Presented at ION GNSS 2007, Sept. 25-28, Fort Worth, Texas, revised version 2007-10-24.

# GPS Block II/IIA Satellite Antenna Testing using the Automated Absolute Field Calibration with Robot

Gerhard Wübbena, Martin Schmitz
*Geo++®, Gesellschaft für satellitengestützte geodätische und navigatorische Technologien mbH*
*D-30827 Garbsen, Germany*

Gerry Mader
*National Geodetic Survey, NOS/NOAA*
*Silver Spring, MD, USA*

Frank Czopek
*Boeing Company*
*Seal Beach, CA, USA*

**BIOGRAPHY**

Dr. Gerhard Wübbena received his degrees in geodesy from the Universität Hannover. He has worked in the field of GNSS since 1983. In 1990 he founded the company Geo++®, which develops satellite navigation and positioning software and systems. Among these are the post-processing system GEONAP and the real time system GNSMART.

Dr. Martin Schmitz received his degrees in geodesy from the Universität Hannover. He has been working in the field of GNSS for the industry and as a research fellow at the Universität Hannover since 1991.

Both authors are currently employed at Geo++®. They are concerned with research and development in satellite positioning. Current projects focus on highly precise RTK phase positioning (GNSMART), absolute GNSS antenna field calibration, GNSS station calibration and real time attitude systems.

Gerald Mader received a B.A. in Physics from Rutgers University in 1969 and a Ph.D. in Astronomy from the University of Maryland in 1975. He joined the National Geodetic Survey in 1983 and currently serves as the Chief of the Geosciences Research Division. Dr. Mader has primarily focused his attention on static and kinematic applications of the Global Positioning System (GPS). Dr. Mader's current research is directed toward using the CORS network to enable rapid ambiguity resolution for efficient precise positioning and the development of web-based tools for processing GPS data, such as OPUS – the On-line Positioning User Service.

Frank Czopek is currently the Program Manager of the On Orbit Support contract for the BLOCK II/IIA satellites. He has worked for Boeing for the last 24 years, mainly on GPS BLOCK II/IIA program supporting satellite and subsystem testing. He has authored other papers on GPS and on advanced satellite technologies. Frank earned his B.S.M.E degree from Michigan Technological University in 1980 and a Master in System Architecture and Engineering from University of Southern California in 2002.

## ABSTRACT

The characteristics of the GPS satellite antenna has an important impact on precise GPS positioning. The transition from relative phase center offsets and variations (PCV) to absolute PCV for the receiving antennas on the ground requires PCV for the satellite antennas. Currently, the IGS is estimating elevation dependent PCV pattern from global networks and from the ionospheric free linear combination.

Absolute PCV field calibration for GPS receiver antennas has been available since 2000. The methodology was developed by Geo++ in cooperation with the Institut für Erdmessung, Universität Hannover starting in 1996. The absolute field calibration provides absolute phase variations of GNSS antennas completely independent from any reference antenna or station dependent effects.

In 2000 NGS attempted a relative PCV calibration on a BLOCK II/IIA antenna which was used as the qualification antenna. This antenna is identical to the flight antennas. Due to the complex design and small beam width results from this test produced limited results.

In 2006 NGS approached the GPS wing who sponsored the shipment of the antenna to Geo++ where the absolute PCV measurement process would be used on the BLOCK II/IIA antenna. The PCV determination proved challenging due to the size of the antenna which caused modifications and redesigns of equipment and procedures use to determine the PCV. Testing was delayed by wet year in the Hanover region of Europe

Experiences and results from the testing of the BLOCK II/IIA antenna are presented which cover elevation and azimuth dependent phase variation (including mean offsets).


## WHY PHASE CENTER MEASUREMENTS ARE IMPORTANT

GPS pseudo ranges are measured from transmitting phase center to receiver phase center. As cited by real world experiences the phase centers are not physical points. To eliminate the errors caused by variation of phase center, there is a need to describe how phase centers change with azimuth and elevation.

After the launch of the first GPS BLOCK II satellite the orbit was estimated to be smaller than what was predicted. The phase center with respect to the satellite's center of mass is critical e.g. for accurate orbit determination.

