

A New Approach for Field Calibration of Absolute Antenna Phase Center Variations¹

Gerhard Wübbena

*Geo++, Gesellschaft für satellitengestützte geodätische und navigatorische Technologien mbH
Steinriede 8, D-30827 Garbsen, Germany*

Falko Menge, Martin Schmitz, Günter Seeber, Christof Völksen

*Institut für Erdmessung, Universität Hannover
Schneiderberg 50, D-30167 Hannover, Germany*

BIOGRAPHY

Dr. Gerhard Wübbena received his degrees in Geodesy from the Universität Hannover, Germany. He works in the field of GPS since 1983 and developed the program system GEONAP. In 1990 he founded the company Geo++, which develops satellite navigation and positioning software and systems.

Dr. Günter Seeber has been Professor at the Institut für Erdmessung, Universität Hannover since 1973, where he teaches satellite geodesy, geodetic astronomy and marine geodesy. He specialized in satellite positioning techniques since 1969 and has published several scientific papers and books in the field of satellite and marine geodesy.

Falko Menge, Martin Schmitz and Christof Völksen received their Dipl.-Ing. in Geodesy from the Universität Hannover and are currently employed as research associates in satellite positioning at the Institut für Erdmessung.

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.

Today it is beside tropospheric and multipath errors the most limiting factor to achieve 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 (UNAVCO 1995, Rothacher et al. 1995a, 1995b). 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 (Schupler 1991). 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 Precise Positioning Service“ (HPPS) of Lower Saxony, the „Satellitenpositionierungsdienst der deutschen Landesvermessung“ (SAPOS) in Germany or the „International GPS Service for Geodynamics“ (IGS).

These high precise GPS applications demand for 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 (Rothacher et al. 1995a, Mader, MacKay 1996) as absolute phase center variations are only determined in anechoic chamber calibrations (UNAVCO 1995, Schupler et al. 1995).

So far field calibration only can determine the difference of phase center variations relative to one

¹ Presented at ION GPS-96, Kansas City, Missouri

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 pattern in an anechoic environment and applying these corrections for a field environment including multipath (UNAVCO 1995, Rothacher et al. 1995a). Thus, multipath must be reduced or the effect of multipath on the chamber pattern must be better understood (UNAVCO 1995).

A combination of chamber and field calibration may use an absolute chamber calibrated antenna as the reference antenna in a relative field calibration to enable indirectly an absolute calibration (Rothacher et al. 1995a, 1995b, Mader, MacKay 1996).

Direct absolute calibration in field procedure 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 by the intersection of the rotation axis of the antenna 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 (Schupler et al. 1995). 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 for some antenna types up to 20 mm considering observations at low elevations. The ionospheric free signal L0 (Wübbena 1989) amplifies any error in the phase by a factor of about 3.1 (UNAVCO 1995).

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. 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 uses undifferenced GPS observables.

