Possibilities of Low Cost GPS Technology for Precise Geodetic Applications

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SUMMARY

The Global Positioning System (GPS) is used for many purposes in surveying and geodesy like cadastral surveys, engineering surveys or intercontinental coordinate frames. In general geodetic two-frequency GPS receivers are used for most of these applications. Despite the reduction of expenses for these geodetic GPS receivers frequently the costs are too high for surveyors in developing countries. Consequently investigations regarding the possibilities of low cost GPS receivers are worthwhile.

The authors will present a procedure to determine precise coordinates by GPS using commercial low cost GPS receivers. These receivers like the Garmin eTrex Vista use phase-smoothed code for positioning. The phase and the code data of the receivers are transferred to a notebook in real-time due to the lack of memory within the used receivers. The stored RINEX file is post-processed using the SKI-Pro software of LEICA thereafter.

Within the paper the post-processing of baselines from 100 m up to 8 km is presented. The maximum three-dimensional deviation of the estimated coordinates of the reference coordinates is 8 cm for 30 minutes observation period, if strong multipath is avoided.

ZUSAMMENFASSUNG

Das Global Positioning System (GPS) wird in vielen Bereichen der Geodäsie wie Katastervermessungen, Ingenieurgeodäsie oder interkontinentale Referenzsysteme eingesetzt. Im Allgemeinen werden geodätische zwei-Frequenz Empfänger für diese Anwendungen genutzt. Obwohl sich die Kosten für geodätische Empfänger deutlich reduziert haben, sind diese Investitionskosten häufig zu hoch für Geodäten in Entwicklungsländern. Aus diesem Grund sind Untersuchungen bezüglich dem Einsatz von Low-Cost GPS Empfängern sinnvoll.

Die Autoren stellen eine Vorgehensweise zu Bestimmung von präzisen Koordinaten mittels Low-Cost GPS Empfängern vor. Low-Cost GPS Empfänger wie der Garmin eTrex Vista nutzen häufig den phasen-geglätteten Code zur Positionsbestimmung. Die Phasen- und die Code-Messungen werden in Echtzeit auf ein Notebook übertragen, da eine Speicherung der Daten im Empfänger nicht möglich ist. Die gespeicherten RINEX-Daten werdem mit der Leica Software SKI-Pro im Post-Processing ausgewertet.

In diesem Artikel werden Auswertungen von Basislinien von 100 m bis 8 km vorgestellt. Die maximale dreidimensionale Abweichung der bestimmten Koordinaten von den Referenzkoordinaten beträgt, wenn extreme Mehrwegeeffekte vermieden werden, 8 cm bei 30 Minuten Beobachtungszeit.

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1. LOW COST TECHNOLOGY FOR DEVELOPING COUNTRIES

The execution of surveying tasks has to be assessed from the financial point of view due to economic restrictions. These restrictions are valid for developed counties as well as for developing countries. But the reasoning for companies carrying out the surveying works are different within the countries. Companies in developed countries streamline their construction processes and try to economize labor costs due to the high wages paid. In some developed countries like Japan the construction companies are understaffed leading to a second reason for streamlining and automatization of construction processes. Against it labor force is available and cheap within most of the developing countries. Consequently the economization takes place for investments like surveying instruments. The FIG Commission 5 aims at "delivery of cost effective surveying technology and techniques to developing countries" (FIG 2004) to aid for cost-effective surveying.

This paper will propose to use GPS receivers that may be purchased for some hundred Euros. Theses receivers may be applicable for geodata acquisition and, even more challenging, for precise geodetic applications. The benefit for the surveyors in the developing countries will be tremendous, because the investment into GPS equipment is reduced by a factor of approximately hundred. In the following paper some investigations regarding the measurement of baselines using Garmin eTrex Vista receivers are presented. In enhancement to SCHWIEGER (2003) two Garmin eTrex Vista were used to determine pure low cost baselines. Additionally the baseline length is extended up to 8 km.

2. POTENTIAL OF LOW COST GPS

The Global Positioning System (GPS) may be used for quite different applications that require different accuracy levels as well as reliability or availability levels. For further details about GPS it is referred to the respective textbooks (e.g. SEEBER 2003). In the following the paper will deal only with the different accuracy levels for static positioning. Table 1 lists receiver classes, typical applications and accuracy levels. The distinction between geodata acquisition and geodetic receivers is not clear in any case. Sometimes one frequency geodetic receivers are used for geodata acquisition.

If we compare these accuracies to the possible GPS measurement techniques, it is obvious that we need phase measurements to reach the accuracy required for geodetic applications. Besides the large difference in accuracy level the purchasing costs for the different receiver classes show large differences too.

Table 1: Receiver classes, applications and accuracy levels of static positioning

receiver class	used signal	applications	accuracy	appr. costs
low cost	code or phase-smoothed code, 1 frequency	car navigaton, location based services, sailing, mass market	1 to 10 m	100 – 500 €
geodata acquisition	phase-smoothed code, 1 frequency	infrastructure planning, architecture, GIS applications	0,5 to 3 m	5 000 – 10 000 €
geodetic	code and phase, in general 2 frequencies	surveying, geodynamics	0,001 to 0,1 m	10 000 € - 30 000 €

For high-quality post-processing of phase measurements high expensive geodetic one or two frequency receivers have to be used. An alternative is the use of so called "original equipment manufacturer boards" (OEM-boards), that may be built into a notebook or another electronic device. Some of these OEM-boards deliver phase data and sometimes they are the same that are built into geodetic receivers. In the latter case the results are similar respectively identical to the ones of geodetic receivers. In this case the boards are expensive, by the way excluding them as an alternative to low cost receivers. Another hindrance is the fact, that OEM-boards are difficult to handle for the employees in a surveying company. So one has to conclude that OEM-boards are not the solution in the sense of cost effective technology.

