On the Accuracy of Absolute GNSS Antenna Calibration and the Conception of a New Anechoic Chamber

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Key words: antenna calibration, anechoic chamber, near-field, GNSS, GPS

SUMMARY

The antenna effects are one of the accuracy limiting factors in relative GNSS positioning. They depend on the direction of the incoming satellite signal and are usually described by the phase centre offset (PCO) and the phase centre variations (PCV). Because these effects are essentially stable for unchanged antennas, it is possible to calibrate the antennas. Beside the relative and absolute field procedures there is an absolute laboratory procedure, which is ideally performed in anechoic chambers in order to avoid multipath effects.

This paper presents some research on determining the accuracy of absolute calibration of GNSS-antennas in anechoic chambers. Because there is no calibration procedure with a superior accuracy, repeatability measurements and comparisons with independent calibration procedure were made in order to achieve an exact estimation of the accuracy. Based on the presented tests, we found that the calibration accuracy at elevations above 10 degrees is mostly better than 1mm (maximal deviations) and still better than 2mm at lower elevations. The major part of the remaining deviations is caused by near-field variations, which can not be separated from the antenna effect, as shown in this paper.

The disadvantage of the laboratory procedure is the low availability of suitable anechoic chambers. Now, a anechoic chamber is being constructed in cooperation between the Institute of Geodesy and Geoinformation of the University of Bonn and the Landesvermessungsamt NRW (surveying and mapping agency of North-Rhine Westphalia). In order to keep the project affordable the test range, i.e. the distance between transmitter and GNSS-antenna, was kept as small as possible. One aspect of our research is the estimation of the effects which result from the short test ranges. The results show that the effects are indeed negligible in our case.

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1. INTRODUCTION

The function of antennas is to convert electromagnetic waves into electrical currents and vice versa. Therefore a GPS/GNSS position refers to the phase center of the receiver antenna. Strictly speaking the last statement contains a contradiction because it implies that the phase center is a point in a mathematical sense. In reality the phase measurement and as a consequence the determined signal path length depend on azimuth α and elevation β of the incoming signal. The purpose of the antenna calibration is to describe these deviations from an ideal point-like antenna. Commonly the results of calibration are given in terms of geometrical signal path length corrections. Different calibration procedures have been developed since the 1980's. The different procedures can be divided into 'absolute' and 'relative' and into 'field' and 'laboratory' procedures. The field procedures use the real GNSS signals from the satellites in view; thus an operable navigation system is an essential condition for the calibration. Whereas the relative field calibration procedure uses differential GNSS measurements to determine relative calibration results of a test antenna with respect to a reference antenna (mainly a choke ring antenna), the absolute field procedure with robot makes it possible to determine absolute calibration data by rotating and tilting the GNSS-antenna (*Rothacher* 2001). The absolute antenna calibration in an anechoic chamber is a standard technique in radio-frequency engineering (e.g. *Kraus and Marhefka* 2003). Based on these principles a laboratory procedure was implemented, adapted and evaluated at the University of Bonn whereby new geodetic issues were considered. Currently a new anechoic chamber is being constructed in cooperation with the Landesvermessungsamt NRW (surveying and mapping agency of North-Rhine Westphalia). In parallel with further research, a calibration service will be offered within the next few months.

2. ANTENNA PROPERTIES

Besides the determination of the deviations from an ideal point-like antenna, which are usually called phase center variations (PCV), it is indispensable to describe the position of the mean phase center (E) in relation to the antenna reference point (ARP). The ARP is usually the center of the bottom surface of the mounting surface of the antenna, whereby the 3D-offset between phase center and ARP is called phase center offset (PCO). This classification can be found in earlier works on this topic (see e.g. *Geiger* 1988). In Fig. 1 the antenna model is illustrated. Obviously, the range s_{ARP} (resp. phase) depends on the direction of the incoming signal:

$$s_{ARP} = r + \mathbf{PCO} \cdot \mathbf{e_0} + \mathbf{PCV}(\alpha, \beta) + \varepsilon \quad ,$$

with r being the error-free value, e_0 the unit-vector in the direction α and β of the satellite and

□ the noise of the observations. The PCO can reach values up to 10cm, whereas the PCV are mainly smaller than 2cm in case of geodetic antennas. Examples of the phase center variations are presented e.g. in Zeimetz and Kuhlmann 2006.

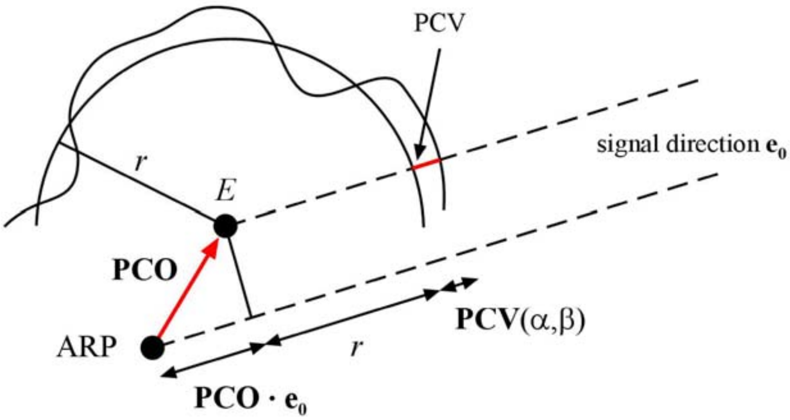

Fig. 1: Antenna model (according to *Zeimetz and Kuhlmann* 2006).

