Investigation Regarding Different Antennas Combined with Low-Cost GPS Receivers

Li ZHANG, Volker SCHWIEGER, Germany

Key words: Low-cost GPS, Monitoring, GNSS, Positioning

SUMMARY

The Institute of Engineering Geodesy (IIGS) is presently developing an automatic low-cost GPS monitoring system, which includes u-blox L1 single frequency GPS receivers.

In the first tests, the u-blox ANN-MS antenna already obtained an accuracy which almost meets the requirements of geodetic applications (see Zhang et al. 2012). To improve the accuracy of the system, particularly in shadowing environment, a choke ring optimized for the L1 single frequency antenna was constructed to reduce the multipath effect. Different low-cost antennas (costs are less than 100 €) were tested.

In this article, the automatic low-cost GPS monitoring systems developed at IIGS will briefly be introduced. The focus of this article is on the evaluation of the different antennas with and without chock ring. These test measurements have been carried through in region of Stuttgart (Germany), they were composed of different baseline lengths (up to 1 km) with different shadowing conditions. The results of the low-cost GPS system will be compared with highly precise pillar network coordinates determined by high-end dual frequency GNSS receivers, tachymeter and leveling measurement. As a result, one antenna with choke ring is able to obtain sub-mm accuracy in shadowing-free environment and millimeter level in shadowing environment; the accuracy meets the requirements of a geodetic monitoring system.

Investigation Regarding Different Antennas Combined with Low-Cost GPS Receivers

Li ZHANG, Volker SCHWIEGER, Germany

1. INTRODUCTION

Monitoring is one of the main tasks in engineering geodesy. The trend in monitoring goes towards the automation and continuity of measurements. Traditional monitoring measurements are carried out at certain time intervals. Today, the information about the monitored objects should be available continuously in near real-time, in order to inform the users of possible dangers as early as possible. This means that the instruments should permanently be set on the monitored objects and therefore the investments would be high.

The geodetic GNSS receivers using carrier phase measurement are able to achieve accuracies in the sub-cm range in relative mode. Beside tachymeters, only GNSS receivers are able to measure the 3-dimensional positions automatically and continuously. For this reason, GNSS receivers have already been used in the monitoring at an early stage. For example, a GPS monitoring system has been developed at the Graz University of Technology (Hartinger 2001). At the same time, the system GOCA (Kälber et al. 2000) has been developed which includes measuring, communication and deformation analysis. In addition to the traditional monitoring methods such as total stations, GNSS and leveling, many new instruments have also been used in monitoring in recent years, e.g. terrestrial laser scanner (Holst & Kuhlmann 2011) and terrestrial radar scanners (Hebel et al. 2011), which enable an areal measurement. In geosensor networks, as presented in Bill (2011), several cost-effective sensors (such as inclinometer, accelerations, pressure and line sensors) are combined in one sensor node. Different sensor nodes are linked by a self-organized wireless network, so that the data transmission and processing will be realized in real-time or in near real-time.

Different measurement methods have their advantages and disadvantages. One advantage of the GNSS receivers is that they can be used under all weather conditions. Furthermore, direct line-of-sight is not necessary for the GNSS measurements. In addition, data collection and processing can be realized automatically and continuously. However, the geodetic GNSS receivers are not suitable for areal measurement due to their high price (some cost more than 20 000 €).

Preliminary research at the Institute of Engineering Geodesy, University of Stuttgart (IIGS) showed that the low-cost single-frequency receivers with the use of carrier phase data are able to achieve similar accuracies as geodetic GNSS receivers (Schwieger & Gläser 2005, Schwieger 2007, 2008, 2009). Those receivers are developed for the mass market and their price is below 100 € (such as u-blox GPS receivers).

In recent years, developments have been made in the relevant research: Graz University of Technology (Lanzendörfer 2007) and ETH Zurich (Limpach 2009) have both achieved accuracies in the sub-cm range for short baselines in their test studies by using u-blox GPS receivers for monitoring landslides and rock glaciers.

The University of Armed Forces Munich has developed a GNSS monitoring system based on cost-effective Novatel receivers (about 1200 €). With this system, an accuracy of a few millimeters can be achieved for landslide monitoring. The system is already successfully applied in several projects. A lot of practical experience was and will be collected (Glabsch et al. 2010).

In this paper, the results of an automatic low-cost GPS monitoring system with the latest u-blox LEA-6T GPS receiver will be presented.

2. LOW-COST GPS MONITORING SYSTEM AT IIGS

As described in the introduction, several low-cost GPS and GNSS systems have already been established. Currently, several groups are working on the application of u-blox receivers in monitoring. Also at the IIGS, an automatic low-cost GPS monitoring system is being developed and in the testing phase.