On the ground, it was realized that especially together with tropospheric scale parameter estimation, height errors were incurred when two different antenna types were used in differential solutions. The need for antenna calibration was served by relative field calibrations (Mader 1999), a very robust and relatively simple technique. The calibration result, however, refer to the used reference antenna model, which was defined to be a AOAD/M_T.

The assumption that the reference antenna had a fixed PCV, i.e. the phase center did not change with direction (particularly elevation) was known to be incorrect. However, for shorter baselines the assumption was valid and the effects of different antenna characteristics could be corrected using these relative calibrations. For baselines long enough that the curvature of the earth caused a satellite viewed by two stations to be seen at significantly different elevation angles, the assumption of zero PCV breaks down.

Early attempts to measure the absolute PCV of the reference antennas in anechoic chambers were done by Schupler et al. (1994). However, when these calibrations were used in the global solutions, scale errors of about 15 ppb resulted. The development of the absolute antenna field calibration (Wübbena et al. 1997, Menge et al. 1998, Wübbena et al. 2000) and subsequent measurements of absolute PCV produced similar scale errors.

A relative field calibration of a BLOCK II/IIA antenna by Mader, Czopek (2001) analyzed the validity of phase offsets for the GPS transmitting antenna, which were based on theoretically computed offsets and was used for all satellites. Satellites passing through the zenith-pointed beam of the antenna provided by Boeing were observed. Several days of observing provided enough multiple satellite occurrences in the beam to obtain a good estimate of the L1 and L2 phase center offsets but insufficient data to compute the PCV. As suspected, the phase centers were about 70 cm closer to the earth than the values being used. This corrected offset removed much of the 15 ppb scale error.

This led to further investigations of the satellite antenna characteristics based on globally distributed GPS data. Schmid and Rothacher (2003) demonstrated the estimation of elevation dependent satellite PCV together with other geodetic parameters. The determination of azimuthal variation has been presented in Schmid et al. (2005). Also low earth orbit satellites have been used to determine GPS satellite's PCV (Bar-Sever et al. 2006).

With consistent absolute receiver PCV and satellite antenna offsets and PCV a better agreement with other geodetic space techniques was finally achieved. The IGS performed the transition from relative to absolute receiver antenna PCV including satellite PCV in November 2006 (Schmid et al. 2007).

The current satellite PCV are limited to the ionospheric linear combination (L0) and the computations are correlated with other parameters, especially station heights and troposphere. Therefore a calibration on the ground is a completely independent approach, which has the advantages to eliminate most of the GPS error components. It is also possible to determine PCV for the L1, L2 observable and to investigate azimuthal variations.

The precise knowledge of PCV for receiving and transmitting antenna has shown to be of high importance. The GPS error budget and consequently application

accuracy will benefit from further insight or improvement.

The current Navstar GPS Constellation Status (07-07-07, http://gge.unb.ca./Resources/GPSConstellationStatus.txt) lists 16 active BLOCK II/IIA satellites. The latest IGS antenna PCV correction file igs05.atx (ftp://igscb.jpl.nasa.gov/igscb/station/general/) contains PCV for 29 BLOCK II (20) and BLOCK IIA (9) satellites derived from GPS data starting back in 1994 (Schmid et al. 2007).

## ANTENNA DESCRIPTION

The antennas of the BLOCK II and II/A satellite have the same configuration. The array comprises of two concentric rings of elements (refer to Fig. 4). The inner quad consists of four equally spaced helical elements. The outer ring is an eight elements octagonal array. The antenna pattern is achieved by a 180° phase shift between inner and outer ring and a certain ratio of power supplied to the two rings. On the BLOCK II/IIA array ninety per cent of the L-band signal is supplied to the inner four elements and ten per cent to the outer elements. For more details see Czopek, Shollenberger (1993), Aparicio et al. (1995), (Mader, Czopek 2002).

## DESCRIPTION OF THE GEO ++ RANGE ENVIRONMENT

Absolute antenna field calibration are carried out operationally on the Geo++ roof since 2000. The roof allows the set-up of different equipment on several pillar (Fig. 1).

Essential parts of the absolute GNSS antenna calibration system are the Geo++ GNSMART software and a robot (Fig. 2). The robot enables observations in different antenna orientations. In particular azimuth dependent PCV can be reliably and accurately determined due to optimized coverage of the antenna's hemisphere. One calibration for receiving antennas takes a few hours.

