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Special tests of phase centre variations of various GPS antennas, and some results

Martin Schmitz

Geo++® Gesellschaft für satellitengestützte
geodätische und navigatorische Technologien mbH
D−30827 Garbsen, Germany
www.geopp.de

1 Introduction

The error budget of GPS measurements has long been generally understood. However the accuracies required and achieved by GPS become ever greater. For certain fields of application the largest sources of error at a given time are an important topic of research, in order to achieve further improvements in accuracy and reliability. Consequently, effects which have been regarded as satisfactorily contained gain in importance and are subjected to further intensive investigation. Until now, the phase centre variations (PCVs) of receiver antennas represented one such error component, but today absolute values of PCVs can be determined with increased accuracy using field procedures. This leads to reliable recording of azimuthal variations by means of homogeneous scanning of the antenna, a higher resolution and the elimination of multipath effects. The general advantages of absolute PCV values (as functions of elevation and azimuth), for differently oriented antennas and thus for real−time applications, have now been demonstrated by experiment (Wübbena et al., 2000a, 2000b).

In this paper, the development of the determination of phase centre variations and their correction is examined. The automated real−time absolute field calibration developed jointly by Geo++® and the Insitut für Erdmessung of the University Hannover is briefly presented, together with the accuracies achieved by the operational procedures. The general accuracy requirements for PCV determination are then discussed. The major part of the paper deals with the special tests and their results for the PCVs of different GPS antennas and configurations.

2 Development and current status of PCV corrections

PCVs were determined and analysed in laboratory experiments from the very start of the development of GPS. Sims (1985) reported absolute values of elevation− and azimuth−dependent PCVs for the antenna of the first civilian TI1400 GPS receiver. However, in practice the same types of antennas and the same orientations were generally used, so that over short distances the PCV effects were not significant. It was simply sufficient to measure the height of the antenna to the same reference point. Moreover at that time it was not possible to distinguish PCV effects on static measurements over long periods at short to medium ranges from other effects.

The use of different types of antenna and measurements over long distances, with satellites being viewed at different elevations from widely separated stations, made it necessary to provide a PCV correction. The absolute PCV values available from relatively costly laboratory calibrations did not give satisfactory results in practice. This led to the introduction of field procedures for antenna calibration. In these simple field calibrations, elevation−dependent PCVs are estimated in relation to a given reference antenna. The PCVs of the reference antenna are assumed to be zero and offsets are fixed at predetermined values (Rothacher, Mader 1996). The absolute PCV component of the reference antenna, with a variation of 28 mm in L0, is not corrected (IfE, Geo++® 2000) and introduces systematic errors (Wübbena et al. 2000b).

Frequently, only manufacturers' data on the offset of the mean L1 phase centre, sometimes with the L2 value in addition, was used in GPS computations. Alternatively, offsets were determined in separate rotation test measurements or were taken from published calibration results. PCV corrections were generally not taken into account. The increasing use of mixtures of antenna types, especially with the introduction of reference stations and reference station networks, now demands full corrections for offsets and PCVs.

In comparisons of relative and absolute PCVs an effect emerges in global networks which represents a scale error of 15 parts per billion as a first approximation (Rothacher et al. 1995, Menge et al. 1998). On the basis of the results of other measurement techniques, absolute PCVs were at first thought to be the source of this. The cost of determining absolute PCVs in the laboratory inhibited thorough investigations. Wübbena et al. (1996) first put forward absolute field procedures for antenna calibration and discussed the disadvantages of relative techniques. Experiments have shown that absolute PCVs can be excluded as the cause of the so−called "scale errors" in global networks. New investigations into other sources of error such as satellite antennas and the troposphere are now therefore required (Wübbena et al. 2000b, Rothacher 2000).

Current comparisons of absolute laboratory calibrations with absolute field calibrations (Rothacher 2000) as well as comparisons with relative PCVs (Mader 2000) confirm the general correctness of the absolute PCVs.

Until now, the elevation−dependent PCV has been regarded as the largest component, and azimuthal PCV effects have been reckoned to be an order of magnitude smaller. The increase in the resolution, accuracy and reliability resulting from absolute field calibrations shows, however, that some antenna types have significant azimuthal variations of comparable magnitude, which must be taken into account, especially for real−time applications. Absolute PCV values for precise GPS applications with tilted antennas can be shown to be equally necessary over short distances (Wübbena et al. 2000b).