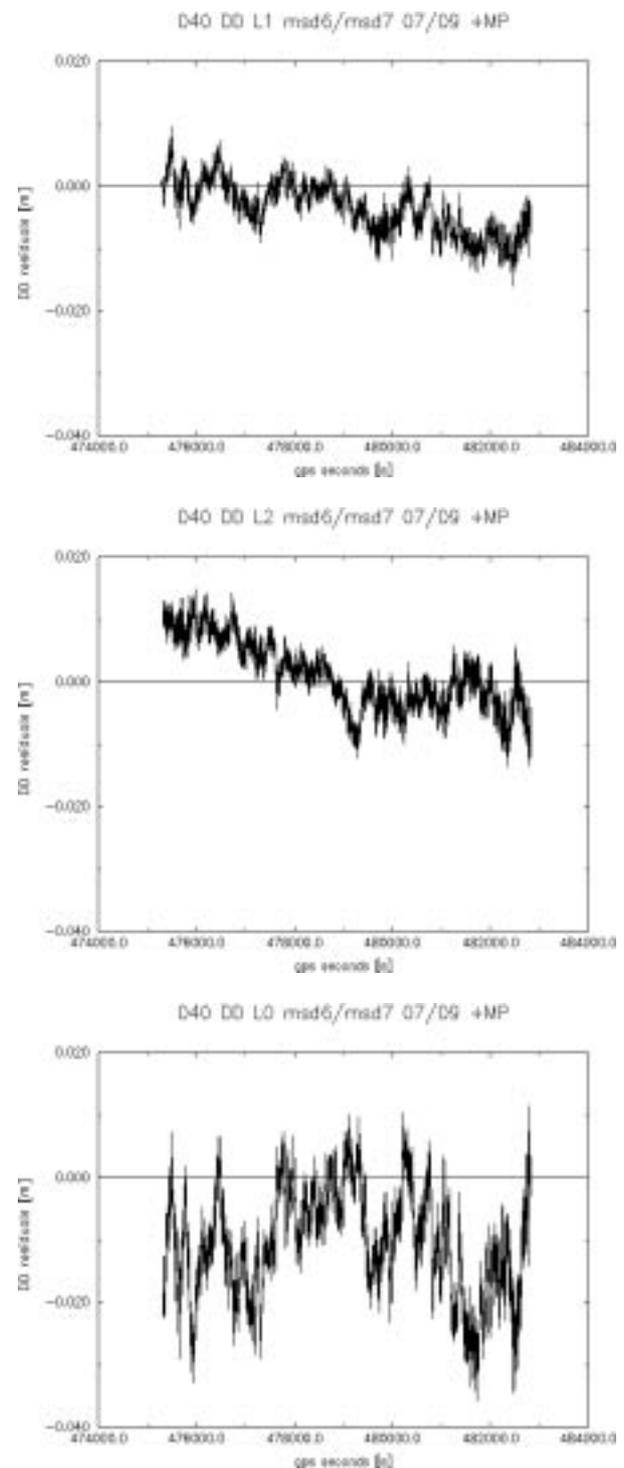


Fig.1: L1, L2 and L0 Double Differences of PRN07/PRN09 on Day 040

Fig.1 shows the double difference residuals of a short 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. Tab. 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 Fig.2 the double differences of L1, L2 and L0 of two successive days were cross-correlated. The cross-correlation function shows a maximum around 236 sec. 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.

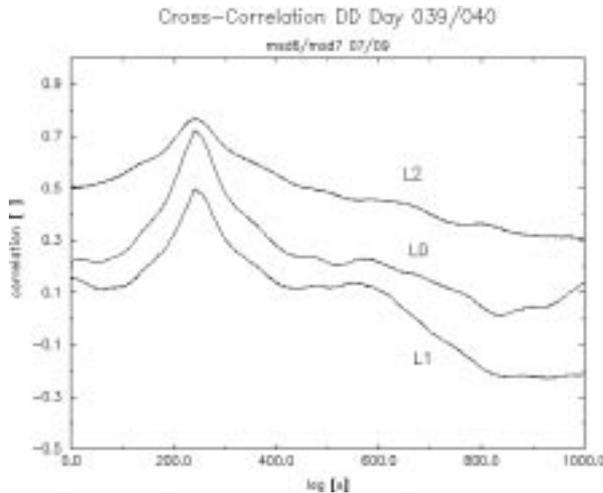


Fig.2: Cross-correlation function of Double Differences from Day 039 and Day 040

The undifferenced GPS observable of two successive days can be subtracted respecting the 3 min 56 sec difference of mean solar and mean sidereal day. As a consequence all errors which repeat themselves after one sidereal day cancel out, and in addition the complete geometric information.

A simplified linearized notation of the phase observation equations l_{ϕ} in meter containing the design matrix sub-vector a , the receiver coordinate corrections x , the receiver and satellite clock error dt and dT scaled to meter by the speed of light c_0 , the ambiguity N scaled to meter by the wavelength λ , the error terms d for ionosphere, troposphere, multipath, phase center variations and the noise of the phase ϵ_{ϕ} reads

$$l_{\phi_i}^j = \underline{a}_i^j \cdot \underline{x}_i + c_0 \cdot (dt_i - dT^j) - \lambda \cdot N_i^j - d_{ION_i}^j + d_{TROP_i}^j + d_{MP_i}^j + d_{PCV_i}^j + \epsilon_{\phi}.$$

The subscript i and superscript j stand for receivers and satellites. 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:

$$\delta^{SID} l_{\phi_i}^j = c_0 \cdot (\delta^{SID} dt_i - \delta^{SID} dT^j) - \lambda \cdot \delta^{SID} N_i^j - \delta^{SID} d_{ION_i}^j + \delta^{SID} d_{TROP_i}^j + \delta^{SID} \epsilon_{\phi}.$$

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 $\delta^{SID} \epsilon_{\phi}$.

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

$$\nabla \Delta \delta^{SID} l_{\phi_{i,k}}^{j,l} = -\lambda \cdot \nabla \Delta \delta^{SID} N_{i,k}^{j,l} + \nabla \Delta \delta^{SID} \epsilon_{\phi}.$$

To demonstrate the elimination of multipath the same baseline has been observed on two days with both 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 Fig. 3 were generated.

