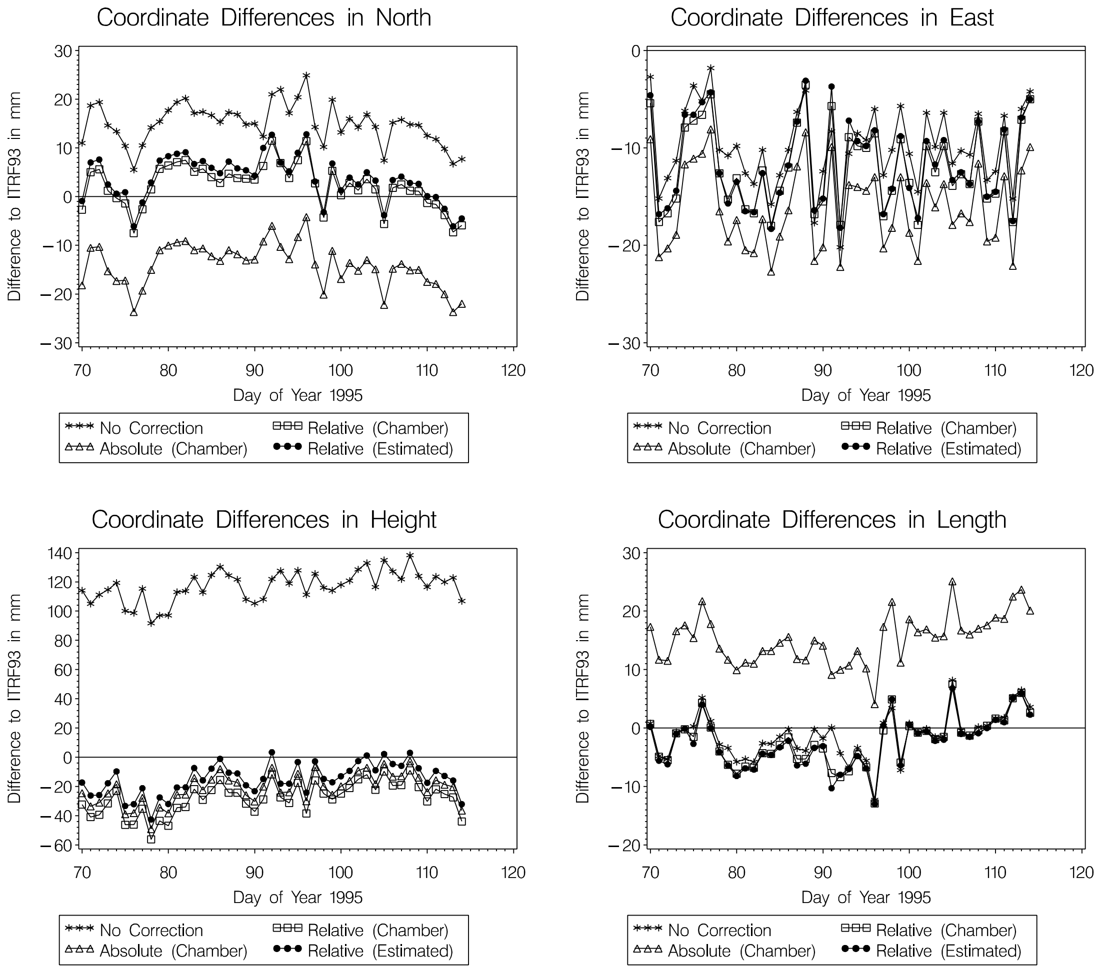

Figure 10. Results for the Baseline Onsala – Zimmerwald (Dorne Margolin B – 4000ST L1/L2 GEOD) Using Different Sets of Elevation-Dependent Phase Center Corrections Compared to ITRF93. “Relative” Corrections: Only Difference Between Antennas Introduced. Chamber Measurements from Schupler (May 1995).

The following tests were performed: (a) no corrections applied, (b) chamber measurements from Schupler for both antenna types (absolute correction) applied, (c) the difference between antenna types from chamber measurements, and (d) our differential estimates assuming the *absolute* PCV for the Dorne Margolin B antenna to be *zero*. The largest effect, the bias of about 11 cm in the height, clearly shows up if *no* corrections are applied. If chamber values are introduced for both antennas, there is a significant bias of about 1.5 cm (or 0.012 ppm) in the baseline length not present for the other phase center corrections showing that there are still problems with the *absolute* calibration. A bias is also present in the north component for "no correction" and "absolute correction". Although the ITRF93 coordinates may also be in error (in particular because the CODE GPS solution using model (c) was part of the ITRF combination), the scaling of the baseline for absolute corrections is clearly too large to be attributed to the ITRF93. The corrections estimated from GPS look very promising, although the underlying assumption that the Dorne Margolin B antenna shows no significant elevation-dependence is questionable.

CONCLUSIONS AND OUTLOOK

From the results shown in this paper it is evident that the estimation of phase center corrections in elevation (and azimuth) from GPS data give important contributions to the problem of phase center variations and the combination of different antenna types. The determined corrections for antennas of the same type and for different days are very consistent.

Multipath is certainly the most critical error source for the estimation of PCV from GPS data, especially for the azimuth-dependence. This problem as well as the problem of the "northern hole" might be reduced by rotating the antenna between the sessions. An experiment with such rotations has been performed by the Institut für Angewandte Geodäsie in Wettzell. We will gain more insight into the multipath problems from analysing these data.

Comparisons of our estimates with chamber test results look promising. The problem of the *absolute* calibration is not solved yet, however. We hope that with the cooperation of exponents using the two techniques — anechoic chamber measurements and GPS — the remaining problems will be solved and a consistent set of antenna offsets and elevation-dependent variations will result which is urgently needed by the GPS community. It seems unavoidable that new GPS calibration campaigns — making full use of the experiences gained in tests reported above — have to be performed in the near future.

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