The use of receivers using phase-smoothed code may be justified for geodata acquisition in GIS applications. Their accuracy is limited by the use of code as the primary measurement quantity. Therefore they can not be used for precise applications without modifications.

In conclusion one needs phase observations to reach accuracy levels assuring the dm- or the cm-level. In HILL et al. (2001) and SCHWIEGER (2003) some experiments using Garmin receivers were reported. The results were encouraging. The accuracy is reported to be below the dm, but still containing outliers up to some dm. This paper will try to widen the application ranges of so-called low cost GPS receivers respective handheld GPS receivers.

In the following it will be outlined how the use of low cost GPS receivers will reduce the costs for surveying tasks in developed and developing countries. For the following contrast labor costs of 66 € per hour for a developed country (Germany; HOAI 2002) and of 7 € per hour for a developing country (India; WIEGEL 2004) are assumed. A low cost receiver is allowed for a price of 500 €, against it a geodetic receiver for 25 000 €. Two receivers are required for the measurements. Additionally two notebooks and the respective software (approximately 3000 €) are taken into account for the low cost variant; post-processing software of around 5000 € is essential for low cost technique as well as for precise geodetic equipment. We assume a depreciation time of 3 years for the investment, 200 working days a year and 8 working hours a day. As a simplification only one engineer should work with the receivers. In figure 1 only these two factors, labor costs and investment are considered.

Figure 1 shows the obviously large difference between the costs in developed and developing countries due to the labor costs. The percentage gain by using low cost GPS is much greater in the developing countries. The cost reduction achieves more than 50 percent. This exposes the tremendous possibilities in cost reduction for companies in developing countries.

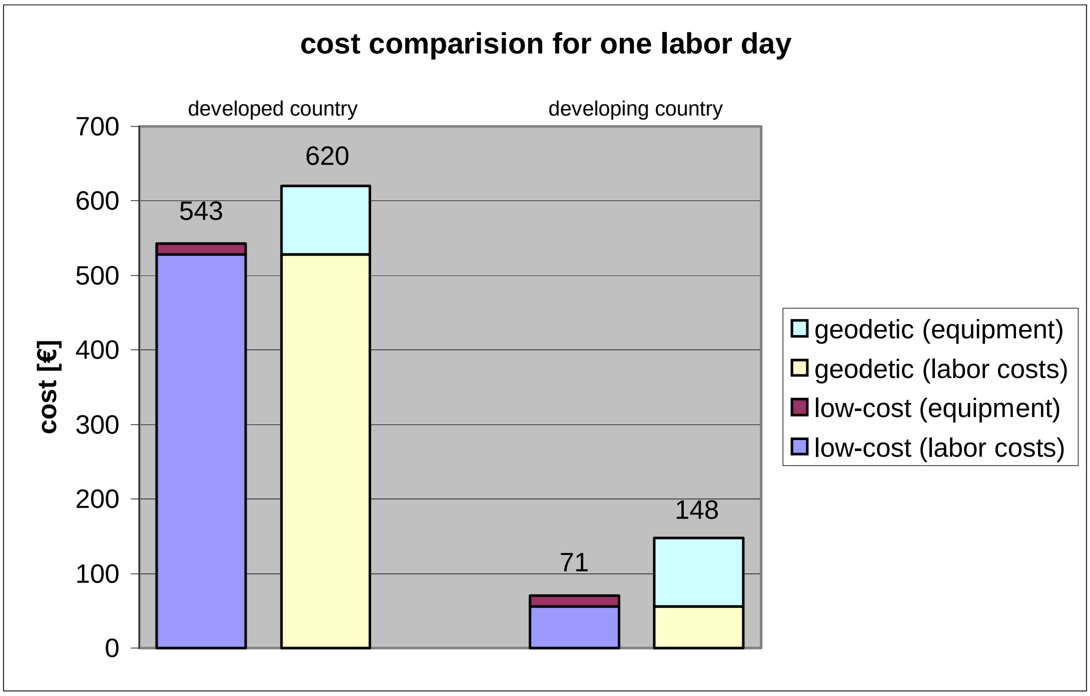

Figure 1: Simplified cost comparison for the use of different GPS receivers

3. IMPLEMENTED PROCESSING PROCEDURE FOR LOW COST GPS OBSERVATIONS

The most basic assumption, using low cost GPS receivers for precise geodetic applications, is the possibility to use the carrier phase information (see chapter 0). In order to smooth the code observations, some low cost receivers like e.g. the Garmin eTrex series use the carrier phase on L1. Because of the fact, that these low cost receivers are not developed for precise positioning in post-processing, there is no possibility to store the raw-data. But the Garmin Device Interface Specification (GARMIN 2004) includes an internal protocol in order to address the raw data through the serial interface (RS232) of the receiver in realtime for testing (GARMIN 2004). This Garmin-specific protocol is not published and there is no guarantee for support during further receiver development. A group of researchers at the Institute of Engineering Surveying and Space Geodesy of University Nottingham nevertheless developed a software-tool called GRINGO to decode and store the Garmin raw-data. This Software is running on a Windows-PC and puts the raw data (code- and phase-measurements on L1) into a RINEX observation file. For more detailed information see (SCHWIEGER 2003). For our investigations we used the GRINGO software. Besides other software packages like ASYNC (GALÁN 2000) exist, that may decode the Garmin data too.

3.1 Measurement Equipment to Generate Observation Files

The low cost GPS equipment of the Institute for Applications of Geodesy to Engineering (IAGB) at the University of Stuttgart is based on two Garmin eTrex Vista receivers (software version 3.60). Because of the fact, that the useful features of this high-end receivers of the eTrex series, like map display, barometer and compass, are not used for precise post-processing applications, other Garmin receivers, for example the whole eTrex-series, may be used to ensure the same post-pocessing quality.

