Station calibration of the SWEPOS GNSS Network

Martin LIDBERG, Per JARLEMARK, Kent OHLSSON, Jan JOHANSSON, Sweden

Key words: GPS, GNSS, Positioning, Reference frames, CORS, absolute antenna calibration, station calibration, PCV

SUMMARY

While the performance of positioning services are improved to the benefit of the users, with uncertainties from densified Network-RTK networks for construction work approaching the sub-centimeter level also in the vertical, the error sources related to the permanent reference stations (CORS) may soon be limiting factors for further improvement of performance. Station dependent effects are thus important and limiting factors in high accuracy GNSS positioning. Electrical coupling between the antenna and its near-field environment changes the characteristics of the antenna from what has been determined in e.g. absolute robot or chamber calibration.

Since the first initial tests back in 2008, Lantmäteriet together with Chalmers technical University and SP Technical research Institute of Sweden has carried out station calibration, in-situ calibration, of its network of permanent reference stations, SWEPOS. The station calibration intends to determine the electrical center of the GNSS antenna, as well as the PCV (phase center variations) when the antenna is installed at a SWEPOS station. One purpose of the calibration is to examine the site-dependent effects on the height determination in SWEREF 99 (the national reference frame). Another purpose is to establish PCV as a complement to absolute calibrations of the antenna-radome pair.

We will present booth the methodology for observation procedure in the field and the method for the analysis, together with results of the station-dependent effects on heights as well as PCV from the analysis. Some strength and weakness of our method for GNSS station calibration are discussed at the end.

Station calibration of the SWEPOS GNSS Network

Martin LIDBERG, Per JARLEMARK, Kent OHLSSON, Jan JOHANSSON, Sweden

1. INTRODUCTION

Site-dependent effects are important and limiting factors in high-accuracy GNSS positioning. Electrical coupling between the antenna and its near-field environment could change the characteristics of the antenna from what has been determined for the isolated antenna (Wübbena and Schmitz 2011). The average position of apparent signal reception, the phase center offset (PCO) and the directional dependent phase center variations (PCV) (Rotacher and Mader 2003) derived for the antenna in e.g. absolute calibration may not be valid when it is mounted for permanent use.

Lantmäteriet has started in-situ station calibration of its permanent reference stations, SWEPOS^{TM}, with focus on the 21 concrete pillar stations that serve as the backbone for SWEREF 99 (the national reference frame). The pillar design is presented in Figure 1.

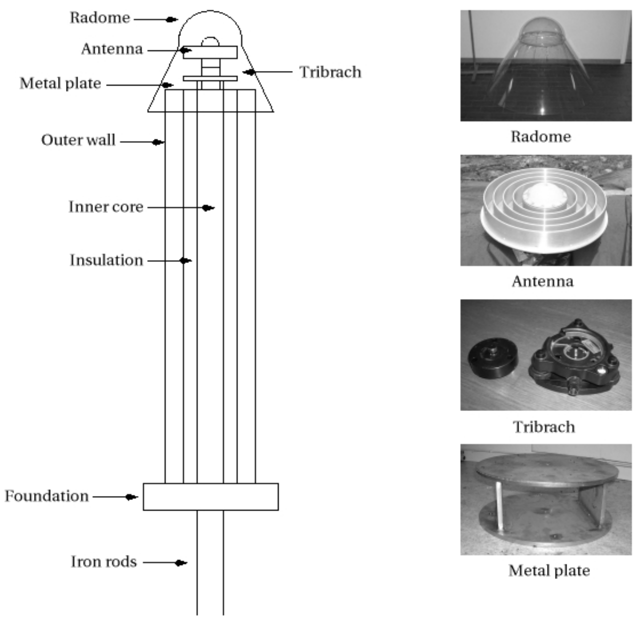

Figure 1. Structure of a concrete pillar foundation in SWEPOS, designed in 1992. The pillar height is ~ 3 m, and is anchored onto crystalline rock. Note the relatively large metal plate used as foundation for the tribrach.

To keep the time series of the 21 fundamental stations consistent, the antenna of these pillar stations will not be changed as long as they work properly. But these old antennas have a pre-amplifier open only for the GPS L1 and L2 frequencies and cannot track all new signals such as Galileo and GPS L5 properly. In 2012 a second monument was installed at 19 of 21 stations with a newer antenna (LEIAR25.R3). To reduce the multipath effects that has been seen from the relatively wide pillar and the large metal plate, a steel grid mast was used for these new monuments (see Figure 2).

Figure 2. The SWEPOS site Vänersborg during a station calibration setup in November 2014. An Eccosorb plate is mounted directly below the choke-ring antenna. Note the typical SWEPOS concrete pillar and the recent steel-grid mast with the LEIAR25.R3 antenna and LEIT radome installed.