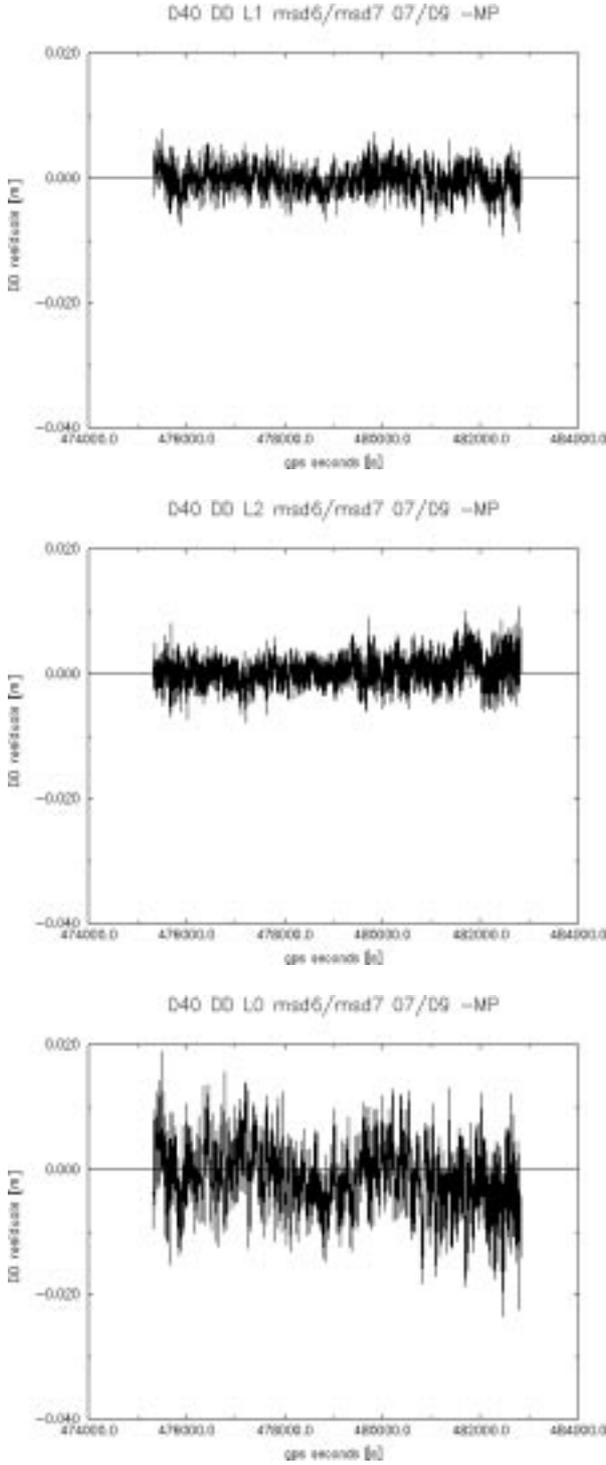


Fig. 3: L1, L2 and L0 Double Differences of PRN07/PRN09 for Day 040, δ^{SID} applied for identical antenna orientation

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 (ref. Tab. 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 at one day 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. On the other station a change in the horizontal orientation of the antenna by 180° 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

$$\delta^{SID} l_{\Phi_i}^j = c_0 \cdot (\delta^{SID} dt_i - \delta^{SID} dT^j) - \lambda \cdot \delta^{SID} N_i^j - \delta^{SID} d_{ION_i}^j + \delta^{SID} d_{TROP_i}^j + d_{PCV_i}^0 - d_{PCV_i}^{180} + \delta^{SID} \epsilon_\Phi$$

or for the double difference

$$\nabla \Delta \delta^{SID} l_{\Phi_{i,k}}^{j,l} = -\lambda \cdot \nabla \Delta \delta^{SID} N_{i,k}^{j,l} + \nabla \Delta d_{PCV_{i,k}}^{0,180} + \nabla \Delta \delta^{SID} \epsilon_\Phi.$$

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

Fig. 4 shows the double difference residuals after the antenna has been turned on the second day. Compared with Fig. 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 (Tab. 1).

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

Tab. 1: Phase noise of different observables in meter after processing with GEONAP

It is worth to note, that the phase center variation signal represents errors, which are introduced by neglecting 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 (Fig. 4).