In practice, it is not possible to divide the effects of PCO and PCV because, for every position of *E*, a specific set of PCV exists which satisfies the equation. This rank defect is obvious when looking at the equation above. Geometrically it resembles an umbrella. It is possible to move the center hub (phase center) to open the umbrella without destroying the spokes (PCV). In order to solve the singularity the condition that the mean phase center is the mean of all measured directions can be used.

3. ANTENNA CALIBRATION IN ANECHOIC CHAMBER

The main idea is to simulate the different signal directions by rotations of the GNSS-antenna. The experimental setup consists of a fixed transmitter on one end and a remote-controlled positioner carrying the test antenna on the other end of the test range (s. Fig. 2). To avoid multipath effects, the calibration measurements are made in anechoic chambers. The effects of the test-signals being reflected from the walls can be minimized by using special absorbers.

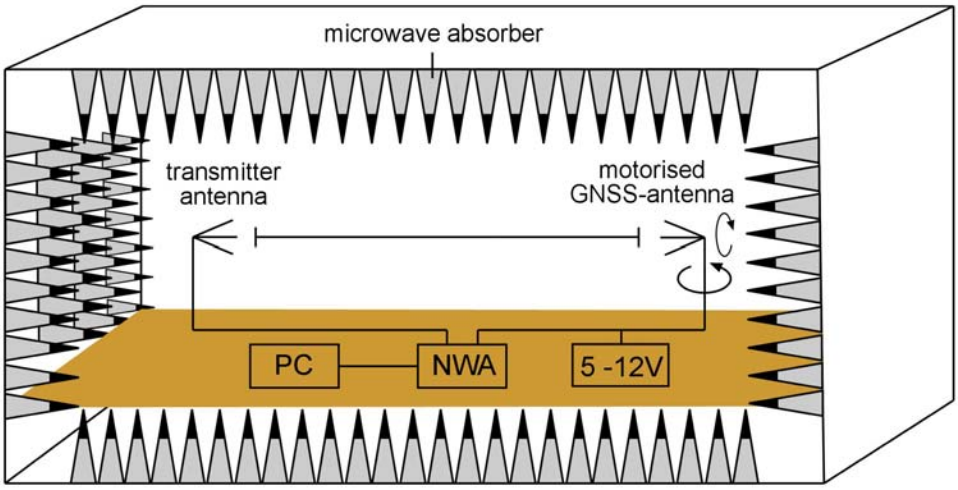

Fig. 2: Setup of the anechoic calibration facility (according to *Zeimetz and Kuhlmann* 2006).

The positioner rotates the test antenna by small amounts of elevation and azimuth. In this way it is possible to simulate the different GPS-satellite directions (*Schupler et al.* 1994). Currently, the calibration measurements are being carried out with sampling steps of 3.6° in elevation and in azimuth.

During calibration a network analyser NWA (here Agilent ENA E5062A), the main component of the setup, measures the phase shift between the outgoing and incoming signals at each of the simulated satellite positions. Additionally the corresponding signal level is measured. The antenna calibration takes approximately 40 minutes and runs completely automatically except for the initial alignment of the GPS-Antenna.

The result of the calibration is a grid of phase corrections and signal levels which directly describes the effects of different signal directions on the GPS range measurements. One advantage of the laboratory procedure is, that calibrations can be performed without having an operable satellite system. Currently, a spectrum from 1.15 GHz to 1.65 GHz is used, whereby only the frequencies of GPS, Glonass and Galileo are analysed. Of course other frequencies are possible. The analysed frequency range of a standard calibration is shown in Fig. 3 (Leica AX 1202GG Antenna). The signal level corresponds to the operational range of the antenna. In this case a calibration of the L5/E5a and the E6 frequencies is not meaningful because of the low signal level.

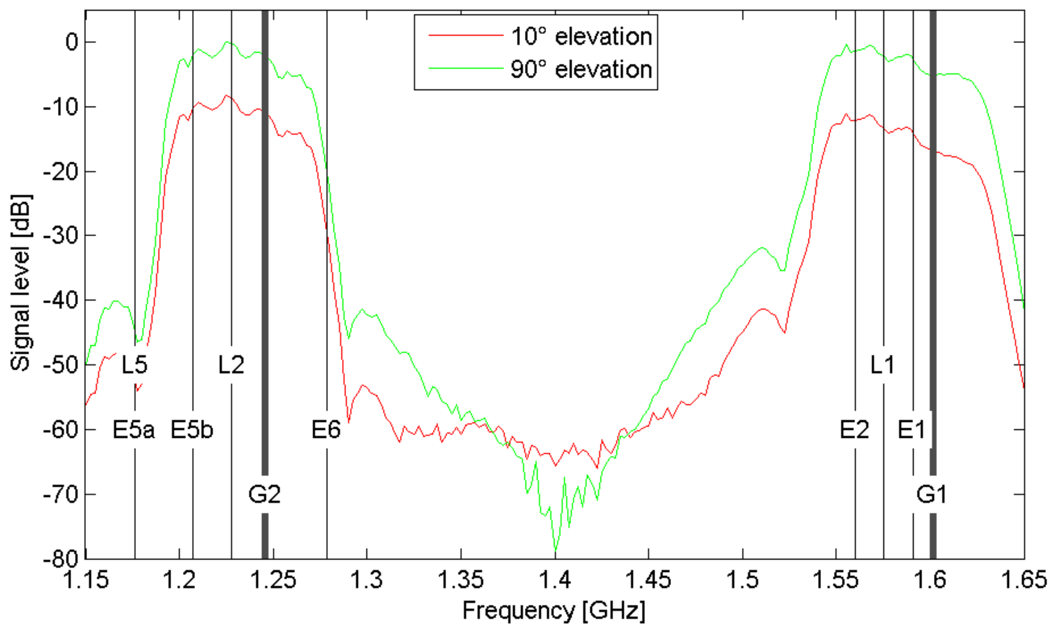

Fig. 3: Transmission characteristics of the Leica AX 1202GG antenna.