A complete description of the phase reception behaviour of an antenna consists of the antenna reference point (ARP), the north mark, data for both frequencies for the mean 3D phase centre (offset) referred to the ARP, and PCVs for L1 and L2 in relation to the given offset. It is important to note that when comparing PCVs they must always be related to the same reference point. PCVs may be converted to other reference points such as a mean phase centre or some other defined ARP.

3 Automated absolute field calibration in real time

In terms of the GPS observation equations, the effects of the station−dependent error components (PCVs and multipath (MP) effects) are indistinguishable. An essential principle of absolute field calibration is the separation and thus the determination or elimination of the various individual sources of error. Undifferenced GPS computation approaches are essential here. At first a procedure including sidereal day differences was used in post−processing. The operationally available automated absolute field calibration in real time (Wübbena et al. 2000b) uses short−term differences. Both approaches to taking multipath effects into account are discussed briefly below.

With sidereal day differences, the multipath error term is eliminated, or at least reduced as far as possible, insofar as identical multipath conditions exist on two observation days (through repetition of the satellite constellation). The PCV differences between static observations on a reference day and the observations with rotated or tilted orientation on a second day are used as input for the PCV determination using spherical harmonic analysis. Through the changes in orientation between the two days of observation, PCVs can be determined, and separated from MP effects. All other parameters in the GPS adjustment are eliminated or estimated. Details are given in Wübbena et al. (1997), Seeber et al. (1998) and Menge et al. (1998).

The undifferenced observation equation forms the basis for the real−time calibration process. In addition to the standard parameters of the GPS adjustment for short distances, the high correlation of multipath effects between successive epochs is used to estimate multipath parameters as stochastic processes. The rapid changes of orientation of the calibration robot allow the separation of PCV and MP effects. In order to describe the undifferenced approach, triple differences can be considered by way of simplification. It is well known that the time differences between successive double differences are free not only of time and atmospheric effects but also of ambiguity terms and of multipath. However, through the arrangement of observations with changing orientations (rotations and tilts) the PCV signal is reintroduced, varying epoch−by−epoch. The procedure is implemented in software based on undifferenced observations.

Fig. 1 shows an example with double differences, sidereal day differences between double differences, and triple differences (by analogy with real−time calibration approaches). The elimination of MP can be clearly discerned both with the sidereal differences and with the triple differences (short−term differences).

The real−time calibration requires rapid changes in orientation using a robot. In addition, comprehensive calibration of the robot itself is required, through theodolite observations, to enable antenna positions to be determined to about 0.2 to 0.3 mm (see Menge et al. 2000, Wübbena et al. 2000b). This makes the process at first seem extremely costly.

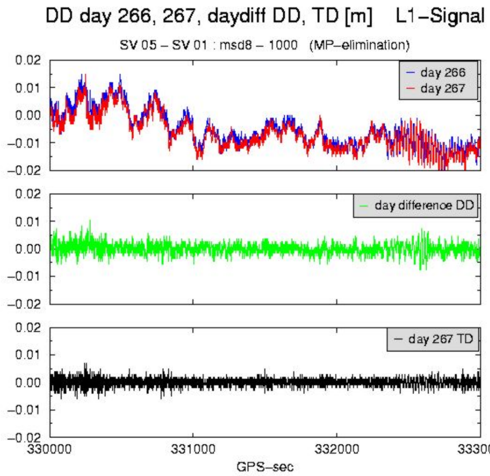

Fig. 1: Elimination of Multipath

On the other hand, however, automation brings additional advantages. With the robot, observations are carried out in several thousand exactly−defined positions. Results from post−processing show that the large number of positions is necessary for high resolution and accuracy of determination of the PCV. The average total of different orientations in one calibration is between 6000 and 8000, depending on time and the satellite constellation. Azimuth−dependent PCVs in particular can be reliably and accurately determined. One calibration takes only a few hours. In addition the measuring programme is automated, while the current satellite constellation is taken into account for the optimisation of the coverage, the observation time and the expected PCV accuracy. Comprehensive and homogeneous coverage of the antenna hemisphere is finally achieved with observations on the horizon (tilted antenna). The observation programmes are variable and therefore reduce the possibility of systematic errors. The calibration is complete when complete coverage of the antenna hemisphere is achieved (with observations currently at least at every 5°). Further information is given in Wübbena et al. (2000a, 2000b).