*Fig. 1: Test range of Geo++ with single drive and robot*

The calibration procedure is a real-time Kalman filter based on undifferenced observable and a feedback process. The currently tracked satellites and their position in the topocentric antenna coordinate system are used to decide on the best suited inclination and rotation of the antenna. The orientation requests are submitted to the robot. The tracking and constellation dependent guidance of the robot ensures independent observation procedures for every calibration.

A continuously adjusted elevation cut-off is applied to mask satellites above a certain threshold or even higher elevations depending on the actual robot inclination. The observation programs are variable and therefore reduce the possibility of systematic errors.

The major error source in antenna PCV estimation is multipath, which is accounted for in the observation procedure. A sufficiently high and dynamic elevation mask is used. Further, multipath is eliminated based on the high correlation between fast executed orientation changes and by stochastic modeling in the Kalman filter. The multipath is generally completely removed or greatly reduced (Wübbena et al. 2000). Further error components such as ionospheric, tropospheric and orbit biases cancel out using a very close-by reference station.

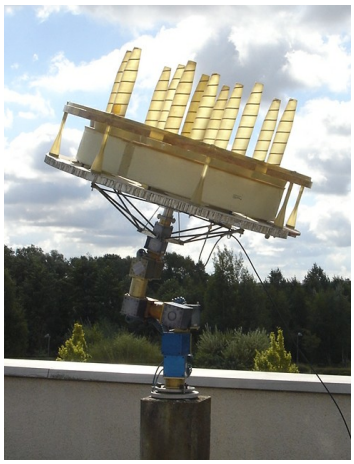

*Fig. 2: GPS BLOCK II/IIA antenna tilted on robot*

The mathematical model for the PCV is a spherical harmonic expansion of optional degree and order. As an additional parameter the carrier-to-noise (CN0) pattern of the antenna/receiver combination is regularly determined during the PCV calibration. Investigations have shown, that the CN0 pattern can be used for the standardization of CN0 values between different receivers and consequently for observation weighting (Wübbena et al. 2006).

In summary, an absolute antenna calibration with a robot provides absolute 3D offsets, absolute elevation and azimuth dependent PCV in a simultaneous adjustment of L1, L2 as well as L1 CN0, L2 CN0 pattern for GPS and GLONASS signals. The internal standard deviation estimated has been verified by analysis of repeated calibration. The standard deviation (1 sigma) is in the order of 0.2 to 0.4 mm (latter for the antenna horizon) for the individual observable L1 and L2.

## TEST SET UP AND METHODOLOGY

The GPS BLOCK II/IIA satellite antenna unit has a weight of 14.4 kg and is heavy compared to receiving GNSS antennas. Special calibrations with antenna constructions amounting to 12 kg have already successfully handled by the robot. However, the dimensions of the BLOCK II/IIA with a diameter of 1.34 m creates additional momentum and forces acting on the robot during operation.

After initial testing, the robot performed good with the BLOCK II/IIA antenna. However, it was necessary to optimize the actual control of the robot modules regarding synchronized movements, time splitting of tilt and rotation movements, intermediate positions to get more safety in any stop situation.

*Fig. 3: Mount and BLOCK II/IIA (15.5 kg, 1.34 m diameter) on robot*

To get more information beforehand, the BLOCK II/IIA was operated static and on a single robot module for azimuthal rotations (Fig. 1). The data on the drive ensured at least data over all azimuths for the elevations of tracked satellites and provides a priori knowledge of PCV pattern.

The measurements served also for investigating the best tracking. The signal from the satellite antenna must be adjusted to a level, that a GPS receiver can operate with it. A dual-frequency antenna pre-amplifier has been taken from an ASH700288A antenna and attached to the BLOCK II/IIA antenna feed.

Different GNSS receivers were tested with the satellite antenna. The gain of the antenna and especially gain differences are significantly different compared to a regular GPS receiving antenna. Correspondingly, the signal fed to the receiver is sometimes out of expectation of the further signal processing within the receiver. Hence, the signal was finally damped by 22 dB to get proper receiver operation. To enable the tracking loop and navigation mode of the receiver an initial period without damped signal was required. For the actual measurements, the damping element of 22 dB was put back in between the antenna cable. The power was externally supplied with 9.5 V.

