The Impact of GNSS Antenna Mounting during Absolute Field Calibration on Phase Center Correction – JAV_GRANT-G3T Antenna Case Study

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Abstract. The phase center corrections (PCC) of an GNSS antenna can be precisely determined using the absolute field calibration procedure with a precise robot. Using the Hannover's automated absolute antenna field calibration technique developed by the Institute of Geodesy (University of Hannover) and Geo++ we demonstrate that the way of antenna mounting on the robot (distance from mechanical structures mounted underneath the antennas) can cause significant changes in the phase center offset and variations. For both the GPS and the GLONASS carrier signals L1 and L2 these changes are in the order of several millimeters. e also analyzed how these changes transfer to the coordinate domain. We investigated the differences between position estimates obtained using two different, individual and type-mean, elevation dependent PCC. There days of GNSS observations on very short baseline were used for these studies. The position time-series were derived using the RTKLib software package. We found that that the differences in the calibrations models propagate directly into the position domain, affecting sub-daily results and giving visible periodic variations in solutions. The best agreement with the "true position" we obtained using PCC from the individual calibrations.

Keywords: individual antenna calibration, near-field multipath, phase center variation, GNSS antenna.

Conference topic: Technologies of Geodesy and Cadastre.

Introduction

The phase center variations (PCV) of the receiving antenna and multipath (MP) are two dominant station dependent errors. The both are of great concern for precise GNSS positioning applications. The PCV of an GNSS antenna can be precisely determined using the absolute field calibration procedure with a robot (Wübbena *et al.* 1996; Falko *et al.* 1998; Rothacher 2001; Schmitz *et al.* 2002, 2004; Schmid *et al.* 2005; Montenbruck *et al.* 2009). The main idea of this method is the separation between multipath and antenna phase center variation. This is achieved using an observation procedure with fast changing antenna orientations through the robot. In this way the estimation of absolute PCV and the elimination of multipath is possible.

The accuracy of the automated absolute field calibration has been analyzed deeply. It was demonstrated (Schmitz *et al.* 2004) that the standard deviation is in the range of 0.2 to 0.4 mm. This corresponds to the repeatability of approximately 1 mm for individual antenna. In Wübbena *et al.* (2006a) the repeatability of two calibrations with the robot and the same setup was demonstrated. The repeatability is generally better than 2 mm, except for the horizon (0 deg elevation). The repeatability of individual antennas has also been verified by comparison results from absolute chamber calibrations. However, it has been proven also, that there may be remaining effects caused by the setup and the environment of the antenna, which can largely modify the phase variations.

GNSS carrier phase multipath together with signal diffraction are still sources of the degradation of high precision positioning accuracy. The large number of developed methods for multipath estimation and mitigation clearly underline the importance of this issue.

In static applications with highest accuracy requirements it is generally assumed that multipath effects average out for long observation periods. This assumption, however is valid only in the case of short periodic multipath signals caused by distant objects located in the far-field region of the antenna. For object in the closest vicinity of the antenna the long periodic multipath errors are non-zero mean distributed and therefore introduce an unmodeled bias in the estimated parameters (Dilßner *et al.* 2008). Antenna near-field effects are caused by multipath interferences induced by reflectors located very close of the antenna as well as other electromagnetic phenomena like diffraction and antenna imaging effects. It is well known that near-field effects are generally caused by surfaces of pillars or special adaptations where the antennas are mounted on (Elosegui *et al.* 1995; Wübbena *et al.* 2006b).

There are several examples that verify the appearance and determine the magnitude of antenna near-field effects. In Lesparre (2006) has been proven that the influence of the mounting mast on a non choke ring GNSS antenna

phase centre can be almost a centimetre. To resolve the problem it was proposed a procedure to calibration of the antenna including the upper part of the mast.

