AUTOMATIC LOW-COST GPS MONITORING SYSTEM USING WLAN COMMUNICATION

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Key words: low-cost GPS, monitoring, wireless mesh network

SUMMARY

Monitoring is one of the main tasks in engineering geodesy. GPS or GNSS receivers are used frequently to acquire time-variant positions and therefore the deformations. The geodetic dual frequency receivers are quite expensive. In the recent years, low-cost single frequency receivers have been proved that they reach almost the same accuracy as geodetic ones.

Currently, the Institute of Engineering Geodesy (IIGS) is developing an automatic low-cost GPS monitoring system. This system includes the newest generation of u-blox LEA-6T GPS receivers. Its power supply is via solar panels and batteries, and its automatic communication is realized by wireless mesh network (WMN). The test system consists of two rovers and a central station as reference site and computation center. Currently the processing of the GPS data can be realized in near real time (e.g. within 20 min).

In this article, an overview of the existing GPS monitoring systems will be given and the first testing results of this system will be presented. These testing measurements had been experimented in the Stuttgart region (Germany), which were comprised of different baseline lengths (up to 1 km) with different shadowing conditions. Furthermore, the line-of-sight transmission between the wireless-network-stations was also investigated. As a result, the obtained accuracy almost meets the requirements of geodetic applications.

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1. INTROUDUCTION

Since the 1970's, the Global Navigation Satellite System (GNSS) has been developed and since then it was used for geodetic applications. At the beginning, there is only the American Global Positioning System (GPS). But now the Russian Glonass is almost completely operable, meanwhile, the European Galileo and Chinese Compass system are still in research and development. In the near future, we will have at least 4 different GNSS which will include more than 100 satellites (Kleusberg 2010).

GNSS was not only used for the absolute positioning, it was also used quite early for geodetic monitoring. The reason is that on the one hand many systematic errors can be reduced in a relative mode, on the other hand, if the carrier phase measurements are available, the accuracy could reach several millimeters. Monitoring is one of the main tasks in engineering geodesy. The automation and the continuity is the current trend of monitoring. The traditional monitoring measurements were carried out at certain time intervals (e.g. once per month or per year), but now the information of the monitored objects should be available continuously, which means the instruments should be set permanently on the monitored objects and thereby the investment costs for these are high. Beside the tachymeter, only GNSS receivers can measure the 3-dimensional positions automatically and continuously.

Bäumker and Fitzen (1996) gathered the first experiences. After that, a number of developments of GPS automatic monitoring systems were carried out. For example, the GOCA system was developed, which includes measurement and evaluation of the communication and the deformation analysis (Kälber, et al., 2000). Besides, a GPS monitoring system was developed at the Graz University of Technology (Hartinger, 2001).

However, the investment costs are very high, if GNSS receivers are applied to monitor a huge object, e.g. bridges, dams and landslides etc. A great number of receivers are necessary to cover a wide area, and the high-end geodetic GNSS receivers are quite expensive (some of them cost more than 20 000€), so the total cost will be too high.

In recent years, more and more researches are working on low-cost GNSS receivers to yield a more economical solution for geodetic applications. Particularly, the Bundeswehr University in Munich has developed a system based on Novatel receivers (about 1000€), which was developed for landslide monitoring in near-real-time (Glabsch et al 2009). Some pre-research works (Schwieger & Gläser 2005, Schwieger 2009) have also been carried out in the Institute of Engineering Geodesy in Stuttgart (IIGS). The testing results showed that low-cost GNSS receivers, which cost less definitely than 100 € (e.g. u-blox receiver), can achieve almost the same level of accuracy as the high-quality GNSS receivers. In this paper, the first results of an automatic low-cost GPS monitoring system at IIGS will be presented.

2. SYSTEM ARCHITECTURE AND COMPONENETS

An automatic low-cost GPS monitoring system has been developed and tested at IIGS. Figure 1 shows the overview of this system. The test system consists of three stations: a master (central station) and two clients. The clients are setup in a monitoring area, while the master is setup in a stable area. The master collects continuously raw data from the two clients via WLAN in real-time. The data of all the stations are transferred to the computer at the central station. The data processing is executed there.

