A New Approach for Field Calibration of Absolute Antenna Phase Center Variations

GERHARD WÜBBENA, MARTIN SCHMITZ

Geo++, D-30827 Garbsen, Germany

FALKO MENGE, GÜNTER SEEBER, CHRISTOF VÖLKSEN

Institut für Erdmessung, Universität Hannover, D-30167 Hannover, Germany

ABSTRACT

The paper introduces a new approach to determine azimuth and elevation dependent phase center biases through a field measurement in an absolute sense. It takes special care of the multipath effects. The model, the conditions for the field procedure and preliminary analysis of results are presented. The absolute antenna phase center calibration procedure is implemented in the GPS processing package GEONAP.

INTRODUCTION

Antenna phase center variation has become an important error source for precise GPS measurements. Beside tropospheric and multipath errors, it is the most limiting factor in achieving a breakthrough to the next accuracy level. The main areas of applications for phase center corrections are engineering surveys at the millimeter accuracy level and precise GPS networks. In the processing of large networks, tropospheric errors and phase center biases cannot be easily separated and result in height errors [1-3]. In addition, absolute phase center corrections are required for long baselines even for receivers and antennas of the same type, because azimuth and elevation are different for one satellite at the remote sites [4]. Phase center corrections are, however, generally important for the use of mixed antenna designs to take into account the different phase pattern of each antenna type. This aspect gets increasing importance as permanent reference networks are established on a regional and worldwide basis. Examples are the „High Precision Positioning Service“ (HPPS) of Lower Saxony, the „Satellitenpositionierungsdienst der deutschen Landesvermessung“ (SAPOS) in Germany, or the „International GPS Service for Geodynamics“ (IGS).

These high precision GPS applications demand the knowledge of phase center variations at the 1 mm-level to correct for this systematic error source.

Up to now, different approaches of the determination of phase center variations have been discussed. Relative phase center variations are commonly defined in field procedures [2][5] as absolute phase center variations are only determined in anechoic chamber calibrations [1][6].

So far field calibration has only determined the difference of phase center variations relative to one particular antenna type. The impact of multipath is in general not accessible and may introduce errors in the phase center variation model.

Anechoic chambers are considered to be free of multipath. However, there exist discrepancies between chamber test antenna patterns in an anechoic environment and applying these corrections for a field environment including multipath [1][2]. Thus, multipath must be reduced or the effect of multipath on the chamber pattern must be better understood [1].

A combination of chamber and field calibration may lead to an indirect absolute field calibration procedure. An absolute chamber calibration is performed for one antenna. Then, the result is introduced as a reference for the relative field calibration of a second antenna [2][3][5].

Direct absolute calibration in the field has not yet been attempted. There are two major problems for absolute phase center calibration in a field procedure (as well as for relative calibration). First of all, there is the necessity to eliminate the phase center variations of the reference antenna, because GPS is used in a differential mode. Secondly, multipath errors must be separated from the phase center variations. One never can assume a multipath-free field environment. Therefore, multipath effects must be especially considered.

CHARACTERISTIC OF PHASE CENTER VARIATION

Usually GPS users have only access to the mechanical center of the antenna defined by the intersection of the rotation axis and, for example, the top of the ground plane. The antenna characteristic describes the difference between the mechanical center and the electrical phase center. This electrical phase center varies with the direction of the received signal. Therefore commonly a phase center and a phase pattern is used.

Multiple definitions of a phase center are possible. Generally a mean offset from a feasible mechanical point is determined from GPS observations, which, however, depends on the elevation mask [6]. Azimuth and elevation dependent phase center variations define the phase pattern. Due to their small magnitude azimuth dependent phase center variations are generally neglected.

The expected range of phase center variations can amount to 20 mm for some antenna types considering observations at low elevations. The ionospheric free linear combination, here nominated L0 [7], amplifies any error in the phase by a factor of about 3.1 [1].

ELIMINATION OF MULTIPATH

The main error source in absolute and relative determination of antenna phase center variations is multipath. An environment, which is completely unaffected by multipath does not exist. Hence, the antenna phase pattern derived especially from field procedures are disturbed by multipath and may create incorrect phase center variations. In order to get undisturbed phase center variations, multipath has to be eliminated or greatly reduced.

The following graphical examples and equations use double differences to demonstrate the basic concept for the elimination of multipath. However, the actual implementation of the approach in the GPS processing package GEONAP [7] uses undifferenced GPS observables.