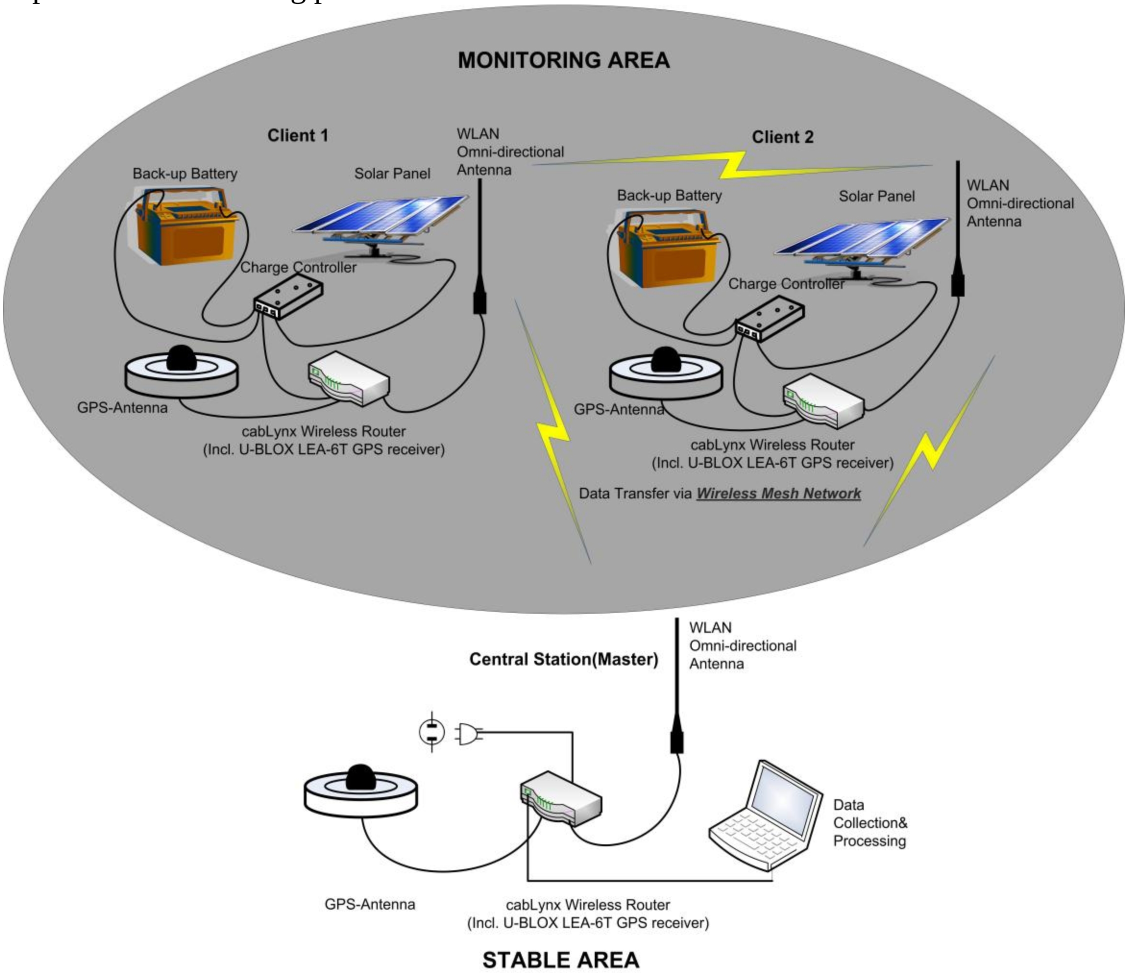

Figure 1: System architecture

Figure 1 shows an overview of this system. The current system consists of three stations. One station is operated as a central station (master), it controls the data communication. The other two stations (clients) transfer the raw data continuously in real-time via Wireless Mesh Networks (WMN) to the central station (see figure 1). The central station is connected to a computer, here, data collection and processing are executed. In principle, the data transmission can also be realized via UMTS. The results, e.g. the information of the baseline can be transferred via UTMS to the network of the University of Stuttgart. However, this is not yet fully implemented.

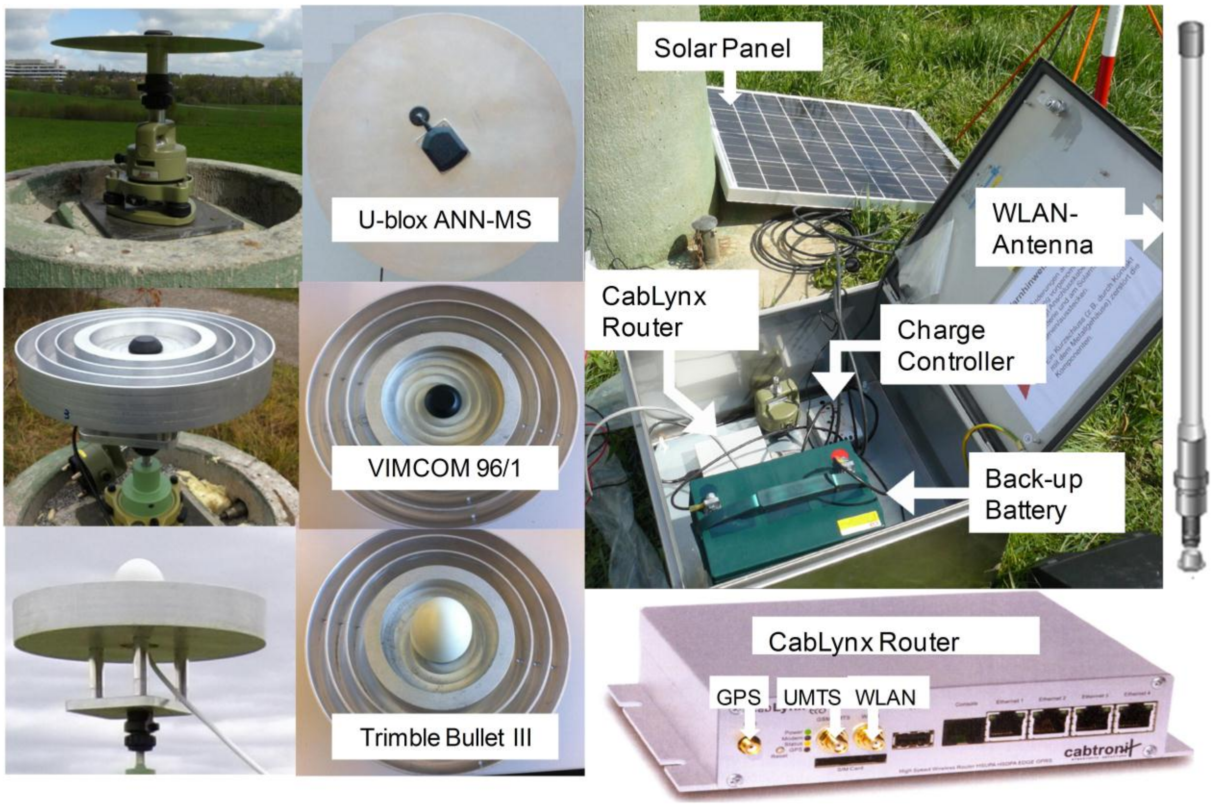

Figure 2: System components of one autonomous station

Figure 2 shows the components of an autonomous station. Each station contains a CabLynx wireless router (Cabtronix 2013). The maximum speed of WLAN transmission is 54 Mbit/s (IEEE 802.11g). After configuring the routers, the stations can be integrated in a WMN. In contrast to a typical star topology, in which the clients can only transfer the data to the master, the data transmission in WMN is also possible among the clients. After starting the system, the IP addresses of the clients are automatically given by the master. The clients can transfer the data to their neighboring clients until the data arrive at the master (Ubéda 2008). The main advantage of this mesh topology is dynamics and stability of the network. If the direct connection of a client to the master is not possible, the data can still reach the master through other clients (which are connected in the mesh network with the master). The functionality of the WMN has been already proved in a test (Zhang et al. 2012).

