STATION CALIBRATION OF THE SWEPOS™ NETWORK

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Abstract – Twelve GNSS stations in the SWEPOS network have been surveyed in order to quantify the effect of the antenna near-field on the GNSS height determinations. Height components ~ 10 mm too low were found. An updated antenna-monument model can, to a large extent, correct the height errors.

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 [1]. The average position of apparent signal reception, the phase center offset (PCO) and the directional dependent phase center variations (PCV) [2] 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™, with focus on the 21 concrete pillar stations that serve as the backbone for SWEREF99 (the national reference frame). The pillar design is presented in Figure 1.

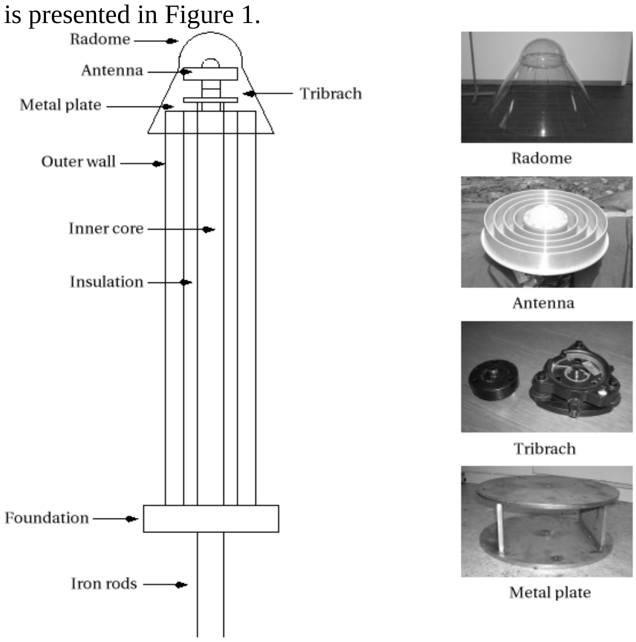


Figure 1. Structure of a concrete pillar foundation in SWEPOS, designed in 1992. The pillar height is ~ 3 m, and is anchored onto crystalline rock. Note the relatively large metal plate used as foundation for the tribrach.

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.

The station calibration campaigns started in 2009 and continued in 2010, so far at twelve stations. Here we present results of the site-dependent effects on height determinations as well as an estimation of PCO/PCV corrections.

2. SURVEYING

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 3. 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.

Figure 2. One of the benchmark setups at Hässleholm, 2010. An Eccosorb plate is mounted directly below the choke-ring antenna.

Figure 3. SWEPOS antenna at Vänersborg together with two reference antennas.

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 [3][4]. In Figure 4 results from 10° for both relative and absolute antenna models are presented. Typically height differences of ~ 10 mm were found. The

