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Monitoring of the Church Tower in Herrenberg with Low-Cost GNSS

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Abstract

The church tower in Herrenberg (nearby Stuttgart) was monitored with leveling to identify the vertical sinking of the church tower. In recent years, some new cracks have been found on the church tower walls which could have been caused by the horizontal deformation of the church tower. To identify the both horizontal and vertical deformation of the church tower, Low Cost GNSS receivers were used. The key limitation factor for accuracy of GNSS (for short baselines) is the multipath effect. Besides, the antenna is very close to the tower walls. For this reason, the influence of the multipath effect will be analyzed and mitigated. Two measurement sessions were realized in May and July 2018, a deformation analysis was done. There are about 5% outliers in the time series, the 3 dimensional standard deviation of single measurement is about 20 mm. After reducing the multipath effect, the 3 dimensional standard deviation of single measurement is improved by about 45%. Deformation analysis shows significant deformation in the north and height component, although there should no significant movement between two sessions, since the movement is very slow and there is only about two months between these two sessions.

Keywords
Low Cost GNSS, Monitoring, Multipath Effect, Deformation Analysis

1. Introduction

Monitoring of artificial structures and natural objects is one of the main tasks of engineering geodesy. Low-Cost single-frequency GNSS receivers are a cost-effective solution compared to traditional geodetic multi-frequency GNSS receivers, particularly for geodetic monitoring tasks where a high number of receivers are applied. Numerous preliminary investigations have shown that Low-Cost single-frequency GPS receivers can achieve similar results as geodetic GNSS receivers (Schwieger and Gläser 2005, Schwieger 2007, Schwieger 2008, Schwieger 2009, Limpach 2009, Glabsch et al. 2010), if the carrier phase measurements of the GNSS receivers are evaluated for short baselines, because the influences of baseline-length-dependent errors, such as ionospheric and tropospheric errors, can be mitigated for short baselines. However, the site-dependent errors, particularly the multipath effects, are the dominant errors of short baselines, particularly in shadowing environment. In practice, it is very often that observation points for GNSS measurements are not selectable, e.g. for the monitoring of high buildings or television towers, where are normally many reflectors there in the antenna vicinity.

The church tower in Herrenberg (nearby Stuttgart in Germany) has a height of about 57 meter and was monitored with leveling to identify the vertical sinking of the church tower. In recent years, some new cracks have been found on the church tower walls which could have been caused by the horizontal deformation of the church tower. To identify both horizontal and vertical deformation of the church tower, Low Cost GNSS receivers can be used. There is only one pillar close to the tower walls which can be used for the GNSS measurement. This means that the multipath could heavily affect the accuracy of the measurement.

Two sessions of GNSS measurements were carried out, the multipath effect was investigated and results of the deformation analysis will be shown in this paper.

2. Test Description

In this test, the U-blox C94-M8P Application Board (C94-M8P 2018) which contains two NEO M8P-2 modules is used (one costs about 300€). NEO M8P-2 is a single-frequency

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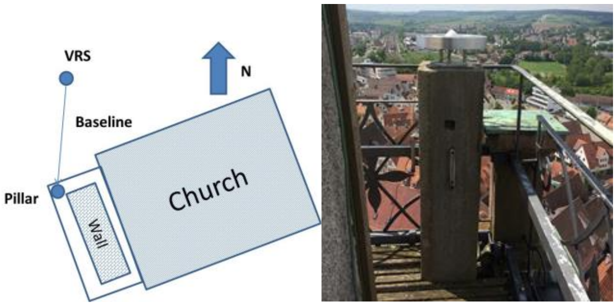
GNSS receiver. It can receive the signals from GPS, GLONASS and Beidou systems. However, it can only receive the signals from two of these systems at the same time, possible combinations are GPS+GLONASS and GPS+Beidou (NEO M8P-2 2018). For the measurements, a low-cost GNSS antenna (about 100€) Tallysman TW3710 (Tallysman, 2018) was used which can receive GPS L1, GLONASS G1 and Galileo E1 as well as Beidou B1.