Regarding GPS, multipath (MP) is one of the most limiting factors in accuracy (e.g. *Wanninger and May* 2000). In case of calibration, the transmitter does not change the position and as a consequence the MP-field is nearly stable except for the reflections from the rotating antenna itself. But because of changing antenna orientation, the effect of MP on the phase shift may vary.

For the measurements described here, two different anechoic chambers were used. The first one is a chamber of the electromagnetic compatibility test center of the Bundeswehr (German Federal Armed Forces). This chamber is ideally suited because of its large extent (Dimension LxWxH (m): 41x16x14) and the characteristics of its absorbers (for frequencies > 0.5 GHz). The second anechoic chamber is a much smaller one (6 meter test range). It is a facility of the Institute of Microwave Engineering of the Technical University of Darmstadt.

4. CALIBRATION ACCURACY

It is difficult to quantify the calibration accuracy because there is no procedure with a significantly better accuracy (factor 3 or better). Nevertheless there are possibilities to quantify the accuracy.

4.1 Required accuracy

One way to define the required accuracy is to estimate the effect of the remaining uncertainty on the GPS-Position. In this case (standard variance propagation) the observation equation and a correct stochastic model of differential GNSS-carrier-phase observations must be known (*Menge* 1998). Afterwards, it is possible to define the required accuracy for any kind of GPS measurement. Instead of regarding the accuracy in the context of the parameters it is possible to consider it in the context of the observations. Based on the research on the weighting schemes for GNSS observations, the GNSS carrier phase noise and the stochastic model for GNSS observations (see e.g. *Collins and Langley* 1999, *Langley* 1997, *Tiberius and Kenselaar* 2003) a standard deviation of about 0.3mm can be assumed for a single phase measurement (zenith direction). The accuracy decreases as a function of decreasing elevation (□ ~ 1mm at 10° elevation).

This means for calibration, that ideally the accuracy should be in the range from □ = 0.1mm (zenith) to □ = 0.3mm (10° elevation). For the low elevations (0° - 10°) the accuracy depends on many parameters such as antenna, multipath situation and tropospheric effects. It is not possible to give a good general estimation. A calibration accuracy of□ = 0.5mm to □ = 1mm is quite probably sufficient for the lowest elevation angles.

4.2 Noise pattern of the calibration setup

In order to quantify the calibration accuracy, the noise level must be determined first. For this purpose, the test setup described in Fig. 2 was used. In contrast to a standard calibration the antenna under test does not move. Fig. 4 shows the results of an exemplary selected L1 time series. Similar results was obtained for other frequencies (e.g. L2) and other antennas. The elevation of the signal is 0°, so it represents the "worst case". The length of the selected time series is roughly 3 times longer than a calibration would take. The sampling rate is 3 times higher than in case of calibration in order to detect short periodical variations.

The noise level in Fig. 4 shows the good precision of the calibration setup. The linear trend and the other systematic effects can be neglected because of their small dimension. The trend is the result of changing temperatures during the measurement. In case of calibration, reference measurements are used to correct this effect. The procedure is described in *Zeimetz and Kuhlmann* 2006. The physical principles can be found in *Robinson et al.* 2003.

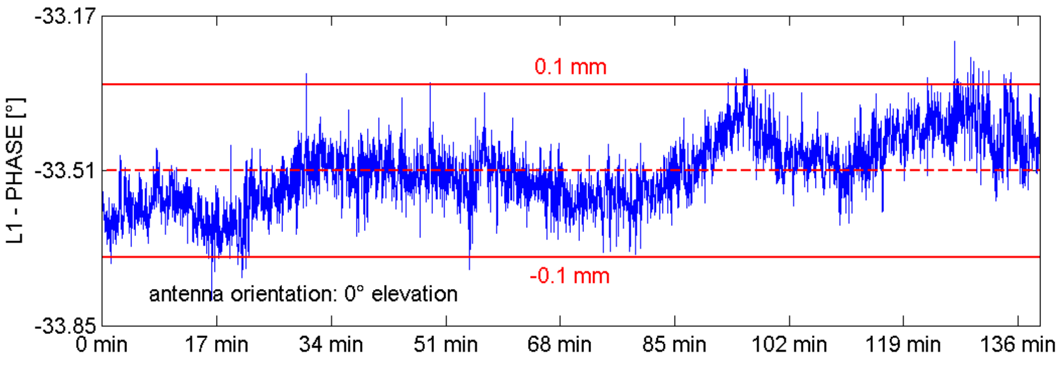

Fig. 4: Typical noise pattern of the calibration setup.

The results of the test above show that the noise of the calibration system is very small, and that these effects can be neglected considering the position determination with GNSS at the current level of GNSS-accuracy.

4.3 Repeatability

In order to evaluate repeatability several measurements with nearly identical conditions were carried out. The differences of two such measurements are shown in Fig. 5. The center of the plot represents the zenith, whereas the horizon is represented by the outer circle. The colours represent the determined differences, as indicated by the colour bar.