The tested receivers showed slightly different tracking performances (carrier-to-noise, number of satellites). Some receivers decoded even false ephemeris and mixed up the real time processing. Generally a zero-baseline configuration with four receivers was used, but JPS LEGACY receivers showed up to give the best and most reliable operation.

The mounting of the BLOCK II/IIA was more complex than expected. Any reduction of momentum and support of acting forces on the robot had to be considered. In addition the weight, dimensions of the mount and the final mounting height had to be optimized. An individually custom-made mount based on carbon elements and fiber fulfilled the requirements (Fig. 3).

The definition of the antenna coordinate system in the robot calibration is the same as for regular receiver antennas. The azimuth counts clockwise from the north towards the east direction. The z-axis points to the zenith. Due to the restricted mounting of the BLOCK II/IIA on the robot, the estimated pattern are not yet aligned to the axis marked on the antenna (X+ X- Y+ Y-) and off by 57°. The red line in Fig. 4 shows the Geo++ north orientation, the blue lines are indicating the antenna feed network symmetry.

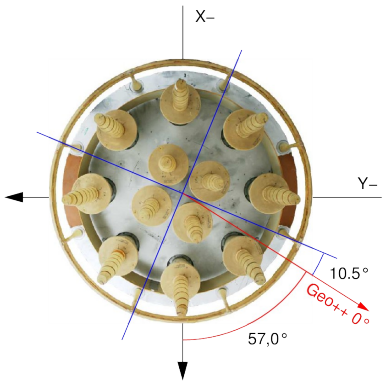


*Fig. 4: North orientation during robot calibration*

The antenna reference point (ARP) for the height (up) offset is top of the BLOCK II/IIA antenna groundplane. For future use, it has to be related to the satellite's center of mass. The sign of PCV follows the Geo++ convention.

Observations only above 30° elevation were used during the real time calibration. All relevant observation data was recorded for post-processing purposes. The standard spherical harmonics expansion of degree and order (8, 5) was selected for PCV and CN0 modeling.

For the processing of the collected observations a sufficient number of at least two satellites must be tracked. The tracking requirements are even further restricted, as the satellites should be preferable in the small cone of 14° to 15° around the zenith. The robot was configured to perform tilts of up to 25° to obtain the required coverage.

The tracking is additionally hampered by the reception characteristic of the antenna, which was already addressed

by Mader, Czopek (2001). Caused by side lobes, there are nulls in elevation, where tracking stops. After passing these areas (around 30° and 60° elevation), tracking is again possible (see also Czopek, Shollenberger 1993). The robot guidance takes this fact currently not into account, which causes loss of data depending on the antenna orientation also for favorable constellations.

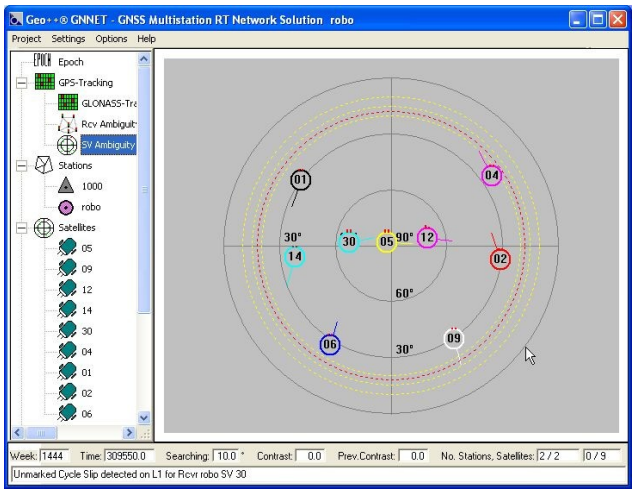

*Fig. 5: Constellation with triplet of GPS satellites*

It is of advantage for the BLOCK II/IIA calibration to have GPS satellites simultaneously visible, which positions are close together to ensure a sufficient high number of satellites in the narrow reception cone. The current GPS constellation offers some satellite constellation with satellites in the same orbital plane and very close slots. During the actual data collection a constellation of a twin and a triplet of GPS satellites (Fig. 5) could be used.

The signals are often corrupted by cycle slips due to robot movements, but also due to the reception characteristics of the antenna. At least for cycle slips not marked by the receiver, a nominal PCV pattern might reduce the residuals in the processing and enhances the capability to recover slips. This approach is intended for post-processing analysis.