To reduce the influence of multipath effects, a self-constructed L1-optimized choke ring ground plane is used. In the preliminary research at the IIGS (Institute of Engineering Geodesy), self-constructed L1-optimized choke rings are developed for Trimble Bullet III GPS antennas. The combination of U-blox LEA-6T GPS receivers and this antenna with the L1-optimized choke rings can already reach an accuracy in the range of millimeters which is comparable to geodetic dual-frequency GNSS antennas and receivers (Zhang and Schwieger 2017). However, it should be noted that the choke rings can only reduce most of the multipath signals from the ground but not from vertical reflectors like walls.

As shown in Fig. 1, the antenna was set up next to the tower walls (corner) of Herrenberg church tower. The horizontal distance from the antenna and the walls are about 0.5 m. Due to the close distance to the tower walls and much multipath effect should show dominating influence. The antenna height is about 1.3 m.

SAPOS (Satellitenpositionierungsdienst der Deutschen Landesvermessung) is the German Satellite Positioning Service, its task is to provide accurate and reliable GNSS correction data based on its permanent GNSS reference stations. A VRS (Virtual Reference Station) station which is calculated by SAPOS is taken as reference station for baseline processing, because the three closest SAPOS stations are about 30 to 40 kilometers away from the church tower. The VRS is about 86 m away from the pillar.



(a) (b)

Fig. 1 (a) Sketch and (b) Photo of Test Field

Two sessions of static measurements are carried out. Session 1 is from 17 to 24 May 2018 and session 2 is from 12 to 19 July 2018, so the measurement duration of each of these two sessions is 7 days.

Due to the fact that up to now the SAPOS service only provides GPS and GLONASS data and the satellite availability of GLONASS is better than that of Beidou in Germany, the combination of GPS+GLONASS is chosen for the U-blox receiver. The GNSS raw data are recorded with 1 Hz and stored on a PC, evaluated and post-processed. The raw data are in UBX binary format and are converted into RINEX format using the RTKLIB (RTKLIB 2018). The VRS and the antenna on the church tower are taken as reference and rover stations respectively for baseline processing baselines. The baseline is processed by software Wa2 provided by Wasoft (Wasoft 2018).

3. Results and Analysis

3.1 Quality Analysis

The results of Wa1 are the baselines in the UTM-system in east, north and height for every second. The outliers in the coordinate's time series, which are probably caused by the unfixed ambiguities, are detected according to the 3σ-rule. Then they are linear interpolated, and the standard deviations are calculated. The percentage of outliers and the standard deviation are regarded as parameter for describing the reliability and accuracy of the measurements, respectively, and reliability and accuracy are two parameters to describe the quality of the GNSS measurement (Zhang 2016). As there is no significant difference between the results within one session (seven days), only the results of the first day of each session will be presented in this paper. Table 1 and Table 2 show the reliability and accuracy of the first day of the two sessions. There are both about 5% outliers in the time series. The standard deviation is about 8 mm and 16 mm in horizontal and vertical direction, so the 3-dimensional standard deviation is about 20 mm. Since the antenna is very close to the tower walls and the multipath effect as mentioned before is dominating, this quality is generally understandable. The measurement quality is worse than that of the test in Zhang (2016), the percentage of the outliers is about 2% and the 3-dimensional standard deviation is about 11 mm. The main reason is that the antenna in Zhang (2016) is about 5 meters away from the main reflector.

Table 1 Reliability of Measurement

		Percentage of Outlier [%]		
Session	E	N	h	Mean
1	4.9	4.5	4.3	4.6
2	4.8	4.7	3.5	4.3

Table 2 Accuracy of Measurement

		Standard Deviation [mm]		
Session	E	N	h	Total
1	7.7	8.2	15.9	19.5
2	8.6	8.4	15.7	19.8

3.2 Multipath Effect Analysis

The main reflectors in the antenna vicinity are the ground and the walls in this test. The reflected signal can cause periodic multipath effects on the carrier phase measurement, and the periodic effects or many harmonic oscillations can be also found in the coordinates (Georgiadou and Kleusberg 1988;