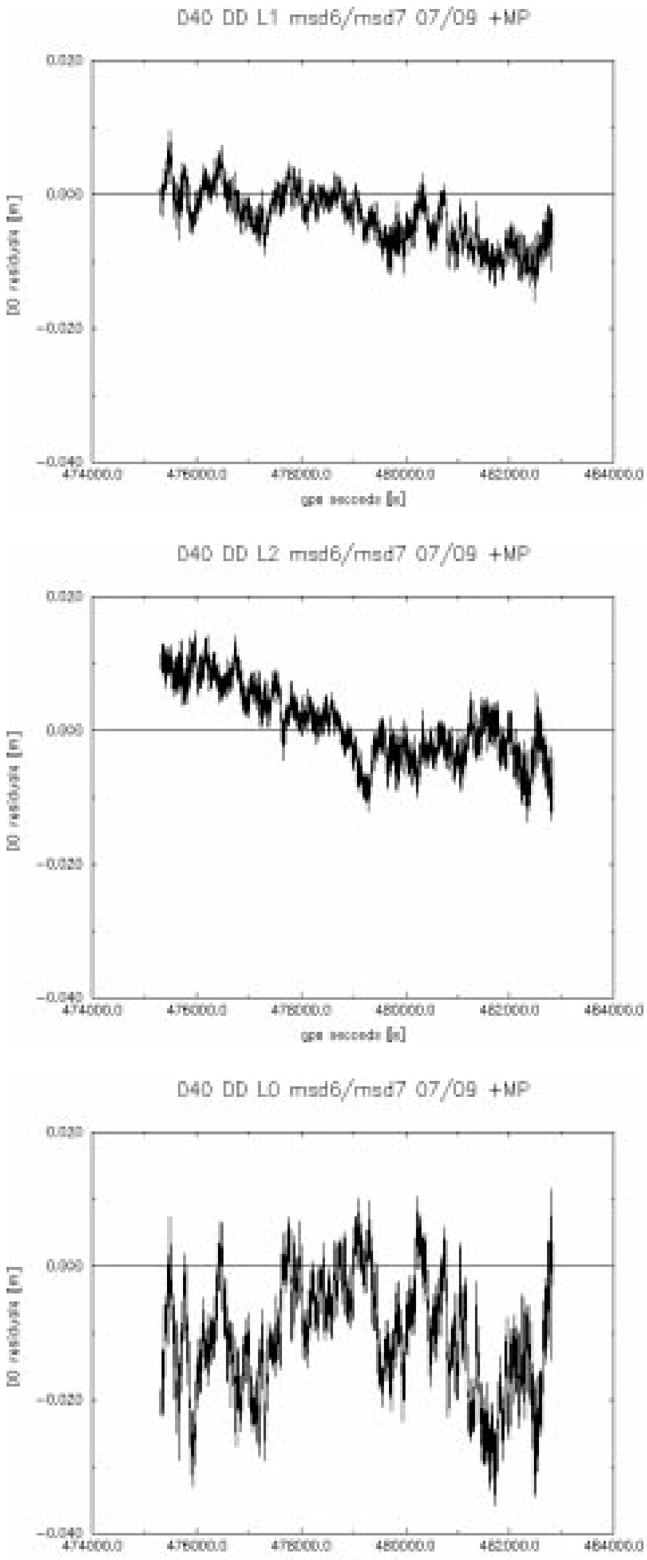

Fig.1- L1, L2 and L0 double differences (DD) of PRN07/PRN09 on pillars msd6 and msd7 on Day 040, including multipath (MP)

Figure 1 shows the double difference residuals of a short (10 m) baseline in a highly reflective environment for L1, L2 and L0. The observations were made with two ASHTECH Z12 receivers using Geodetic II antennas. The ambiguities were resolved for L1 and L2, and as a consequence for any possible linear combination. Table 1 gives the noise level for the phase measurements after the adjustment process with GEONAP. Clearly systematic effects with periods of several minutes up to one hour can be detected as typical multipath signals. As expected, multipath signal and noise are amplified in the ionospheric free signal L0.

Multipath signals are known to repeat at specific sites every mean sidereal day, i.e. every day the same systematics repeat themselves some minutes earlier. In Figure 2 the double differences of L1, L2 and L0 of two successive days were cross-correlated in the time domain. The cross-correlation function shows a maximum around a time lag of 236 seconds. This clearly indicates the periodical appearance of multipath after a mean sidereal day. This fact can be used to greatly reduce the effect of multipath on the GPS signal.

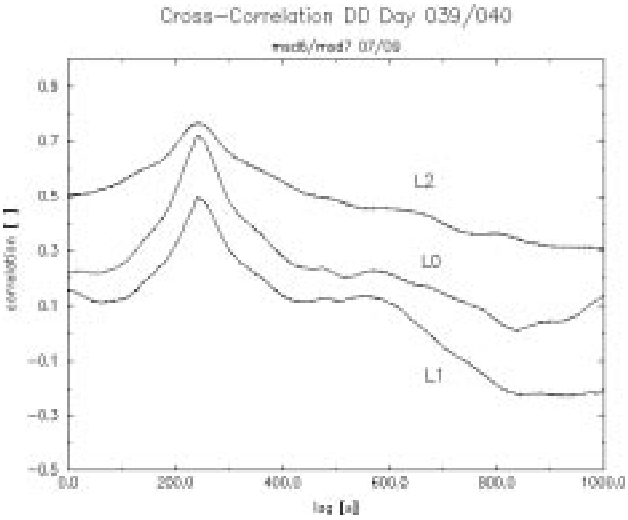

Fig.2- Cross-correlation function of double differences from Day 039 and Day 040

Respecting the 3 min 56 s difference of mean solar and mean sidereal day, the undifferenced GPS observables of two successive days can be subtracted As a consequence all errors which repeat themselves after one sidereal day cancel out.