Since the WMN is self-organized and thus the direction of data transmission is variable and previously unknown, here an omni-directional antenna (Vimcom 2013) is necessary. The range of the WLAN communications has been tested up to 2 km with line of sight (Zhang et

al. 2012). To make sure that this system is running continuously and autonomously, the power of each station is provided with a solar panel, a solar charge controller and a back-up battery. The most important part of each station is the latest u-blox GPS receiver LEA-6T (Ublox 2013), which is integrated in the CabLynx router and able to output the GPS raw data in binary format (figure 2, right).
In Takasu & Yasuda (2008), several low-cost GPS L1-frequency antennas and receivers were tested in combination. The tests show that good antennas have much more positive impact on the result than good receivers. For this reason, the three low-cost antennas u-blox ANN-MS, Vimcom 96/1 and Trimble Bullet III (each of them costs less than 100 €) were tested in combination with the u-blox LEA-6T receiver. To reduce undesirable multipath effects, the u-blox ANN-MS antenna is shielded with a self-constructed ground plate. Vimcom 96/1 and the Trimble Bullet III antennas are shielded with self-constructed choke rings (figure. 2, left).
As described in Filippov et al. (1998), multipath effects can be reduced by a certain depth of the choke ring antenna. The depths of the choke rings should be about 1/4 of the wavelength of the signal, for frequency of L1 and L2 they are approximately 4.7 cm and 6 cm. The commercial choke rings have depth of about 5.6 cm, which is a compromise between L1 and L2 and so the multipath effects are not reduced most optimally for single frequencies. The self-constructed choke ring has a depth of 4.5 cm and is thus optimized for L1-frequency.

3. QUALITY ANALYSIS

3.1 Test Scenario

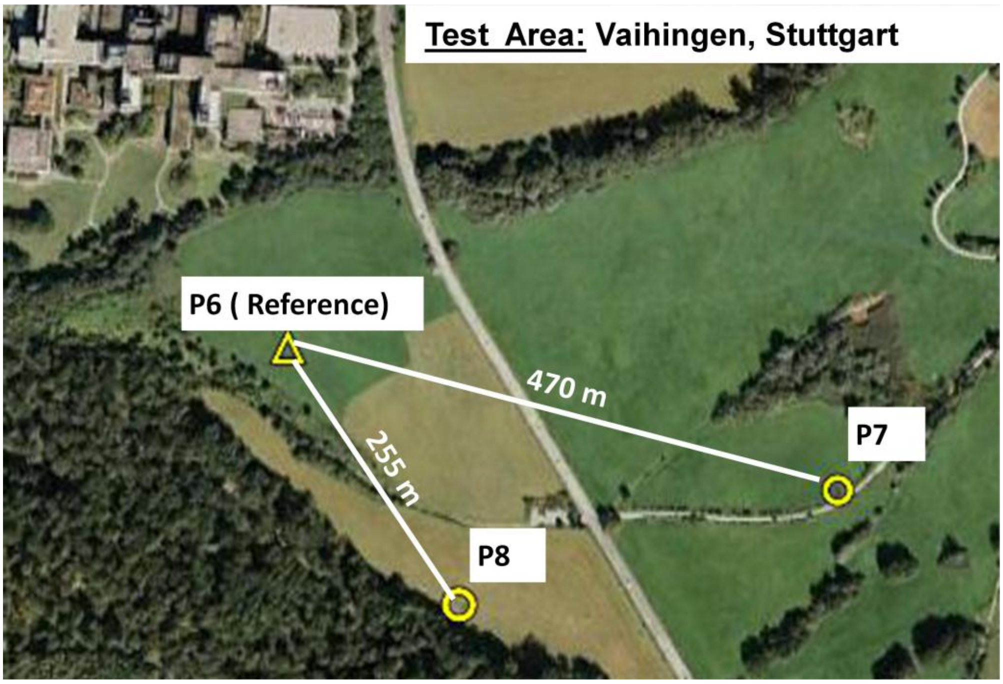

Figure 3: Test scenarios in Stuttgart-Vaihingen

A couple of tests have been carried out in Stuttgart-Vaihingen. The results of the measurements in November 2011 and 2012 are shown here as examples. In the test area, there are several pillars, which were re-measured in 2012 using total stations, geodetic GNSS receivers and leveling. The resulting coordinates are regarded as given coordinates with millimeter accuracy (Wang 2013). The aim of the measurements is to evaluate the quality of the low-cost system, as described above, under different conditions. Firstly, the lengths of baselines vary from 255 m to 470 m. Secondly, pillars with different shadowing condition were selected for the test. In addition, the performances of three different low-cost antennas were to be tested with the different shields. The test scenario is illustrated in figure 3. The reference station P6 and the rover station P7 stand in a shadowing free environment; while the rover station P8 is nearby a forest (southwest), so that more disturbed signals are expected there.

Table 1 shows the characteristics of the measured baselines. Both baselines P6-P7 and P6-P8 were measured with all three antennas, thus there are 6 sessions in total. Since a router was broken on 02.11.12, the baselines with Vimcom and Trimble antennas were not observed on this day (compare table 1). The duration of the measurements was all about 1 hour.