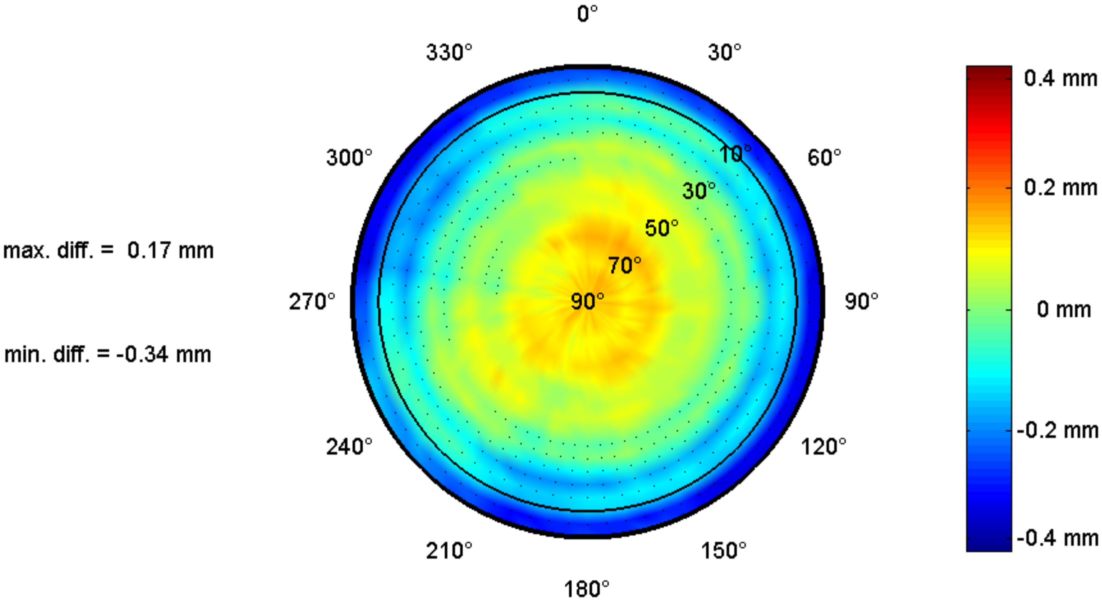

Fig. 5: Comparison of two measurements (identical setup, L2 GPS frequency).

Between 0° and 10° elevation there are maximum differences of about 0.34mm. Above 10° elevation there are no deviations higher than 0.2mm and the majority is smaller than 0.1mm. The test antenna was a Leica AX1202GG. Other antenna types and other frequencies were tested, too. The results are comparable, the deviations presented here are slightly greater than the average. It can be pointed out that the requirements are largely fulfilled. The decrease of accuracy at the borders (low elevations) cannot be explained by the position accuracy or by the phase measurements themselves. Possible reasons will be discussed in chapter 4.4.

Of course in the case of the experiment described till now, not all systematic effects could be detected because the setup does not change. In order to show such systematic effects, different setups were used which vary primarily in the distance between transmitter and GNSS-antenna, the antenna height above the ground and the distance to the walls. Beside these well controllable differences, there were unavoidable changes e.g. in the remaining multipath situation and in the antenna near-field (e.g. cable placement). The result of such an experiment is shown in Fig. 6. Whereas the deviations of the higher elevations (middle of the graphic) are still on a low level, the deviations at the low elevations rise sharply. The corresponding table 1 points out the sharp rise in more detail.

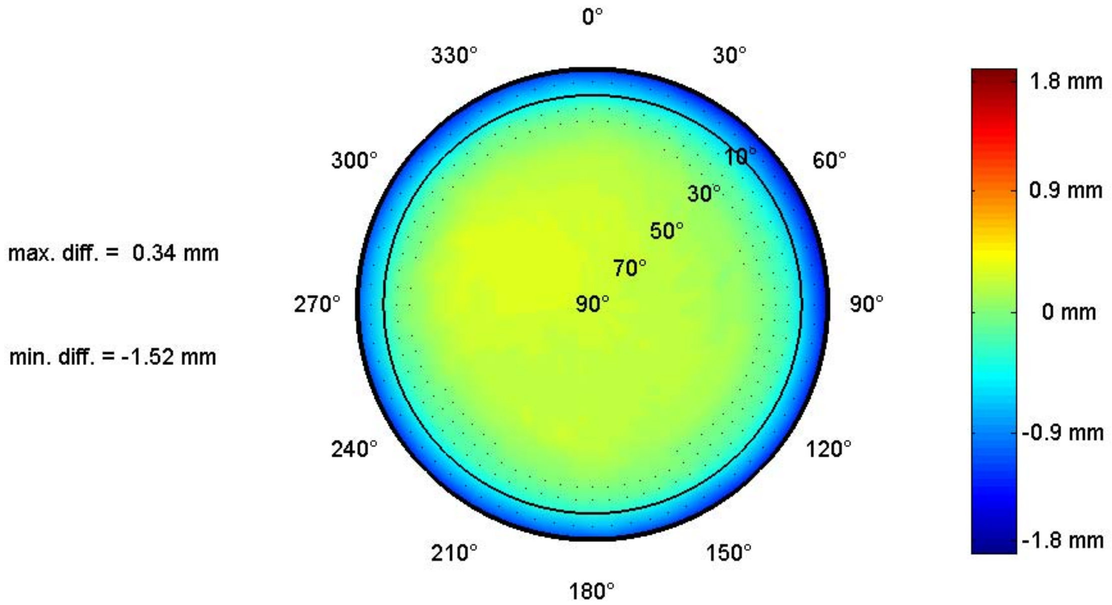

Fig. 6: Comparison of two measurements (changed setup, L2 GPS frequency).

elevation	0° - 5°	5° - 10°	10° - 15°	15° - 90°
max. differences	1.5 mm	1.0 mm	0.7 mm	0.3 mm

Table 1: Elevation dependent differences.