A simplified linearized notation of the phase observation equations l_Φ in meters containing the design matrix sub-vector **a**, the receiver coordinate corrections **x**, the receiver and satellite clock error dt and dT scaled to meters by the speed of light c_0, the ambiguity N scaled to meters by the wavelength λ, the error terms d for ionosphere (ION), troposphere (TROP), multipath (MP), phase center variations (PCV) and the noise of the phase ε_ϕ reads

$$l_{\phi\,i}^{\;j} = \mathbf{a}_i^j \cdot \mathbf{x}_i + c_0 \cdot (dt_i - dT^j) - \lambda \cdot N_i^j - d_{ION\,i}^{\;\;j} + d_{TROP\,i}^{\;\;j} + d_{MP\,i}^{\;\;j} + d_{PCV\,i}^{\;\;j} + \varepsilon_\Phi . \tag{1}$$

The subscript i and superscript j stand for receivers and satellites, respectively. Building a mean sidereal day time difference δ^{SID} eliminates the multipath, phase center variation and the complete geometric information. The following observation equation does not contain any information about geometry, since the design elements **a** are almost identical on two successive days:

$$\delta^{SID} l_{\Phi i}^{\ j} = c_0 \cdot (\delta^{SID} dt_i - \delta^{SID} dT^j) - \lambda \cdot \delta^{SID} N_i^j - \delta^{SID} d_{ION\,i}^{\ \ j} + \delta^{SID} d_{TROP\,i}^{\ \ j} + \delta^{SID} \varepsilon_\Phi . \tag{2}$$

The remaining terms comprise the mean sidereal time differences of the components, which are small for a short baseline (i.e. atmospheric errors) and/or are correctly modeled in the GEONAP package (i.e. clock errors). The noise level of the observable changed due to error propagation to $\delta^{SID}\varepsilon_\Phi$.

A double difference as used in the graphs eliminates clock and atmospheric terms ending up with

$$\nabla\Delta\delta^{SID} l_{\Phi i,k}^{\ j,l} = -\lambda \cdot \nabla\Delta\delta^{SID} N_{i,k}^{j,l} + \nabla\Delta\delta^{SID} \varepsilon_\Phi . \tag{3}$$

To demonstrate the elimination of multipath the same baseline has been observed on the days 038 and 040 with the antennas orientated to the north. On both days the ambiguities were resolved with the GEONAP software package. Then the time difference δ^{SID} of the GPS observables between the two days has been computed. From these measurements, the double differences in Figure 3 were generated.

Obviously, the multipath is greatly reduced applying a time difference of one mean sidereal day on the double differences. The noise level increases by a factor of $\sqrt{2}$ due to error propagation. Nevertheless, the systematic multipath is dramatically reduced. The phase noise for L1, L2 and L0 decreases by a factor of 1.5 (refer to Table 1). Hence, an approach to eliminate multipath has been found.

ACCESS TO THE PHASE CENTER VARIATION SIGNAL

The sidereal time difference clearly eliminates multipath, but also the phase center variations. To gain information on the antenna phase center variation a change in the antenna setup for one of the days is required. A simple example is given in the next section. For this case the reference station will be kept fixed for the first and second day. At the other station, a change in the horizontal orientation of the antenna by 180 deg from one day to the other produces a signal, which includes phase center variation caused by the rotation of this particular antenna.

The linearized observation equation for the time difference δ^{SID} of the rotated antenna is

$$\begin{aligned}\delta^{SID} l_{\Phi i}^{\ j} = {} & c_0 \cdot (\delta^{SID} dt_i - \delta^{SID} dT^j) - \lambda \cdot \delta^{SID} N_i^j - \delta^{SID} d_{ION\,i}^{\ \ j} + \delta^{SID} d_{TROP\,i}^{\ \ j} \\ & + d_{PCV\,i}^{0\ \ j} - d_{PCV\,i}^{180\ \ j} + \delta^{SID} \varepsilon_\Phi .\end{aligned} \tag{4}$$

Here, the terms d_{PCV}^{0} and d_{PCV}^{180} represent the phase center variations for the unrotated and the rotated antenna, respectively. The double difference then reads

$$\nabla\Delta\delta^{SID} l_{\Phi i,k}^{\ j,l} = -\lambda \cdot \nabla\Delta\delta^{SID} N_{i,k}^{j,l} + \nabla\Delta d_{PCV\ \ i,k}^{0,180\ \ j,l} + \nabla\Delta\delta^{SID} \varepsilon_\Phi . \tag{5}$$