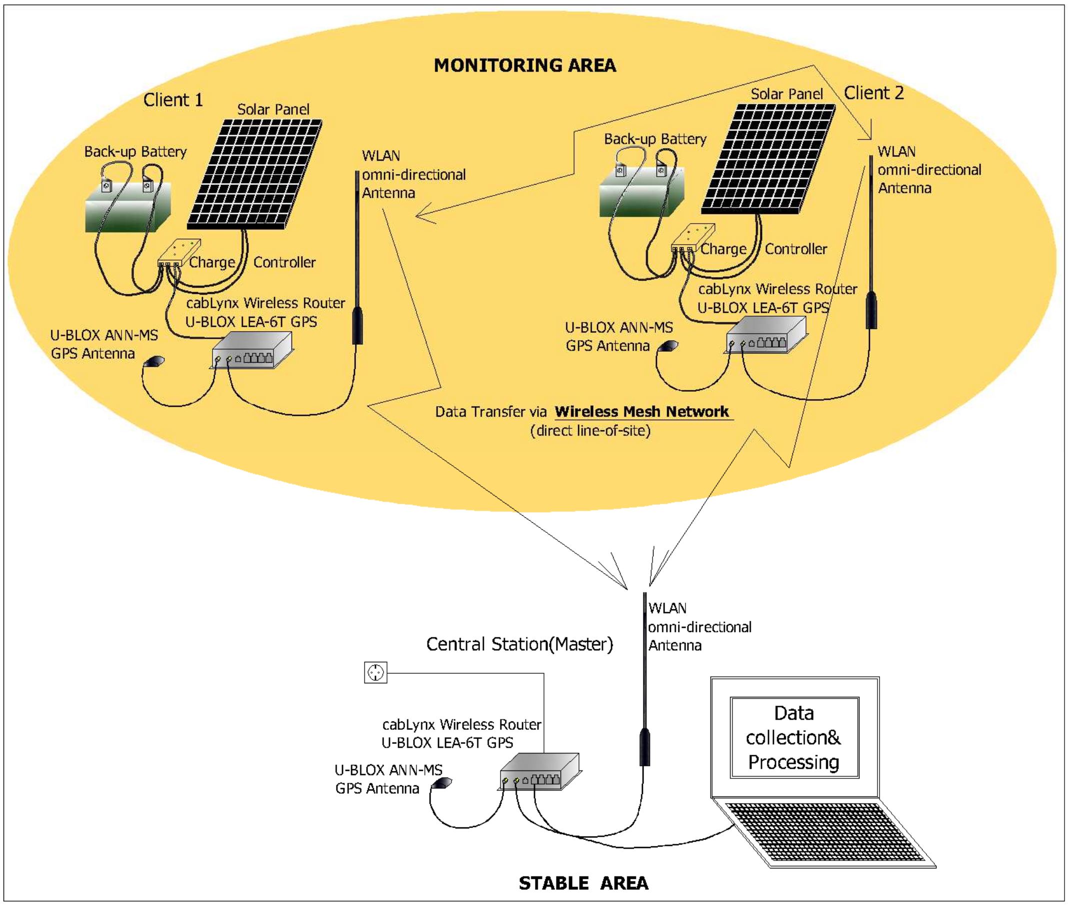

Figure 1: System architecture (Roman 2011)

Figure 2 shows the components of one autonomous station. Each station has one CabLynx router (Cabtronix 2012) which is the wireless router and has been configured for realizing the data transfer via wireless mesh network (WMN, compare section 3.1). With WMN, data of the clients can automatically find their own path to reach the master. Basically, the router can also realize data transmission via GPRS or UMTS.

Since the network is self-organized and the data transmission direction is variant and previously unknown, an omni-directional antenna (VIMCOM 2012) is necessary here. Additionally, to make sure that this system can run continuously and autonomously, the power supply of each station is provided with one solar panel, one charge controller and one back up battery. The most important parts of the router are the u-blox (UBLOX 2012) GPS antenna ANN-MS and the latest-generation u-blox GPS receiver LEA-6T. The GPS antenna is shielded with a ground plate to reduce undesirable multipath effects (compare figure 2 left up). By using the LEA-6T receiver is possible to output the GPS raw data in binary format (UBX-format). These basics are preconditions to reach results within accuracy in cm level.

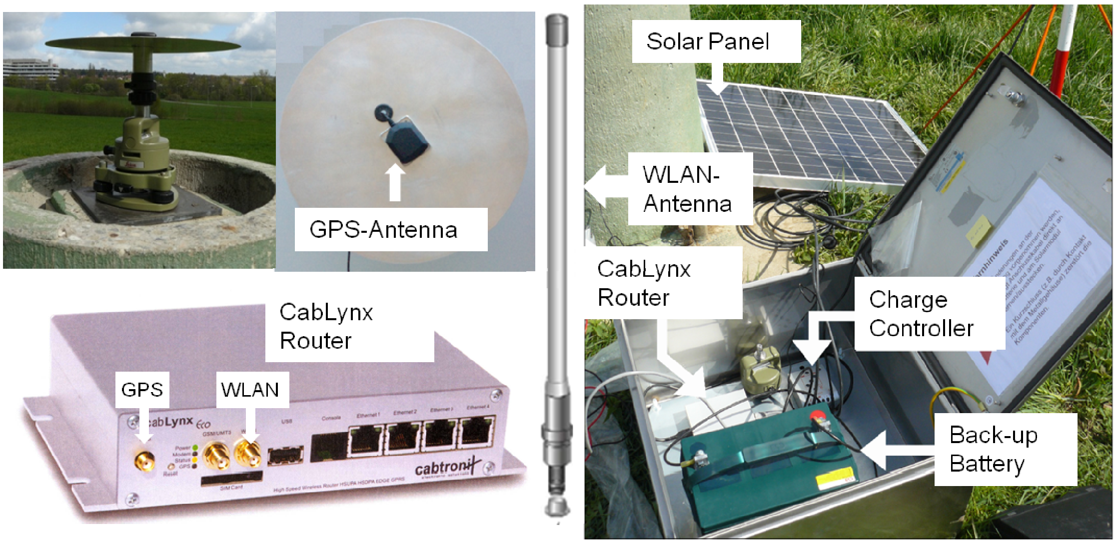

Figure 2: System components of one autonomous station (Roman 2011, Schwieger & Zhang 2012)

3. AUTOMATIC COMMUNICATION, DATA COLLECTION AND PROCESSING

3.1 Automatic Communication via Wireless Mesh Network (WMN)

As noted in chapter 2, the data transmission is realized via WMN. In the classical network topology, the master plays a role as the access point and the clients can just transfer the data to the master (center station in section 2). However, in the mesh network, each client/node can act as an access point. The data transmission between the clients (nodes) is also possible (compare figure 3). The data from one client can be transferred via the other clients in the mesh net until it reaches the master. If one client could not operate, the remaining clients could still communicate with each other. That means the mesh network, which is self-organized and self-healed, provides a higher reliability and redundancy.

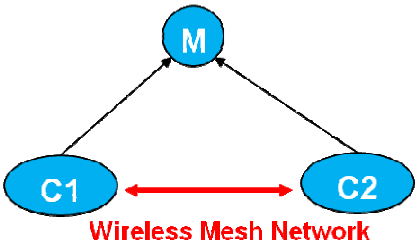

Figure 3: Wireless mesh network

In addition, the master is set as a DHCP (Dynamic Host Configuration Protocol) server. So the IP addresses of the clients are given by the master automatically and dynamically.

3.2 Automatic Data Collection and Processing

The routers have been configured at IIGS, so that the WMN and the DHCP can be realized. After starting the system, each client gets automatically an IP address from the master. Then the WMN can be built among the routers. And the clients transfer data to the master that is connected to a computer for data processing. Since all the routers (clients and master) transfer data to the computer through the same port, the belonging of the data should be identified previously. A C-program has been written for this purpose, the raw data are identified by the IP address from which they were sent and stored directly in different files in the computer (compare figure 4).