In Wübbena *et al.* (2006b) two typical geodetic setups with a tribrach on a quadratic and a round pillar reconstruction were selected to show up the influence of the near-field multipath on a Dorne Margoline choke ring antenna. The influence of the near-field effect had a magnitude of up to 7.5 mm in low elevations (for some regions even larger) and even 5 mm for 10 deg elevation. This is probably the reason, why even for individually calibrated GNSS antennas height changes are observed for some sites, when the antenna is changed. It was pointed out that the systematic bias caused by near-field multipath effects can be calibrated with a representative reconstruction together with the antenna's PCV on the robot. The difference with a regular antenna calibration reveals the actual near-field influences. A separation of near-field and far-field multipath is proposed to correct for these two differently acting error components. In this paper it was also demonstrated that repeatability of two calibrations with the robot and the same setup is generally better than 2 mm.

Using the Hannover's automated absolute antenna field calibration technique developed by the Institute of Geodesy (University of Hannover) and Geo++ we demonstrate that the way of antenna mounting of the robot (distance from mechanical structures below the antenna) can cause significant changes in the phase center offset and variations.

JAV_GRANT-G3T antenna calibration

In investigation we used an JAV_GRANT-G3T GNSS antenna manufactured by JAVAD GNSS, which is named after the IGS naming convention JAV_GRANT-G3T NONE. For the purpose of this text, the setup of the JAV_GRANT-G3T with a 120 mm spacer will be called JAV_GRANT-G3T$_{spacer}$. Figure 1 show the setups during the calibration on the robot. In first mode the antenna was mounted directly on the robot. Then, the antenna test candidate was installed on a 120 mm spacer which moves away the antenna from the robot and, it is expected that, reduces more significantly the effects of near-field multipath.

Fig. 1. JAV_GRANT-G3T calibration: without a spacer (left) and with a 120 mm spacer (right)

Calibration was performed in Institute of Geodesy, University of Hannover, Germany using Hannover's automated absolute field calibration approach. The antenna calibration setups are summarized in Table 1.

Table 1. The antenna calibration setups

	Set #1	Set #2	Set #3	Set #4	Set #5	Set #6
Elevation Mask [deg]	18.0					
Max. Negative Elevation [deg]	5.0					
Calibration Type/Date	*without spacer* / 2014-12-03					
Duration [s]	17166	8777	7832	8412	8233	6165
Number of Epochs	27241	14297	12341	13437	13621	10013
Calibration Type/Date	*with spacer* / 2014-12-04					
Duration [s]	16568	8291	9480	10490	7180	7400
Number of Epochs	31053	16091	19357	19677	12317	13341

Phase Center Corrections comparison

In this paper, with the aid of Hannover's automated absolute antenna field calibration technique developed by the Institute of Geodesy (University of Hannover) and Geo++®, we demonstrate that way of antenna mounting on the

robot can cause significant changes in the phase center offset and variations. For both GNSS carrier signals these changes are in the order of several millimeters. Detailed analysis of obtained results are presented below.

PCO analysis

The antenna offset components computation is up to now not standardized and is depending on several parameters. This is especially true for relative calibration approach but also in absolute calibration approach can be dependent on (Schmitz *et al.* 2004): – minimum condition for PCV for offset determination, – processing strategy, – remaining multipath effects. All the mentioned above effects can affect the interpretation of offset differences, however, in our case the calibration and processing of the two setup JAV_GRANT-G3T was identical. Table 2 present comparison of NORTH, EAST and UP offsets for tested JAV_GRANT-G3T antenna. The offsets differences are clear for the horizontal components, in some cases, for L2 frequency, reach about 2 mm. For the Up component differences are even larger. Between two individual calibration the maximum difference is 2.5 mm (GPS L2 solution). When we compare individual calibration results with type-mean calibration results these differences increases up to 5 mm (GLONASS L1 solution).