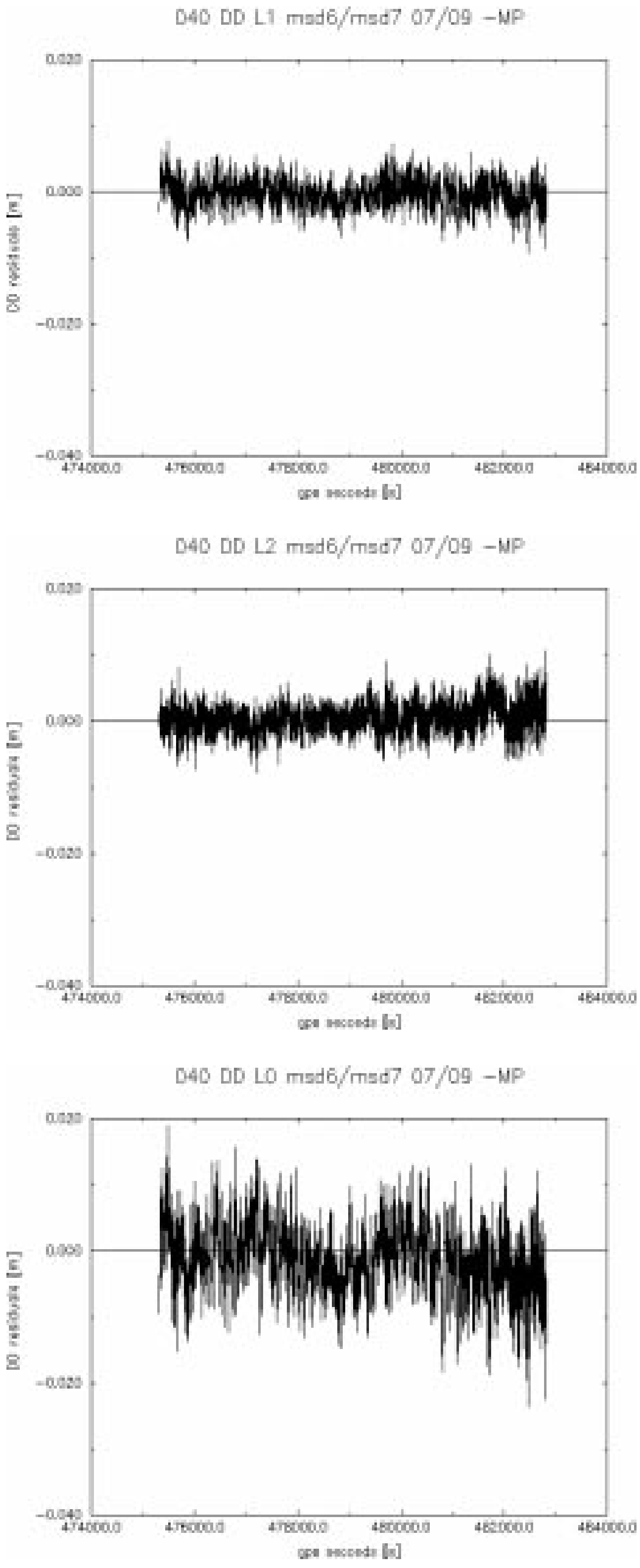

Fig. 3- δ^{SID} of double differences for identical antenna orientation on days 038 and 040, multipath eliminated

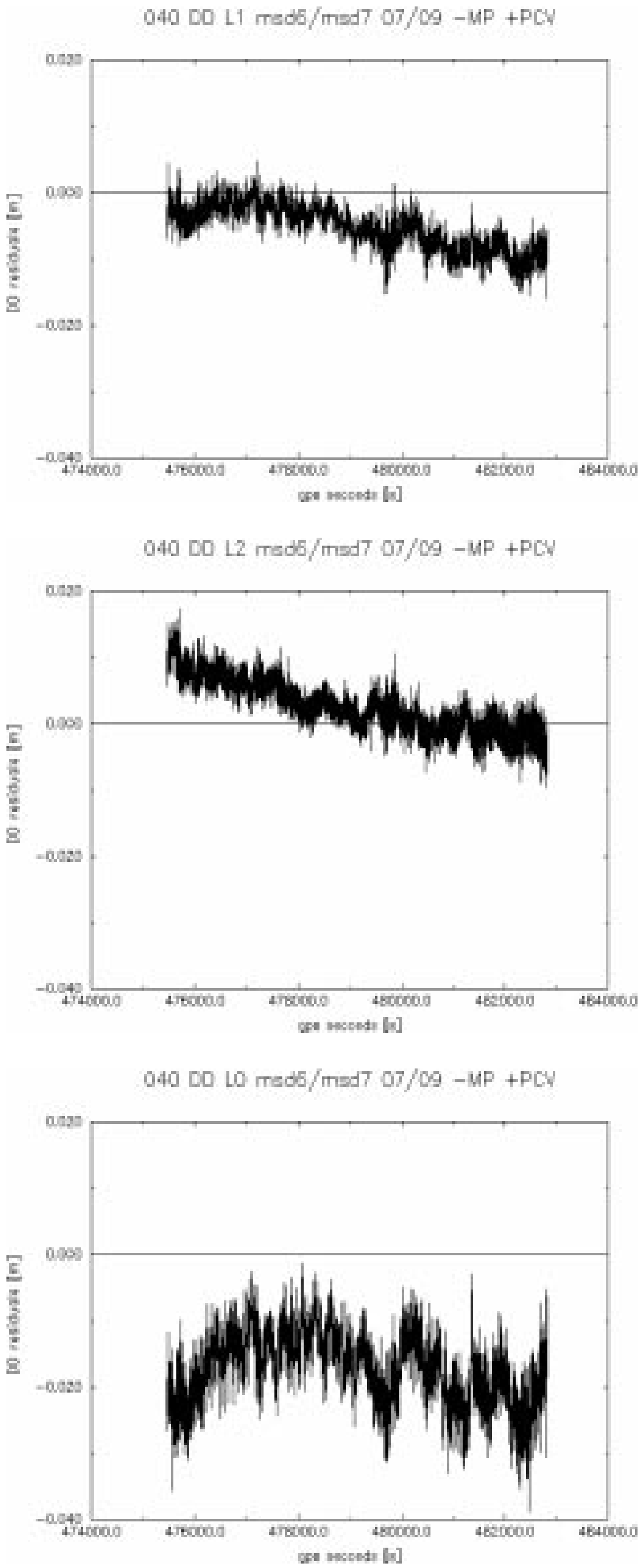

Fig. 4- δ^{SID} *of double differences for rotated antenna on days 039 and 040, multipath eliminated, phase center variations (PCV) introduced*