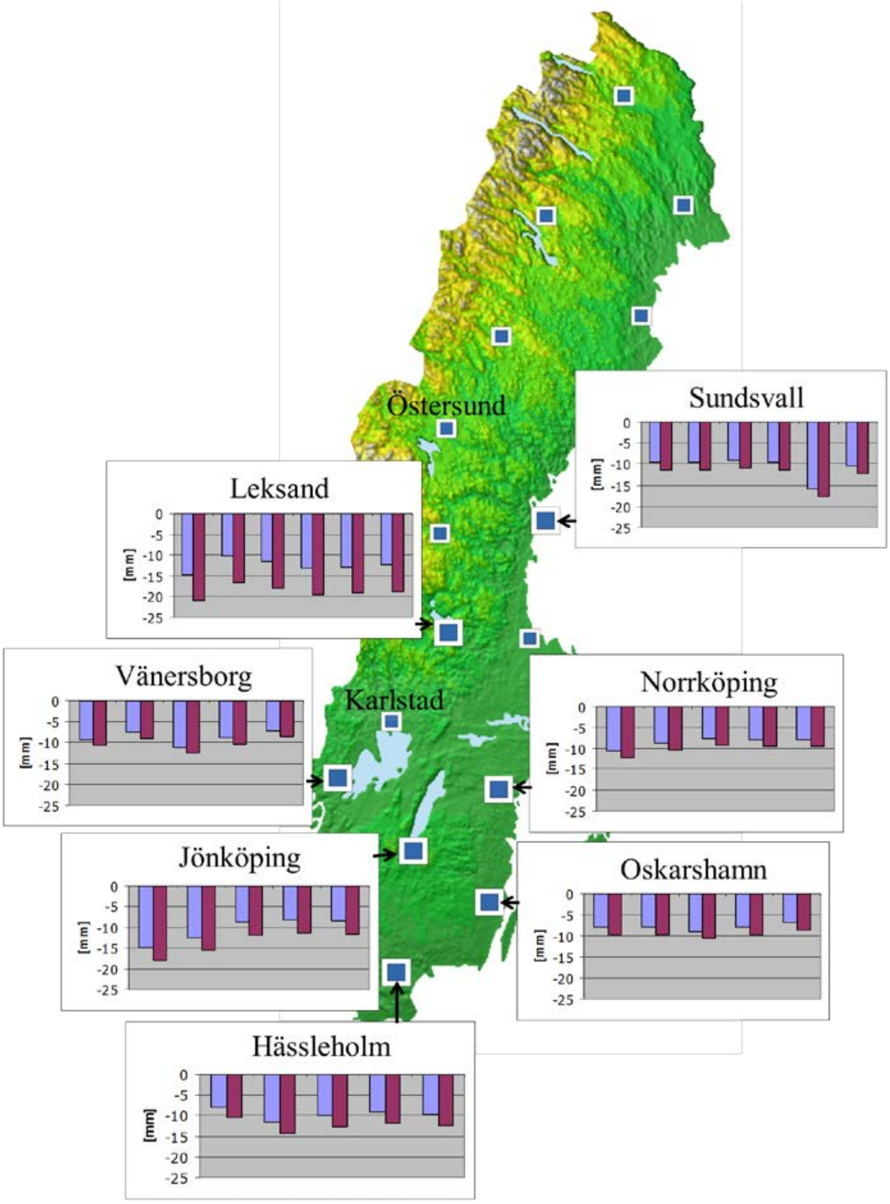


Figure 4. Diagrams showing daily repeatability of the estimated height bias for seven SWEPOS stations. Blue color denotes processing with relative antenna models and red denotes processing with absolute antenna models.

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. [5]). 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 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 5 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 [6]. 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).

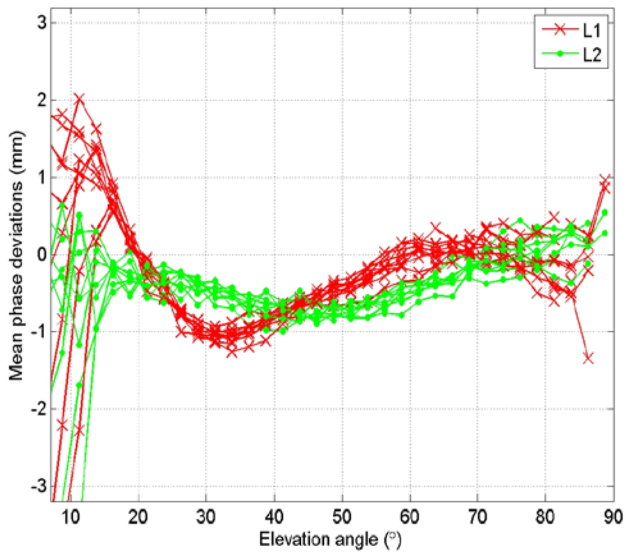


Figure 5. Phase deviations of the nine SWEPOS stations investigated. The deviations are formed by sorting the residuals into 2.5° bins and calculate the mean value for each bin.

The total resulting vertical PCO errors, sum of the results from the two iterations, are presented in 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.

Table 1. Estimated vertical PCO offsets

Station	L1 vertical offset (mm)	L2 vertical offset (mm)
Östersund	2.6	3.2
Sundsvall	-0.3	0.4
Leksand	1.5	3.3
Karlstad	1.1	1.0
Vänersborg	-0.3	0.9
Norrköping	-0.3	1.6
Jönköping	-0.6	0.6
Oskarshamn	0.8	1.8
Hässleholm	-0.7	0.4
Mean	**0.4**	**1.5**

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 6) 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.