In contrast to the first test (Fig. 5) the results depend on the tested antenna type. Here the results of a Trimble Zephyr Geodetic Antenna are presented. Almost similar results can be obtained for Leica AX1202 antennas. Several other antenna types (e.g. Leica AT502) show differences up to 2mm (and sometimes larger). The better the shielding, the smaller are the deviations between the various measurements. This is a first indication that the near-field effects and the multipath signals are the main source of uncertainty, whereas the random deviations are nearly negligible.

In the following, the possible causes of the systematic effects will be analysed. In this context it will be important to clarify whether the effects are a specific problem of the calibration procedure or a general problem of microwave phase measurements.

4.4 Near-field Effects, Sensitivity of the Setup

Multipath effects and specially the near-field effect are the largest remaining GNSS error influences (*Wübbena et al.* 2006). In case of calibration there are the same problems, but by optimizing the setup (e.g. material, geometry) it is possible to minimize the effect and, as a consequence, to increase the calibration accuracy. Unfortunately, this does not necessarily mean that the accuracy of GNSS becomes better, because the near-field effect on the GNSS site remains. One idea to reduce this problem is to calibrate the near-field effect. For this purpose some parts of the setup (e.g. the tribrach) were mounted on the positioner together with the antenna during calibration. Some more details about the procedure can be found in, e.g. *Wübbena et al.* 2006.

At this point, some experiments, which are necessary to explain the deviations in Fig. 6, are presented. Two calibration measurements with an identical setup, except for the cable placement (s. Fig. 7), were made. At the first test, the cable formed a loop before entering in the axis. The loop, hardly recognizable on the left photo, has an diameter of about 6 cm. At the second test, the cable was coiled around the axis.

Fig. 7: Differences in cable placement.

The differences between the measurements (L1) are shown in Fig. 8. The results for the L2 frequency are similar concerning the characteristic and slightly higher (up to 1.2mm) in absolute values. As in Fig. 6 the highest values, up to 1mm, are located at the lowest elevations. That could be expected because at high elevations the cable is shielded by the antenna itself. Because the results are reproducible, the cable was identified as the basic cause for the effects in Fig. 8. It can be excluded that the effects are the result of changed transmission properties as a consequence of cable bending. This could be checked by forming the loop with an additional, unplugged cable.

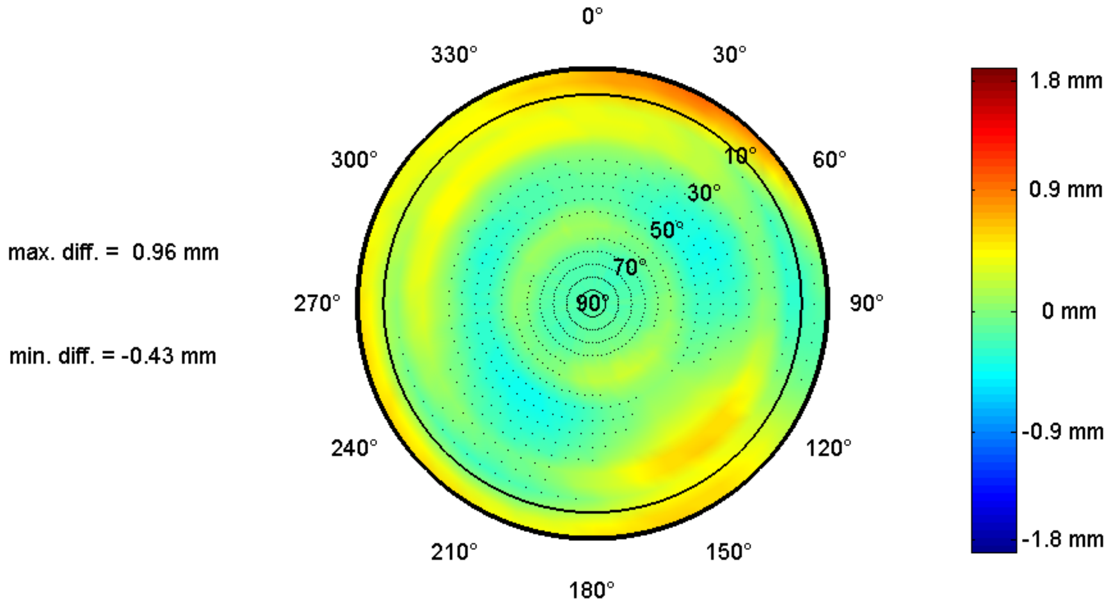

Fig. 8: Effect of different cable placement (L1 GPS frequency).

Considering these results and taking into account the small variations in cable placement, it is not surprising that there are differences between the measurements with a varied setup (Fig. 6). Of course the differences presented in Fig. 8 are smaller than in Fig. 6 in absolute terms (1.4mm vs. 1.9mm). But considering that in Fig. 6 are a lot of more changes in the setup (e.g. test range, height above ground, distance to walls, multipath, further changes in nearfield) it becomes obvious that the near-field effect is one of the greatest remaining problems.

In case of calibration it is possible to reduce the nearfield effect to a neglectable level or to hold the effects stable for all calibrations at least. In practise it would be very difficult to obtain an identical near-field effect in case of calibration and in case of GNSS site, with such a level of detail. It is to be pointed out, that the sensitivity and precision of the calibration are of a very high level and that the existing deviations are almost certainly produced by the near-field and not by the calibration procedure itself. To minimize the remaining near-field effects (at GNSS site) the activities on this topic will be intensified after the completion of the new anechoic chamber.