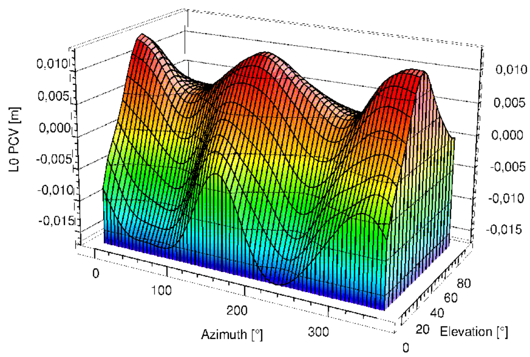

Fig. 2: Absolute L0 PCV with LEIAT303_LEIC

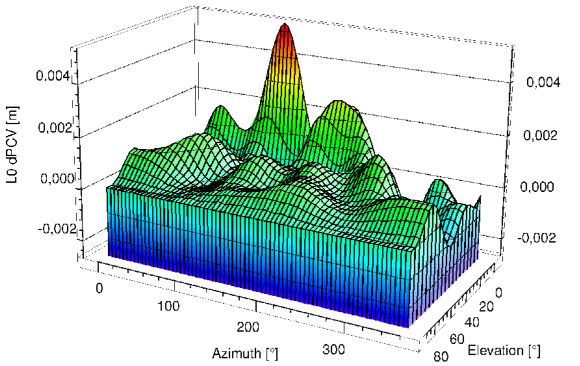

Fig. 3: Difference of two L0 PCV LEIAT303_LEIC calibrations five months apart (elevations from 90° to 0°)

The repeatability of the absolute PCV field calibration is demonstrated using the results for a Leica LEIAT303 LEIC. The antenna shows azimuthal variations of ± 6 mm for the L0 linear combination (Fig. 2). The differences between two calibrations carried out five months apart are shown in Fig. 3. In general the differences are less than 1 mm and only reach larger values on the horizon. The standard deviation (s) of the PCV from the calibration is of the order of 0.2 to 0.3 mm and is identical with the values derived from the double measurements of the repeat calibration. The standard deviations relate to the complete PCV including offsets. The influence of the PCV on position determination is thus less than 1 mm. The excellent repeatability has been proven (IfE, Geo++ ® 2000, Wübbena et al. 2000b) through further comparisons of calibrations of other types of antenna with different robots, at different stations and at different times of day (differences in robot calibration, multipath, weather, constellation, measurement programme, station surroundings and structures) and confirms the high quality of the PCVs so derived, as well as their independence of the station at which the antenna is placed.

4 *Accuracy requirements* for PCV corrections

The accuracy of the antenna calibration is not separated in the estimation of the offset and the PCV, but is derived jointly for PCV and offset. This is obvious, if the propagation of errors and the ionosphere−free linear combination (L0) for an estimate of the effect of antenna offset and PCV on GPS position determination are considered. The standard deviation of the L0 PCV is about three times that of the L1 and L2 PCVs. For position fixing in periods of high ionospheric activity the L0 value is relevant. Often the separate accuracies of 1 to 2 mm for the L1 and L2 offsets as well as the 1 to 2 mm for the L1 and L2 PCVs are deemed to be satisfactory. With these values, the standard deviation of the PCV for the linear combination L0 then lies in the region of about 4 to 7 mm.

The effect on the GPS positional accuracy is defined in terms of the standard deviation of position s_P and the standard deviation of phase measurements s_R , together with a measure of the satellite geometry, the position dilution of precision (PDOP), as follows:

$$s_P = s_R * PDOP$$

With a PDOP value of 1 to 3, uncertainties in the PCV effects give rise to positioning uncertainties in the range of about 4 to 21 mm. For high precision applications this is not sufficiently accurate. The best possible accuracies for the combination of offset and PCV are therefore required for a PCV determination. The question is also often posed whether individual antenna calibrations are necessary, rather than a general calibration for an antenna type. The same also applies to the differences between individual antennas.