Table 1: Characteristics of baselines

Session No.	Date	Observation Time	Antenna Type + shielding	Baseline	Length[m]
1	18.11.11	11:38-12:54	u-blox (ANN-MS) + ground plate	P6-P7	468.638
2	02.11.12	12:32-13:43	Vimcom (96/1) + Choke-Ring		
3	02.11.12	14:08-15:09	Trimble (Bullet III) + Choke-Ring		
4	18.11.11	11:38-12:54	u-blox (ANN-MS) + ground plate	P6-P8	254.913
5	02.11.12	10:51-11:53	Vimcom (96/1) + Choke-Ring		
6	02.11.12	09:23-10:24	Trimble (Bullet III) + Choke-Ring		

3.2 Data Processing Procedure

Figure 4: Data Processing Procedure

The raw data are in binary format (UBX format). They are converted into a standard exchange format (RINEX 2.3 format) and edited (for example, entering the coordinates of the reference station and the antenna heights, antenna types) by using free software TEQC (TEQC 2013). TEQC can also be used to check the quality of the RINEX data, so that possible reasons for bad results can be found.

The baseline computations are done by means of the GNSS software Wa1 of the company Wasoft (Wa1 2013). At the end of the baseline processing, a solution and a log file will be produced. Each coordinate solution is accompanied by a solution type (in our measurements "FloatDGNSS" and "FixedL1") and a rough quality indicator ("low", "medium" and "high"). If a measurement result in a "FloatDGNSS" solution (in the following text written as "float" solution), it means the percentage of fixed ambiguity is too low and the result is regarded as unacceptable. If a measurement result in a "FixedL1" solution (in the following text written as "fixed" solution), this means that certain percentage of fixed ambiguity is reached. A solution quality indicator "high" is given, if certain requirements are fulfilled, such as minimum of percentage of fixed ambiguity, standard deviation of unit weight, number of satellites and PDOP (Wa1 Manuel 2010). This means that the result with quality indicator "high" is more reliable than the results showed "medium". In the log file the calculation steps of baseline processing are described in detail, so that the user will be able to find possible reasons for not optimal results quickly and easily. The output coordinates can be given as Cartesian, ellipsoidal or UTM coordinates.

Quality is a comprehensive definition (Schweitzer & Schwieger 2011). In order to describe the quality of the GPS baseline, in this paper the term quality The results of the measurements in November 2011 and 2012 are shown here as examples.is first of all restricted to the "correctness", "accuracy" and "reliability".

Each GNSS receiver needs some time to fix the ambiguity. The longer the observation time is, the better should be the result. For a real-time or near real-time system, it is important to know in which time interval a reliable result can be delivered. Therefore, a time interval of one hour was first evaluated and then several short time intervals of 10, 15, 20 and 30 minutes were evaluated.
The percentage of fixed ambiguity of some time intervals is too low, so that they are assigned as float solution in Wa1. The parameter "reliability" is defined as percentage of the time intervals with fixed solutions of total results.
The measured baselines (from the measurements) and given baselines (from the given coordinates) will be compared, their differences of UTM coordinates are calculated. The mean values and standard deviations of the differences for variable time periods (10, 15, 20, 30 minutes) can be calculated. Only the time intervals with fixed solutions are considered for calculating the mean values and standard deviations.

The mean values of the differences between the given and measured baseline can be defined as "correctness". The standard deviations which describe the repeatability of the measurements can be defined as "accuracy" of the measurements. For monitoring, repeatability or accuracy of the measurements are the most important and deciding parameters. For this reason, mainly the standard deviations will be discussed in this paper.

As not all antennas are calibrated or calibrated without shielding, all the baselines are processed first without antenna correction. If two stations of the baseline have the same antennas with identical orientations, the antenna correction should not have influence on the results, assumed that the same type of antenna has the same phase center offsets and -variations. The elevation angle is set at 10°.

3.3 Test Results

3.3.1 Original Results

Table 2: Results of the baseline P6-P7 (session 1-session 3)

Session No.	**Time Interval**	**Mean [mm]**			**Standard Deviation [mm]**			**Reliability**
		m□dN	**m□dE**	**m□dh**	**s□dN**	**s□dE**	**s□dh**	
Session 1 (U-BLOX)	**10min**	2.8	-3.0	13.3	0.8	2.1	4.7	100.00%
	15min	2.8	-3.1	13.3	0.7	2.3	4.9	100.00%
	20min	2.8	-2.9	13.4	0.5	2.2	3.8	100.00%
	30min	2.7	-2.0	13.4	0.2	1.1	3.7	100.00%
	60min	2.9	-2.3	14.7	-	-	-	100.00%
Session 2 (Vimcom)	**10min**	3.4	-7.4	7.8	0.8	0.8	1.0	100.00%
	15min	3.4	-7.4	7.7	0.5	0.6	0.5	100.00%
	20min	3.4	-7.4	7.8	0.7	0.9	0.5	100.00%
	30min	3.4	-7.4	7.8	0.1	0.5	0.4	100.00%
	60min	3.4	-7.4	7.7	-	-	-	100.00%
Session 3 (Trimble)	**10min**	2.8	-5.8	10.9	0.6	0.4	1.2	100.00%
	15min	2.8	-5.8	11.0	0.6	0.2	0.9	100.00%
	20min	2.8	-5.8	10.9	0.3	0.1	0.7	100.00%
	30min	2.8	-5.8	11.0	0.1	0.1	1.1	100.00%
	60min	2.7	-5.8	10.8	-	-	-	100.00%

Table 2 shows the results of sessions 1 to 3 for baseline P6-P7. The 100% reliability shows that all time intervals with 10 minutes or more have fixed solutions. The small standard deviations (in horizontal position less than 2.5 mm and in height less than 5 mm) show that the results are very stable. The main reason for this is that the two stations P6 and P7 are both in shadowing free environment. The mean values of the differences between measured and given baselines are less than 1 cm in horizontal position and less than 1.5 cm in height.