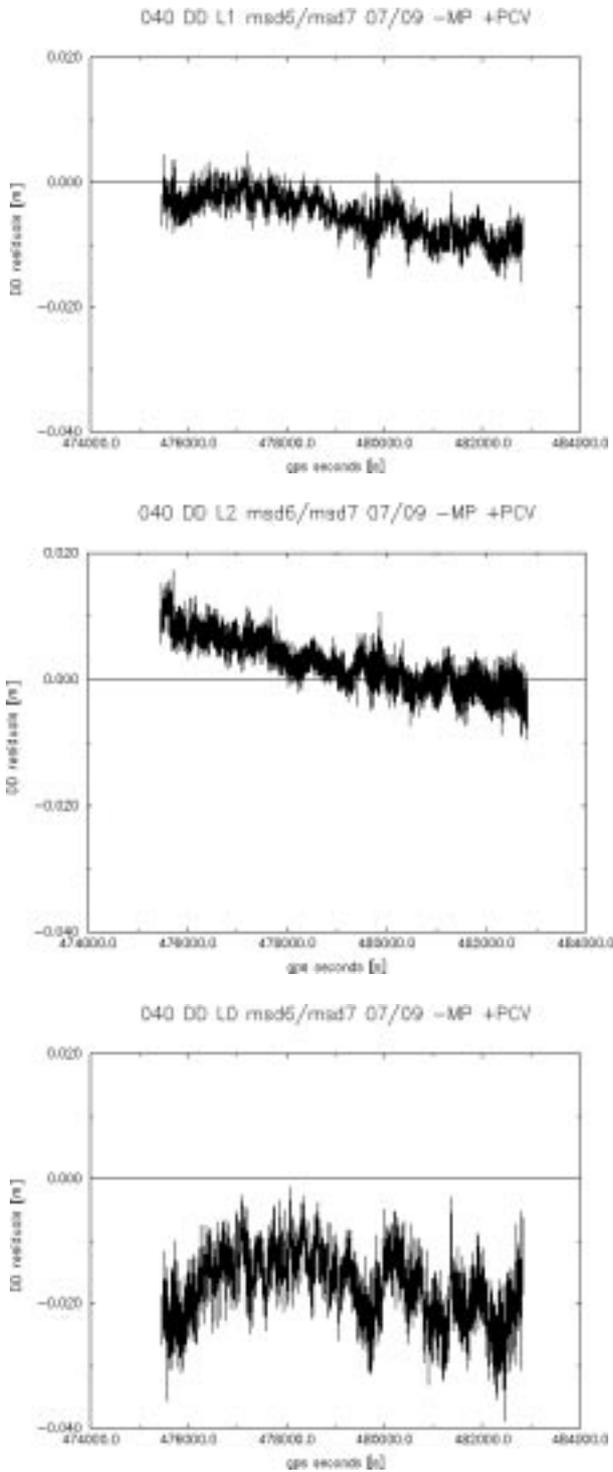


Fig. 4: L1, L2 and L0 Double Differences of PRN07/PRN09 on Day 040, δ^{SID} applied, antenna orientation of msd7 changed by 180°

Modeling the Phase Center Variations

As demonstrated, all systematic errors can be eliminated, including daily repeating errors, or are modeled correctly (e.g. clock errors) in the GPS processing. 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, we focus 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. 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, the antenna pattern is turned underneath the satellite signal while performing a change of antenna orientation. 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):

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

with

$$\Delta\alpha = \alpha_i - \alpha_j, \Delta z = z_i - z_j$$

defined in a coordinate system of the antenna.

Fig. 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. 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 in different elevations, a tilt of the antenna is necessary. Fig. 5 shows also the vertical case, when the axis labeled north is directed towards the zenith. The tilts of the antenna result in phase center variation differences in vertical direction on the sphere. The combination of tilted and rotated differences finally defines the shape of the antenna's phase center variations.

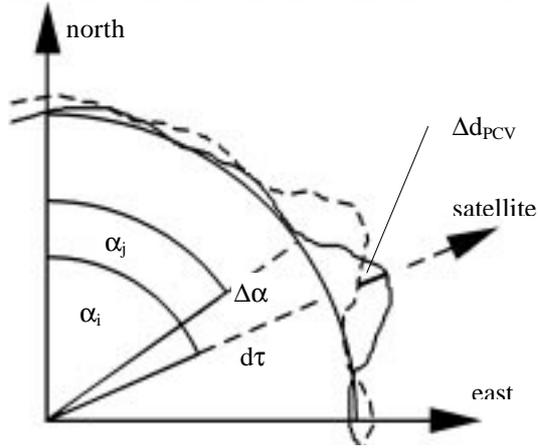


Fig. 5: Phase center variation difference Δd_{PCV} from δ^{SID} observable after rotating the antenna pattern (dotted line) horizontally by an angle $\Delta\alpha$ (solid line pattern)

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 Fig. 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 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 Rothacher et al. (1995a) 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:

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

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 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° in the horizontal plane and a stepwise rest of 2.5° for vertical tilts. To minimize errors of the antenna mount due to temperature changes (e.g. direct sunlight) the observations have been performed after sunset.