5 PCV tests and results

5.1 Effects of UHF aerials in the vicinity of the GPS antenna

An aspect which has been little researched up to now is the influence on GPS reception characteristics of additional telemetry aerials. Additional aerials in the immediate vicinity of the GPS antenna elements fundamentally alter their electromagnetic reception properties. A DSNP DSNDGU_002* antenna was calibrated absolutely, with and without an attached UHF aerial (Fig. 4). The UHF aerial was passive, that is, it was neither supplied with power nor was data transmitted or received. Fig. 5 shows the differences for an antenna with and without the 70 cm band aerial supplied by the manufacturer. The differences in the PCV reached values of ± 12 mm. The PCVs are converted to a common offset. To enable a strict comparison, this has been carried out for all of the graphs. In general, offset data is not representative for the description of the complete antenna. In this case, however, the offsets clearly show the general difference between the antenna properties (Table 1). Positional offsets are in general sub−millimetric, but changes exceeding 3 mm have already occurred here.

Fig. 4: DSNDGU_002_UHF during absolute calibration using the robot*

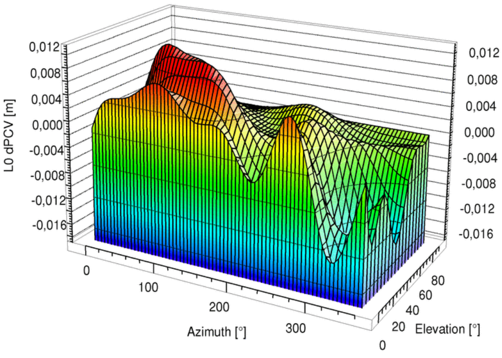

Fig. 5: Absolute L0 PCV differences for DSNDGU_002 with and without passive UHF aerial*

Thus the effect of a UHF aerial in the immediate vicinity of the GPS antenna is not small enough to be considered negligible. Further research is necessary, however, especially during active operation and with UHF aerial components which are integrated within the GPS antenna housing.

* Proposed for inclusion in the IGS rcvr_ant.tab, however not yet official International GPS Service (IGS) nomenclature.

	dNord [mm]	dOst [mm]	dHöhe [mm]
L1	2.63	0.22	−1.46
L2	0.32	3.53	−2.76

Table 1: Differences between offsets for DSNDGU_002 with and without passive UHF aerial*

5.2 PCVs of integrated antenna and receiver systems

The effect of a UHF aerial in the vicinity of the GPS antenna has already been demonstrated. Because of the immediate proximity of receiver and aerial in integrated equipment, the PCV in these systems is also of considerable interest. The housing of the Zeiss GePoS CZJRD24* receiver has a square base with cut off corners (Fig. 8). The antenna element is placed above the receiver electronics in the same housing. Fig. 6 shows the absolute L0 PCV with clear azimuthal variations, caused, among other things, by the angular housing. In Fig. 7 the purely azimuthal L0 PCV component of ± 15 mm can be seen, after removal of the elevation−dependent PCV. In Figs. 6 and 7 the PCV components due to offsets are not included. With values of 5 to 7 mm in northing and 10 to 15 mm in easting for each of L1 and L2, the offsets for the CZJRD24* are also very large.