The standard deviations of session 2 (with Vimcom antenna) and session 3 (with Trimble antenna) are similar. They are all in the sub-mm range in horizontal position and almost less than 1 mm in height. The standard deviations of the u-blox antenna here are worse than with the other two antennas, especially in east direction (less than 3 mm) and height (less than 5 mm). The standard deviations are not getting better with longer observation time.

Table 3 shows the results of the baseline P6-P8 of sessions 4 to 6. Firstly, we can see the session 5 with Vimcom antennas shows very bad results. The differences between the measured and given baselines are several decimeters in all coordinate components, although float solutions are not considered here, even the one hour measurement has a float solution. The reason for this is that P8 is near the forest and the Vimcom antenna at P8 received signals from only 3 to 4 satellites on average. Although some time intervals have fixed solutions, their quality indicator in Wa1 is either "low" or "medium", that means the result of session 5 with Vimcom antenna is not reliable and cannot be accepted. However, there are actually 7 to 8 satellites visible during the session 5. Compared to session 2 we can see that it is difficult for the Vimcom antenna to receive satellite signals in shadowing environment. As the results of session 5 are unreliable, they will not be analyzed further in detail.

Table 3: Results of the Baseline P6-P8 (Session 4-Session 6)

Session	**Time**	**Mean [mm]**			**Standard Deviation [mm]**			**Reliability**
No.	**Interval**	**m□dN**	**m□dE**	**m□dh**	**s□dN**	**s□dE**	**s□dh**	
Session 4 (U-BLOX)	**10min**	-0.7	-6.0	-3.3	1.6	2.8	10.4	83.3%
	15min	-0.9	-6.6	-5.3	2.2	2.6	8.1	75.0%
	20min	-1.2	-5.7	-2.7	1.5	1.8	8.3	100.0%
	30min	-1.4	-6.1	-3.6	2.4	1.2	10.0	100.0%
	60min	-1.1	-5.6	-2.4	-	-	-	100.0%
Session 5 (Vimcom)	**10min**	533.7	-314.4	-294.1	590.3	322.5	422.4	66.7%
	15min	457.5	-281.3	-325.7	559.1	305.7	436.3	100.0%
	20min	454.2	-214.5	-319.5	644.8	341.3	447.5	100.0%
	30min	399.9	-108.9	-210.1	-	-	-	50.0%
	60min	-	-	-	-	-	-	0.0%
Session 6 (Trimble)	**10min**	-1.2	-5.7	1.1	0.8	2.5	5.3	83.3%
	15min	-1.1	-5.6	1.4	0.5	1.9	4.5	100.0%
	20min	-1.1	-5.7	1.3	0.5	2.0	4.0	100.0%
	30min	-1.1	-5.6	1.4	0.1	1.8	4.7	100.0%
	60min	-1.0	-5.0	1.7	-	-	-	100.00%

Not all the time intervals of sessions 4 and 6 have reached 100% reliability due to the shadowing at P8. The time intervals with 10 and 15 minutes have partially float solutions. The standard deviations of sessions 4 and 6 are greater than the ones of sessions 1 and 3, especially in height. The mean values of the differences between measured and given baselines are below 1 cm in horizontal position and less than 6 mm in height.

Generally, the Trimble antenna with choke ring (session 6) shows a better result than the u-blox antenna with ground plate (session 4). On the one hand, all time intervals with more than 10 minutes with Trimble antenna have reached the fixed solutions. On the other hand, the standard deviations in north and height of the Trimble antenna are only half as large as the ones of the u-blox antenna. The standard deviations of the Trimble antenna are in sub-mm range in north, up to 3 mm in east direction and up to 6 mm in height. The standard deviations of the u-blox antennas are up to 3 mm in horizontal position and up to 11 mm in height.

3.3.2 Results with extra data handlings

The results could be improved, if extra data handlings like increasing the elevation angle and elimination of satellites are applied. Therefore, the results of the measurements will be analyzed using extra data handlings.

- *Increasing the elevation angle*

The elevation angle was increased to 15° for sessions 1 to 3. However, the final results do not change considerably. Since the two stations P6 and P7 are both in shadowing-free environment and 8 to 10 satellites are available during the measurement, the satellites with low elevation angle do not have a strong influence on the results.
The elevation angle was also increased to 15° for sessions 4 and 6. In this case, the final results change more significantly than those in sessions 1 to 3. Some time intervals change from float solution to fixed solution. Unfortunately, there are also time intervals that change from fixed solution to float solution. As the P8 stays in shadowing environment, there are fewer satellites for the evaluation. In session 4 there are about 10 satellites available, however some satellites have low elevation angles (between 10° and 15°). Other satellites move through obstructions (trees) but have high elevation angles. If the elevation angles are increased to 15°, the satellites that move through obstructions but have high elevation angles will have disturbed signals due to multipath effects. In this case, the ambiguities can not be fixed. In session 6 there are only about 5 to 6 satellites available. If the elevation angle is set to 15° and therefore the satellites with low elevation angle are excluded (between 10° and 15°), it might happen that too few satellites are available for the calculation of the ambiguities, so that the results have float solutions. At the end, an elevation angle of 10° was set for all data processing.

- *Elimination of satellites*

Furthermore, with the help of the log file of Wa1 and the satellite visibility chart of Leica Geo Office (LGO, Leica 2013), the satellites lead into float solutions can be found and eliminated. No satellites are eliminated for the time intervals that already have fixed solutions, although it would lead to better results (Wang 2013). Therefore, only the results of the time intervals would be changed, which had been marked in table 3. Here, the results are presented in a simplified table (table 4). All time intervals have fixed solutions at the end, and thus the reliability of all the time intervals is 100%.