Heister et al. 1997). In Irsigler (2008), the frequency of multipath on the carrier phase can be estimated for horizontal and vertical reflectors using the equation (1):

$$f_{\delta\varphi}(t) = \frac{2}{\lambda} \cdot \begin{cases} h \cdot \cos E^s(t) \cdot \dot{E}^s(t) & \text{Horizontal} \\ -d \cdot \sin E^s(t) \cdot \dot{E}^s(t) & \text{Vertical} \end{cases} \qquad (1)$$

λ is the wavelength (19 cm approximately for the L1-frequency); *h* and *d* are the vertical and horizontal distances between the antenna and the reflector. The closer the reflector is located, the longer is the period. E^s and $\dot{E}^s$ are the elevation of the satellite and its change over time (velocity). A satellite with high elevation can cause long and short periodic multipath effects respectively for horizontal and vertical reflectors. The faster the satellite is moving, the shorter is the generated period of the multipath effect. The wavelength is constant for one antenna, the distance *h* and *d* does not change so much. However, the elevation of the satellite changes all the time and the velocity of elevation is not constant, either. For this reason, the frequency of multipath effects varies all the time.

Using the mean value of the velocity of the elevation 0.07 mrad/s and equation (1), the period caused by the multipath effects can be calculated. The period caused by the ground should be more than 18 minutes (that means the frequency should be smaller than 0.92 mHz), and that from the tower wall varies from about 45 minutes to about 4 hours (that means the frequency should be between 0.07 and 0.37 mHz). So, totally, the multipath frequency in this test is less than 0.92 mHz. It should be known that these calculated periods or frequencies are only the roughly estimated values, since the satellite velocity is not constant.

The multipath effect in this test is reduced by using the algorithm developed in Zhang (2016) which considers the temporal correlation of GNSS coordinates. The multipath frequencies are estimated precisely and iteratively. This algorithm was described in Zhang (2016); since it is not the focus of this paper, it will not be explained in detail in this paper.

Fig. 2 shows the comparison of the residuals of the baseline of one day and after applying the developed algorithm. It is obvious that the periodic oscillations in the original residuals are reduced significantly. Table 3 shows the baseline standard deviation of the first day in each session after applying the developed algorithm. The improvement of the standard deviation is almost 45%. The improvement of the standard deviation by using the developed algorithm is about 50% in Zhang (2016).

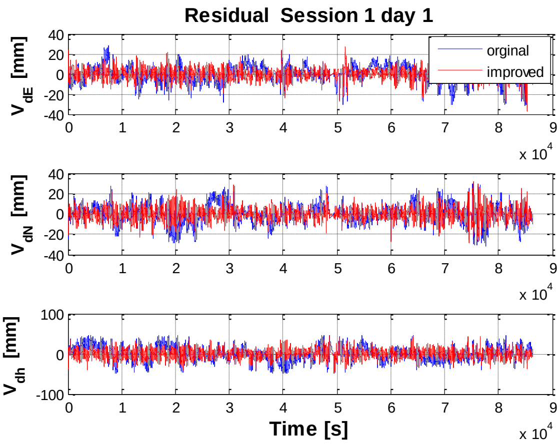


Fig. 2 Coordinates residuals before and after using the algorithm

Table 3 Accuracy of Measurement (after reducing the multipath effect)

	Standard Deviation [mm]			
Session	E	N	h	Total
1	4.1	4.9	8.7	10.8
2	4.2	4.7	8.2	10.3