For geodetic baseline-measurements an exact and reproducible definition of the antenna phase center of each receiver is very important. For this reason the workshop of the IAGB has constructed an adapter for each receiver (figure 2) that allows the fixing on a tribrack. Therefore the exact definition of the antenna phase center is possible within a reproducibility better than 1mm. For calibration of the receiver-adapter-system see chapter 0. Furthermore the adapter contains a ground plate to shield against multipath effects.

Figure 2: Garmin eTrex with adapter on tripod connected to a rugged outdoor notebook

As mentioned above an external PC (practically a notebook) in combination with GRINGO software is necessary to decode and store the Garmin raw data. During the current investigations the GRINGO Version 2.0.0 is used. GRINGO runs on all Pentium®-systems, or systems with similar processors. It was developed for Windows95®, but also successfully tested by the IAGB on Windows98®- and Windows2000®-systems. The notebook needs a serial RS-232 interface to be connected to the receiver. In order to have a weatherproof outdoor measurement equipment, we use rough notebooks like Panasonic® ToughBook CF28 (figure 2). Moreover an external battery-back is used for sessions, longer than 2 hours in order to provide the receiver and the notebook with power. We test the measurement system by a long time baseline measurement of twenty-four hours. One Garmin receiver worked very well, but the other one shut down after eight hours without any obvious reason. The power supplies of both measurement systems has worked correctly. Further investigations will deal with this problem.

3.2 Post-processing Procedure Using Commercial Software

After a baseline measurement each of the two notebooks contains a RINEX 2.1 formatted observation file generated by GRINGO. This data format is very useful, because all commercial and scientific GPS post-processing software packages have the possibility to import and post-process RINEX files. At the University Stuttgart we have the post-processing software SKI-Pro (Version 2.5) of the Leica company at one's disposal.

SKI-Pro and other commercial GPS-software are able to detect full cycle slips and fix the ambiguities of the phase data. But in the Garmin data half cycle slips occur. In result SKI-Pro is not able to fix the ambiguities, but a so-called float solution is estimated. This fact has to be taken into account for setting the evaluation parameters and may lead to a decrease in accuracy for the baseline determination.

The whole post-processing procedure by using SKI-Pro can be divided into several steps (see figure 3). After the import of the two RINEX files (reference- and rover-station) it is necessary to supply SKI-Pro with satellite orbits. Because of the fact, that GRINGO does not store the broadcast orbits, we have to use external orbit data. In our investigation we used rapid orbits from the IGS (http://igs.ifag.de/). In the next step each of both stations have to be linked to the particular antenna. The antenna, defined in SKI-Pro includes the antenna offsets. In our case the adapter-eTrex-combination represents an antenna (see chapter 4). Furthermore the antenna height, measured in the field, has to be typed in for each station. After defining the coordinate of the reference station, the next work item includes the setting of the evaluation parameters. We used the SKI-Pro standard evaluation parameters with some changes. These changes include the use of rapid orbits, the float solution and an elevation mask of 15 degrees. By starting the calculation of the baseline all satellites are active at first. The following analysis of the double difference phase- and code-residuals gives an impression of the data quality. Because of multipath and other disturbances some satellite data are not usable. In the next calculation the satellite with the greatest residuals is

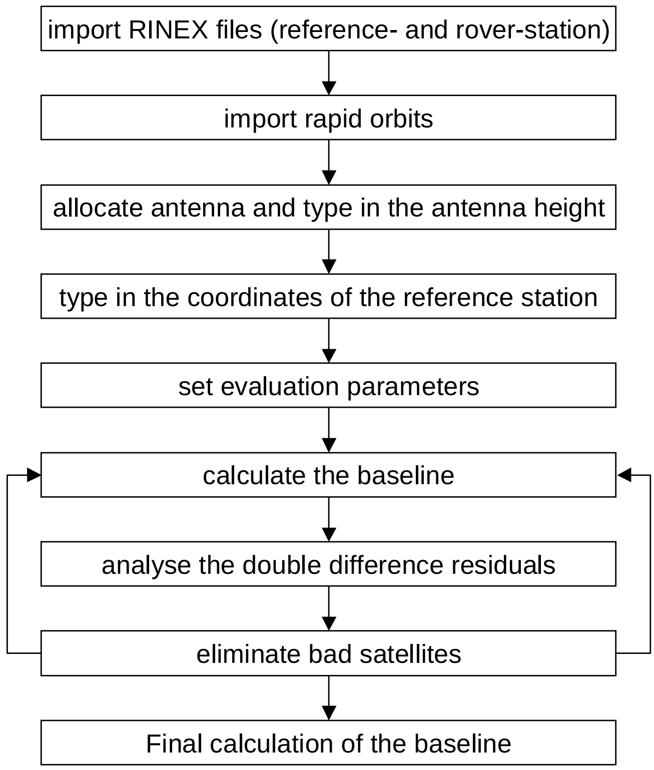

Figure 3: Steps of the postprocesing prcedure

not used. The standard deviation of the base line components (*dx*, *dy*, *dz*) should get smaller. By elimination of additional satellites in consideration of the residual quality and the comparison of the standard deviation of the baseline components the optimal result is found.

4. ANTENNA CALIBRATION

For precise positioning the accurate electronic antenna phase center with respect to the geometric center, the so-called antenna offset, has to be known. For the most applications there is only a need for the difference to the antenna offset to a known reference antenna. For the experiment carried through at the University Stuttgart the antenna offset of the Leica AT502 antenna was known and the respective ones of the two Garmin eTrex Vista have to be determined. For the correct determination of the offset the adapter-systems (figures 4 and 5) have to be used and oriented correctly. The antenna heights have to be measured to a reference surface. The exact geometric definition of this reference surface is given in figure 4.