One purpose of the calibration is to examine the site-dependent effects on the height determination in SWEREF 99 when the presently available antenna PCO/PCV models are used. Another purpose is to establish corrected PCO/PCV descriptions for antennas mounted at SWEPOS stations as alternatives or complement to those resulting from absolute calibrations of the isolated antenna. In this paper we focus on the PCO/PCV values. Some first results, including analysis of the height determination, have been reported in (Jarlemark et al 2012).

2. SURVEYING

The station calibration campaigns started in 2009 and continued in 2010. 12 stations was calibrated during these two years. Four of the stations was calibrated one more time during November 2014 during wet and rainy conditions. In September 2015 these four stations was calibrated a third time and two other stations was also calibrated for the second time.

We used three well calibrated antennas on tripods as references. Microwave absorbing material (Eccosorb®) was installed in order to reduce multipath from the ground (see Figure 2). The reference antennas were placed on markers in a local network surrounding the concrete pillar where the SWEPOS antenna is installed. The configuration is illustrated in Figure 2. The distances between reference antennas and the pillar are of the order of 10 m. The height differences were determined to sub-mm using terrestrial methods. Each campaign lasted five full 24 h sessions.

3. HEIGHT DETERMINATION

The data from the campaigns were processed with daily solutions for each single antenna, and the resulting height differences between the SWEPOS antennas and their associated reference antennas were compared to the height differences derived in the terrestrial survey. The L3 (ionosphere-free) linear combination of the observables was used, and troposphere parameters were estimated together with coordinates and receiver clock errors.

Different processing strategies have been applied, e.g. regarding elevation cut off angle, and the use of relative and absolute antenna models (Shmidt et al 2003) (Jivall 2011). Typically height differences of ~ 10 mm were found. The GNSS determined heights of the SWEPOS antennas were significantly lower than expected from the terrestrial survey. There was, however, a significant variation in the results depending on which processing strategy was used. Using absolute antenna models gave lower estimated heights than using relative models.

4. PCO AND PCV ESTIMATIONS

We aim to quantify the influence of the SWEPOS pillars on the phase observables. In order to accomplish this we estimated the baselines between the reference and SWEPOS antennas from phase differences (see, e.g. Hoffman-Wellenhof et al 1994). For each baseline processed, the recorded phase data from the two antennas involved were subtracted, and the resulting phase differences were used as observables.

For all antennas we first compensated the phase data by their PCO and PCV values as determined from absolute calibrations. By assuming that the PCO and PCV descriptions of the surrounding reference antennas give a "correct", bias free, representation of the observed phase we can associate deviations in the estimated baselines, as well as systematic signatures in the post-fit residuals, as originating from imperfections in the PCO and PCV of the SWEPOS antenna when mounted on the pillar. The baseline estimation scheme was performed for GPS observation on L1 and L2 separately.

The post-fit residuals had no significant variation with azimuth angle. They had, on the other hand, significant elevation angle dependence, with different structure on L1 and L2. We sorted the residuals into 2.5° elevation angle bins. The mean values for the data in each bin were taken to represent the PCV error introduced by the pillar mounting. Also the vertical components of the baselines were slightly different from what was expected from the terrestrial survey; a few mm discrepancies were typically found. These differences were regarded as measures of the errors in the vertical PCO for the SWEPOS antennas. Unfortunately, the horizontal components of the baseline are not as accurately determined by terrestrial methods, but from the circular symmetry of the antenna setup we do not expect any large horizontal biases.

The baseline estimation scheme also contains a parameter taking care of clock and hardware delay differences between the two receivers in the baseline. This "clock parameter" will, however, absorb a fraction of the phase deviation that we would like to detect as PCO or PCV errors. In order to minimize this effect we iterated the baseline estimation.

After the first iteration we made a preliminary updated version of the PCO and PCV descriptions for the SWEPOS antennas. We added 3 mm to the vertical part of the PCO, and added the approximate values of the PCV errors found from the elevation bins to the corresponding PCV components in the original PCO/PCV description of the SWEPOS antennas

We then used this updated preliminary PCO/PCV description file for correcting the SWEPOS antenna observations in a second iteration of baseline estimation. Again we sorted the residuals into 2.5° bins and derived PCV error values from the mean values in each bin. This time the sizes of the PCV errors were only about 1/10 of the error sizes found in the first iteration.

The total resulting PCV errors, the sum of the results from the two iterations, are presented in Figure 3 (left) for the nine SWEPOS antennas we analyzed. Each curve is formed from the mean values of the (very similar) contributions from the three baselines associated with the three reference antennas around the SWEPOS antenna. The elevation structure of the curves (~ 1 oscillation over the elevation range 0-90°) is typical for electromagnetic interaction with a surface located ~ ½ wavelength below the antenna (Elósegui 1995). It could therefore be associated with the metal plate (in combination with the top of the concrete pillar) ~0.1 m below the SWEPOS antennas (see Figure 1)

The total resulting vertical PCO errors, sum of the results from the two iterations, are presented in the two first columns of Table 1. Again, the values for each SWEPOS station are the mean value of the results from the three surrounding baselines.