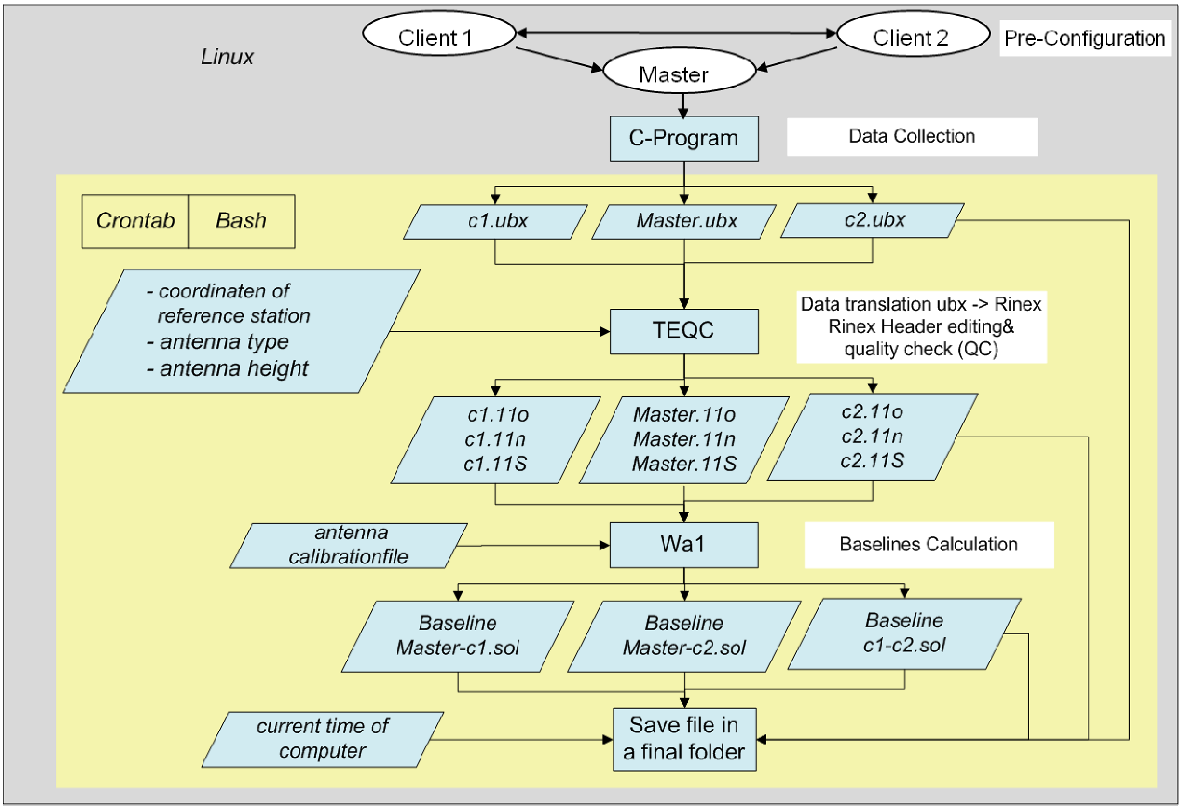

Figure 4: Flow diagram of automatic data collection and processing

The raw data are stored in proprietary binary format (UBX format). But they should be transformed to standard exchange format (RINEX format) for further processing. This step can be realized with the powerful free software TEQC (TEQC 2012) developed by UNAVCO (UNAVCO 2012). Moreover, the RINEX data header should include name, type and heights of antennas as well as coordinates of the reference station. This can also be realized by TEQC. In order to analyze the data more in detail, the quality check module of TEQC has also to be executed, so that the reasons for bad results may be found.

The last task is the calculation of the baseline or coordinates of the rover stations related to the reference station. That can be solved by the software Wa1 (Wa1 2012), which has been developed by Prof.-Ing. Lambert Wanninger from Technical University of Dresden.

The whole system is running under the Linux system. Many free available programs can be used. To process the data automatically in near-real-time, a bash program has been written. This bash program is run by "crontab" (Crontab 2012) periodically (e.g. each 20 or 30 min). Then the original raw data and the results etc. of these time intervals are saved in different folders after each time sequence (compare figure 4).

4. FIRST RESULTS

4.1 Test of the WLAN Communication

4.1.1 Test of the WLAN Range

The range of the WLAN communication of the system is a relevant factor for the network planning. For a monitored object, the number of the measurement stations should be as small as possible but no less than necessary.

The WLAN range depends on many transmitter parameters (such as the frequency, power, antenna parameters), receiver parameters (such as its sensitivity, the antenna parameters) and some environmental factors. The theoretical WLAN range for this system can be 5.7 km with a line-of-sight. A Test has been carried out in Neuhausen (close to Stuttgart airport) to measure the range in reality. This area is a flat area with a few hilly terrains, trees and plants. Different distances starting from 1 km has been tested. The longest distance that can be tested in this area is about 2.6 km. In other words, the data can be transmitted for this distance but there was some data loss because of few obstructions. (Roman 2011)

However, for some distances shorter than 2.6 km, no data communication can be detected, because some hilly terrain and vegetation break the line-of-sight transmission between the antennas. Obviously the line-of-sight is very important for the WLAN communication, because all the radio communication have the so-called Fresnel zone, which can be defined as a long ellipsoid that stretches between two radio antennas (see Figure 5). There are many possible Fresnel zones, but normally the antennas are located at the first Fresnel zone. (Roman 2011)

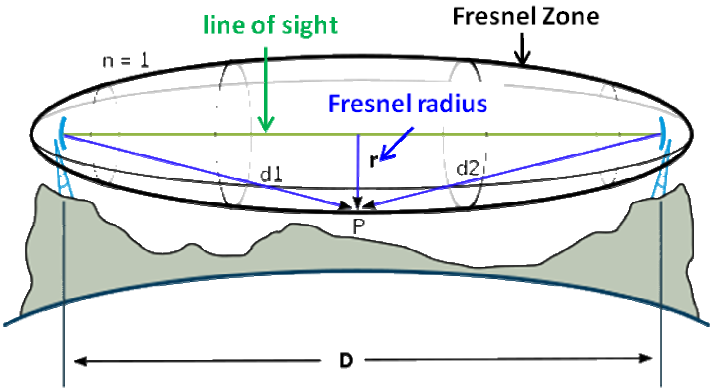

Figure 5: Fresnel zone (after Wiki 2012)