Table 2. Offsets comparison

Position component	L1 frequency			L2 frequency		
	type-mean	individual	individual+	type-mean	individual	individual+
GPS signals calibration dependent offsets [mm]						
North	0.56	−0.17	0.74	−3.10	−1.29	−3.06
East	1.16	−1.49	−1.32	−1.38	−0.96	0.51
Up	50.28	48.32	47.83	46.83	45.49	47.99
GLONASS signals calibration dependent offsets [mm]						
North	0.56	0.92	2.18	−3.10	−2.08	−2.06
East	−1.35	−1.35	−1.30	−2.08	−2.08	−1.42
Up	50.28	45.56	44.87	46.83	44.23	44.31

Elevation dependent PCC analysis

The elevation dependent PCC are computed using elevation dependent spherical harmonic (expansion of degree 8 and order 0). The elevation dependent corrections are often applied in kinematic applications where knowledge of the orientation of the antenna is unavailable. Figs 2 and 3 show the elevation dependent phase center corrections (reduced to a common MPC) for JAV_GRANT-G3T antenna (individual calibrations without spacer, individual calibration with spacer, type-mean calibration).
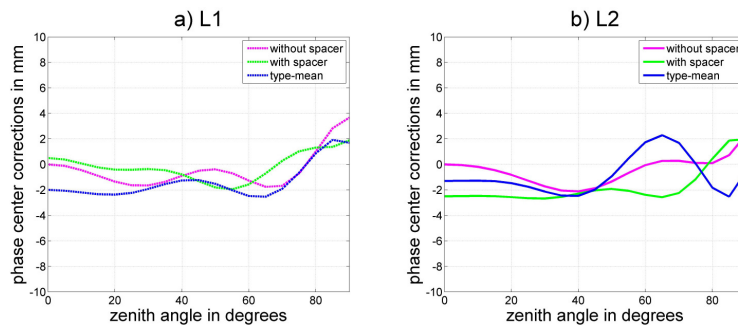

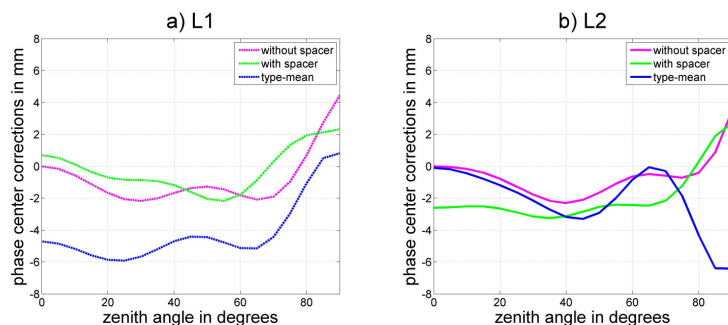Fig. 2. GPS elevation dependent PCC for JAV_GRANT-G3T antenna:L1 frequency, b) L2 frequency

Fig. 3. GLONASS elevation dependent PCC for JAV_GRANT-G3T antenna:L1 frequency, b) L2 frequency

Generally the shapes of GPS L1 frequency elevation dependent PCC from individual calibrations are comparable (in 1–2mm). There are larger differences for L2 frequency. There are also visible clear differences between individual calibrations and type-mean calibration for GLONASS signals. For L2 frequency, at low elevation, the difference reach 8 mm.

Absolute PCC pattern analysis

Figs 4–5 show elevation and azimuth dependent PCC difference (reduced to a common MPC) between the regular JAV_GRANT-G3T setup, the JAV_GRANT-G3T$_{spacer}$ setup and type-mean calibration results.
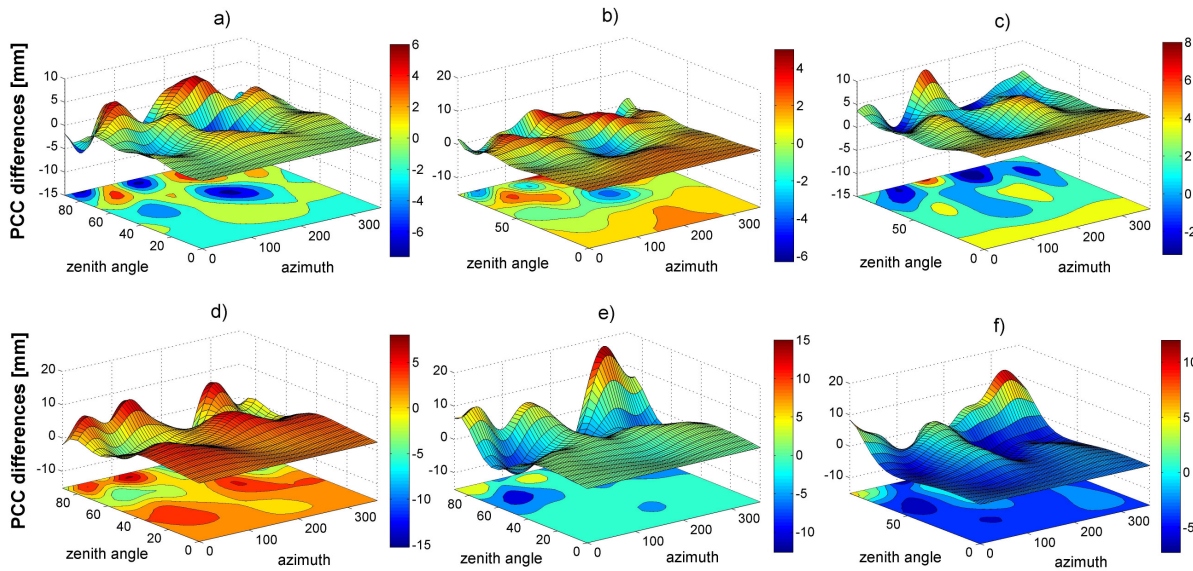