Table 4: Improved results of the baseline P6-P8 by elimination of satellites

Session No.	**Time Interval**	**Mean [mm]**			**Standard Deviation [mm]**			**Reliability**
		m□dN	**m□dE**	**m□dh**	**s□dN**	**s□dE**	**s□dh**	
Session 4	**10min**	-0.8	-5.3	-2.0	1.5	3.0	9.9	100.0%
	15min	-1.1	-5.7	-2.5	1.9	2.7	8.7	100.0%
Session 6	**10min**	-0.9	-4.8	1.8	1.0	3.2	5.1	100.0%

Originally, there was one 10- and one 15-minute time interval that had float solutions in session 4 (see table 3). The satellites PRN G32 and PRN G28 were eliminated with the help of log file of Wa1, because most unfixed ambiguities are caused by these two satellites. Unfortunately, after the elimination of these two satellites, the result is still a float solution.

Using the satellite visibility chart of LGO, the satellite PRN G01 is eliminated, because this satellite moved through obstruction during the measurements (see figure 5, left).

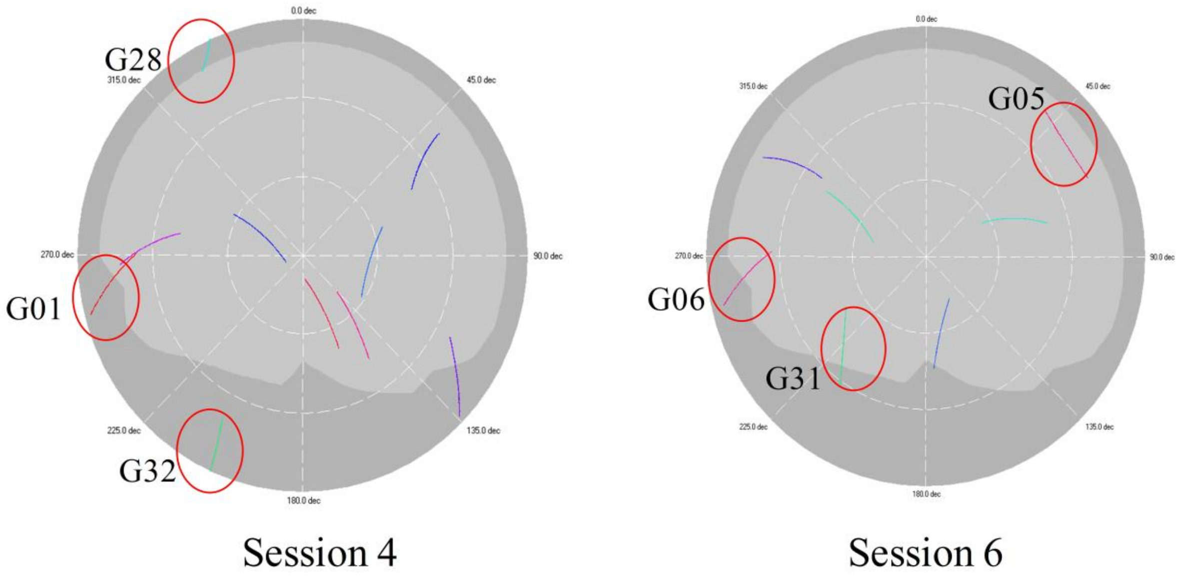

Figure 5: Visibility of Satellites (LGO 2013)

In session 6, there was originally only one 10-minute time interval with "float" solution. With the help of log file of Wa1, the satellite PRN G05 with low elevation angles was eliminated. After that, the time interval has the fixed solution. The satellite visibility chart of LGO shows that the satellites PRN G06 and PRN G31 move partially through the shadowing area (figure 5, right), but their influences did not lead to float solution. For this reason, only the satellite PRN G05 was excluded from the data processing for session 6.

When table 3 is compared with table 4, we can find out that the standard deviations are increased in height but partially worse in horizontal position. This shows that the reliability increases after deleting the unreliable satellites, but the accuracy was not improved significantly. Further detailed data handling can be done until the standard deviation minimizes, but it must be done manually and iteratively. This is complicated and not suitable for near real-time automatic data processing.

It should be noticed that the results are really bad and not reliable, if they have the quality indicator "medium" in the Wa1. In order to minimize "false alarms" in monitoring, time intervals having the float solution and the quality indicator "medium" should not be used and excluded automatically. The problem is that there will be too many results in shadowing environment which cannot be used and thus there will be many data gaps in a continuous series of observations. This means the reliability will be low. As shown before, satellites with disturbed signal and large elevation angles (more than 40°) have great influence on the results. A possible solution for increasing the accuracy and reliability simultaneously is to find out the satellites with disturbed signals automatically and eliminate them.

- *Applying the antenna corrections*

Individual calibration was carried out for each Trimble antenna choke ring by University of Bonn, Institute of Geodesy and Geoinformation, making use of absolute anechoic chamber calibration (Zeimetz & Kuhlmann 2008). This means each antenna has its own calibration data. The baselines were processed with the individual antenna corrections (antenna phase centers offsets and variations). The differences in the results (with minus without calibration data) are shown in table 5. If we compare the results of the session 3 and 6 that were measured with Trimble antennas, we can see that the mean values change between -0.5 mm and 0.3 mm in horizontal position and between -0.7 mm and 0.2 mm in height. The values do not change significantly, since the antenna corrections of each antenna are very similar. The standard deviations change between -0.1 mm and 0.2 mm in horizontal position and between 0.1 mm and 0.5 mm in height. The change of mean value is bigger than the standard deviation. Furthermore, the change for the baseline P6-P8 is bigger than that of baseline P6-P7. It may be because of the shadowing environment of P8. Generally, the standard deviations become better particularly in height. The individual antenna calibration is expensive and costs much more than the antenna itself. The question arises whether type calibration for those low-cost antennas is enough or whether single calibration is necessary.

As another try, the baselines were then processed with only one antenna calibration data (simulation of antenna type calibration). The results are exactly the same as the results without calibration data. The reason is that two stations of the baseline have the same antennas with identical orientations, the effects of antenna corrections are identical if the baselines are very short. However, the antenna type calibrations could be necessary for long baselines.