The radius of the first Fresnel zone can be calculated as:

$$r = 17.31 \cdot \sqrt{n \frac{d_1 \cdot d_2}{f \cdot D}}$$

Where:

r = Fresnel radius
n = zone to calculate (n=1)
d_1 and d_2 = distances from the obstacles to the link end points in meters
D = total distance
f = frequency in MHz

If this area had some obstructions, such as trees or buildings, the signal would be diminished or blocked. Theoretically, about at least 60% of the first Fresnel zone should be kept free from the obstructions, in order to have a good signal quality (Vias 2012). The maximum of Fresnel radius is at the center ($d_1 = d_2 = 0.5 \cdot D$). For D =1 km, the maximum Fresnel radius for WLAN (f=2.4 GHz) is about 5.6 meters with the line of sight.

A test for the WLAN range and Fresnel zone was carried out in Stuttgart Vaihingen within the master thesis Roman (2011). As shown in figure 7, there are some trees between master and client 2, but almost all the trees are out of the Fresnel zone, so the data can be sent from the client 2 to master. But the data transmission was blocked between the client 1 and client 2. From a rough graphic estimate shows that about 30% to 40% of the Fresnel zone are covered with trees. In this case, digital terrain model (DTM) and digital surface model (DSM) would be helpful.

In conclusion, for planning the wireless network, not only the range of WLAN, but also its Fresnel zone should be taken into consideration. The WLAN antennas should be set up as high as possible during the measurement, in order to have less obstructions within the Fresnel zone.

4.1.2 Test of the Wireless Mesh Network (WMN)

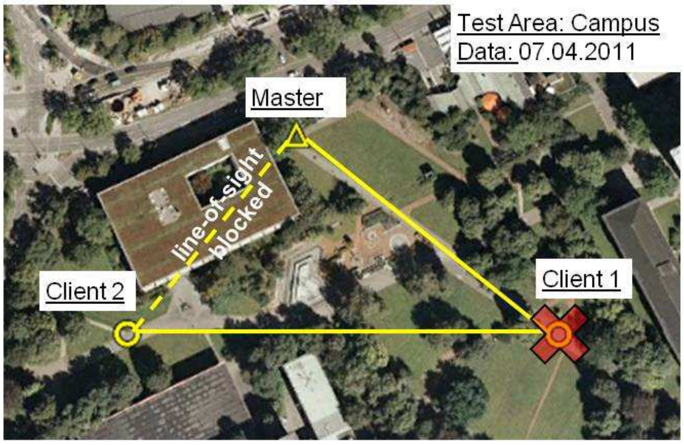

Figure 6: Test of wireless mesh network

In practice, the line-of-sight between the antennas can be completely blocked by various obstructions. So the direct data communication between the master and clients is almost impossible. As shown the figure 6: the line-of-sight between the master and client 2 was blocked by a building and trees. This was a test at the campus of the University of Stuttgart, to make sure the WMN can really work after configuring of the routers.

So after starting all the routers, all data packets could be received at master. Then client 1 was interrupted, while the master and client 2 were still running. As a result, the data from client 2 could no longer be received at the master. So evidently the data from client 2 were sent to master via client 1. That means the WMN was constructed automatically. It shows again the advantage of the mesh topology. So if there is no line-of-sight between the master and a client, some alternative ways to transfer the data to master are available. The communication of WMN is more flexible and stable.

4.2 Accuracy Analysis

4.2.1 Test Scenarios

Several Tests have taken place in April and November in Vaihingen and University campus (in Stuttgart), to test the accuracy of this system depending on observation time and base length as well as shadowing conditions. In this paper, the results of the test, which was carried out within a master thesis (Jiang 2012) in November in Vaihingen, are presented. Figure 7 shows the test scenarios.

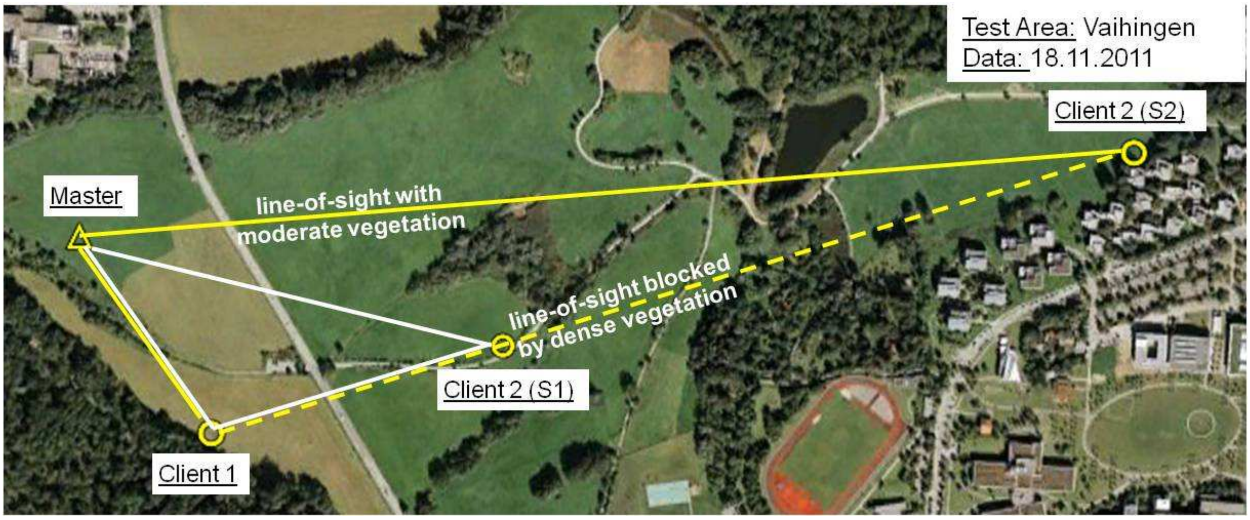

Figure 7: Test scenarios in Stuttgart Vaihingen

In this area, there are several pillars. And their coordinates in WGS 84 are known better than millimeter. Two sessions have been carried out and each of them took about one hour. Table 1 shows the pillar number of the routers and the length of baselines as well as the observation duration. As shown in table 1, the baseline varies from about 250 to 1100 meters. The positions of the master and client 1 have not changed in session 1 and session 2. Only the position of client 2 has been changed for testing a longer baseline.