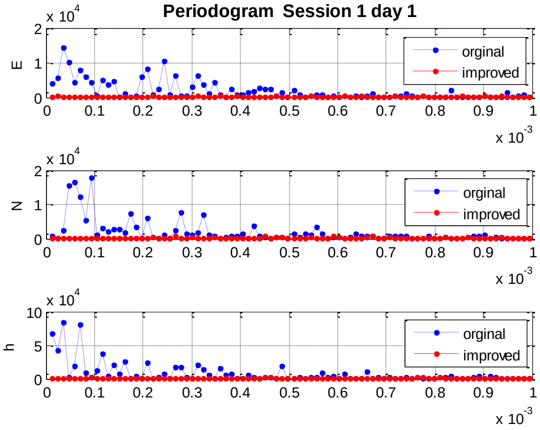


Fig. 3 Periodogram before and after using the algorithm

Fig. 3 shows the periodogram (up to 1 mHz) of coordinates' time series of the baseline on the first day of session 1. The frequencies with high amplitude or energy distribution are mainly between 0 and 0.5 mHz in the periodogram of original residuals (compare Fig. 3). These results match the explained theory very well. Between 0.5 and 0.92 mHz, the amplitude is not high, a possible reason is that multipath signals from the ground were mainly reduced by the self-constructed L1-optimized choke rings; this result is quite similar to the results in Zhang and Schwieger (2017). Furthermore, after applying the algorithm, the high amplitudes are almost disappeared (compare Fig. 3), which leads to the improved results shown in Fig. 2.

3.3 Deformation Analysis

Table 4 shows the mean value of the baseline of the first day in two sessions.

Table 4 Comparison of Baseline in two sessions

	Baseline			
Session	E [m]	N [m]	H [m]	Length [m]
1	15.1643	-43.7118	73.8421	83.1397
2	15.1643	-43.7092	73.8527	83.1474
Diff. [mm]	0.0	-2.6	10.6	10.9

$$t = \frac{d}{s_d} \tag{2}$$

$$s_d = \sqrt{s_{\bar{x}_1} + s_{\bar{x}_2}} \tag{3}$$

$$s_{\bar{x}} = \frac{s_x}{n_{eff}} \tag{4}$$

$$n_{eff} = \frac{n}{1 + \sum_{k=1}^{m} \frac{(n-k)}{n} K(k)} \tag{5}$$

The differences between the two baselines are 3 mm in north direction and 11 mm in height. A simple deformation analysis can be done by using the t-distribution for each coordinate component (compare equation (2)). The standard deviation of the difference should be calculated by using equation (3). The standard deviation of the mean value of two sessions can be calculated by with the standard deviation of single value and the so-called number of effective observations (compare equation (4)). The reason that the number of effective observations should be used is that the time series is normally temporal correlated. If the number of observations is directly used, the calculated standard deviation of mean value is normally too optimistic (see Heunecke et al. 2013). The number of effective observations can be estimated by using the equation (5). K(k) is the autocorrelation function and m is the normally taken as n/10, n is number of observations (Taubenheim 1969).

If the original standard deviation (from Table 2) is taken, the test value is 0, -3.2 and 2.63 for east, north and height component respectively. If the improved standard deviation (from Table 3) is taken for the significant tests the test values will increase, since the numbers of effective observations increase, because the temporal correlation is reduced by using the developed algorithm. So that means if the quantile of 1.96 is taken (with a probability of 95 %), the significant test shows that there is deformation in north and height component. However, there should no deformation between the two days. Since the church tower moves only very slowly, there should be no movement within the two months which is detectable with a GNSS receiver. So, for this reason the data should be analyzed more details in the future. One possible reason could be that the antenna calibration data is not used (the antenna is not calibrated with the L1-optimized choke rings) and the antenna orientation is not the same in both sessions. And it is assumed that the antenna height is exactly the same, however it is possible that the antenna height is slightly different.

However, it should be kept in mind that the improvement of the measurement accuracy can increase the probability of detection of deformation (see Zhang 2016).

4. Conclusions

In this paper, measurement of the church tower with Low Cost GNSS receivers and its results are shown and analyzed. Since the GNSS antenna is very close to the tower wall, the multipath effect is analyzed intensively. The multipath effect is reduced by the self-constructed L1-optimized choke rings and also by using an algorithm which considers the temporal correlation (see Zhang 2016). The accuracy is improved by about 45% which shows similar results as in Zhang (2016).

The significant test shows that there is significant deformation between the two sessions, although there should no significant movement between two sessions, since the movement is very slow and there is about two months between these two sessions. So, in the future, the data of other sessions should be analyzed and more measurement could be done to identify possible deformations of the church tower.

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