It should be pointed out that the baseline estimation scheme contained estimation of neither atmospheric delay nor phase biases. The ambiguous phase biases were adjusted prior to the baseline estimation (cycle fixing), so was the small correction for the expected atmospheric delay difference due to height differences between the two antennas in the baseline. For these short baselines we expect that the remaining atmospheric delay differences typically are smaller than 0.1 mm. The baseline estimation scheme only contains parameters for three coordinates per day and one clock difference per epoch. In the results presented here 15 s epochs were used.

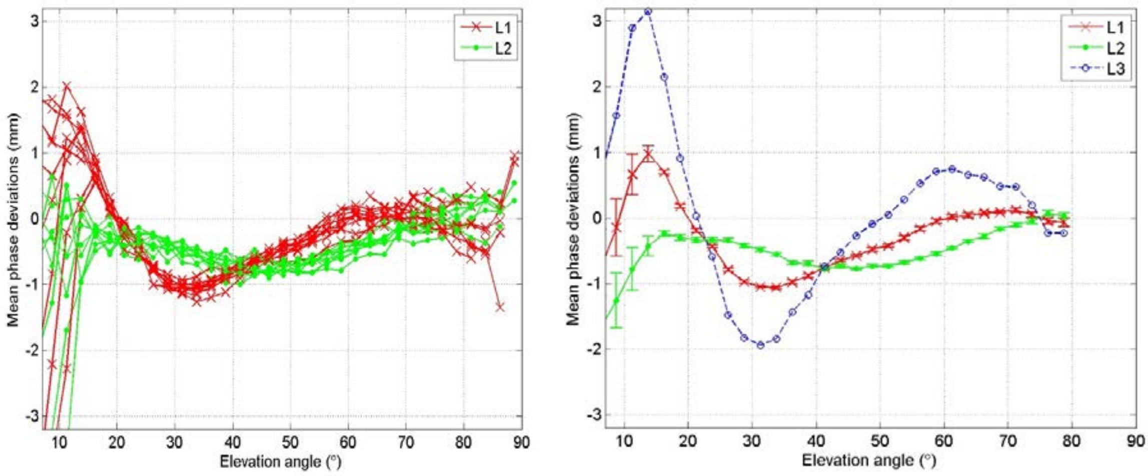

Figure 3. *Left*: Phase deviations of the nine SWEPOS stations investigated. The deviations are formed by sorting the residuals into 2.5° bins and calculate the mean value for each bin. *Right*: Mean of the phase deviations for the nine SWEPOS stations for L1 and L2 based on the data of the graph to the left. An L3 curve (forming the ionosphere free linear combination of L1 and L2 observations) is also included, generated as an “ionosphere free” linear combination of the L1 and L2 curves. Notice the significantly larger amplitude of the L3 curve.

4.1 A common antenna description file

The similarities between different stations vertical PCO and PCV errors suggest that a common “monument specific” PCO/PCV description file could be made. The original PCO/PCV descriptions for all stations, except Leksand, were identical. The Leksand descriptions differed only slightly from the others. We therefore formed mean PCV errors for both L1 and L2 (see Figure 3, right) and corrected the most common original PCV description with these values. The vertical components of the L1 and L2 PCO were also corrected using the mean values, 0.4 mm and 1.5 mm, found in Table 1.

In order to test the applicability of this updated PCO/PCV we repeated the baseline estimation, but this time with the original PCO/PCV descriptions replaced by the updated version. Again we looked at the vertical component estimates compared to those derived from terrestrial surveying. The agreement is presented in the last two columns of Table 1. We also sorted the post-fit residuals by elevation angle. The result is shown in 4. In the elevation angle range 15°- 75° the mean residuals are significantly smaller than was the case when using the original PCO/PCV description file. For the lower elevation angles the surroundings around each reference antenna can have an influence on the observed phase. At elevations >75° there are typically a reduced number of observations, so the measurement noise on the individual observations have larger influence.

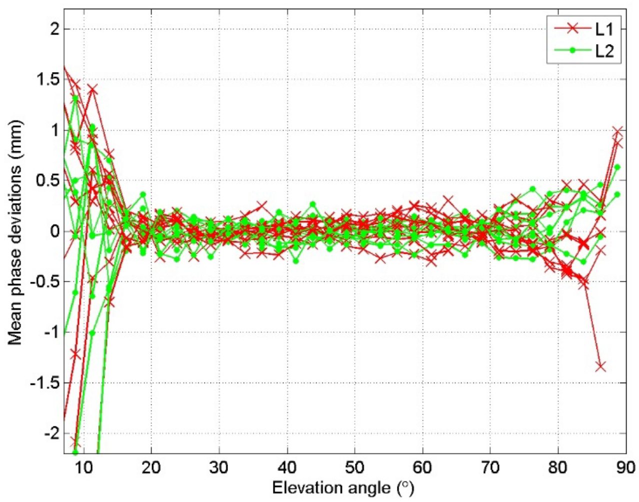

Figure 4. Phase deviations of the nine SWEPOS stations investigated when using the updated PCO/PCV description file for SWEPOS antennas. The signature in the region 15° to 75° is significantly smaller than in Figure 3 (left) .