4.5 Comparison with absolute field calibration

So far, it becomes clear that the internal accuracy of the laboratory calibration is compatible with the requirements. But it cannot be ruled out that there are further systematic effects, which could not be detected because they were constant for all the measurements done so far. One possibility for the detection of such systematic effects lies in the comparison of the laboratory results with those of the absolute field technique of Geo++ which uses the real GPS signal from the satellites in view (*Wübbena et al.* 2000). The basic idea of the absolute field calibration of Geo++ is to determine the antenna effects by rotations and tilts of the antenna using a robot. The absolute field procedure may be regarded as a completely independent method.

The results of the comparison presented below (Fig. 9, Trimble Zephyr Geodetic antenna) originate from measurements in 2005/2006. A more detailed comparison can be found in *Zeimetz and Kuhlmann* 2006. Because of a modified determination algorithm there are small differences in the results presented here.

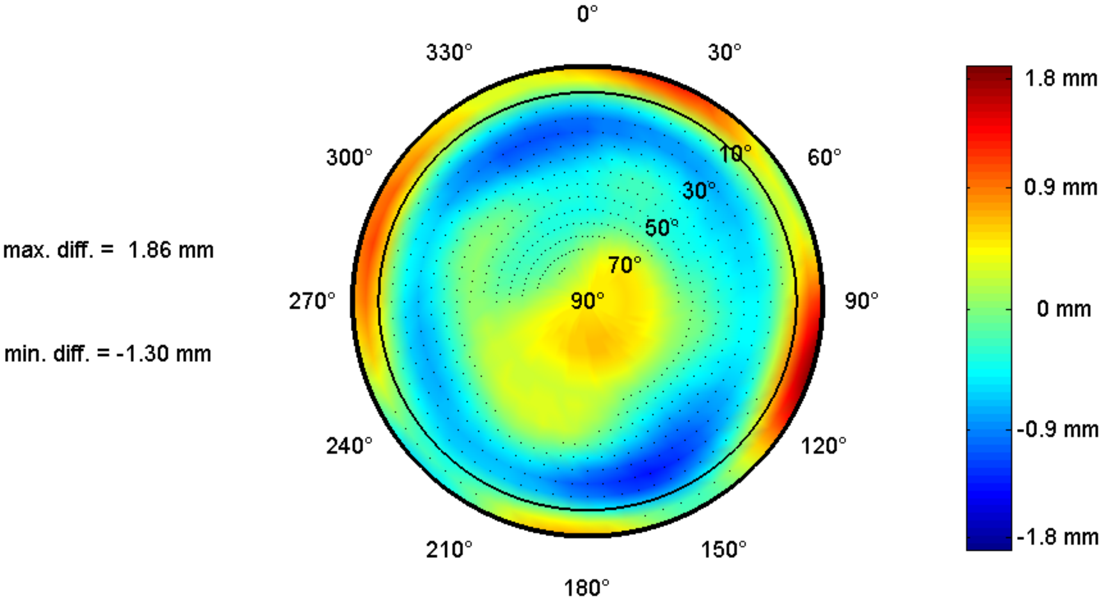

Fig. 9: Comparison of the results (L1) of the laboratory procedure with the field procedure of Geo++

The maximal differences are here, as usual, in a range of up to 2mm. At the low elevations the differences can be higher than 2mm, whereas the differences from 10° upwards remain on a level below 1mm. These values are valid for typical geodetic GNSS antennas (e.g. Trimble Zephyr Geodetic, Leica AX1202, Choke Ring antennas). For the L2 frequency there are larger differences in some cases. Currently, the reasons are not clear. At least for the chamber calibration, a lower accuracy is not expected for frequencies in the range from 1.1 GHz to 1.3 GHz. Considering the different antenna environments, the results show a good agreement. The dimension and characteristics, larger differences at low elevations, indicate that the near-field effects limit the accuracy. Here, it is surely necessary to make further investigations.

5. CONCEPT OF THE NEW ANECHOIC CHAMBER

As already mentioned, currently a new anechoic chamber is being constructed. In this chapter we shall demonstrate that a compact 6 meter test range is suitable for our purposes.

5.1 Test range: theoretical assumptions

Valid calibration results can be obtained, if the test signal is very similar to the ordinary GNSS signal. Here one aspect is the planarity of the wavefront, which becomes better the larger the distance between transmitter and GNSS antenna. This is one aspect of designing a new anechoic chamber. To calculate the effect in a simplified approximation, a geometric approach can be used. The planarity of the wave front depends on the distance between transmitter and GNSS antenna. In Fig. 10 the model is illustrated.

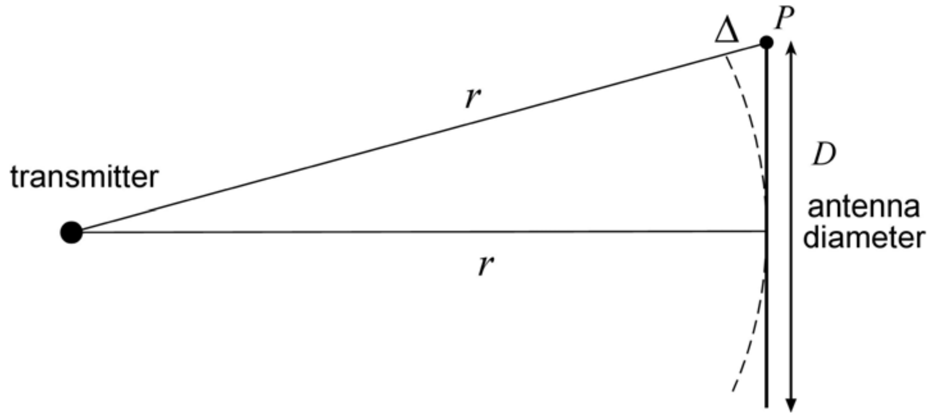

Fig. 10: Problem of short range measurements (see e.g. *Kraus and Marhefka* 2003).