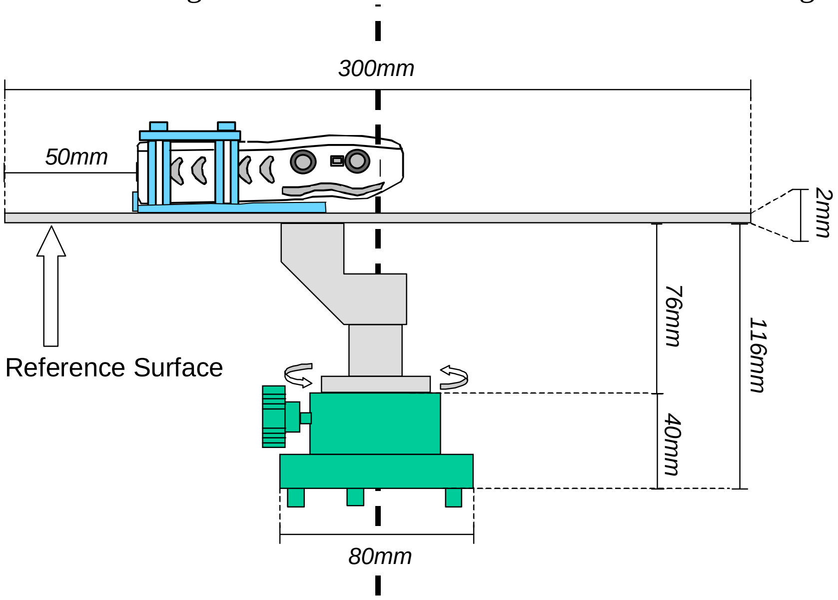

Figure 4: Adapter for fixing the Garmin eTrex Vista on a tribrack

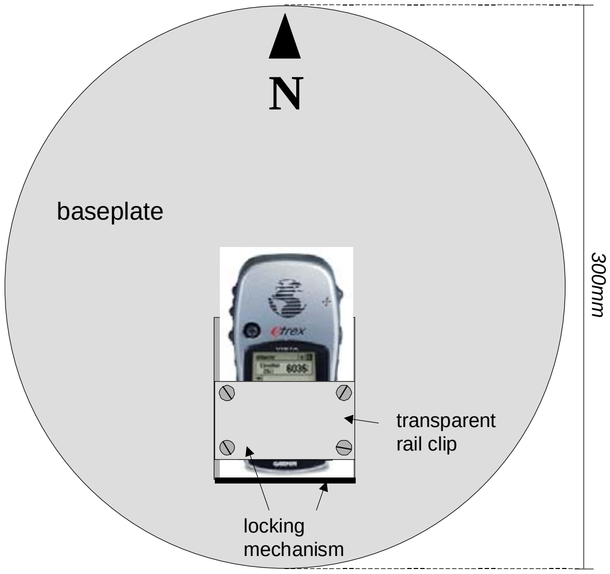

Figure 5: Adapter in topview with locking mechanism and baseplate against multipath effects

For the calibration measurements an environment with low multipath effects was chosen. One Leica AT502 antenna and one Garmin receiver were installed on pillars that have known coordinates within the mm level; points 3 and 4 for the first Garmin eTrex Vista (eTrex 1) and points 5 and 6 for the second Garmin eTrex Vista (eTrex 2) in figure 6. First of all eTrex 1 was mounted on point 3 and the reference measurement system Leica SR530 on point 4. Both antennas were oriented to north and the receivers logged data for approximately 2 hours. Thereafter the antennas were changed, oriented and again the receivers measure for 2 hours. The same was realized for eTrex 2 on points 5 and 6. Although the determination of the offsets could be realized by the antenna swap procedure, the calibration was carried through using the accurate known coordinates of the points. The results of the two determinations were averaged.

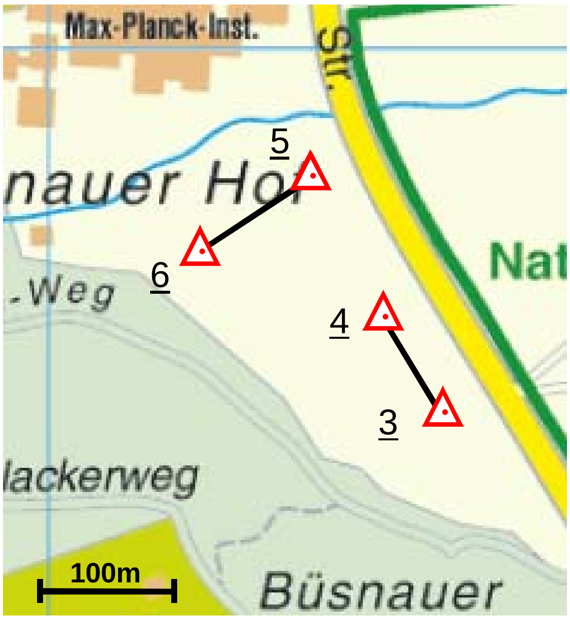

Figure 6: Antenna calibration mesurement configuration

The results of the parameter determination are given in figure 7. Obviously the antenna offsets of the two Garmin eTrex Vista are similar within a span of 1.7 cm. At first sight this variation seems to be not satisfactory, but comparing it to the results in chapter 5, one has the accuracy level that may be reached for the time being. The determined offsets are applied to the post-processing of the baseline measurements described in chapter 5.