Compared with equation 3 (no rotation of the antenna between the days) this double difference equation contains the additional term $\nabla\Delta d_{PCV}$, representing the phase center variations (PCV) of only one antenna.

Figure 4 shows the double difference residuals after the antenna has been turned on the second day. Compared with Figure 3, a signal is present, which purely represents the phase center variations caused by the rotation of the antenna. Another indication for the phase center variations is given by the increase of the phase noise of the observables L1, L2 and L0. But still multipath is eliminated since the noise is much smaller if compared with undifferenced observations (see Table 1).

Table 1- Phase noise of different observables in meters after processing with GEONAP

[m]	L1	L2	L0
Φ	0.0030	0.0031	0.0095
$\delta^{SID}\Phi$	0.0020	0.0020	0.0056
$\delta^{SID}\Phi+(d^{0}_{PCV}-d^{180}_{PCV})$	0.0024	0.0024	0.0071

It is worth noting that the phase center variation signal represents errors, which are introduced by not considering the orientation of two antennas. Today`s precise real-time GPS applications are therefore affected by such errors, which reach a magnitude up to 1 cm (Figure 4).

MODELING THE PHASE CENTER VARIATIONS

As demonstrated, all systematic errors can be eliminated, including daily repeating errors, or they are included in the adjustment model of the GPS processing software (e.g. clock errors). Changes in the orientation of one antenna create phase differences, which are completely independent from the antenna used at the reference site of the baseline. The phase differences, which originate from the antenna can therefore be used to model phase center variations.

In the following, the focus is on the antenna to be calibrated. For simplification, it is assumed that during a full rotation of the antenna the azimuth and the elevation of the satellite is constant (see Figure 5). The actual model takes the motion of the satellites properly into account. The reference antenna has the identical orientation and environment on both observation days and does not contribute any information of interest to the phase pattern.

Considering one particular GPS satellite as a sensor while performing a change of antenna orientation, the antenna pattern is rotated underneath the satellite signal. The difference in the phase measurements between two different antenna positions Δd_{PCV} to an identical satellite is the observable for modeling phase center variations (here i and j denote a different orientation):

$$\Delta d_{PCV}(\alpha_i, z_i, \Delta\alpha, \Delta z) = d_{PCV}(\alpha_i, z_i) - d_{PCV}(\alpha_j, z_j), \tag{6}$$

with $\Delta\alpha = \alpha_i - \alpha_j$, $\Delta z = z_i - z_j$ defined in a coordinate system of the antenna.

Figure 5 shows the phase pattern in two orientations, different by an angle $\Delta\alpha$ and the observable Δd_{PCV} for the horizontal case.

For the observable it is essential, that the antenna is rotated stepwise, to cover the full antenna pattern. Continuous observations without changing the orientation give no additional information required for the modeling of phase center variations. After one full rotation of the antenna the tracked satellite describes the shape of the phase pattern in horizontal directions for the particular elevation of the satellite. To connect the horizontal distributed pattern information from different satellites at different elevations, a tilt of the antenna is necessary. Figure 5 shows also the vertical case, when the axis labeled north is directed towards the zenith. The tilt of the antenna results in phase center variation differences in the vertical direction on the sphere. The combination of tilted and rotated differences finally defines the shape of the antenna's phase center variations.

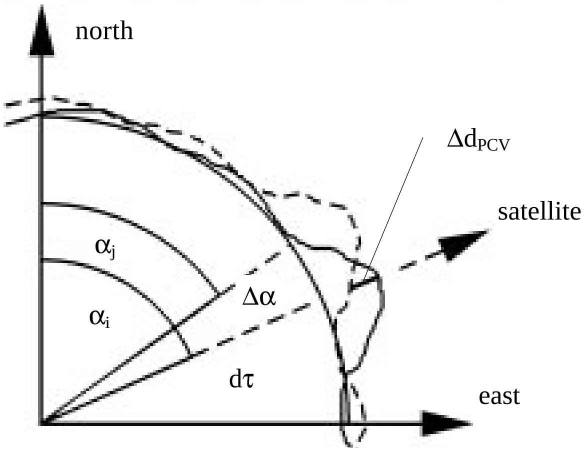

Fig. 5- Phase center variation difference Δd_{PCV} from δ^{SID} observable after rotating the antenna pattern (dotted line) horizontally by an angle $\Delta\alpha$ (solid line pattern)

As already pointed out, relative phase center variation observables are used to generate the absolute phase pattern. As relative observables are used, only the topology of the pattern can be described. The absolute size is not known. However, it acts like a constant clock error or a hardware delay on the GPS evaluation (circle with radius $d\tau$ in Figure 5). Therefore it will be absorbed through the estimation of the receiver clock error.