## RESULTS OF THE GEO ++ TESTING

The analysis of the results is focusing on the general question of the shape of the PCV pattern and the magnitude of elevation and azimuth dependent PCV for the actual transmitting region. The direct comparison with results from the IGS working groups and the relation to the center of mass is left out for future analysis.

The results are based on data collected with a JPS LEGACY receiver and processed in real time with the Geo++ GNSMART software. The observation were collected on four consecutive days on Sept. 11 to 14, 2007. The daytime constellation was used during several different periods. The individual PCV estimations are stored and all results are finally combined in a rigorous adjustment using the complete variance-covariance information. The complete length of used data is about 21 h with over 24650 robot positions.

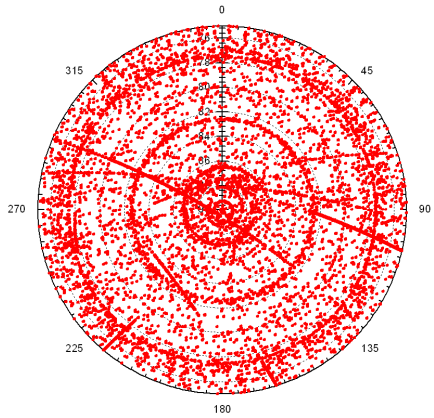

*Fig. 6: Coverage with observations for elevation 75° to 90°*

The actual observations in the antenna area from 75° to 90° elevation, which were input to the combined PCV estimations are displayed in Fig. 6. There are also satellite tracks from periods without meaningful orientation changes visible.

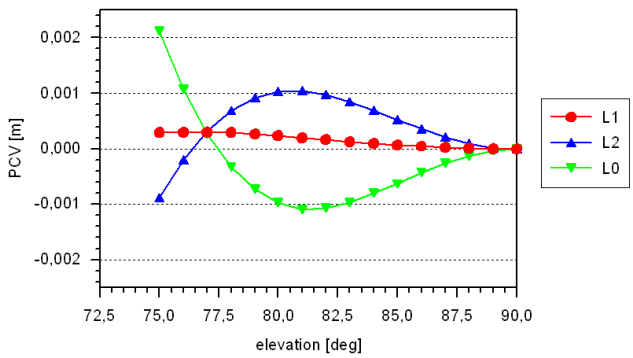

*Fig. 7: BLOCK II/IIA pure elevation dependent PCV [m], offset removed*

Pure elevation dependent PCV can be computed from the combined real time calibration results. In Fig. 7 the PCV for the L1, L2 and ionospheric free linear combination L0 are shown. The magnitude of the PCV is generally smaller than a few mm.

However, there are significant azimuthal variation especially for the L1 signal visible (Fig. 8), which average out in the computation of the pure elevation dependent PCV. The L1 PCV range from -8 mm to +6 mm and show two significant maximums. The L2 PCV (Fig. 9) pattern shows more maximums, but has a smaller magnitude with values from -4 mm to +2 mm. One can detect four maximums for the L2 PCV, which corresponds to the four center elements of the antenna array. It is notable, that the four elements are not recognized in the azimuthal L1 PCV.