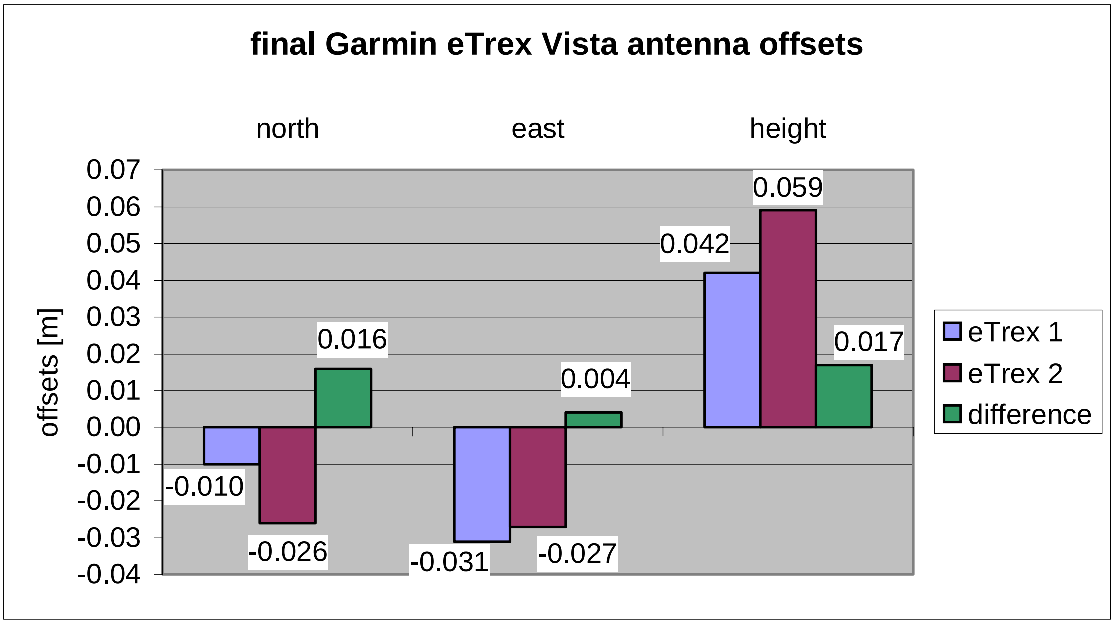

Figure 7: Results of antenna calibration

If the offsets are compared to the ones determined in SCHWIEGER (2003) differences of more than 5 cm for the north and the east component occur. This is surprising especially for eTrex 1, because it is the same like the receiver investigated in SCHWIEGER (2003). The reason for the large deviations may be found in the changed shielding against multipath effects. This shows that the antenna offsets change significantly, if the antenna-adapter-system changes.

The sensitivity of the measurement system to the elevation mask is small (figure 9), but the elimination of satellites (figure 8) is essential for the determined offsets. The large differences of the offsets, if a satellite (PRN) is eliminated, is probably caused by multipath effects.

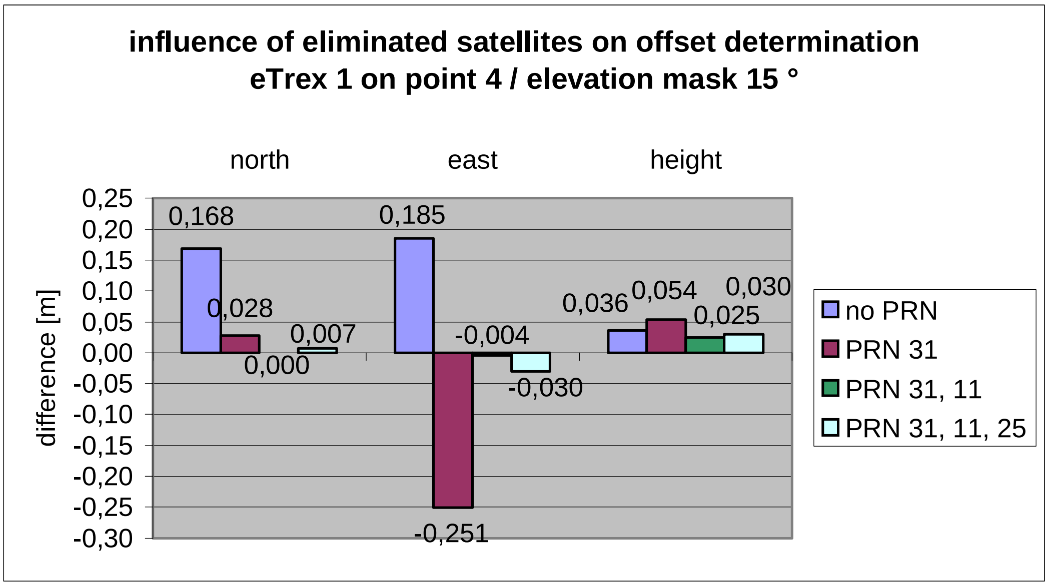

Figure 8: Variation of offsets due to eliminated satellites (typical example)