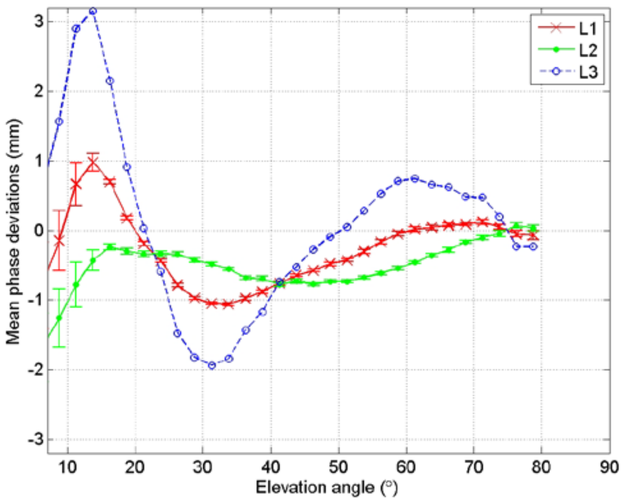


Figure 6. Mean of the phase deviations for the nine SWEPOS stations for L1 and L2 based on the data of Figure 5. An L3 curve is also included, generated as a "ionosphere free" linear combination of the L1 and L2 curves. Notice the significantly larger amplitude of the L3 curve.

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 Table 2. We also sorted the post-fit residuals by elevation angle. The result is shown in Figure 7. 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. The mean values of the curves of Figure 7 are presented in Figure 8. No great systematic errors can be seen for L1 and L2. However, for the L3 combination some structure remains, especially at very low and very high elevation angles.

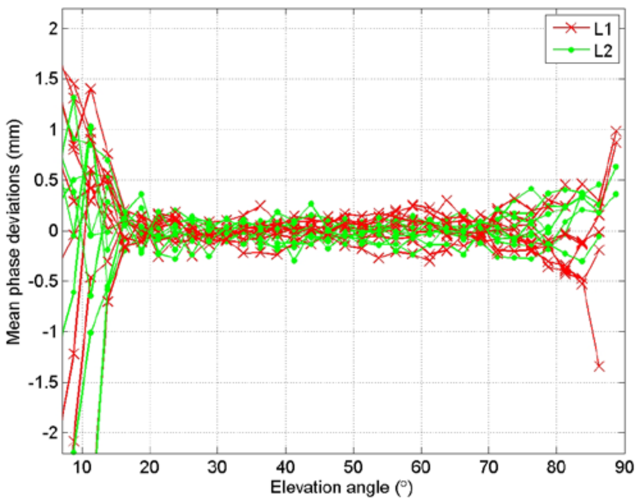


Figure 7. Phase deviations of the nine SWEPOS stations investigated when using the updated PCO/PCV description file for SWEPOS antennas. The signature in the region 15° to 75° is significantly smaller than in Figure 5.

Table 2. Estimated vertical PCO offsets using the updated PCO/PCV description file

Station	L1 vertical offset (mm)	L2 vertical offset (mm)
Östersund	2.2	1.9
Sundsvall	-0.8	-0.9
Leksand	0.2	1.4
Karlstad	0.7	-0.3
Vänersborg	-0.7	-0.3
Norrköping	-0.7	0.4
Jönköping	-1.0	-0.6
Oskarshamn	0.5	0.6
Hässleholm	-1.0	-0.8
Mean	**-0.1**	**0.2**