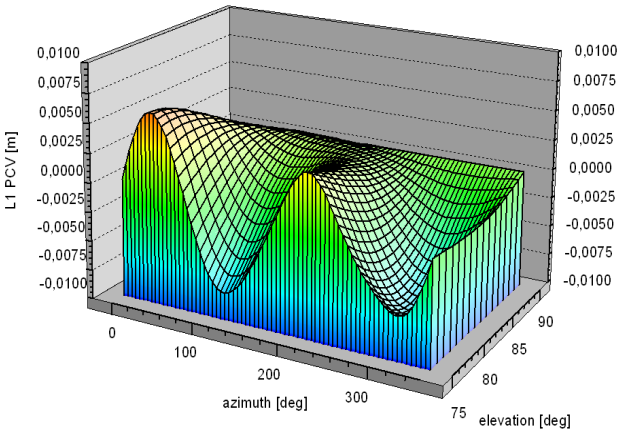


*Fig. 8: BLOCK II/IIA L1 PCV [m], offset removed*

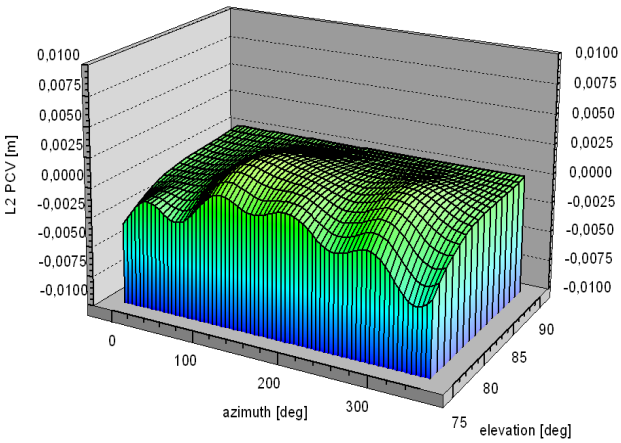


*Fig. 9: BLOCK II/IIA L2 PCV [m], offset removed*

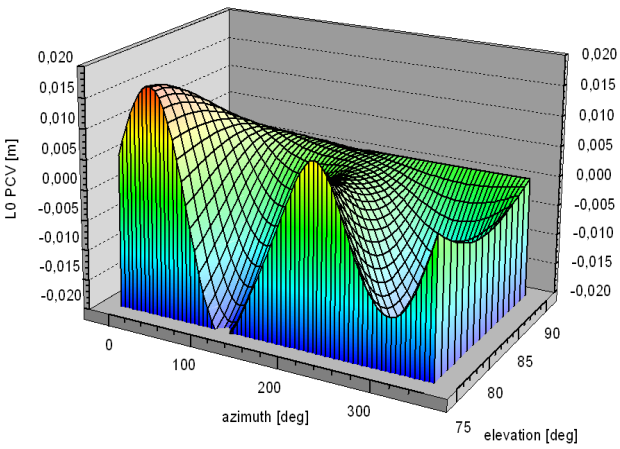


*Fig. 10: BLOCK II/IIA L0 PCV [m], offset removed*

Fig. 10 shows the L0 PCV with maximum values of -21 mm and +17 mm. The two maximums from the L1 PCV pattern are dominating and the L2 PCV maximums do not significantly show up.

The standard deviation derived from the combination of results from four days is depicted in Fig. 11 and Fig. 12, which amounts to approximately 0.4 mm at 15° zenith distance for both frequencies.

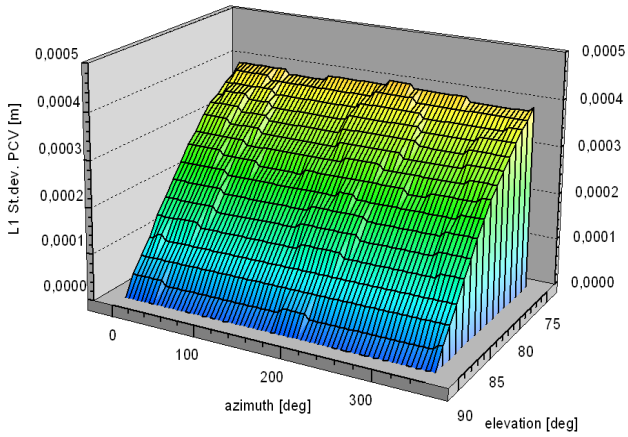


*Fig. 11: L1 PCV standard deviation [m]*

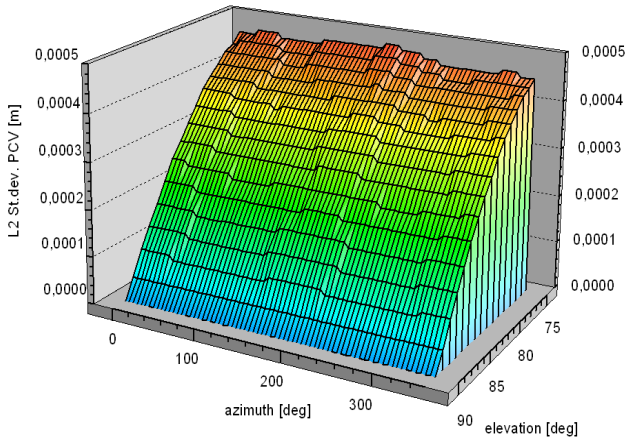


*Fig. 12: L2 PCV standard deviation [m]*

The L0 linear combination is the relevant observable for global applications using satellite antenna PCV and it is used by the IGS groups to estimates satellite PCV and offsets from worldwide observation data. The elevation dependent PCV have a similar magnitude (igs05.atx). The azimuthal PCV pattern has been estimated by Schmid et. al (2005). The BLOCK II/IIA showed in their analysis an asymmetric azimuthal variation with a magnitude of +/- 4 mm for L0 PCV.