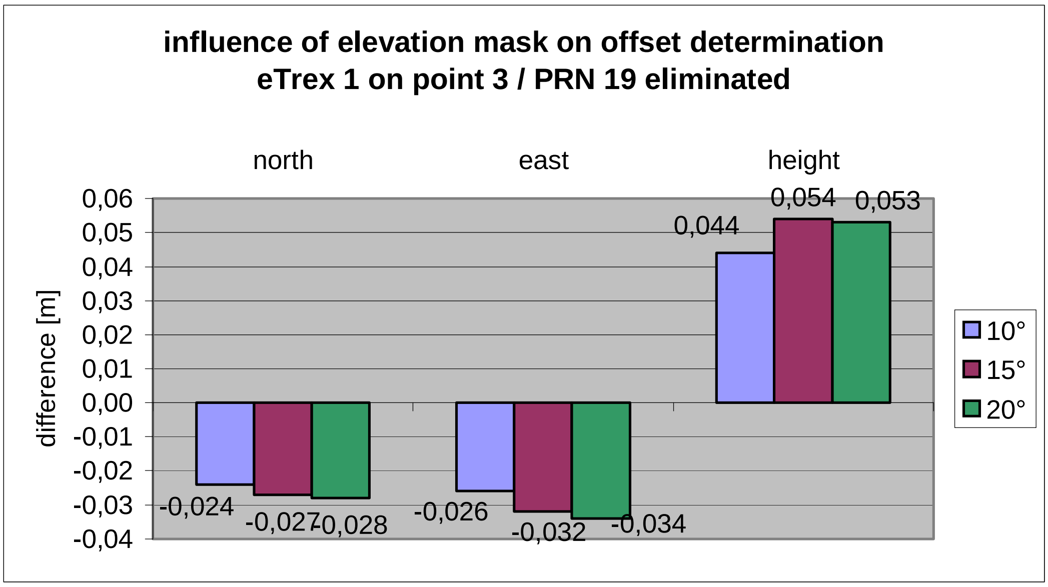

Figure 9: Variation of offsets due to elevation mask (typical example)

The essential is to use the offsets for the baseline measurements and to scan the residuals of the individual satellites carefully for outlyers respectively erroneous observation phases to eliminate satellites. More about this theme is presented in chapter 5.

5. BASELINE MEASUREMENTS

The aim of the measurement campaign was to establish accuracy values for the Garmin eTrex Vista in dependence of the baseline length. In SCHWIEGER (2003) baselines below 1 km were determined using one Leica SR530 and one Garmin receiver. Here the baseline length was extended and two Garmin receivers were used.

For the distances up to 1 km the points of the pillar network (points 1, 4, 5, 6, 7, 10) described in chapter 4 and presented in figure 10 were used. Those coordinates are well-known within the mm-level. The coordinates of the points 11 and 101 (compare figure 10) were determined by 0.5 hour baseline measurements using Leica SR530 receivers. Tribracks with forced centring were used on these points. The accuracy of the determined coordinates is estimated to approximately 1 cm.

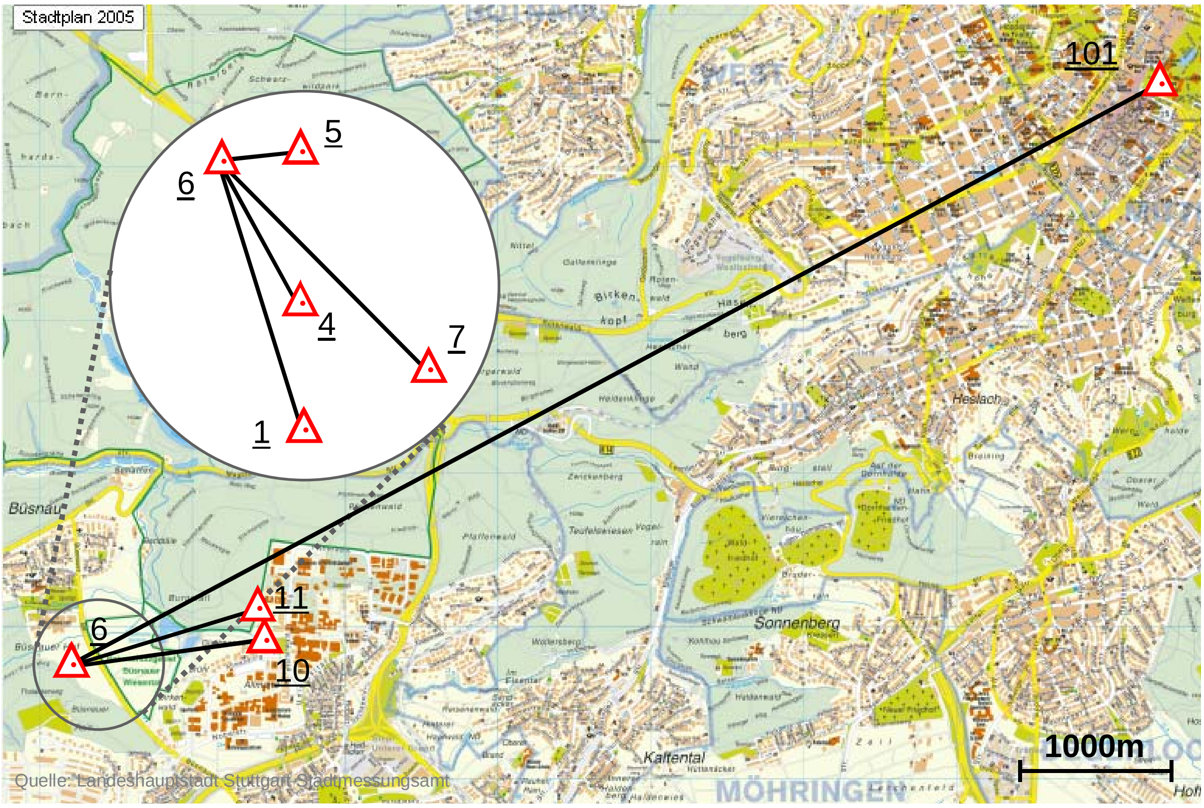

Figure 10: Baseline measurement configuration in the city zone of Stuttgart

For each baseline the two Garmin eTrex measure approximately 0.5 hours with a data rate of 1 second. The eTrex 1 stayed stable on point 6 for the whole measurement campaign. The eTrex 2 was placed on the other points in the different sessions. An elevation mask of 15 degrees was used for the post-processing using Leica Ski Pro. The points 1 and 10 are located in the victinity of trees respectively buildings. For these points disturbances caused by multipath and diffraction are expected due to the results presented in SCHWIEGER (2003). Table 2 summarizes the baseline lengths, observations regarding multipath and the processing details regarding eliminated satellites.