Table 1. Estimated vertical PCO offsets using original and updated PCO/PCV description file.

Station	Original antenna model		Updated antenna model	
	L1 vertical offset (mm)	L2 vertical offset (mm)	L1 vertical offset (mm)	L2 vertical offset (mm)
Östersund	2.6	3.2	2.2	1.9
Sundsvall	-0.3	0.4	-0.8	-0.9
Leksand	1.5	3.3	0.2	1.4
Karlstad	1.1	1.0	0.7	-0.3
Vänersborg	-0.3	0.9	-0.7	-0.3
Norrköping	-0.3	1.6	-0.7	0.4
Jönköping	-0.6	0.6	-1.0	-0.6
Oskarshamn	0.8	1.8	0.5	0.6
Hässleholm	-0.7	0.4	-1.0	-0.8
Mean	**0.4**	**1.5**	**-0.1**	**0.2**
Std	**1.1**	**1.1**	**1.1**	**1.0**

4.2 Consequences of un-modelled phase deviations

When doing L3t estimation, i.e. estimating atmospheric delay together with coordinates and clock parameters from L3 data in a least squares sense, the estimation process has at least three parameters that potentially can absorb an elevation dependent source of error. In the case of our height determination from L3 we think that the un-modelled part of the L3 PCV signature (which we depicted in Figure 3, right) has partly been absorbed as a (negative) extra height component. In order to understand this model misfit we made numerical experiments with the un-modelled L3 PCV found in Figure 3 (right). We found that a combination of excess atmospheric delay, height, and clock difference could produce a change in the observed L3 that had a resemblance with the L3 PCV, at least below ~70°elevation angle, where most of the observations occur. The numeric experiment is presented in Figure 5. This suggests that an excess height of -9 mm originate from the L3 PCV. From the mean L1 and L2 PCO offsets of 0.4 mm and 1.5 mm (see Table 1) a mean L3 PCO offsets of about -1 mm results. The combined expected height error due to the un-modelled PCO/PCV is then expected to be approximately -1 mm - - 9 mm = - 10 mm.

A more thorough analysis is required in order to quantify the consequences of estimating coordinates and atmospheric delay from L3 data using the original PCO/PCV descriptions. We again used the baseline estimation scheme. This time we added a parameter representing atmospheric delay difference to the scheme. For each baseline to process we made L3 phase differences that were fed to the estimation scheme. An elevation cut off angle of 12° was used, in order to avoid too much disturbances from the surroundings of the reference antennas. The resulting height differences between these L3 estimates and the terrestrial survey as well as the estimated atmospheric delay differences are presented in Table 2. The mean values suggest slightly larger deviations than those predicted by the numerical experiment. However, significant variations between the stations are found.

We repeated the baseline estimation scheme with atmospheric delay estimation using L3 data, but this time using the updated PCO/PCV description file for the SWEPOS antennas. The results are presented in Table 2. There is still a noticeable variation from station to station, but the mean values for the height error and atmospheric delay difference is now significantly reduced.

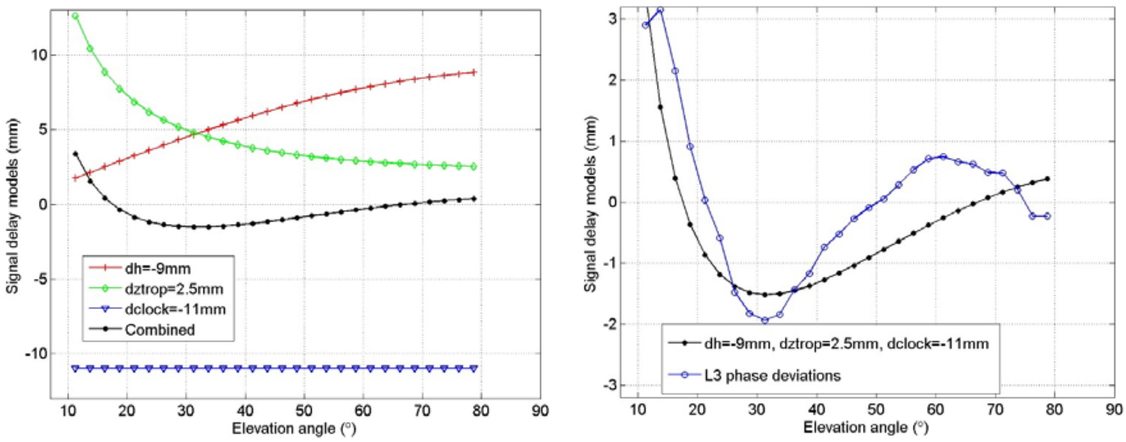

Figure 5. *Left*: graphs depicting the phase changes due to separate changes in height, atmospheric delay, and clock difference, and the sum of the changes (black curve). *Right*: the sum of the phase changes (from upper part) together with the un-modelled L3 PCV.