Table 5: Difference in results with and without calibration correction of the Trimble antennas

Session No.	**Time Interval**	**Mean [mm]**			**Standard Deviation [mm]**			**Reliability**
		m□dN	**m□dE**	**m□dh**	**s□dN**	**s□dE**	**s□dh**	
Session 3 (Trimble)	**10min**	0	0.3	-0.1	0	-0.1	0.1	100.0%
	15min	0	0.3	0	0	0	0.1	100.0%
	20min	0	0.3	-0.2	0	0	0.1	100.0%
	30min	0	0.3	-0.1	0	0	0.2	100.0%
	60min	0	0.3	-0.1	-	-	-	100.0%
Session 6 (Trimble)	**10min**	0.2	-0.4	-0.7	0	0.1	0.1	100.0%
	15min	0.2	-0.4	-0.6	0	0.2	0.2	100.0%
	20min	0.2	-0.5	-0.6	0	0.2	0.4	100.0%
	30min	0.2	-0.4	-0.6	0	0	0.5	100.0%
	60min	0.2	-0.3	-0.6	-	-	-	100.0%

3.4 Summary and Discussion

From the test results we can find out that, depending on shadowing conditions, an observation time of 10 to 20 minutes is necessary to solve the ambiguities steadily. An observation time of more than 20 minutes, does not lead to significant changes in the standard deviations. Therefore, a solution with 20-minutes observation time is recommended for a near real-time evaluation. The results are, as expected, very sensitive to shadowing. An elevation angle of 10° in shadowing environment is necessary; otherwise there are not enough satellites available for the calculation.

Comparing the three different antennas with shielding with each other, we can find out that the Vimcom antenna has an excellent performance in the shadowing-free environment (the standard deviations of the all the coordinate components are less than 1 mm). However, it is not suitable for a shadowing environment. This indicates that the correct selection of low-cost antennas is very important. If float solutions are not considered, the u-blox antennas with ground plate have standard deviations of up to 3 mm in horizontal position and 5 mm in height in the shadowing-free environment, and up to 3 mm in horizontal position and 6 mm in height in the shadowing environment. The Trimble antenna with choke ring has the best performance on average. It reaches accuracies in the sub-mm range in horizontal position and almost less than 1 mm standard deviation in height in the shadowing free environment, and up to 3 mm in horizontal position and 6 mm in height in the shadowing environment. However, it is unclear whether this is just a coincidence that the Trimble choke ring antenna has the best performance, as the measurements were carried out at different times. Furthermore, it is unclear whether the best performance due to the Trimble antenna or the choke ring, or due to the combination of both components. Since the production of a choke ring is expensive, it should be proved that the choke ring is able to reduce the multi-path effect better than the ground plate. To answer these questions, further measurements shall be carried out, in which the two antennas with identical shielding and the same antennas with different shielding are set up close to each other and tested simultaneously.
Individual antenna calibrations are done for the Trimble antenna with choke ring. The individual antenna calibration can lead to improvements in the results, but not significantly for the short baselines. The type calibration does not bring improvement for the short baselines, if the baselines are measured with same type of antennas (here the Trimble antenna) that have the same orientation during the measurements.

4. CONCLUSION AND OUTLOOK

In this paper an automatic monitoring system using u-blox GPS receivers which was developed at the IIGS was presented. Our focus is on the evaluation of quality of this GPS monitoring system. The three different antennas with different shields are tested under different shadowing conditions. Generally, accuracies from sub-mm up to a few mm in horizontal position and up to 6 mm in height can be achieved by using the Trimble antenna with choke ring. Compared to the target values the coordinate differences are in the millimeter range in horizontal position and up to 15 mm in height.
In the future, further research should be carried out to obtain better accuracy. The mean values of the coordinate differences between the measured and given baselines are a few centimeters. If the coordinate differences remain almost constant with the time, they will be irrelevant for monitoring.
As shown, low-cost GPS receivers can already achieve good accuracy in horizontal position, so they provide a cost-effective way for GPS monitoring. However, the accuracy in height should still be improved, especially for the stations in shadowing environment.
Only when accuracy of all coordinate components can be safely achieved in the range of a few mm, the system can be applied for monitoring. The accuracy and reliability of the results should be improved, particularly in shadowing environment.

The results shown are calculated in post-processing. The system can already run automatically from the data communication, data collection to data analysis (Zhang et al. 2012) in real-time. This means that the results can be available in near real-time (e.g. every 20 minutes).
In the future, the results (information on baselines), the status of the power supply and metrological data (additional information to support the monitoring measurements) should be available for the user in near real-time via Internet.

ACKNOWLEDGEMENT

The authors thank Ms. Alexandra Roman, Ms. Qian Jiang and Ms. Wang Jinyue for preparing, realizing and partly analyzing the measurements within their theses at the IIGS, University of Stuttgart.

The Wa1 software provider, Prof. Dr. Wanninger from Geodetic Institute of Technical University of Dresden is also highly appreciated. The authors thank also the Institute of Geodesy and Geoinformation, University of Bonn for the antenna calibrations.

Finally, the authors thank Mr. Mathias Stange and Mr. Martin Knihs of the IIGS for their help with the practical measurement and the construction of the ground plate and the choke ring.

REFERENCES

Bill, R. (2011): Geosensornetzwerke als Komponente im Geomonitoring. In Busch, Niemeier, Sörgel (Ed.): GeoMonitoring Tagung 2011 – Ein Paradigmenwechsel zur Beherrschung von Georisiken. TU Clausthal. S. 115 – 127. ISBN 3-938924-11-X.

Cabtronix (2013): http://www.cabtronix.ch/. Last accessed: February 2013.

Filippov, V., Tatarnicov, D., Ashjaee, J., Astakhov, A., Sutiagin, I. (1998): The First Dual-Depth Dual-Frequency Choke Ring, Proceedings of the 11th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 1998), September 15 - 18, 1998. Nashville, TN.

Glabsch, J., Heunecke, O., Pink, S., Schubäck, S. (2010): Nutzung von Low-Cost GNSS Empfängern für ingenieurgeodätische Überwachungsaufgaben. GNSS 2010 – Vermessung und Navigation im 21. Jahrhundert. DVW-Schriftenreihe, Band 63. S. 113-129. Wißner-Verlag, Augsburg.