Additionally, the master and client 2 in session 1 had a shadowing free environment, while client 1 in both sessions (pillar 8) and client 2 in session 2 (pillar 10) trapped in shadowing environment. One of them stayed nearby the forest (pillar 8) and the other one is located nearby buildings and trees (pillar 10).

Table 1: Pillar number, length of baselines and observation duration of the sessions

Session No.	**From**		**To**		**Distance**	**Start**	**Stop**
	Router	Pillar No.	Router	Pillar No.	**[m]**		
1	Master	6	Client 1	8	254.913	11:38	12:54
	Master	6	Client 2	7	468.638		
	Client 1	8	Client 2	7	322.313		
2	Master	6	Client 1	8	254.913	13:21	14:24
	Master	6	Client 2	10	1128.809		
	Client 1	8	Client 2	10	1024.573		

4.2.2 Accuracy Analysis Procedure and Results

For the accuracy analysis, the given and the measured values of baselines are compared. They can be calculated from the given coordinates and the measurement results. So, their coordinate's differences $\Delta d\lambda, \Delta d\varphi, \Delta dh$ in WGS 84 can be calculated. For a better interpretation, $\Delta d\lambda, \Delta d\varphi, \Delta dh$ will be converted into the local ellipsoidal coordinate system in north, east and height.

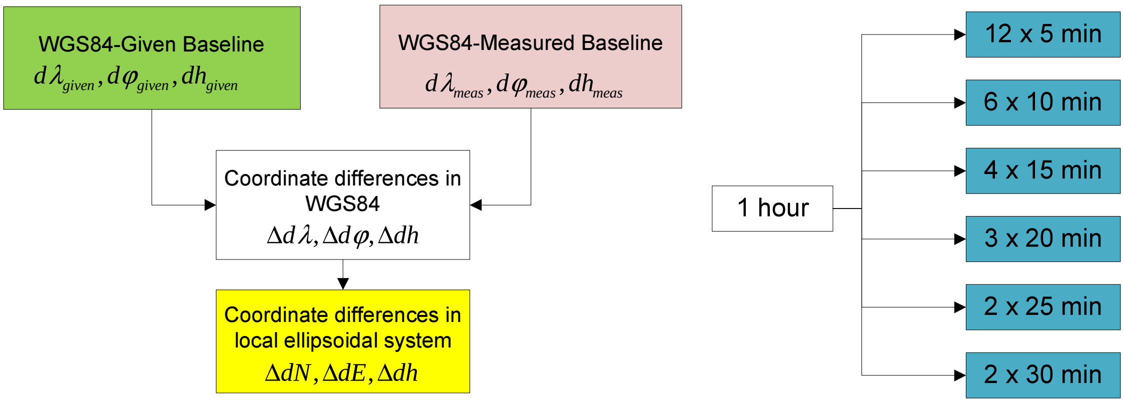

Figure 8: Accuracy analysis procedure

It should be noticed, that the Rinex navigation files (*.11n) are necessary for the Wa1 to determine the baseline. We had problems that there was not enough Rinex navigations information from u-blox receivers, so that there were many float solutions. So the Rinex navigation files from a Leica receiver were used for data processing as temporary solutions. The results shown in this paper have used the navigation files from a Leica receiver. Now the u-blox receivers are configured so that the navigation data can be polled automatically in specified time intervals (e.g. every 2 minutes).

In order to analyze the accuracy depending on the length of observation time, the observation time interval of one hour was divided into several short time intervals: 5, 10, 15, 20, 25 and 30 minutes. The results of 5 minutes intervals are not accurate and unreliable. Only about 50% of the measurements have solutions with fixed ambiguities. For this reason, only the results of 10 to 30 minutes time intervals will be presented.

The standard deviations calculated by Wa1 software are very good, they are all smaller than 1 mm. The standard deviations obtained by the adjustment programs are mostly too optimistic. For this reason, the results of the different time intervals are compared among each other. That means, for example, there are 6 results for the 10 minutes time intervals. The mean value and the standard deviation of these 6 results are calculated. The mean value can be regarded as the reproducibility (absolute) accuracy compared with the true value. And the standard deviation can be regarded as the repeatability (relative) accuracy for the stability of the measurements. Besides, only the fixed solutions are taken for the data analysis. So the value "reliability" can be determined, which is the percentage of the fixed solutions of the total results. The table 2 and 3 show the results for both sessions. The same results are displayed in figures 9-14 for each baseline.

4.2.3 Results of Session 1

Table 2: Accuracy analysis for session 1 (Vaihingen)

Time Interval	**Session1**	**Mean [mm]**			**Standard Deviation [mm]**			**Reliability**
		mΔdN	**mΔdE**	**mΔdh**	**sΔdN**	**sΔdE**	**sΔdh**	**[%]**
10min	Master(p6)&Client1(p8)	***-11.4***	-3.8	-5.9	4.8	2.6	6.9	100.00%
15min		***-11.2***	***-3.5***	-5.2	4.7	0.9	6.2	100.00%
20min		-10.5	***-2.4***	-2.7	2.5	0.4	1.3	66.67%
25min		-11.0	-3.2	-5.2	4.8	1.0	5.0	100.00%
30min		-10.9	***-3.0***	-4.0	4.3	0.3	3.5	100.00%
10min	Master(p6)&Client2(p7)	***-9.9***	***9.9***	-10.6	2.1	0.8	4.7	100.00%
15min		***-10.0***	***9.9***	-10.7	2.2	0.7	4.9	100.00%
20min		***-9.9***	***10.0***	-10.5	2.2	0.4	3.7	100.00%
25min		***-9.6***	***9.8***	-10.6	1.5	0.2	6.0	100.00%
30min		***-9.8***	***9.9***	-10.6	0.2	0.4	3.7	100.00%
10min	Client1(p8)&Client2(p7)	2.1	***13.6***	-4.0	5.1	2.4	9.8	100.00%
15min		2.1	***13.4***	-4.4	4.8	1.6	8.9	100.00%
20min		1.8	***13.1***	-5.0	3.0	0.7	4.5	100.00%
25min		2.2	***13.1***	-4.8	5.3	0.9	9.0	100.00%
30min		1.9	***13.5***	-4.6	3.7	1.6	8.1	100.00%

Almost all the divided time intervals have fix solutions. Only one of 20 minutes time intervals shows a float solution.