Table 2. Estimated vertical offsets and atmospheric delay difference when using L3 observables with original and updated PCO/PCV description file.

Station	Original antenna Model		Updated antenna model	
	Vertical offset (mm)	**Atmospheric delay offset (mm)**	**Vertical offset (mm)**	**Atmospheric delay offset (mm)**
Östersund	-10.4	3.6	2.4	0.1
Sundsvall	-13.6	3.5	-1.4	0.2
Leksand	-9.2	2.4	-1.4	-0.1
Karlstad	-7.0	2.4	4.7	-0.8
Vänersborg	-13.6	3.5	-2.1	0.4
Norrköping	-14.1	3.1	-2.6	0.0
Jönköping	-15.7	4.0	-4.2	0.8
Oskarshamn	-12.3	3.5	-0.8	0.3
Hässleholm	-13.0	3.2	-1.5	0.1
Mean	**-12.1**	**3.2**	**-0.8**	**0.1**

5. CALIBRATION OF THE NEW STEEL GRID MAST INSTALLATIONS

Based on the calibration values we have derived above for the SWEPOS pillar station installations, we “calibrate” the newly installed steel grid mast stations equipped with the LIAR25.R3 antennas and LEIT radoms, relative to the pillars.

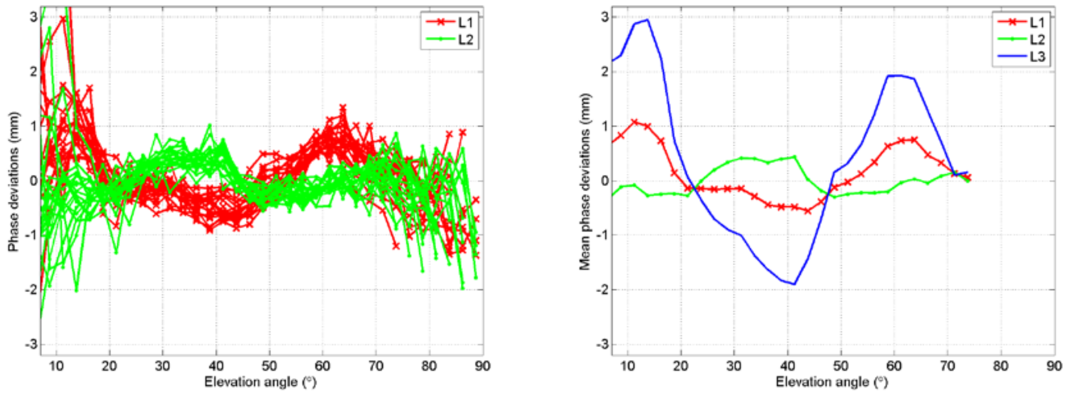

Figure 6. *Left*: The estimated L1 and L2 phase deviations from the original model PCV for the 19 mast stations studied. Right: The mean of the estimated L1 and L2 phase deviations from the original model PCV, as well as the result when combining them to L3.

We assume that the derived model is valid for the 19 pillar stations where we have co-located "new" steel grid mast stations. We can then use the pillars to calibrate the antenna installations on the new mast stations. Data from two weeks in 2013 was used to calibrate each pillar and antenna pair, and comparison was done to height difference determined using terrestrial surveying technic. For the LEIAR25.R3 and LEIT antenna and radoms on the mast stations, the type calibration values from Geo++ was used in the analysis. The analysis gave a distinct deviations from the type-PCV in L1 and L2 according to Figure 6 (left). The average deviations for the PCV deviations in L1 and L2 are given as the red and green curves in Figure 6 (right). The deviation is amplified when forming L3 (blue curve).

The deviation of PCV för L3 cause a considerable vertical bias (mean value of -11.5 mm) while simulate L3t solutions for the new mast stations, see Table 3.

Table 3. Estimated vertical offsets when using L3 observables and the original PCO/PCV description file.

Station	Offset (mm)	Station	Offset (mm)	Station	Offset (mm)
Arjeplog	-19.0	Lovö	-17.4	Skellefteå	-12.6
Hässleholm	-5.2	Mårtsbo	-16.3	Sundsvall	-15.5
Jönköping	-11.0	Norrköping	-7.4	Sveg	-12.6
Karlstad	-19.2	Oskarshamn	-7.1	Umeå	-17.6
Kiruna	-9.0	Östersund	-3.5	Vänersborg	-4.4
Leksand	-10.3	Överkalix	-13.9	Vilhelmina	-8.1
				Visby	-11.5
Mean			**-11.5**		
Std			**5.0**		

There is a considerable scatter in the results, standard deviation of 5 mm according to Table 3, despite a more "clean" setup when the mast installations are calibrated relative to the pillar stations. E.g. the influence from vegetation are limited compared to when temporary calibration antennas on tripods are used. There are some influence due to limitations in the general correction model for the pillar stations, but likely less that the 2.6 mm std found from the calibration of the pillar stations. Subtraction i quadratur give the uncertainty for the mast station installations of 4.2 mm.