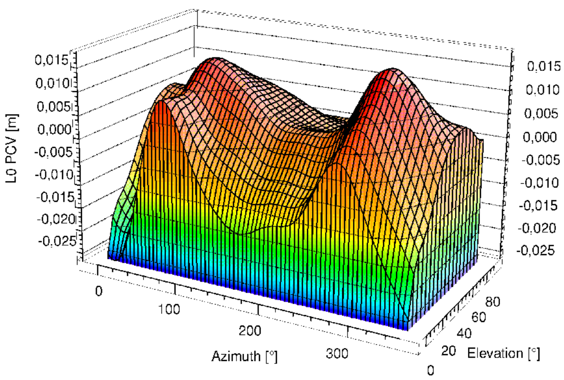

*Fig. 6: Absolute L0 PCV of CZJRD24*integrated antenna/receiver system*

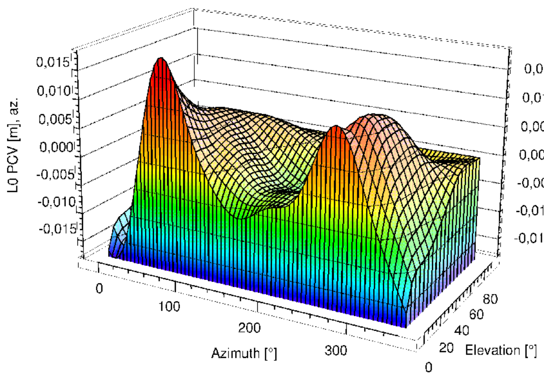

Fig. 7: Pure azimuthal L0 PCV of CZJRD24 integrated antenna/receiver system*


Fig. 8: CZJRD24 integrated antenna/receiver system*


Fig. 9: TRM4800 during absolute calibration on the robot

In contrast, with the integrated Trimble TRM4800 system only very small L0 PCVs of ± 2 mm are detectable from an elevation of 10° up to the zenith, together with a very slight azimuth dependency. Only below 10° is a larger azimuthal effect detectable, with values of up to 8 mm which coincide with the control panel on the south side of the receiver. In plan view the TRM4800 is circular (Fig. 9). The purely azimuthal PCVs are given in Fig. 11, which only shows values exceeding 2 mm below 10° elevation.

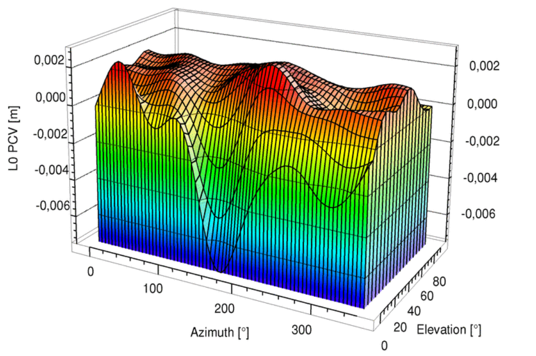

Fig. 10: Absolute L0 PCV of TRM4800 integrated antenna/receiver system

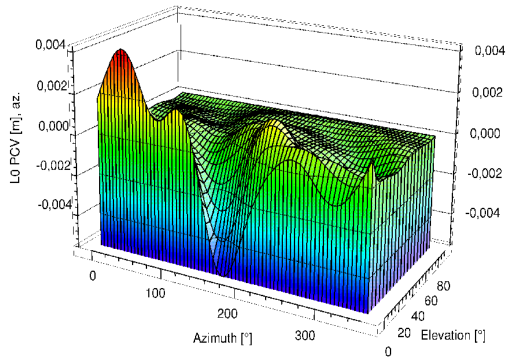

Fig. 11: Pure azimuthal L0 PCV of TRM4800 integrated antenna/receiver system

Thus, in principle, small PCV values and virtually symmetrical PCV characteristics are possible even with an integrated system, given sufficient shielding combined with a suitably shaped housing. However it cannot be generally assumed that every model of integrated antenna exhibits this.

5.3 Effect of antenna domes on PCVs

A further factor influencing phase reception behaviour is the addition of an antenna dome. In general an antenna with a dome is regarded as a different type of antenna with its own receiver characteristics. However the effect is often underestimated and ignored. Constant differences in PCV do not appear to be important. Nevertheless any constant PCV difference which gives rise to a region of steep gradients will adversely affect the quality of GPS observations.

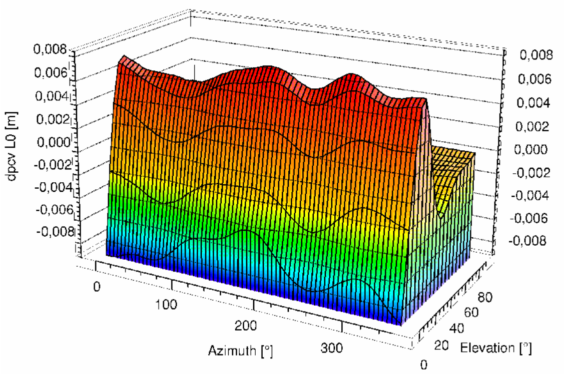

Fig. 12: Differences of absolute L0 PCV for TRM29659.00 with and without TCWD

Fig. 13: Construction of Trimble TCWD dome

Fig. 12 shows the difference between a Trimble TRM29659.00 with and without a TCWD dome. The dome is fixed with a metal band onto a separate ground plane beneath the actual antenna (Fig. 13). The PCV without the dome is clearly different from that with the dome construction attached. It is primarily the large additional ground plane which changes the absolute PCV for L0 over a range of 16 mm (Wübbena et al. 2000b). The changes are mainly at low elevations, but do extend above the usual elevation masks.

Several other types of dome, without additional ground planes, such as the Ashtech SNOW or the Leica LEIC, have smaller effects of ± 1 to 2 mm on the phase reception properties. Fig. 14 shows the difference of the absolute L0 PCV of a LEIAT303 with and without the conical LEIC "dome". The comparison is for the same antenna with and without its dome. The differences are mostly small and only increase on the horizon. Between elevations of 30° and 0° values are about 2 mm, exceeding 2 mm only on the horizon.