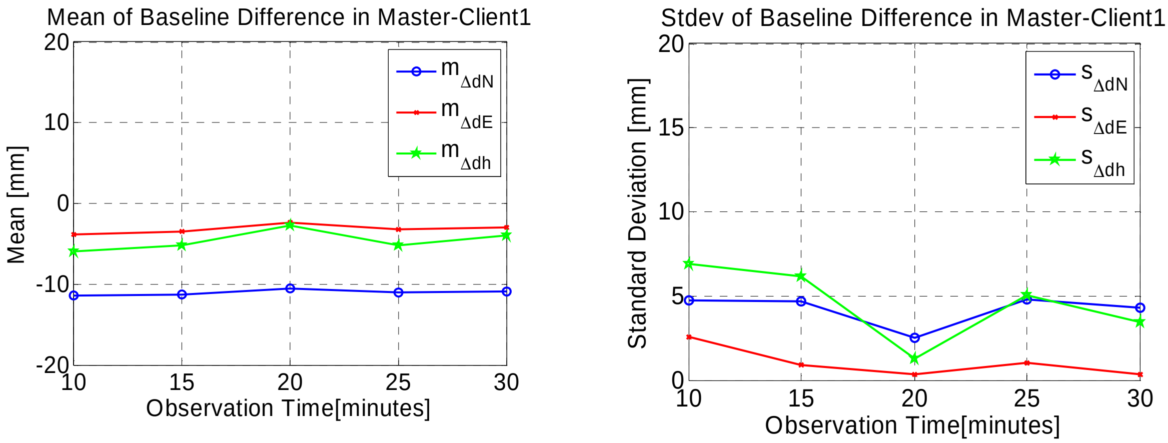

Figure 9: Accuracy analysis for baseline of master- client1 in session 1

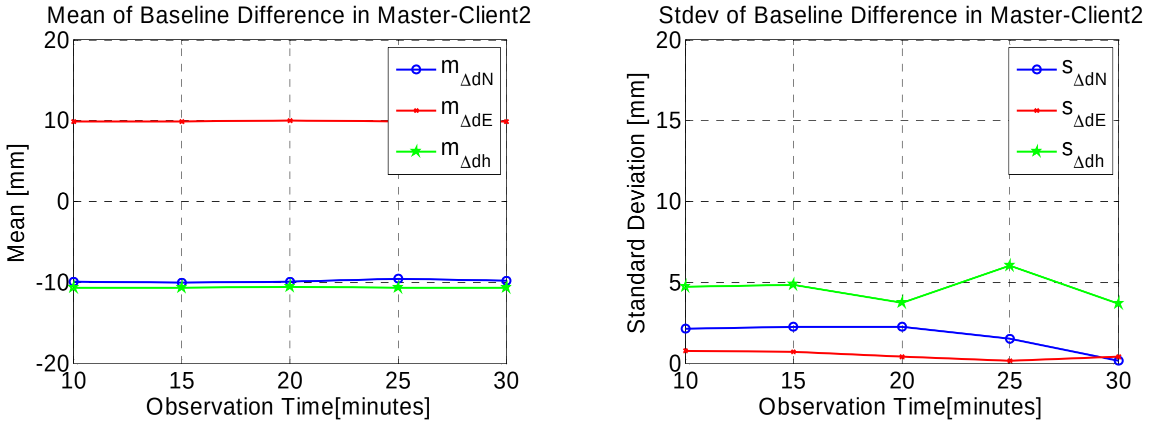

Figure 10: Accuracy analysis for baseline of master- client2 in session 1

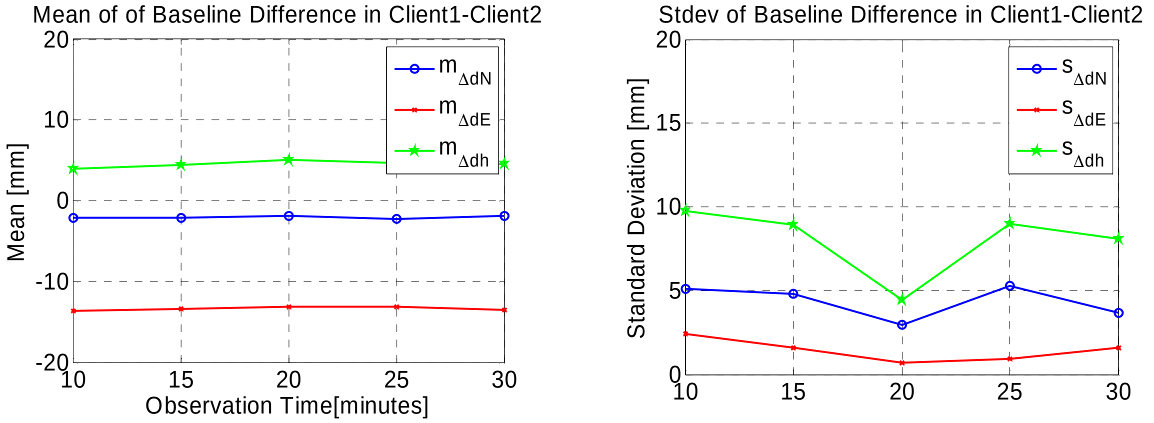

Figure 11: Accuracy analysis for baseline of client 1- client2 in session 1

The mean values of the absolute differences compared with the given values are less than 2 cm for all coordinates' components. The mean values indicate that there may exist some systematic errors in the coordinates. However, if the statistical significance t-test is executed here (compare the mean values with their standard deviation), with a confidence level of 95%, only some of these differences (cursive and bold values in table 2) are significantly different from the true value 0. It means, with a probability of 95%, only these coordinates' components have systematic errors. Although the heights are all negative, they are not significantly different from the true value 0 according to the significance tests.