Fig. 4. Elevation and azimuth dependent PCC difference for GPS signals: a) L1 without spacer/with spacer, b) L1 without spacer/type-mean c) L1 with spacer/type-mean, d) L2 without spacer/with spacer, e) L2 without spacer/type-mean f) L2 with spacer/type-mean
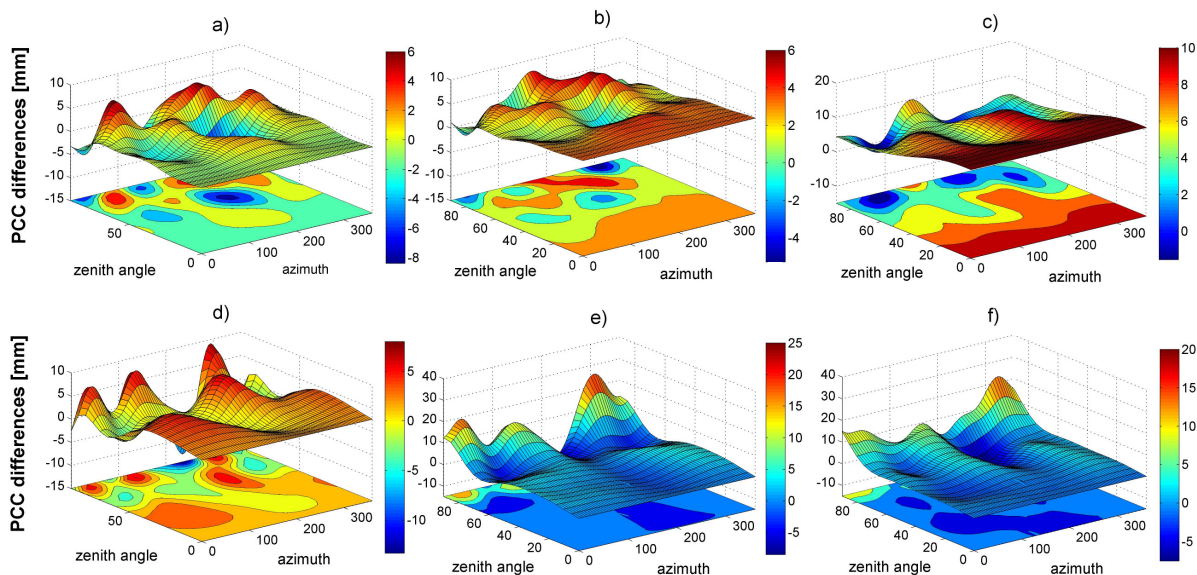

Fig. 5. Elevation and azimuth dependent PCC difference for GLONASS signals: a) L1 without spacer/with spacer, b) L1 without spacer/type-mean c) L1 with spacer/type-mean, d) L2 without spacer/with spacer, e) L2 without spacer/type-mean f) L2 with spacer/type-mean

The PCC difference between two antenna calibration setup is shown. We mounted antenna directly on the robot and then antenna was installed on a 120mm spacer which moves away the antenna from the robot. The obtained differences has a magnitude of up to 10 mm in low elevations. For some areas in the horizon the effects is even larger.