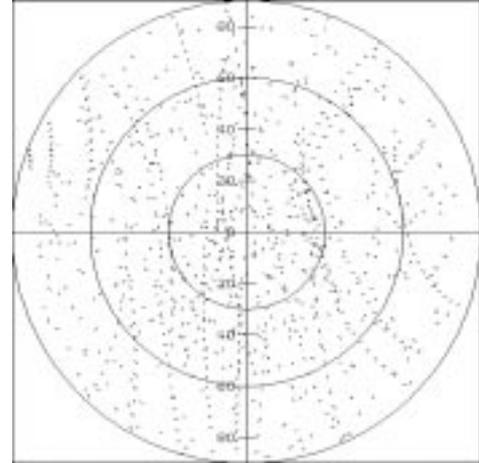


Fig. 6: Sky-Plot of the observed satellite tracks

The observations were performed at two successive days with an ASHTECH Geodetic II antenna. On the first day one antenna was rotated horizontally at three different inclinations ($z=80^\circ, 90^\circ, 100^\circ$) with a stepwidth of 20° . In addition the antenna was tilted $\pm 22.5^\circ$ in three different azimuth positions ($\alpha=0^\circ, 90^\circ, 270^\circ$) with a stepwidth of 2.5° . In every position 2 minutes of data were recorded using no elevation mask. The recording interval was adjusted to suit the mean sidereal time difference.

The distributions of the observed satellite tracks on a sphere are given in Fig. 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. Other approaches can therefore estimate no correction for these parts of the sphere and create a dependency of phase corrections on the calibration site.

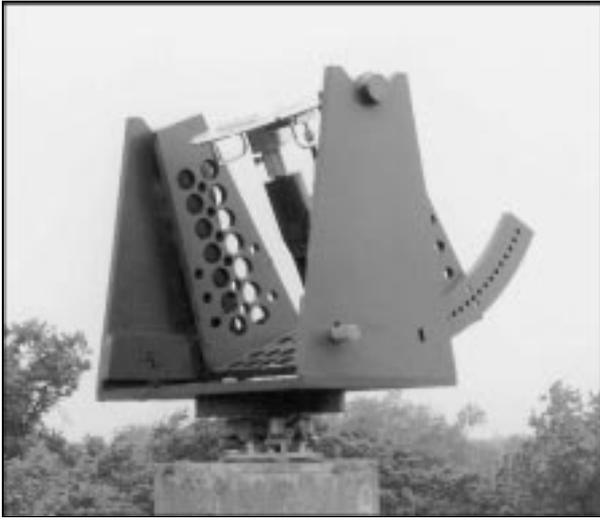


Fig. 7: ASHTECH antenna Geodetic II in a tilted position on the antenna mount

The antenna mount has been calibrated using the Wild Theodolite Measuring System (TMS) comprising two Wild T3000. Correction 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.

Two independent data sets were used to generate L1 phase center variations. The data sets differ in time and sites and therefore in multipath conditions as well as in GPS satellite constellation.

Fig. 8 shows the highly correlated phase patterns in a two dimensional representation. 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.

The range of the phase center variations is approximately 10 mm (Fig. 9). There are no outages due to the northern hole. 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 succeed.

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 used 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 some seconds is considered rather small. Nevertheless, an examination is requisite.

Detailed comparisons with other data sets (chamber and relative phase center calibrations) are necessary

and the verification of the phase center corrections while applying in operational GPS evaluations.

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.

ACKNOWLEDGMENTS

The Geodätische Institut, Universität Hannover, namely Dipl.-Ing. J. Grabowski greatly supported the work by making the WILD TMS system accessible.

REFERENCES

- Mader, G., J.R. MacKay (1996). *Calibration of GPS Antennas*. Geoscience Laboratory, Office of Ocean and Earth Sciences, NOS, NOAA, WWW-Server, Silver Spring, Maryland.
- 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, W. Schlüter, H.O. Hase (1995b). Azimuth- and Elevation-Dependent Phase Center Corrections for Geodetic GPS Antennas Estimated from GPS Calibration Campaigns. 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.
- Schupler, B.R., T.A. Clark, (1991). How Different Antennas Affect the GPS Observable. *GPS World*, 2, No. 10, November/December.
- 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.
- 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.