Generally, the offsets and the phase center variations together define the reception characteristic of an antenna. This also holds for the transmitting BLOCK II/IIA antenna. The height offset depends on the elevation mask used for the computation. In addition, it is geometrically difficult to derive height offset values for the area of interest, the 15° cone.

From the combined adjustment of the four days the offsets listed in Tab. 1 are derived. The up offset refers to the top of the groundplane. The horizontal offsets refer to the rotation center of the mount, which was attempted to be centric. The offsets indicate, that it has been successfully achieved. The horizontal offsets are derived from the lower coefficients, which include all observation above 30° elevation. The height offsets are based on an elevation mask of 75°.

The offsets cannot directly compared with the offsets given by Mader, Czopek (2002), because of different elevation masks.

| Frequency | North [m] | East [m] | Up [m] |
|---|---|---|---|
| L1 | +0.00195 | -0.01079 | +0.26867 |
| L2 | +0.00291 | +0.00020 | -0.18817 |
| L0 | | | +0.97481 |

*Tab. 1: Offsets referring to center of mount and top of BLOCK II/IIA groundplane*

The height offset, however, affects precise application significantly. A difference of 0.5 m in nadir direction will be attributed to the clock error in a processing, but causes a range error of about 0.017 m for 15° nadir distance.

The derived carrier-to-noise pattern (CN0) are shown in Fig. 13 and Fig. 14. The hardware setup of the complete antenna is affecting the CN0. Hence, the CN0 value for the zenith is set to null and the resulting decrease function is used. The decrease function is independent on any hardware setup or changes in the calibration (antenna cable, splitter, etc.).

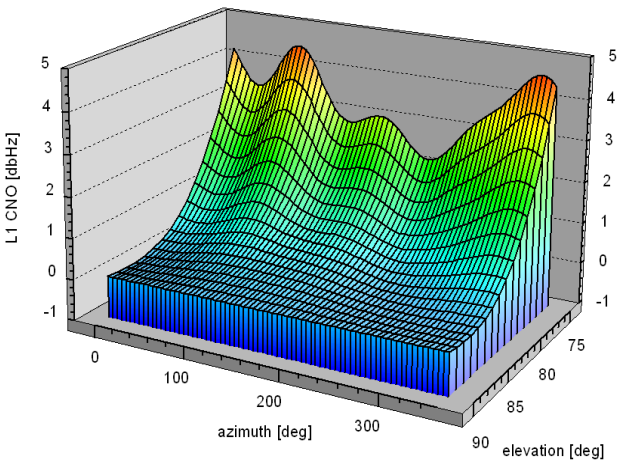


*Fig. 13: L1 CN0 decrease function [dbHz], zenith set to null*

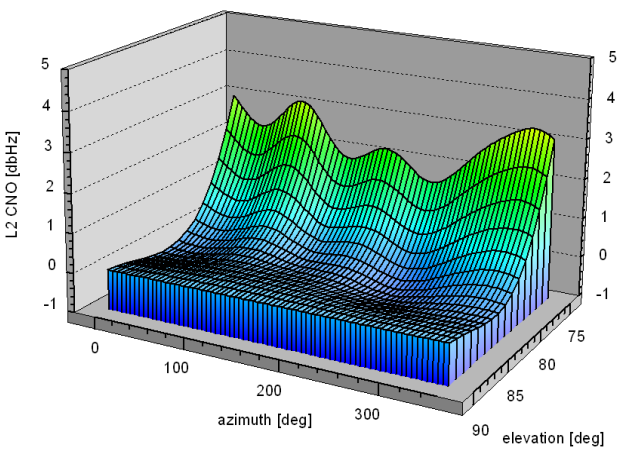


*Fig. 14: L2 CN0 decrease function [dbHz], zenith set to null*

The decrease of the CN0 is approximately 3 dbHz for both frequencies for the displayed elevations from 75° to 90° elevation, slightly less for L2. The maximums resemble a symmetry with the four center elements. Only a small part the CN0 values are slightly higher than the zenith value.