Additionally we compare our results with type-mean calibration table. In the comparison "without spacer" setup an type-mean table it is visible that the influence of calibration type has a magnitude of up to 7 mm in low elevations (L1 frequency). For L2 frequency in low elevations at the horizon the effects is much larger – up to 20mm. It was observed also that shape of pattern differences for GPS and GLONASS signals is similar. Finally "with spacer" setup an type-mean PCC were compared. For L1 frequency the influence of calibration type has a magnitude of up to 10 mm in low elevations and for L2 frequency, as previously – up to 20mm.

It is worth to mentioning that the offsets as well as PCC obtained during calibration are a mean values determined over the complete hemisphere of the antenna. Such satellite coverage is never available in practical applications, so analysis aimed at getting insight into possible effects for short observation times or kinematic applications are highly recommended (Dawidowicz, Krzan 2016a).

Field experiment

The measurements were done using a test device which consists of 1.8 m long steel beam mounted on the roof (Fig. 6). The height differences between each potential antenna location were very precise determined. On the test device three 24-hour measurement session was conducted. The following GNSS parameters were assumed for the session: sampling interval 5s, minimum satellite' elevation 0°. As a reference, the point with the TRM59900.00 SCIS antenna was chosen. At the second end of the steel beam tested JAV_GRANT-G3T antenna was mounted.

Fig. 6. Test installation

The post-processing was done using the RTKLIB ver. 2.4.2. Three parallel baseline runs, leaving all processing options identical, except the antenna/radome calibrations, were performed:
  – a baseline run using the type mean PCC (igs08.atx),
  – a baseline run using the individual PCC (JAV_GRANT-G3T antenna without spacer),
  – a baseline run using the individual PCC (JAV_GRANT-G3T antenna with spacer),
  – analysis of the difference.

Because all error sources may be considered identical in both runs, differences in the final solutions are only affected by variations in the antenna/radome calibrations. For installed antenna/radome pair, the height differences between the pseudo-kinematic (15 minutes session) results provide the offset caused by the change of antenna calibration model. In this study only height differences are analyzed because, as is well known, inaccuracies in phase center variation modeling mostly affected vertical position component.

In computation standard processing strategy was used. Some options are presented below:
  – 0° elevation mask,
  – troposphere correction: Saastamoinen
  – ionosphere correction: Broadcast
  – satellite ephemeris/clock: Precise
  – fixed ambiguities,
  – processing frequency: L1.

L1 frequency processing was chosen because over very short baselines, higher precision can be obtained using single frequency measurements. This has two reasons. Because the baseline distance is short, the atmospheric and orbit effects will cancel when processing the baseline data. Second, the observational noise of the L3 linear combination is larger by a factor of ~3 than that for L1 only observations and L3 combinations also considerably amplify systematic effects due to multipath, antenna phase center offsets and variations, etc (Seeber *et al.* 1999; Dawidowicz, Krzan 2016b; Sieradzki, Paziewski 2015; Stępniak *et al.* 2015).

To analyze height differences on JAV_GRANT-G3T antenna point, caused by the usage of different antenna calibration models, on first step two parallel GPS-only and GLONASS-only run was performed. In this processing type mean PCC were used. Fig. 7 present these preliminary results: height differences (true height versus GNSS

height). True height of antenna JAV_GRANT-G3T point was obtained with precise geometric measurements in reference to fixed height of TRM59900.00 SCIS antenna point. Table 3 shows a summary of results presented on Figure 7 (mean, minimum, maximum height differences and standard deviation).
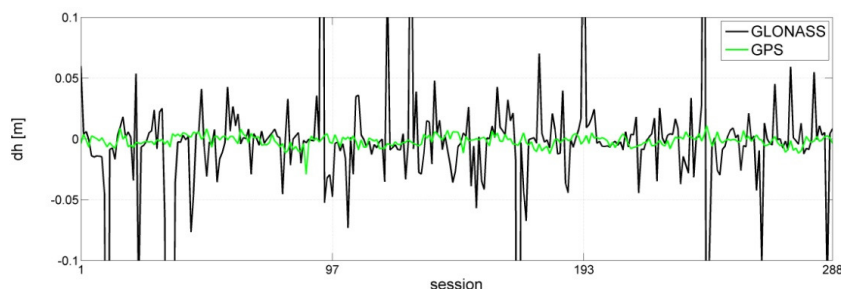