The term absolute antenna calibration, however, is still valid for the approach, because the phase center variations are determined independently from a reference antenna.

The modeling of the phase center variations is based on three conditions. First, the radius $d\tau$ cannot be estimated, but is not explicitly required, because it will be treated as a clock error. The second and third condition require a continuous and periodical function in the horizontal and vertical directions for the actual phase center variation model, because only relative observables are used. Therefore a spherical harmonic function as proposed by [2] is used to describe azimuth and elevation dependent phase center variations.

The coefficients A and B are estimated for a specific maximum degree n_{max} and order $m_{max} \leq n_{max}$ of a series of spherical harmonic functions to describe the phase center variations:

$$d_{PCV}(\alpha, z) = \sum_{n=0}^{n_{max}} \sum_{m=0}^{n} (A_{nm} \cos m\alpha + B_{nm} \sin m\alpha) P_{nm}(\cos z). \tag{7}$$

P_{nm} are normalized Legendre associated functions. Azimuth α and zenith angle z refer to the position of a particular satellite in the antenna coordinate system.

DETERMINATION OF ABSOLUTE PHASE CENTER VARIATIONS

To enable horizontal rotations and vertical tilts of the GPS antenna an antenna mount (Figure 7) has been used. The mount is constructed from synthetic material to reduce any effect on the antenna phase pattern due to changes in the electrical field. It allows a stepwise rest of 10 deg in the horizontal plane and a stepwise rest of 2.5 deg for vertical tilts. To minimize errors of the antenna mount due to temperature changes (e.g. direct sunlight) the observations should be performed after sunset.

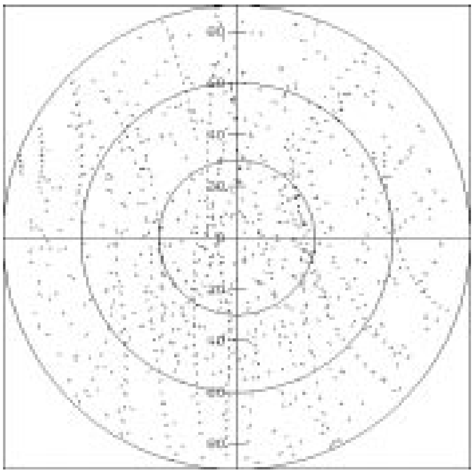

Fig. 6- Sky-Plot of the observed satellite tracks

Each absolute antenna calibration consists of measurements at two successive days. One day serves as a reference with unrotated antenna. On the other day one antenna is rotated and tilted following a certain schedule. In our test the antenna was rotated horizontally at three different inclinations (z=80 deg, 90 deg, 100 deg) with a stepwidth of 20 deg. In addition the antenna was tilted +/- 22.5 deg in three different azimuth positions (α=0 deg, 90 deg, 270 deg) with a stepwidth of 2.5 deg. In every position 2 min of data were recorded at a rate of 4 seconds using no elevation mask.

The distribution of the observed satellite tracks on a sphere are given in Figure 6. The coverage of the sphere is greatly improved by the rotations and tilts of the antenna compared to continuous passes of the satellites during the same observation window. The collected observations are also not disturbed by the northern hole. The northern hole depends on the latitude of the observation site and is the area, where no satellites are visible. Alternative approaches without sufficient orientation changes can therefore estimate no correction for these parts of the sphere and create a dependency of phase corrections on the calibration site.

Fig. 7- ASHTECH antenna Geodetic II in a tilted position on the antenna mount

The antenna mount has been calibrated using the Wild Theodolite Measuring System (TMS) comprising two Wild T3000 theodolites. Corrections for the horizontal and vertical steps were computed and introduced into the phase center variation determination. Offsets of the antenna reference point due to misalignments of the vertical and horizontal axis will be incorporated in future software implementation. However, first evaluations detected only rather small errors.

PRELIMINARY RESULTS

The new approach for field calibration of absolute phase center variations is implemented in the GPS processing package GEONAP, which is based on undifferenced GPS observables. A spherical harmonics development of degree 10 and order 5 was used in initial investigations to model ASHTECH Geodetic II antenna's absolute phase center variations.

The phase center variations are estimated in one adjustment without separating phase offset and phase pattern. Furthermore, it is not necessary to estimate station coordinates beforehand or to introduce a priori phase offsets. The lower degree and order coefficients describe the phase center offset. Nevertheless, the set of phase center variation coefficients together with spherical harmonic functions describes the antenna phase center variations in total without the explicit knowledge of the offset. The observation procedure also allows the determination of phase center variations even at elevation zero.

In order to verify the calibration procedure, two independent experiments were performed at the days 219/220 and 221/222, respectively. The data sets differ in time of the day and sites and therefore in GPS satellite constellation as well as in multipath conditions.