The relatively large variation in L3 was noted already from the individual antenna calibrations from Geo++, see Figure 7.

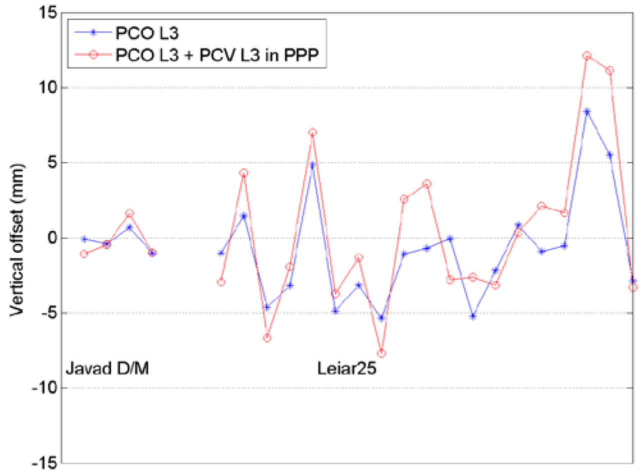

Figure 7. Deviations in individual antenna calibration models from type-specific models from GEO++. The right blue curve: The deviations of the vertical L3 PCO components of the 19 individual Leiar25.3 antennas. The right red curve: The deviations when also (azimuth independent) PCVs were included in a simulated L3t solution, i.e. troposphere estimation included in the solution. The left curves: similar analysis performed on four individually calibrated Javad D/M antennas S/N 182, 244, 275, and 368. The Javad antenna calibration did not include radomes.

6. RE-CALIBRATION VISITS AT 6 SITES IN 2015

In the second part of 2015, six sites were re-visited and site calibration was performed during about 6 days using 3 reference antennas individually calibrated at Geo++. The sites have been visited in earlier campaign, giving the possibility to check the performance of the developed PCV/PCO models.

The analysis was done booth for the old pillar monuments as well as for the new steel grid mast stations.

6.1 Pillar stations

The developed general antenna pillar model was applied. The mean residuals in Figure 8 do not indicate any major deviations in PCV from the applied model. The high noice at low elevations is probably caused by problems with vegetation around the visiting antenas. There has been an attempt to remove observations in directions where disturbancies are suspected, but the cleaning is not perfect, so disturbed observations remains. The noice at high elevations are due to the few observations at high elevation (thanks so our location at high latitude) to average from.

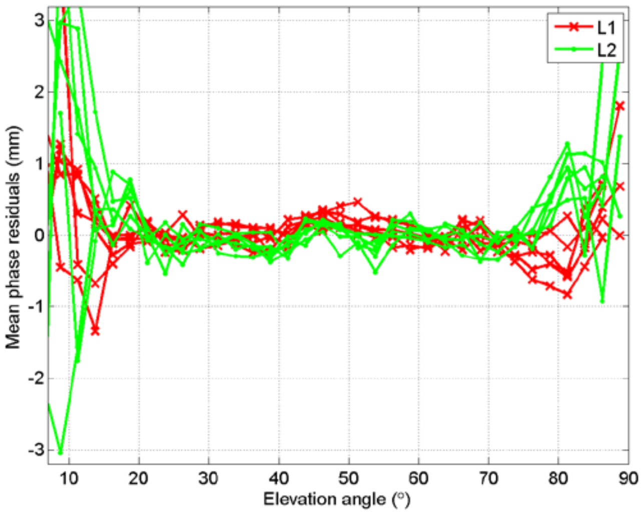

Figure 8. The L1 and L2 residuals when processing the pillar data with the model with updated PCV.

The antenna heights estimated using L1 and L2 agree to the model at the 1 mm level, and L3 at the 2 mm level, see Table 4. While determining the heights using L3t, a standard deviation of 3.5 mm is achieved. This is somewhat larger than the 2.6 mm in the original calibration, but there are somewhat more vegetation in the vicinity of the visiting antenna during this visit.

Table 4. Pillar, general model.

	L1	**L2**	**L3**	**L3t**
Hässleholm	-2.3	-1.6	-3.3	3.2
Jönköping	-1.3	-1.2	-1.5	2.2
Karlstad	0.7	-0.1	1.7	6.8
Norrköping	-1.5	-0.2	-3.6	4.1
Oskarshamn	-1.5	-0.2	-3.6	4.1
Vänersborg	-2.0	-1.1	-3.3	-3.6
Mean	-1.2	-0.9	-1.9	2.3
Std	1.0	0.6	2.0	3.5

6.2 Steel grid mast stations

First the developed general antenna mast model was applied. The mean residuals in Figure 9 are reasonable small, with some signature in L1 at 45 to 75 degrees elevation.