Fig. 7. Differences between true heights and GNSS heights

Table 3. Summary of height differences obtained at test point (preliminary results)

Processing variant	mean dh [m]	min. dh [m]	max. dh [m]	standard deviation [m]
GPS	−0.0016	−0.0290	0.0109	0.0045
GLONASS	−0.0109	−0.9442	0.5854	0.1048

In analyzing the results presented on Fig. 7 and in Table 3 it can be seen large scattering in GLONASS results. It is well known that GLONASS-only measurements provide less accurate results as GPS-only measurements (Alcay *et al.* 2012). However we didn't expect so big differences. To explain it further analysis are ongoing, also using other scientific software, e.g. NAPEOS.

This large scattering in GLONASS results was the reason why only GPS data are selected to further analysis.

Analysis of PCC dependent height differences

The result of GPS observation post-processing (true height versus GNSS height) are presented on Fig. 8. This figure present height differences from three parallel baseline runs leaving all processing options identical, except the antenna/radome calibrations:
– a baseline run using the type mean PCC (igs08.atx): *mean PCC*,
– a baseline run using the individual PCC (JAV_GRANT-G3T antenna without spacer): *indiv PCC*,
– a baseline run using the individual PCC (JAV_GRANT-G3T antenna with spacer): *indiv+ PCC*.
Table 4 shows a summary of results presented on figure 9 (mean, minimum and maximum height differences).
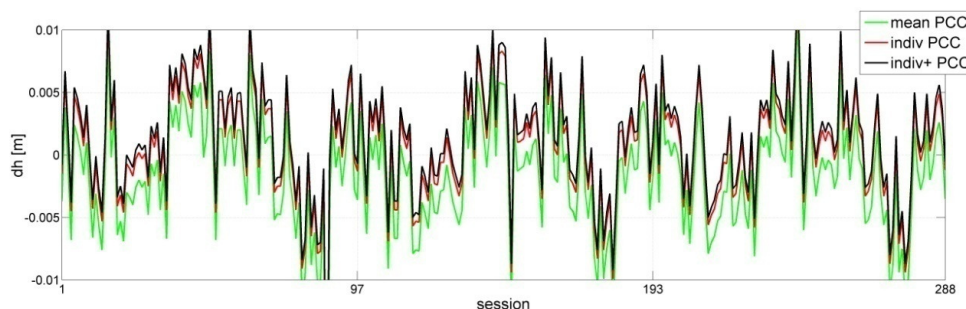

Fig. 8. L1 frequency GPS-only heights differences (true height versus GPS height)

Table 4. Summary of height differences obtained at test point (GPS-only results)

Processing variant	mean dh [m]	min. dh [m]	max. dh [m]
mean PCC	−0.0016	−0.0290	0.0109
indiv PCC	0.0007	−0.0268	0.0129
indiv+ PCC	0.0014	−0.0261	0.0136

The obtained heights reveal the following:
– the presented station exhibits periodic biases up to 40 mm (mostly up to 20 mm),
– differences experience rapid changes within short time periods,

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– variations in differences have periods close to 12 hours, which corresponds to the orbital period of the GPS satellites.

In analyzing the results presented in table 4 it can be seen also that the difference between two extreme solution (mean PCC and indiv+ PCC) reach 3 mm. This indicate that differences in PCC models transfer directly into position domain affecting the value of vertical component.

It is also seen that the best agreement with true height were obtained for indiv PCC solution (0.7 mm difference to true height), for indiv+ PCC 1.4 mm difference was obtained and for mean PCC solution –1.6 mm respectively.