Figure 8 and Figure 9 show the L1 phase patterns of both experiments in three and two dimensional representations. The results are highly correlated. However, some systematic differences are present, which may be contributed to the antenna mount (no correction of misalignments of vertical and horizontal axis has been applied yet). Additionally, shading effects at low elevations or changes in the multipath due to the antenna mount may affect the result.

There are no outages due to the northern hole or to elevation cut-offs. The range of the phase center variations is approximately 10 mm. An azimuth dependency is clearly present, which recommends the use of azimuth and elevation dependent phase center variations.

DISCUSSION AND SUMMARY

The fact of repeated GPS satellite geometry after one mean sidereal day has been used to greatly reduce the influence of multipath on the determination of phase center variations. At the same time the dependency of a reference antenna could be eliminated allowing the absolute determination of phase center variations in a field procedure. The approach does also not rely on a priori coordinate estimations affected by multipath and phase center variations. The phase center variations consisting of a mean phase center offset and a phase pattern are estimated in one rigorous adjustment.

The observation procedure avoids areas without any observations (northern hole) by using rotations and tilts of the antenna, thus the estimated phase corrections will be independent from the calibration site. Otherwise errors from multipath and non-homogenous coverage of the antenna sphere may be introduced while applying such phase center corrections. The corrections from the new approach are worldwide rigorously applicable at any site.

The technical constraints for the new approach are rather high (adequate antenna mount), however, the benefits of being able to eliminate multipath and to get absolute phase center corrections from a field procedure clearly succeeded.

For the future, further investigations are necessary in the refinements of the use of spherical harmonic functions for the modeling of phase center variations. More insight must be gained in the interaction of multipath and weather condition. The antenna’s rotations and inclinations have to be precisely known. Therefore, the antenna mount must be calibrated and the corrections properly considered in the processing. Analyses of shading effects or influences of the mount on multipath are pending.

First experiments with cross-correlations of the different data sets indicated, that the satellite constellation does not repeat exactly after one mean sidereal day. Differences of a few seconds were detected analyzing the orbiting times of GPS satellites from ephemeris. The influence of a few seconds is considered rather small. Nevertheless, an examination is requisite.

The preliminary results are very promising. A procedure for the determination of absolute phase center variation has been defined, which solves several major limiting error sources in a field calibration.

Detailed comparisons with other data sets (chamber and relative phase center calibrations, e.g. [8]) and the application in operational GPS will finally verify the approach.

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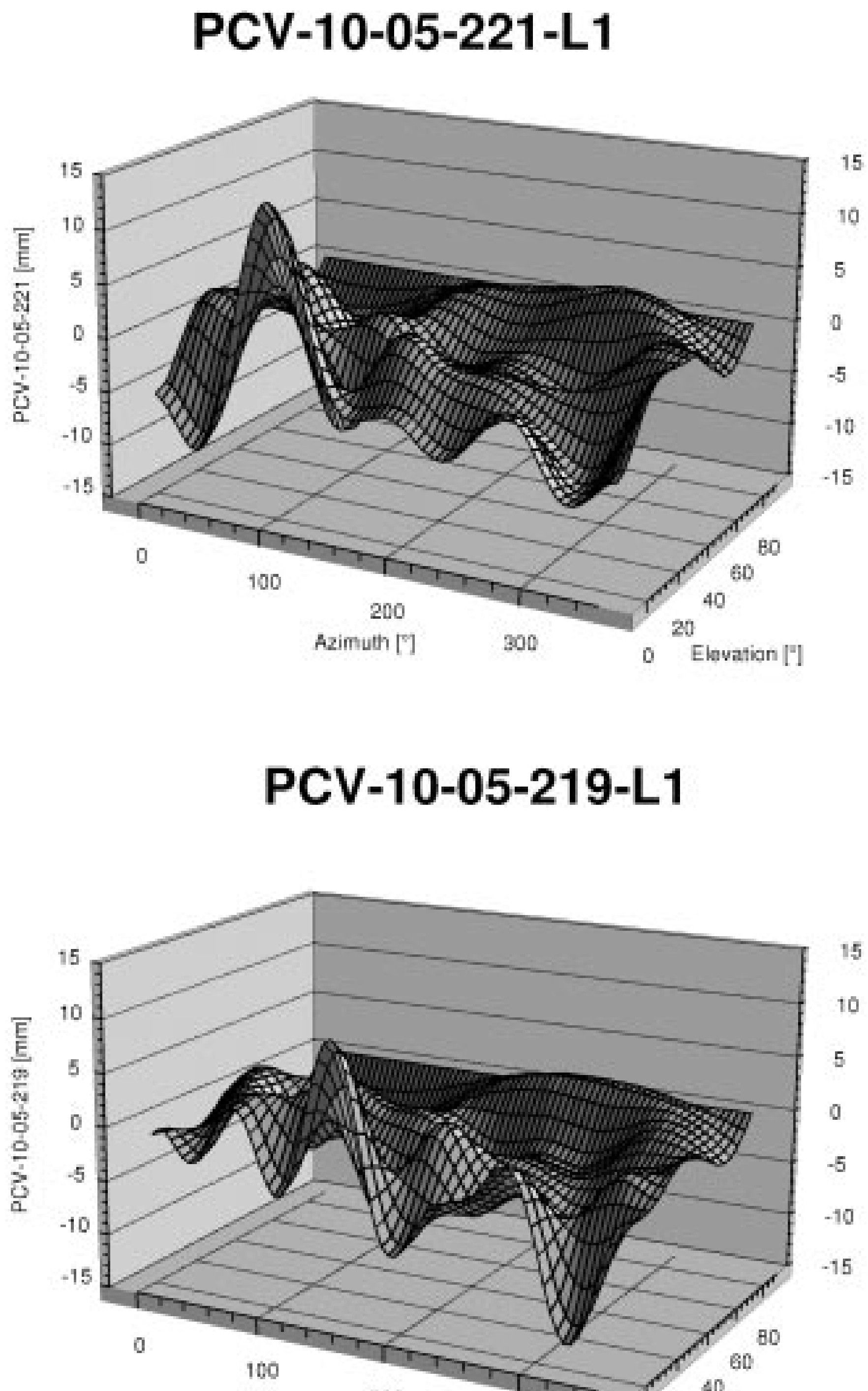