The standard deviations are quite small and less than 1 cm in all the coordinates' components. That means the absolute differences are quite stable, especially for the baseline of master-client 2. The reason is that both of them have a shadowing free environment. The standard deviations of heights are worse than the horizontal position (north and east directions). This phenomenon is normal for GPS measurements. The standard deviations in the east direction are generally 2 or 3 times better than in the north direction in this session. The reason of this fact is unclear here.

Moreover, the mean values and the standard deviations do not become much better with longer observation time (starting from 10 minutes).

4.2.4 Results of Session 2

Table 3: Accuracy analysis for session 2 (Vaihingen)

Time	**Session2**	**Mean [mm]**			**Standard Deviation [mm]**			**Reliability**
Interval		**mΔdN**	**mΔdE**	**mΔdh**	**sΔdN**	**sΔdE**	**sΔdh**	**[%]**
10min	Master(p6)&Client1(p8)	***-13.7***	***-3.7***	-13.0	2.5	1.6	10.5	83.33%
15min		***-14.3***	-4.1	-15.4	2.1	2.4	7.0	75.00%
20min		***-13.3***	-4.3	-12.7	1.9	1.5	8.6	100.00%
25min		***-13.7***	-4.8	-12.3	1.3	2.0	9.1	100.00%
30min		***-13.7***	-4.5	-13.3	1.0	2.4	9.5	100.00%
10min	Master(p6)&Client2(p10)	***-17.5***	***28.9***	-9.8	2.4	1.2	7.9	83.33%
15min		***-16.7***	***29.3***	-7.8	0.3	0.8	5.6	75.00%
20min		***-18.0***	***28.8***	-10.4	2.7	1.0	7.7	100.00%
25min		***-17.6***	***28.8***	-9.6	2.0	1.7	9.6	100.00%
30min		***-17.7***	***28.9***	-10.0	2.4	1.2	8.4	100.00%
10min	Client1(p8)&Client2(p10)	-5.3	***33.6***	-0.5	2.1	2.2	7.7	50.00%
15min		-4.6	***32.4***	-0.9	2.8	1.8	3.3	50.00%
20min		-5.7	***33.5***	-2.4	0.9	1.5	3.6	66.67%
25min		***-6.3***	***32.4***	-1.7	0.3	3.1	1.2	100.00%
30min		***-6.5***	***32.3***	-0.8	0.1	2.4	1.6	100.00%

In this session, results of the baseline client 1- client 2 is quite unreliable and the solution of 10 and 15 minutes intervals are not completely fixed for all the baselines, because both clients have shadowing environment.