Significant differences in PCV are also caused by the design of the dome (in terms of materials, etc.) and how close it is to the receiver elements of the antenna. Fig. 15 shows the Leica LEIS and SCIS domes for the LEIAT504 choke ring antenna. These two domes are somewhat different but both have an essentially spherical shape. The SCIS dome is fixed with steel screws and is more robust, being made of hard plastic. The diameter of the SCIS is about 3 cm greater than that of the antenna itself, so that a complete hemisphere covers the antenna. The LEIS is screwed directly to the choke ring of the antenna with plastic screws, forming a hemispherical cover with vertical sides. For the PCVs of the same antenna with the different domes there are clear differences of about 6 mm, rising to 12 mm between 25° elevation and the horizontal (Fig. 16).

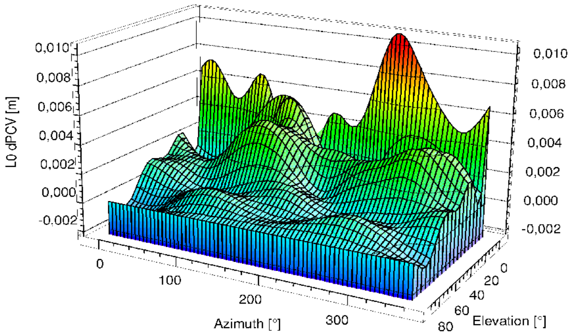

Fig. 14: Differences of absolute L0 PCV for LEIAT303 with and without LEIC dome (elevations from 90° to 0°)

Fig. 15: Leica LEIS and SCIS domes for LEIAT504

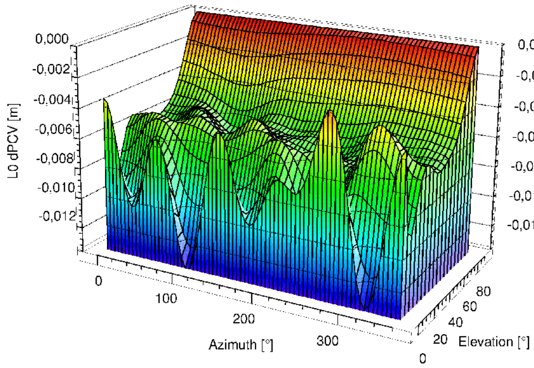

Fig. 16: Differences of absolute L0 PCVs for AT504 with LEIS or SCIS

Figs. 17 and 18 show the differences compared with the calibration of the AT504 without a dome. In this case the LEIS dome shows a smaller effect on the PCV than the SCIS dome. For measurements with the SCIS the PCV clearly changes between 90° and 60° with gradients sometimes exceeding 1 mm per degree, and with a mean value of 11 mm at an elevation of 10°. From 65° elevation to the horizon the LEIS exhibits differences which mostly average about 2 mm.