*Fig. 8***-** *Perspective view of elevation and azimuth dependent L1 phase center variations from two independent data sets (ASHTECH Geodetic II antenna)*

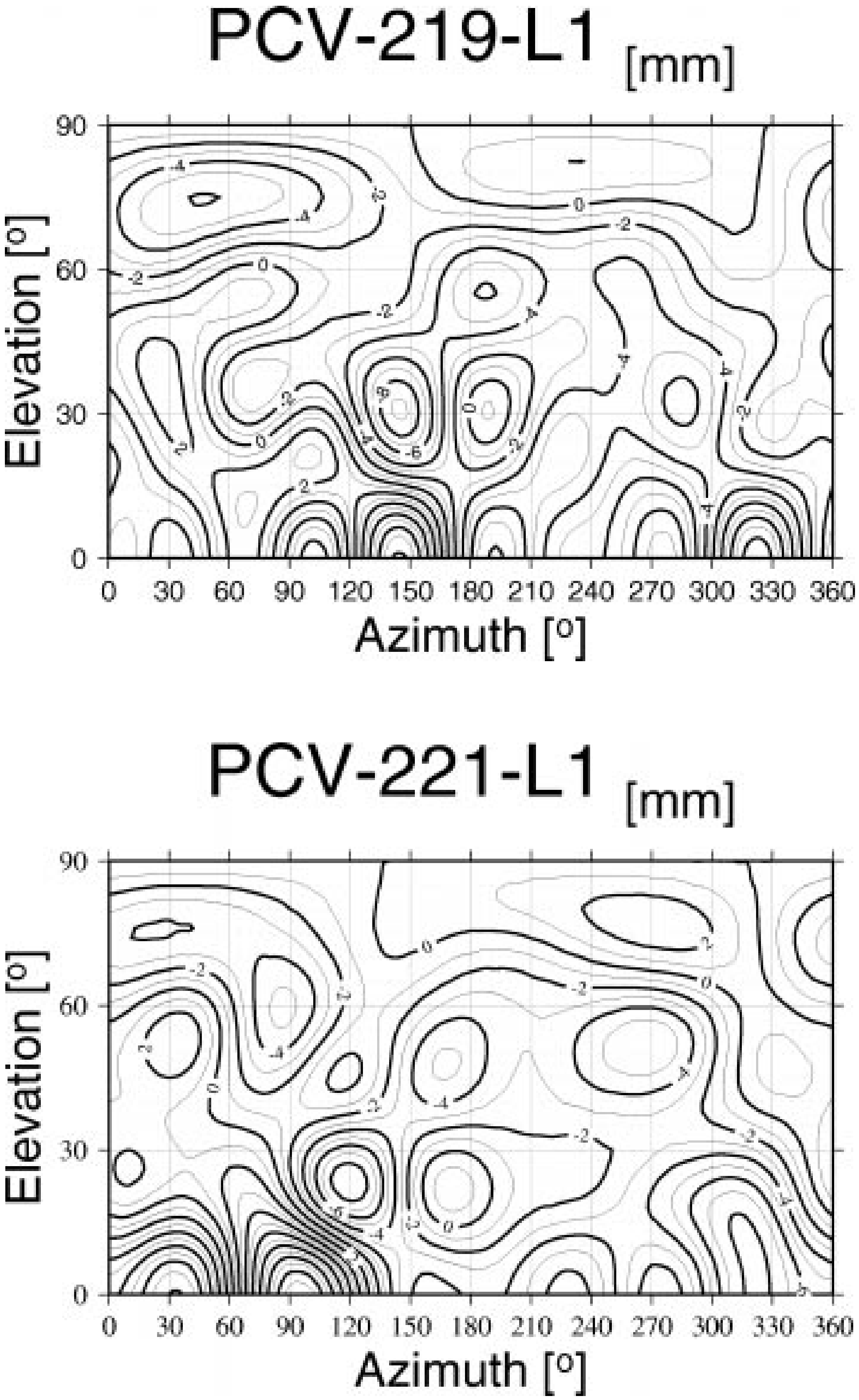

Fig. 9- Absolute elevation and azimuth dependent L1 phase center variations of an ASHTECH Geodetic II antenna from two independent data sets