The phase delay Δ in a point *P* depends on the distance *r* and the antenna diameter *D*. The problem in calculating Δ is to determine the antenna diameter. *D* does not correspond to the outer diameter of the antenna, *D* is the diameter of the effective antenna area, which basically depends on the antenna type and the wavelength λ. Generally speaking the effectivity of antennas increases with the diameter of the antenna. For the practise the antenna manufacturers try to produce effective but also small antennas. Often so called λ/2-antennas are used as a good compromise. In the following the relevant antenna size will be discussed using the example of a patch antenna. Because the results are very similar for mircostrip antennas (*Kraus and Marhefka*, 2003), a large sample of antenna types are considered (e.g. Trimble Geodetic, Trimble Zephyr Geodetic, chokering). The results are not valid for antennas with a larger diameter D, but such antennas are usually not used in geodetic practice. The basic principle of a patch or microstrip antenna is shown in Fig. 11.

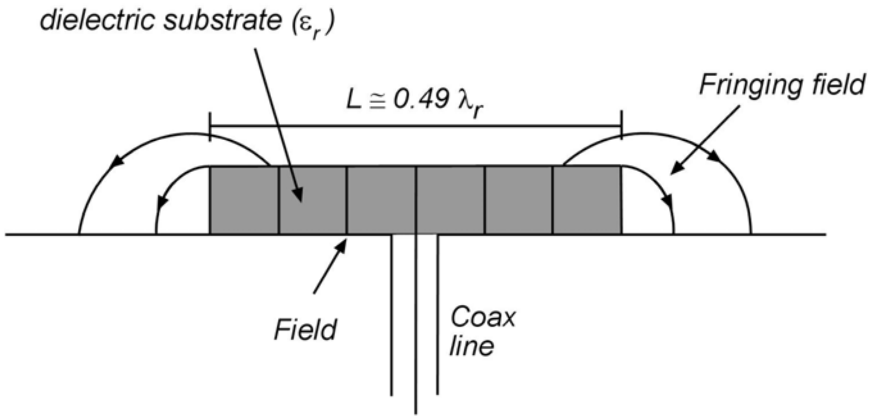

Fig. 11: Patch antenna (according to *Kraus and Marhefk* 2003)

The diameter of the effective antenna is equal to the half of a wavelength (λ/2), which depends on the relative permittivity ε_r of dielectric substrate and can be determined by

$$\lambda = \frac{\lambda_0}{\sqrt{\varepsilon_r}} \quad ,$$

whereby λ_0 is the wavelength in vacuum. ε_r is usually in a range from 2 to 20 in the case of patch antennas. For the sake of completeness it should be mentioned that the size of the antenna patch is a little bit smaller (0.49λ instead of 0.5λ) because of the fringing field, which increases the effective antenna diameter. The patch size is:

$$L \approx 0.49 \frac{\lambda_0}{\sqrt{\varepsilon_r}} < 0.5 \frac{\lambda_0}{\sqrt{\varepsilon_r}}.$$

For the determination of the resulting phase error as a consequence of a non-planar wave front the L5 frequency is regarded. This frequency is the lowest one (long wavelength) of all currently known GNSS-frequencies. The wavelength in vacuum is about 25.5 cm. Assuming a relative permittivity of $\varepsilon_r = 2$, the reduced wavelength is around 18 cm. The antenna diameter is then $D = 9$ cm. With this diameter and a given range of $r = 6$ m it is possible to calculate a phase error of □ = 0.2mm by using the theorem of Pythagoras, cf. Fig. 10. The received field is not in phase for the different parts of the GNSS-antenna. This maximal deviation □ describes the phase deviation at the outer part of the antenna.

In Fig. 12 an Trimble Geodetic Antenna is shown. In this case the diameter of the antenna element is about 6 cm, whereby it is not clear which element is visible (L1 or L2).

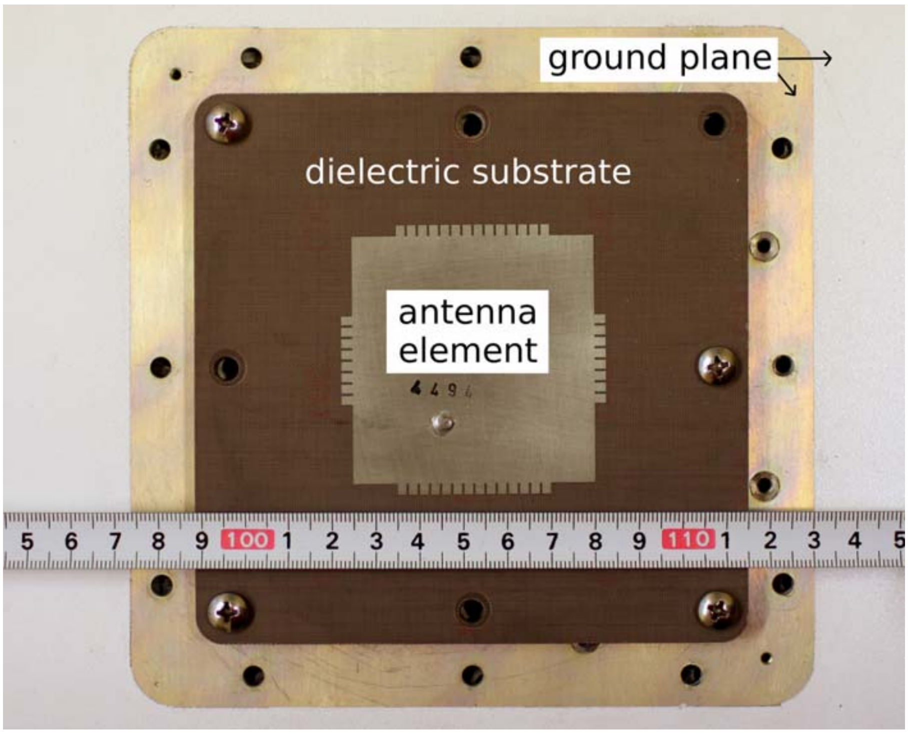

Fig. 12: Antenna element of a Trimble Compact Antenna**.**

Because of the many underlying assumptions, in the following the results are validated by empirical tests.