Glabsch, J., Heunecke, O. Schuhbäck, S. (2009): Monitoring of the Hornbergl landslide using recently developed low cost GNSS sensor network. Journal of Applied Geodesy, de Gruyter Verlag, Heft 4, 2009.

Hartinger, H. (2001): Development of a Continuous Deformation Monitoring System using GPS. Shaker Verlag, Aachen 2001.

Hebel, H., Knsope, S., Busch, W. (2011): Terrestrischer Radar-Scanner (TRS) – neuartiges Instrument für die Böschungsüberwachung. In Busch, Niemeier, Sörgel (Ed.): GeoMonitoring Tagung 2011 – Ein Paradigmenwechsel zur Beherrschung von Georisiken. TU Clausthal. S. 171 – 178. ISBN 3-938924-11-X.

Holst, C., Kuhlmann, H. (2011): Bestimmung der elevationsabhängigen Deformation des Hauptreflektors des 100m-Radioteleskops Effelsberg mit Hilfe von Laserscannermessungen. Terrestrisches Laserscanning – TLS 2011 mit TLS-

Challenge. DVW-Schriftenreihe, Band 66. S. 161-180. Wißner-Verlag, Augsburg.
Kälber, S., Jäger, R., Schwäble, R. (2000): A GPS based online control and alarm system. GPS Solutions, Vol. 3, Issue 2, 2000.
Lanzendörfer, H. (2007): Zum Einsatz von Low-Cost GPS-Empfängern für kontinuierliches Monitoring eines Rutschhanges. Master Theses, TU Graz, May, 2007.
Leica (2013): http://www.leica-geosystems.de/de/Leica-Geo-Office_4611.htm. Last accessed: February 2013.
Limpach, P. (2009): Rock glacier monitoring with low-cost GPS: Case study at Dirru glacier, Mattertal. AHORN 2009, Zürich.
Schweitzer, J., Schwieger, V. (2011): Modeling of Quality for Engineering Geodesy Processes in Civil Engineering. In: Journal of Applied Geodesy, Vol. 5, Heft 1/2011, S. 13–22, 2011.
Schwieger, V, Gläser, A. (2005)**:** Possibilities of Low Cost GPS Technology for Precise Geodetic Applications. Proceedings on FIG Working Week 2005, Kairo, Ägypten, 16.-21.04. 2005.
Schwieger, V. (2007): High-Sensitivity GNSS – the Low-Cost Future of GPS?. Proceedings on FIG Working Week 2007, Hongkong SAR, 13.-17.05. 2007
Schwieger, V. (2008): High-Sensitivity GPS - an availability, reliability and accuracy test. Proceedings on FIG Working Week, Stockholm, Schweden, 14.-19.06.2008.
Schwieger, V. (2009): Accurate High-Sensitivity GPS for Short Baselines. FIG Working Week, Eilat, Israel, 03.-08.05.2009.
Takasu, T., Yasuda, A. (2008): Evaluation of RTK-GPS Leistungsfähigkeit with Low-cost Single-frequency GPS Receivers. Funai Laboratory of Satellite Navigation, Tokyo University of Marine Science and Technology. Tokio, Japan, 2008.
TEQC (2013): http://facility.unavco.org/software/teqc/teqc.html. Last accessed: February 2013.
Ubéda, S. (2008): Ad Hoc Networks: Principles and Routing. In H. Labiod (Hrsg.): Wireless Ad Hoc and Sensor Networks, Wiley-ISTE, London, UK.
UBLOX (2013): http://www.u-blox.com/. Last accessed: February 2013.
Vimcom(2013): http://www.vimcom.ch/. Last accessed: February 2013.
Wang, J. (2013): Neuvermessung des Pfeilernetzes Vaihingen und Vergleich mit Low Cost GPS-Ergebnissen. Bachelor thesis, Institute of Engineering Geodesy, University of Stuttgart, January 2013. (unpublished).
Wa1 (2013): http://www.wasoft.de/wa1/index.html. Last accessed: February 2013.
Wa1 Manuel (2010): User's Guide Wa1 v2.3, May 2010. (unpublished)
Zeimetz, P.; Kuhlmann, H. (2008): On the accuracy of absolute GNSS antenna calibration and the conception of a new Anechoic Chamber, FIG Working Week 2008, 14.-19.06, Stockholm, Sweden.
Zhang, L., Stange, M., Schwieger, V. (2012): Automatic Low-Cost GPS Monitoring System Using WLAN Communication. FIG Working Week 2012, 6.-10.05.2012, Rom, Italy.

BIOGRAPHICAL NOTES

Dipl.-Ing. **Li Zhang**

2002 – 2003	Studies of Geodesy in China (University of Wuhan)
2004 – 2009	Studies of Geodesy and Geoinformation in Germany (University of Stuttgart)
2009	Research Associate at Institute of Engineering Geodesy, University of Stuttgart

Prof. Dr.-Ing. habil. **Volker Schwieger**

1983 – 1989	Studies of Geodesy in Hannover
1989	Dipl.-Ing. Geodesy (University of Hannover)
1998	Dr.-Ing. Geodesy (University of Hannover)
2004	Habilitation (University of Stuttgart)
2010	Professor and Head of Institute of Engineering Geodesy, University of Stuttgart
2012	Chair Elect FIG of Commission 5 "Positioning and Measurement"

CONTACTS

Dipl.-Ing. Li Zhang/ Prof. Dr.-Ing. habil. Volker Schwieger
University of Stuttgart
Institute of Engineering Geodesy
Geschwister-Scholl-Str. 24 D
D-70174 Stuttgart
GERMANY
Tel. + 49/711-685-84049 | -84040
Fax + 49/711-685-84044
Email: li.zhang@ingeo.uni-stuttgart.de/volker.schwieger@ingeo.uni-stuttgart.de
Web site: http://www.uni-stuttgart.de/ingeo/