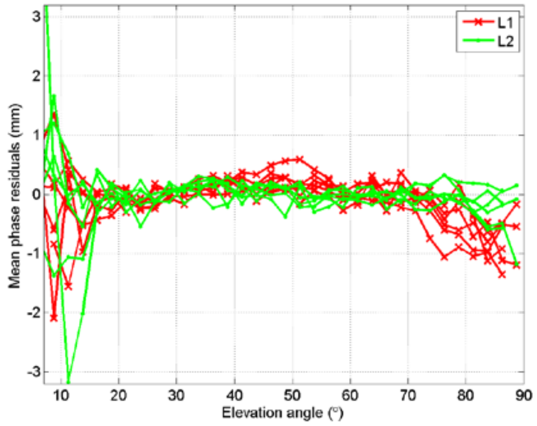

Figure 9. The L1 and L2 residuals when processing the steel-grid mast data with the model with updated general PCV.

The estimates antenna heights from computing using L1 and L2 agrees to the model at the 1 mm level, but increase to 3 mm level for L3, see table 5 (left part). While using L3t, the variations increase to a standard deviation of about 7 mm.

Table 5. Steel grid mast. *Left part*; general model. *Right part*; model with individual PCO and PCV.

	General model					Model with individual PCO and PCV			
	L1	**L2**	**L3**	**L3t**		**L1**	**L2**	**L3**	**L3t**
Hässleholm	1.6	1.0	2.5	9.8		-0.7	-0.8	-0.7	4.8
Jönköping	-1.1	0.3	-3.3	-4.6		-1.2	-0.2	-2.6	-3.3
Karlstad	-1.5	0.5	-4.6	-4.0		0.9	0.7	1.1	4.2
Norrköping	-0.7	0.5	-2.5	-1.4		-1.3	0.0	-3.2	-5.4
Oskarshamn	0.1	0.6	-0.6	-1.7		-0.9	0.0	-2.4	-5.4
Vänersborg	0.0	-1.9	3.0	10.6		0.3	-0.2	1.2	1.8
Mean	**-0.3**	**0.1**	**-0.9**	**1.5**		**-0.5**	**-0.1**	**-1.1**	**-0.6**
Std	**1.1**	**1.0**	**3.1**	**6.9**		**0.9**	**0.5**	**2.0**	**4.7**

Applying the for each station individually suggested PCO and PCV corrections from the work in 2013, the scatter in height are reduced for computation using L3 and L3t to about 2 mm and 5 mm respectively (Table 5, right part). These relatively large values may partly be due to problems with vegetation in the vicinity of the calibrating reference antennas.

7. COMPLICATIONS WHILE USING THE APPLIED CALIBRATION METHOD

7.1 Antenna models of the calibrating antennas

In order for the calibration to be accurate the models of calibrating antennas, derived in absolute calibration, must be valid when used in the field.

It is an ongoing task to evaluate the accuracy of the antenna pattern models, both regarding the quality of their calibration, and how well the patterns are preserved when mounted in the field on a tripod. In this analysis we have used antenna models from absolute calibration on robot from Geo++. A number of our antennas have also been calibrated in Bonn in chamber calibration. Some differences seems to be present, but will be discussed elsewhere.

On order to limit influence of multi-path, we have used microwave absorbing material at the calibrating antennas. It has however been reported that also the use of such material may cause some changes of the antenna phase center variation (Aetrs et al 2016). The L3t results presented above are most effected by the expected pattern errors, and preliminary analysis indicate that L3t heights could have been influenced on the level of a couple mm.

7.2 Vegetation

While performing in-situ calibration in the field, we would like to receive un-disturbed observations at the calibration antennas down to 10 degree elevation (and beyond) in order to be able to calibrate PCV of the visited station down to 10 degrees. However, the visiting antennas usually do get a relatively low setup, and at several stations we do have a “growing” problem with vegetation in the low elevation signal path.

8. SUMMARY AND DISCUSSION

When using the presently available antenna models GNSS determination of the height difference between the SWEPOS pillar antennas and the surrounding reference antennas gave ~ 10 mm too low heights for the SWEPOS antennas. This error was derived from a comparison with conventional terrestrial surveys. The result varied significantly between days, and also between different processing strategies. PCO/PCV errors derived from GNSS phase differences showed elevation angle signatures that can explain the low estimated height components, in combination with too high atmospheric delay estimates. Electromagnetic coupling between the antenna and a metal plate below the antenna is probably contributing to the systematic PCO/PCV errors found.

Simulations using the derived PCO/PCV errors suggest 7-16 mm lower heights due to these errors, i.e. approximately of the same sizes as was found in the “real” GNSS height determination. In the simulations the PCO/PCV descriptions of the reference antennas were considered to be known after being calibrated. During calibration they were mounted on a "robot arm" that might have introduced systematic errors. The possible size of this effect is, at present, unknown to us. It has been suggested that in-situ calibration could be done with antennas mounted on something that mimic the top of the robot arm during local calibrations in order to reduce the possible effect (Wübbena and Schmitz 2011).