5.2 Test range: empirical validation

In order to validate the theoretical assumptions, measurements with varying distances were accomplished. For this purpose, a 41 meter long (height =14m, width = 16m) anechoic chamber could be used, which was kindly provided by the electromagnetic compatibility test center of the Bundeswehr (German Federal Armed Forces). So, it was possible to make a reference measurement with a 16 meter test range. An additional extension of distance is not necessary and would decrease the accuracy (because of e.g. cable effects). Subsequent to the reference measurement, the distance between transmitter and test antenna was reduced to 5 meter by moving the transmitter. The other parts of the setup had not been moved. The differences between both measurements are shown in Fig. 13.

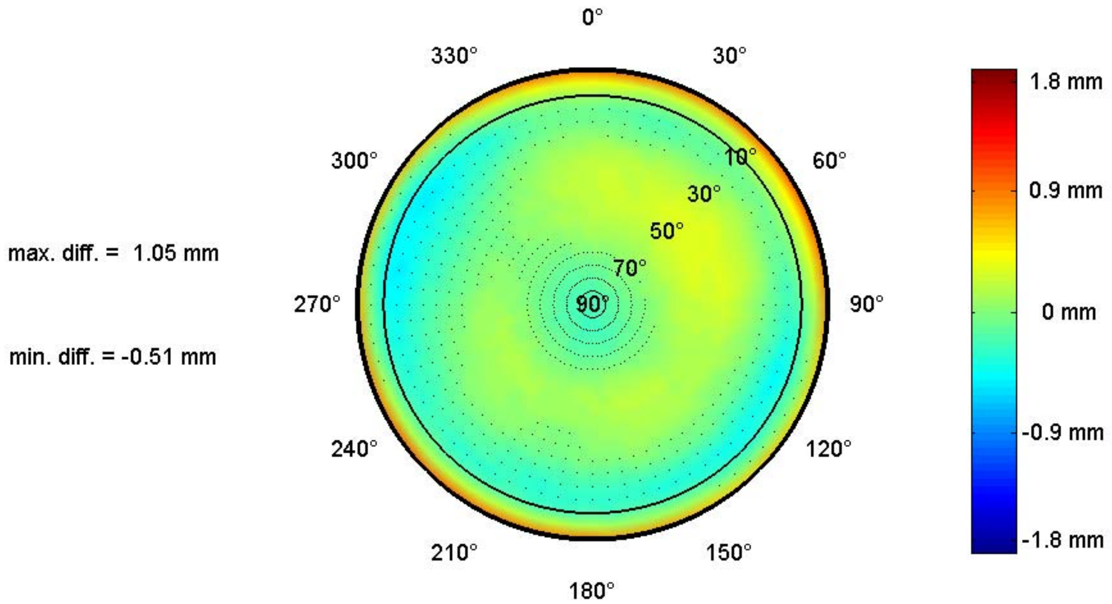

Fig. 13: Results of reducing the test range from 16 to 5 meters (L1 GPS frequency**)**

Here again the L1 results are shown. In this test the L2 results not visualised here are slightly better. At elevations above 5° the maximum differences show differences up to 0.5mm. Only for lower elevations the differences go up to 1mm, as the small red ring indicates. This effect, more precisely the limitation on the low elevations, could not be explained by the reduced calibration range. The cause for the differences is still unknown. It is not an effect of the near-field; that was nearly stable in this case. Altogether, and considering GNSS-measurements, the differences are very small in absolute terms (cf. Fig. 6). A test range of 6m (means at least 8 m anechoic chamber) appears to be suitable for the calibration of GNSS-antennas.

6. CONCLUSIONS

In order to determine the accuracy of the absolute chamber antenna calibration method several different types of repeatability measurements were carried out with identical antennas. In addition the results were compared to results from a completely independent absolute field calibration method with robot mount. The maximal differences are mostly smaller than 1mm at elevations above 10°. At lower elevations differences increase up to 2mm. These values are valid for typical geodetic GNSS antennas. The major part of the remaining deviations is caused by near-field variations, as shown in this paper.

Furthermore it was demonstrated that it is possible to reduce the distance between transmitter and GNSS antenna to 5 or 6 metres without a significant loss of accuracy. Based on these results a new anechoic chamber has been designed , which is being constructed in cooperation with the Landesvermessungsamt NRW (surveying and mapping agency of North-Rhine Westphalia).

Considering section 4.2 - 4.5 and the accuracy derived from there (10°-0° elevation: □ <2mm, 90°-10° elevation: □ <1mm) one can see that, especially at the low elevations, the actual accuracy does not completely fulfil the claims we have pointed out in section 4.1 (10°-0° elevation: □ <0.5-1mm, 90°-10° elevation: □ <0.1-0.3mm). The experiments show that the main effects are results from the the near-field. The calibration procedure itself is accurate enough. Further research on the near-field problem is necessary, so that the GNSS-measurements can benefit from the high calibration accuracy.

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