## DISCUSSION AND FUTURE PLANS

An absolute PCV field calibration of a GPS BLOCK II/IIA has been successfully performed with a robot. Elevation and azimuth dependent PCV for the original L1, L2 observable and consequently for the ionospheric free linear combination L0 have been determined. In addition the calibration provided CN0 decrease functions.

The results show, that the azimuthal variations of the transmitting antenna are significantly larger than the pure elevation dependent PCV pattern. The currently applied elevation dependent corrections account only for 10% of the effect. Hence, there is a potential for improvement in precise GPS application, if nadir and azimuth dependent PCV are used.

The collected data during the BLOCK II/IIA calibrations with the robot will be additionally analyzed in post-processing. Further calibrations with enhanced robot guidance concepts are intended to further improve the coverage with observation data in the small 15° reception cone.

Detailed comparison and discussion with the results from other working groups determining satellite PCV will be of interest and are aspired.

## REFERENCES


Aparicio, M., P. Brodie, L. Doyle, J. Rajan, P. Torrione (1995): *GPS satellite and payload.* In: Parkinson, BW, JJ. Spilker (eds). Global Positioning System. Theory and Applications. Vol **I**., American Institute of Aeronautics and Astronautics, Inc., Washington, 209–244.

Bar-Sever, Y., W. Bertiger, S. Byun, S. Desai, B. Haines, G. Hajj (2006): Calibrating the GPS Satellites Transmit Antenna. Presentation at IGS Workshop 2006, May 8-12, ESOC, Darmstadt, Germany.

Czopek, F.M., S. Shollenberger (1993): *Description and Performance of the GPS Block I and II L Band Antenna and Link Budget*. ION GPS-93, Salt Lake City, Utah, 37-43.

Mader, G.L. (1999): *GPS Antenna Calibration at the National Geodetic Survey*. GPS Solution, **3**, No.1, 50-58.

Mader, G.L. (2001): *A Comparison of Absolute and Relative GPS Antenna Calibrations*. GPS Solutions, **4**, No. 4, 37-40.

Mader, G.L., F. Czopek (2001): *Calibrating the L1 and L2 Phase Centers of a Block IIA Antenna*. ION GPS-01, September 11- 14, Salt Lake City, Utah, USA.

Mader, G.L., F.M. Czopek (2002): *Calibrating Antenna Phase Centers. The Block IIA Satellite.* GPS World, **13**, May, 40-46.

Menge, F., G. Seeber, C. Völksen, G. Wübbena, M. Schmitz (1998): *Results of Absolute Field Calibration of GPS Antenna PCV*. ION GPS-98, September 15-18, Nashville, Tennessee, USA..

Schmid, R., M. Rothacher (2003): *Estimation of Elevation-Dependent Satellite Antenna Phase Center Variations of GPS Satellites*. Journal of Geodesy, **77**, 7-8, 440-446.

Schmid, R., M. Rothacher, D. Thaller, P. Steigenberger (2005): *Absolute Phase Center Corrections of Satellite and Receiver Antennas*. GPS Solution, **9**, No. 4, 283-293.

Schmid, R., P. Steigenberger, G. Gendt, M. Ge, M. Rothacher (2007): *Generation of a Consistent Absolute Phase Center Correction Model for GPS Receiver and Satellite Antennas*. Journal of Geodesy, 18 April, on-line first.

Schupler, B.R., R.L. Allshouse, T.A. Clark (1994): Signal Characteristics of GPS User Antennas. Navigation, Journal of The Institute of Navigation, Vol. **41**, No. 3, 277-295.

Wübbena, G., M. Schmitz, G. Boettcher (2006): *Absolute GNSS Antenna Calibration with a Robot: Repeatability of Phase Variations, Calibration of GLONASS and Determination of Carrier-to-Noise Pattern*. Paper submitted to IGS Workshop 2006, May 8-12, ESOC, Darmstadt, Germany.

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 Institute of Navigation, Vol. **44**, No. 2, 247-256.

Wübbena, G., M. Schmitz, F. Menge, G. Seeber, V. Böder (2000): *Automated Absolute Field Calibration of GPS Antennas in Real-Time.* ION GPS-00, September 19-22, Salt Lake City, Utah, USA.