Table 2: Measured baselines and their characteristics

point	**5**	**4**	**1**	**7**	**10**	**11**	**101**
baseline length [km]	0,12	0,26	0,45	0,45	1,1	1,1	7,8
observation			trees		building		
eliminated satellites	13 / 25	19	19 / 20	19	01 / 20	11	26
number of satellites *(after elimination)*	5	7	5	7	4	5	7

The post-processing to determine reliable and accurate results was rather sophisticated as shown in chapters 3 and 4. To estimate accurate positions satellites have to be eliminated as shown in table 2 and figure 8. If it was not obvious which satellites have to be eliminated, the one with the best standard deviaton indicated by the Ski Pro software was chosen. Generally this leads to the solution presented in the following. Nevertheless it has to be mentioned that these standard deviations are by far to optimistic.

The 3D - differences between the Garmin baselines and the references coordinates are presented in ascending order regarding the baseline length in figure 11. The difference of point 11 includes the horizontal components only, because the antenna height measurement was erroneous.

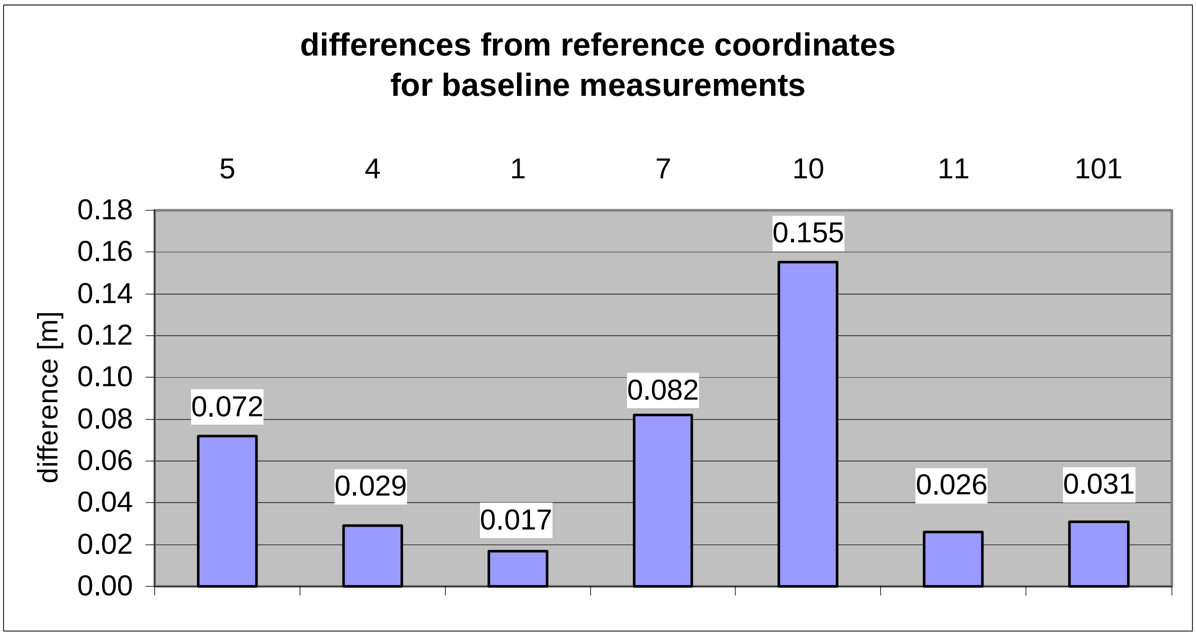

Figure 11: Difference from reference coordinates for baseline measurement

Obviously the magnitudes of deviations are independent of the baseline length. Point 10, that is located near a building, shows a high difference to the reference coordinates, that may be caused by multipath effects. Further elimination of satellites to increase the accuracy is impossible, because only four satellites remain for the evaluation (compare table 2). Against it for point 1 only a small difference of 1.7 cm is estimated although the environment is a typical multipath and diffraction environment due to the surrounding trees. Here the decision for the satellites to be eliminated was rather difficult and, to say the truth, the knowledge about the reference coordinates helps to find this solution. If these coordinates would have not been known, one would not get a reliable solution.

In general a high number of satellites gives the possibility to eliminate satellites and to increase the accuracy and reliability of the respective coordinate estimation, like for the baselines to points 4 and 101 (table 2 and figure 11). A low number of satellites lead to a worse solution, like for the baselines to points 5 and 10. But not all the results fit into this pattern (see e.g. baseline to point 7 with 7 satellites after elimination and a rather bad difference to the reference coordinates). In general the elimination of all GPS signals, that are disturbed by multipath is not possible up to number less than four, because in this case the number of available pseudo-ranges is not sufficient for positioning.