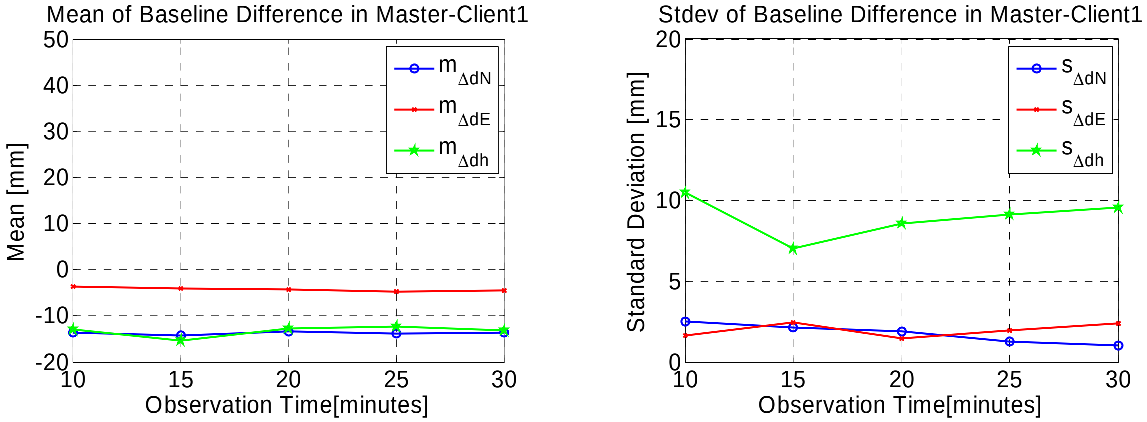

Figure 12: Accuracy analysis for baseline of master- client1 in session 2

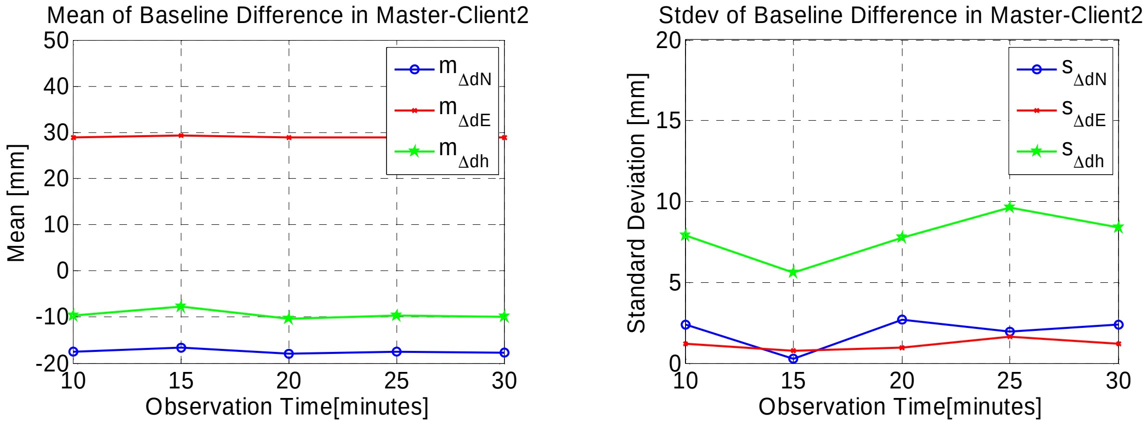

Figure 13: Accuracy analysis master- client2 session 2

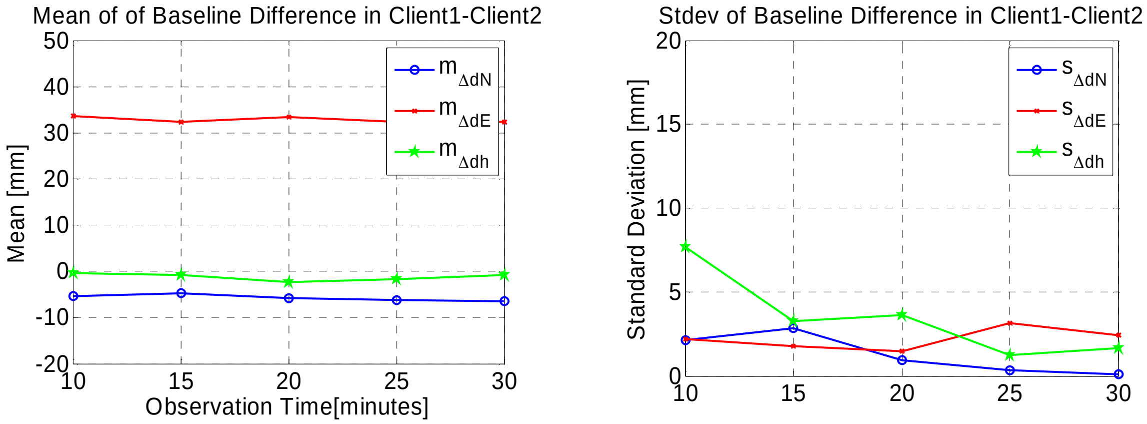

Figure 14: Accuracy analysis for baseline of master- client2 in session 2

The mean values of absolute differences in all the components are less than 3.5 cm in session 2. Considering the mean values, the same effects as in the session 1 can be found. There exist some systematic errors with same tendency, even larger than in session 1. The statistical significance t-tests are also executed for the absolute differences. The coordinates' components with systematic errors are marked with cursive and bold in table 3.

Firstly, there is something worth to note that the baselines of master– client1 are the same in both sessions. But the standard deviations of the heights for this baseline are worse than in session 1. That may caused by the satellites availability in session 2 (about 8 to 9 satellites) are less than that in session 1 (about 10 to 11satellites). Moreover, it seems that the mean values in session 1 and 2 are different in all the coordinates' components. The statistical significance t-tests are also executed, to verify whether the mean values of two sessions are significantly different. The result shows that they are the same at a confidence level of 95%.

Secondly, in session 2, the baselines of master-client 2 and client 1-client 2 are different from that in session 1. Besides, it should be noticed that the antennas at the master and client 1 are not changed. Only the antenna of client 2 has changed its position from pillar 7 to pillar 10 (from session 1 to session 2). The baselines of master-client 2 and client 1-client 2 have the same tendency of systematic error as in session 1 and even larger.

The first possible reason for theses systematic errors is that the calibration files used for the data processing are the same as in Schwieger (2009). The calibration in Schwieger (2009) is realized for an antenna without the ground plate. In our measurement, the antennas are shielded with a ground plate. Besides, the same calibration file was used in the data processing for all the antennas. Probably, the antennas are really different and individual calibrations of each antenna with ground plates are necessary.

But if the systematic errors are only due to the antennas, the systematic errors should be almost the same for the baselines of master- client 2 and client 1- client 2 in both sessions. As 1 km is still a short distance, it is almost impossible that the length of the baseline may affect the absolute accuracy. So, some of the systematic errors should be occurred by the shadowing environment of pillar 10 (client 2 in session 2).

The standard deviations, which are almost all smaller than 1 cm, are nearly the same as in session 1. The reason is that the float solutions are neglected. Compared with the results from session 1, the standard deviation in the east direction is almost the same level as that in the north direction. The standard deviations of the heights are still worse than that in the horizontal position.

Like in session 1, the mean values and the standard deviations also do not become much better with longer observation time (starting from 10 minutes).

5. CONCLUSION AND OUTLOOK

In this paper, the automatic low-cost GPS monitoring system using WLAN communication at IIGS was introduced. The tests for the WLAN regarding the range and the line-of-sight as well as the wireless mesh network were carried out. The range of the WLAN communication of this system can be longer than 2 km in line-of-sight case. This range is for plenty monitoring sufficient. Moreover, for the WLAN transmissions, at least 60% of Fresnel zone should be kept free from the obstructions. For planning the network, this should be taken into consideration.

Then, the first result for testing the positioning accuracy was carried out in Stuttgart region and presented. The reproducibility accuracy and repeatability accuracy do not improve with longer observation time (starting from 10 minutes). But in shadowing environment, the reliability will be better with longer observation time (starting from 20 minutes).

The repeatability accuracy of the measurements is almost less than 1 cm in all the coordinates' components. However, the reproducibility accuracy (compared with the true values) is not ideal and only below 3.5 cm. They should definitely be improved. There are some systematic errors in the horizontal directions. Possible reasons have been discussed in the paper. Furthermore, more tests with expanded observation time and different net configurations should be carried out, to have more data to analyze the problems and find the main reasons.

To apply the system on large monitored objects, such as bridges, landslides and dams, the system should achieve mm-level precision, the accuracy should be improved. For instance, the individual calibration of each antenna with a ground plate may enhance the reproducibility accuracy of the positioning. Besides, the development of an improved ground plate and a "low cost" chock ring may reduce multipath effects. Other alternative low-cost antennas can be tested. Additionally, to have better results, filter algorithms can be applied. This will be a very fascinating and challenging research work in the future.

Besides, the results in section 4.2.2 and 4.2.3 have been evaluated in post processing mode. And the near-real-time data processing described in section 3.2 should be tested and further improved.

It is also planned to expand the system, so that the remote control of the system can be realized via Internet. This will be necessary, if the system is set up permanently at distant monitored objects, and the results should be continuously sent to the controllers in real time. Here the data security should be taken into consideration.

In the future, if Glonass, Galileo and Compass are added to GNSS receivers, availability and reliability will grow. The economic potential of a low-cost GNSS system for monitoring tasks should not be underestimated.

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