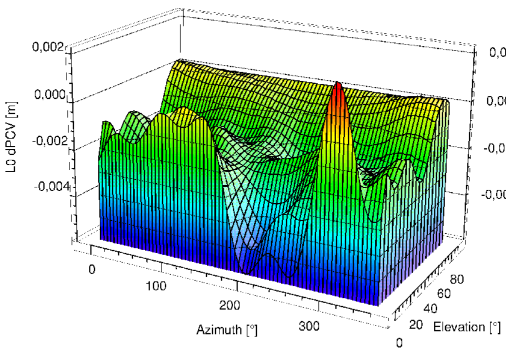

Fig. 17: Differences of absolute L0 PCVs of LEIAT504 with and without LEIS

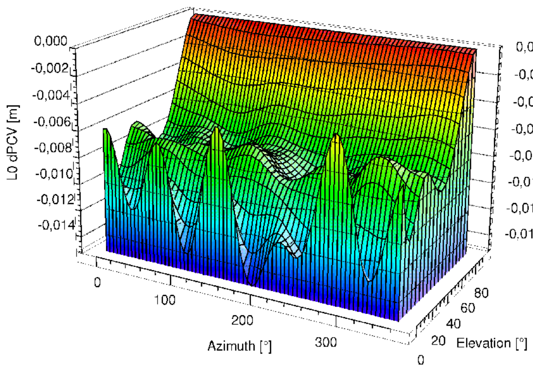

Fig. 18: Differences of absolute L0 PCVs of LEIAT504 with and without SCIS

5.4 Effect of a ground plane plate on PCVs

On the Trimble TRM22020.00 compact antenna the 48 cm diameter ground plane is detachable. Fig. 19 shows PCVs over a range of 30 mm for the TRM22020.00 without the ground plane, clearly indicating large azimuthal variations. The minima and maxima of the variations are correlated with the corners and sides of the angular antenna housing respectively. When the detachable ground plane is fixed to the antenna the reception behaviour changes radically (Wübbena et al. 2000b). There is then no comparable azimuthal PCV, but instead there are large elevation−dependent PCV gradients of up to 1 mm per degree at high elevations (Fig. 20). It is the ground plane (its diameter, thickness and material) which defines the fundamental receiver characteristics.

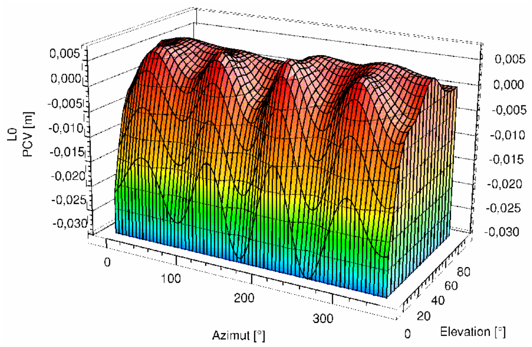

Fig. 19: Absolute L0 PCV for TRM22020.00 without ground plane

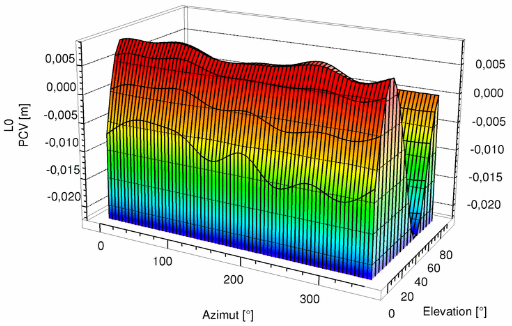

Fig. 20: Absolute L0 PCV for TRM22020.00 with ground plane

5.5 PCVs of rover antennas

Rover antennas are characterised by their generally small diameter, making them lighter and more manageable. The small ground plane diameter is presumably also the reason for their PCVs often having a very small range (of a few mm), and thus coming close to representing an absolutely calibrated point−form antenna. Various rover antennas have already been presented by Wübbena et al. (2000b).

One interesting rover antenna is the NovAtel NOV600*, which, according to information from the manufacturer, exhibits no positional offsets, identical height offsets for L1 and L2, and no elevation or azimuth dependency. The calibration of the NOV600* shows an increased noise level in the observations in relation to comparable antenna types. It is quite clear that, in addition to the PCV, further statistical quantities need to be devised for the full description of antennas.

The positional offsets are of the order of 1 to 2 mm, while the differences between the L1 and L2 height offsets are about 3.7 mm. Fig. 21 shows the L0 PCV of the NOV600*, which above 10° exhibits variations of about ± 1 to 2.5 mm and no significant azimuthal PCV.

The Leica LEIAT502 also shows small PCV values (Fig. 22). The PCV at the horizon does reach 12 mm for L0, but for most part the PCVs of this antenna are in the range of 2 to 5 mm.