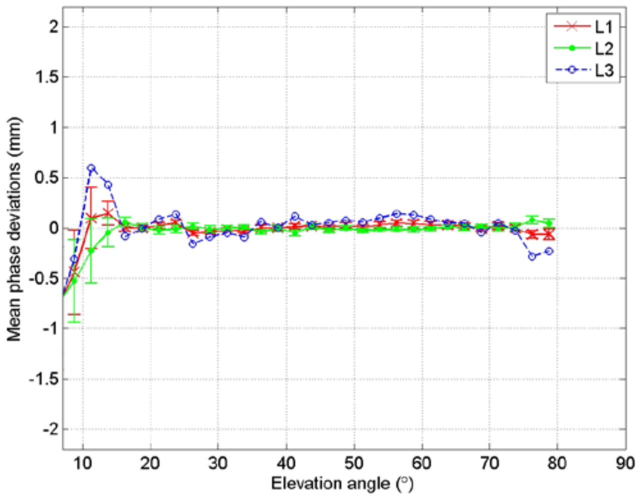


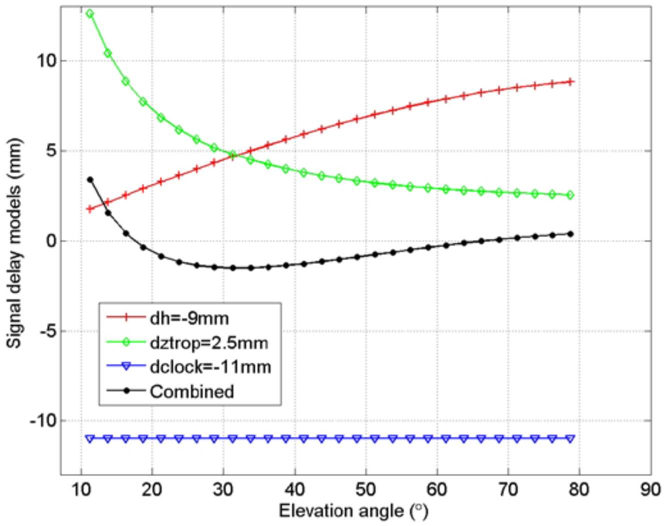
Figure 8. Mean of the phase deviations for the nine SWEPOS stations for L1 and L2 when using the updated PCO/PCV description file for SWEPOS antennas. An L3 curve is also included, generated as a "ionosphere free" linear combination of the L1 and L2 curves.

4.2. Consequences of unmodelled phase deviations

When estimating atmospheric delay together with coordinates and clock parameters 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 unmodelled part of the L3 PCV signature (which we depicted in Figure 6) has partly been absorbed as a (negative) extra height component. In order to understand this model misfit we made numerical experiments with the unmodelled L3 PCV found in Figure 6. 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 9. 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 unmodelled 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 3. 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 4. 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.



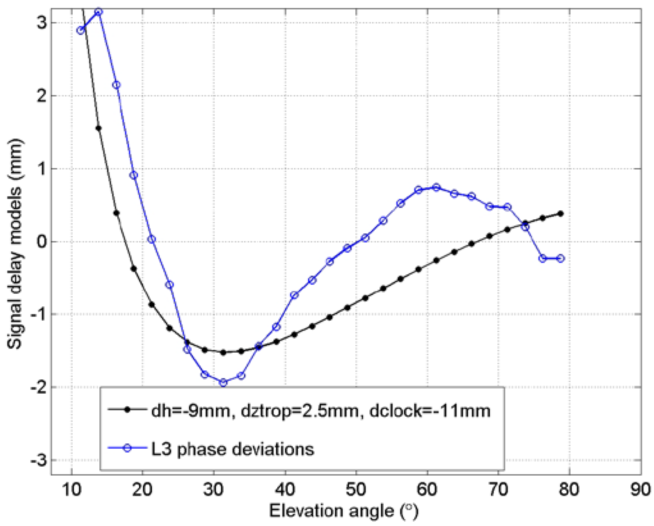


Figure 9. Upper part: graphs depicting the phase changes due to separate changes in height, atmospheric delay, and clock difference, and the sum of the changes (black curve). Lower part: the sum of the phase changes (from upper part) together with the unmodelled L3 PCV.

Table 3. Estimated vertical offsets and atmospheric delay difference when using L3 observables

Station	Vertical offset (mm)	Atmospheric delay offset (mm)
Östersund	-10.4	3.6
Sundsvall	-13.6	3.5
Leksand	-9.2	2.4
Karlstad	-7.0	2.4
Vänersborg	-13.6	3.5
Norrköping	-14.1	3.1
Jönköping	-15.7	4.0
Oskarshamn	-12.3	3.5
Hässleholm	-13.0	3.2
Mean	**-12.1**	**3.2**

Table 4. Estimated vertical offsets and atmospheric delay difference when using L3 observables and the updated PCO/PCV description file

Station	Vertical offset (mm)	Atmospheric delay offset (mm)
Östersund	2.4	0.1
Sundsvall	-1.4	0.2
Leksand	-1.4	-0.1
Karlstad	4.7	-0.8
Vänersborg	-2.1	0.4
Norrköping	-2.6	0.0
Jönköping	-4.2	0.8
Oskarshamn	-0.8	0.3
Hässleholm	-1.5	0.1
Mean	**-0.8**	**0.1**

5. 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 [1].

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

[1] Wübbena, G., and M. Schmitz, “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, 2011.

[2] Rothacher, M., G. Mader, “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, 2003. (http://igs.org/igscb/resource/pubs/02_ott/session_8.pdf)

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

[4] Jivall, L. “Hur antenn-modeller påverkar GNSSmätning”, GNSS/SWEPOS- seminariet 2011, Gävle Sweden, 2011. (In Swedish)

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

[6] Elósegui P., J. L. Davis, R. T. K. Jaldehag, J. M. Johansson, A. E. Niell, and I. I. Shapiro, “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, 1995.