The very long periodic multipath and electromagnetic interaction of the antenna and objects in the vicinity are the main reason of the near-field effect (Schmitz *et al.* 2004). A small near-field effect can have big impact on the positioning accuracy. It may explain the significant height error that sometimes disappeared in up coordinate even PCC differences was not too big (Lesparre 2006). Probably, the influence for a choke ring antenna would have been less. Nevertheless, we were surprised that the influence of the antenna mounting can have on the PCC and on vertical component such a large impact.

It should be point out here that the results were obtained for L1 only frequency. As is seen in PCC COMPARISON section for that frequency the lowest differences in PCC corrections occurred. It should be expected that for L2 frequency or for linear combinations height differences will be much larger.

Unexpectedly mean height difference obtained using indiv+ PCC setup proved to be larger than using indiv PCC setup. This issue need further study. These analysis should focus on multipath effect. Due to the fact that multipath decor relates very fast, multipath effects will not be eliminated even in very short baseline.

The height differences presented on Fig. 8 reveal some periodicity. To confirm this observation and find exact period, the calculation of Lomb-Scargle spectrum for the data was performed. This type of periodogram is used for frequency/period analysis of data that is not collected at a regular time interval or has missing data. As we know such situation occurs quite often in GNSS permanent observations. Fig. 9 present the results: power of detected periodic signals in cycles per day (cpy), for indiv PCC results.
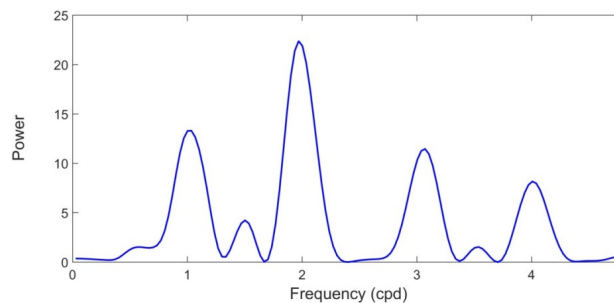

Fig. 9. Lomb-Scargle periodogram for indiv PCC results

The strongest power (22.82) was obtained at 1.97 cpd. However there are also some peaks at about 1, 3 and 4 cpd.

If we consider that:
– $10 < power < 14$ – the periodicity might be real, worth investigating more,
– $14 < power < 20$ – the periodicity is most likely real,
– $power > 20–30$ – the periodicity is definitely real,
– it is visible that there are found some periodicity. To find the reason of these oscillations further analysis with more data are needed.

Conclusions

The objective of this paper is to analyze the impact of GNSS antenna mounting during absolute field calibration on phase center correction. Using the Hannover's automated absolute antenna field calibration technique developed by the Institute of Geodesy (University of Hannover) and Geo++ we demonstrate that the way of antenna mounting of the robot (distance from mechanical structures mounted underneath the antennas) can cause significant changes in the phase center offset and variations (PCV). For both the GPS and the GLONASS carrier signals L1 and L2 these changes are in the order of several millimeters.

A JAV_GRANT-G3T antenna calibration results (individual calibrations without spacer, individual calibration with spacer, type-mean calibration) has been compared which reveals differences in the estimated PCC up to 10 mm for the low elevation regions. For precise applications, the question is often posed whether individual antenna calibrations are necessary, rather than a general calibration for an antenna type. The same question applies to the differences between individual antenna setups in different environments. Our analysis reveal that type of antenna mounting on the robot can have visible effect on estimated PCC.

We found that that the differences in the calibrations models propagate directly into the position domain giving 3 mm mean height difference between two extreme solution (mean PCC and indiv+ PCC).

Unexpectedly mean height difference obtained using indiv+ PCC setup proved to be larger than using indiv PCC setup. This issue need further study. These analysis should focus in detail on multipath effect.

The obtained height differences (true versus GNSS) reveal the presence of rapid changes, up to 40 mm, within short time periods. Calculation of Lomb-Scargle spectrum for the data confirmed periodicity that occur in station height with a periods close to 12 hours, which corresponds to the orbital period of the GPS satellites.

Acknowledgements

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