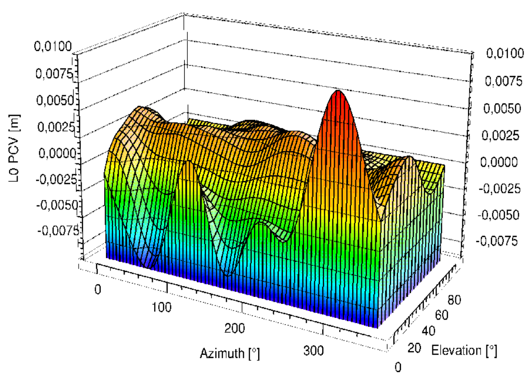

*Fig. 21: Absolute L0 PCV for NOV600**

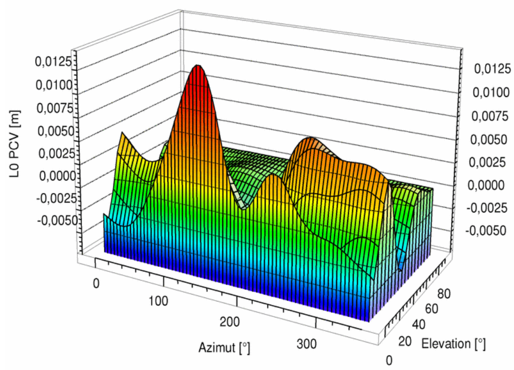

Fig. 22: Absolute L0 PCV for LEIAT502

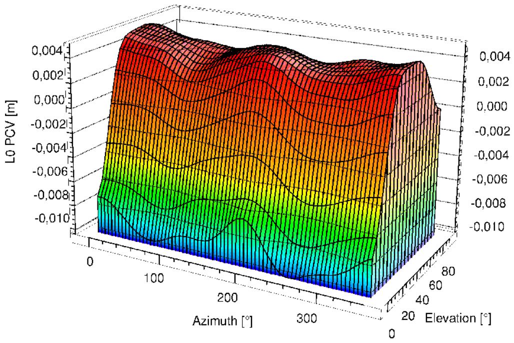

Fig. 23: Absolute L0 PCV for JPSLEGANT

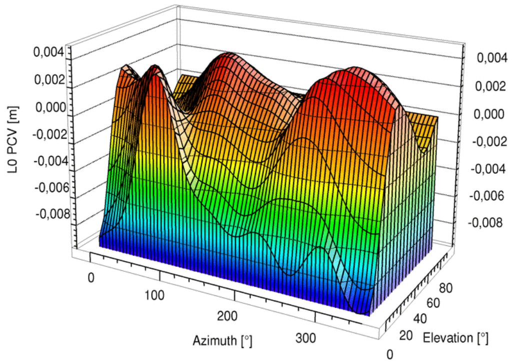

*Fig. 24: Absolute L0 PCV for DSNNAP_002**

The Javad JPSLEGANT antenna in Fig. 23 has variations over a range of 14 mm for L0. At the same time this antenna has only small azimuthal PCVs of ± 1.5 mm. In comparison with the previous rover antennas it has a clearly larger and predominantly elevation−dependent PCV component.

Fig. 24 shows the absolute L0 PCV of a DSNP DSNNAP_002* antenna. This antenna exhibits relatively asymmetrical behaviour. A comparison of several antennas of this type, however, showed basically very good agreement in the shape of their PCVs. The PCV values are around ± 4 mm and only reach larger amounts at the horizon.

The PCVs of rover antennas can also reach larger magnitudes which cannot be ignored. Azimuthal variations are especially prevalent (for example the TRM22020.00 without ground plane, Fig. 19). Modern rover antennas strive for characteristics with minimal variations (Wübbena et al. 2000b), even if, in general, offsets occur in addition.

6 Summary

Absolute field calibration of PCVs in real time is an operational procedure with a high resolution for both azimuth− and elevation−dependent components, and was used throughout the tests presented here. Repeatability was demonstrated on an antenna with azimuthal PCVs. The accuracy requirements for antenna calibration have been discussed. In order to eliminate uncertainties in GPS coordinate fixation, the quality of determination of the sum of the effects of offsets and PCVs should be clearly superior to 1 mm standard deviation. For high−precision work individual antenna calibrations are imperative.

From the examples presented here, it is clear that the PCV of an antenna can only be determined through a detailed investigation by means of an appropriate calibration with high resolution and accuracy. The factors influencing the PCV characteristics are too complicated for them to be described only in general terms. It has been shown that significant alterations are caused in the neighbourhood of the antenna by UHF aerials, by the shapes of antenna housings, by the detail of the construction of the dome and by the presence of ground planes.

Various different characteristics of antennas were exhibited by the several rover antennas tested. Modern rover antennas often show a very small range of PCV (a few mm), and thus come close to the ideal of an absolutely calibrated point−form antenna. However large PCV values, especially azimuthal PCVs, can also occur on rover antennas, making individual calibration necessary in accordance with the required accuracy of the application.

The development of absolute field calibration and the reliable determination of absolute PCVs opens new perspectives for future research. In the coming years the multipath error component (especially for real time applications) and tropospheric effects will increasingly be investigated. In particular the PCVs of satellite antennas constitute an error source which has not up to now been analysed in sufficient detail for geodetic applications.

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