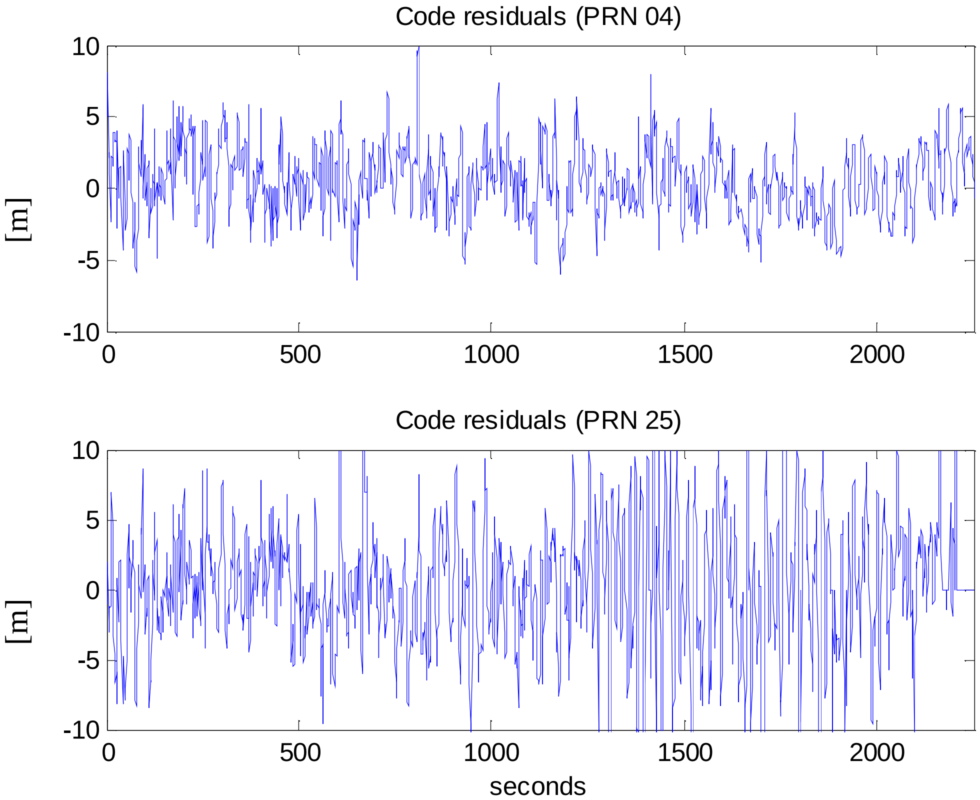

Figure 12: Code residuals of PRNs 4 and 25 of the baseline 6 – 5

Figure 12 presents a typical residual pattern (baseline 6 – 5) of the post-processing procedure. The PRN 25 shows a very noisy multipath-like residual pattern. Additionally the phase residuals show obvious outlyers (figure 13). Against it, for PRN 4 the noise level is much smaller for code as well as for phase data (figures 12 and 13). PRN 25 was eliminated because of this noisy pattern. This was the first step to get the correct result for this baseline.

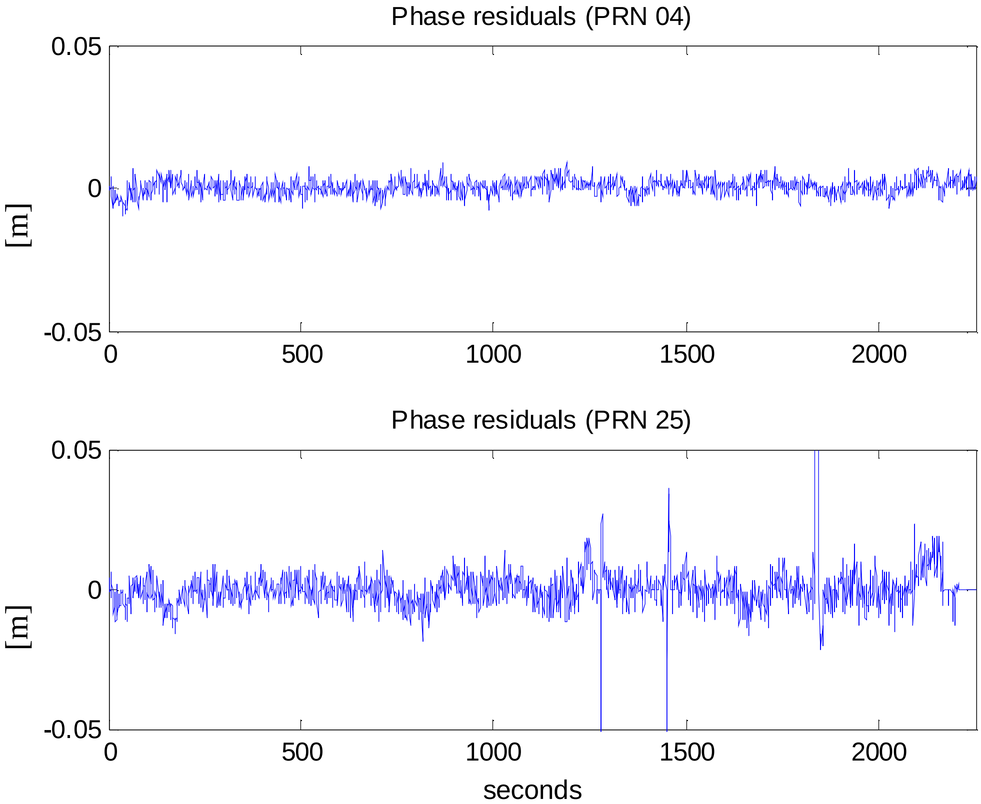

Figure 13: Phase residuals of PRNs 4 and 25 of the baseline 6 - 5

The investigations reveal that up to now the post-processing results deliver small deviations only for an environment with less multipath effects. The commercial software like Ski-Pro can not deal with this sort of measurement-errors of low-cost GPS receivers in a proper way. The problem is intensified by the occurance of half-cycle slips in the phase measurements. These cycle slips can not be detected by commercial software, too.

6. SUMMARY AND OUTLOOK

The investigated GPS receivers are a cost effective tool to solve problems like rough setting out within construction processes or to achieve medium or low accuracy in engineering surveys as well as for control networks. The obtained accuracy is well suited for GIS applications too.

Within this paper we have shown that

- baselines up to approximately 8 km may be measured with two Garmin eTrex Vista in half an hour with deviations up to 8 cm under low multipath conditions,
- the accuracy of the baseline determination is independent of the baseline length (up to 8 km),
- multipath and diffraction severely decrease the accuracy and especially the reliability of the baseline determination,

- the measurement is not user friendly due to the prototype character of the measurement system,
- and the data handling is not user friendly due to the disturbed GPS signals and the non-Garmin-adapted post-processing software.

Consequently these results should lead to the following further developments:
- software to solve for half cycle slips,
- algorithms to eliminate disturbed signals automatically,
- realtime or quasi-realtime procedures adapted to typical Garmin measurements.

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