In this paper we have excluded three stations (Kiruna, Skellefteå, and Visby). For these stations features in the surroundings of the pillars made the recorded phase variations to differ from what was found for the other nine stations. However, for the nine remaining stations the common "monument specific" PCO/PCV model derived describes fairly well the phase data, and this model can serve as a first guess for the behavior at other, not yet calibrated, stations.

REFERENCES

Aerts, W., Bruyninx C., Defraigne P. (2016) *On the influence of RF absorbing material on the GNSS position*. GPS Solution 29:1-7. DOI 10.1007/s10291-014-0428-y

Elósegui P., J. L. Davis, R. T. K. Jaldehag, J. M. Johansson, A. E. Niell, and I. I. Shapiro (1995): *Geodesy using the Global Positioning System: The effects of signal scattering on estimates of site position.* J. Geophys. Res., Vol. 100, No. B6, pp 9921-9934.

Hoffman-Wellenhof, B., H. Lichtenegger, and J. Collins (1994): *GPS: Theory and practice*, Springer Verlag, New York.

Jarlemark, P., Lidberg, M., Kempe, C., Jivall, L., Johansson, J. M., Ning, T,. (2013): *Station calibration of the SWEPOS™ network (revised version 2013-09-25)*. Proceedings of the EUREF symposium in Saint-Mandé, June 6-8, 2012, http://www.euref.eu/symposia/2012Paris/P-02-p-Kempe.pdf (Sited 2016-02-15)

Jivall, L. (2011): *Hur antenn-modeller påverkar GNSSmätning*. GNSS/SWEPOS- seminariet 2011, Gävle Sweden. (In Swedish)

Lilje, M., Wiklund, P., and Hedling, G., (2014) *The Use of GNSS in Sweden and the National CORS Network SWEPOS*. FIG Congress 2014 Engaging the Challenges – Enhancing the Relevance Kuala Lumpur, Malaysia 16-21 June 2014

Rothacher, M., G. Mader (2003): *Receiver and satellite antenna phase center offsets and variations*. In: Tétreault, P., Neilan, R., Gowey, K. (eds.) Proceedings of the Network, Data and Analysis Centre 2002 Workshop, pp. 141-152, Ottawa. (http://igs.org/igscb/resource/pubs/02_ott/session_8.pdf)

Schmid, R., G. Mader, and T. Herring (2005): *From relative to absolute antenna phase center corrections*. In: Meindl, M. (ed.) Proceedings of the IGS Workshop and Symposium 2004, Bern. (http://igs.org/igscb/resource/pubs/04_rtberne/Session10_1.pdf)

Wübbena, G., and M. Schmitz (2011) *On GNSS Station Calibration of Antenna Near-Field Effects in RTK-Networks*. International Symposium on GNSS, Space-based and Ground-based Augmentation Systems and Applications, October 10-11, 2011, Berlin.

BIOGRAPHICAL NOTES

Dr. Martin Lidberg
Dr. Lidberg is head of the Reference frame section at the Geodetic Infrastructure Department at Lantmäteriet, the Swedish mapping, cadastral and land registration authority. He has a M.Sc in Surveying and mapping from the Royal Institute of Technology (Stockholm, Sweden) in 1988, and got his PhD from Chalmers University of Technology (Gothenburg, Sweden) in 2007. He has been working at Lantmäteriet since 1988. Martin is also a member of the EUREF Technical Working Group.

Dr. Per Jarlemark
Dr. Jarlemark is Senior Scientist at the Department of Measurement Technology at SP Technical Research Institute of Sweden. He has a M.Sc in Engineering Physics from Uppsala University (Uppsala, Sweden) in 1986, and got his PhD from Chalmers University of Technology (Gothenburg, Sweden) in 1997. He has been working at SP Technical Research Institute of Sweden since 1999, where his main focus has been in timekeeping technology and space geodetic techniques.

Mr. Kent Ohlsson
Mr. Ohlsson holds a MSc. in Geodesy and Geoinformatics from the Royal Institute of Technology in Stockholm, Sweden. He is since year 2014 working at the Geodetic Infrastructure Department of Lantmäteriet, the Swedish mapping, cadastral and land registration authority, mainly with GNSS analysis and development of SWEPOS services.

Dr. Jan Johansson
Jan Johansson is professor in space geodetic techniques at the department of Earth and Space Sciences at Chalmers University of Technology and responsible for National Metrology Program in Sweden hosted by SP Technical Research Institute of Sweden. He has a M.Sc. in Electrical Engineering, 1985, and a Phd in 1992 from Chalmers University of Technology. His research focus on high-precision space geodetic techniques and associated error sources.

CONTACTS

Dr. Martin Lidberg
Lantmäteriet
Land and Geographic Information Services – Geodetic Infrastructure Department
SE-801 82 Gävle
SWEDEN
Tel. +46 26 633856
Fax +46 26 610676
Email: martin.lidberg@lm.se
Web site: www.lantmateriet.se/geodesi