# Using Handheld GPS Receivers for Precise Positioning

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**Key words**: GPS, handheld GPS receivers, static positioning, kinematic positioning.

## SUMMARY

In general handheld GPS receivers are used for absolute positioning or for relative positioning using DGPS-services or WAAS/EGNOS signals. The positioning is realized using code pseudo-ranges. Moreover it is well known that some of the handheld receivers use phase-smoothed code for positioning. This means that the phase signal is available and may be used for Precise Differential GPS (PDGPS) positioning. Using GARMIN handheld receivers the phase and the code information may be transferred in realtime on a computer and stored in a RINEX file. Combining the RINEX file created by a handheld receiver with a RINEX file of another GPS site, the baseline could be solved in post-processing mode using phase pseudo-ranges.

The paper describes the possibilities and limits of static and kinematic positioning using the handheld GPS phase information by using commercial post-processing software. Moreover the results of an antenna calibration that was carried through are presented.

Accuracy analysis is the main part of the investigation. The analysis reveal that multipath and diffraction effects disturb the phase signals severely leading to a less reliable and accurate positioning result. In general the investigations show that the obtained static accuracy is well suitable for GIS applications. Under special conditions the accuracy reaches the realtime accuracy of precise geodetic receivers. Kinematic positioning does not lead to an accuracy increase due the available phase signal.

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## 1. INTRODUCTION

Sustainable development requires urban as well as rural planning. Nowadays these planning issues are generally solved in an automated digital way using Geographic Information Systems (GIS). GIS have to base on reliable and reasonable accurate geo data that may be acquired in different ways. In general there are two ways to acquire geo data: primary and secondary data acquisition methods. The first dealing with techniques that acquire new geo data like terrestrial and satellite-based positioning, photogrammetry and remote sensing. The second utilize geo data that is already available in analogue or digital maps. The respective techniques are digitizing and scanning of analogue maps as well as the import of digital data that is available on the geo-data-market e.g. through Worldwide Web.

Very often the available maps, independent of the digital or analogue character, are not reliable or they are not of adequate accuracy; sometimes they are even not available at all or at the necessary scale. In all these cases data has to be acquired using the primary data acquisition techniques. In this paper we will focus on satellite positioning. A technique is presented that use handheld GPS receivers for static and kinematic positioning. Handheld GPS receivers may be purchased by 100 - 500 € depending on their features making them a cheap and effective tool for geo data acquisition.

## 2. POSITIONIG WITH GPS

### 2.1 Basics of GPS Positioning

Generally the signals of four GPS satellites have to be received by a GPS receiver to solve for the three coordinates and the receiver clock error. If only one receiver is used, one talks about absolute positioning leading to positioning accuracies of about 10 m. The reason for this limited accuracy are different error sources like: satellite orbit and clock errors, ionospheric and tropospheric delays as well as multipath effects (e.g. SEEBER 2003).

One possibility to increase the accuracy is the computation of a position with respect to a second receiver due to the fact that most of the error sources are eliminated or reduced to a large extend because of the almost identical ray paths of the signals from each satellite to the two receivers. This relative position may be computed in realtime or in post-processing mode. In the first case corrections of the second receiver are transmitted via wireless broadcast or mobile phones to the first receiver. The first receiver uses the information for the estimation of the relative position. In the second case the raw data of two or more receivers is stored during the measurements and the relative position is estimated in the office. The later has the advantage of a more reliable and accurate positioning; the first of the availability in the field. The realtime solution is called differential GPS (DGPS). The accuracy using correction data delivered by an own reference receiver, a DGPS service or WAAS/EGNOS signals may be specified to approximately 1 to 5 m.

The positioning methods mentioned up to now are generally used to fulfill the needs of military and navigation users. Geodetic positioning and geo data acquisition generally requires higher accuracies. For these purposes the carrier phases of the GPS signals are used for relative positioning. For GIS GPS receivers used for geo data acquisition generally carrier-phase-smoothed code data is used for positioning. This means that the more accurate phase signal is used to increase the quality of the code signal. One may obtain coordinates with an accuracy between 0.5 and 3 m. All accuracy information is valid for civil users that utilize the c/a – code of the GPS system. Military users, that have access to the p-code, have the possibility to reach a higher accuracy.

For precise geodetic positioning the carrier signal is used directly. Since the wavelength of the carrier waves are around 20 cm and unambiguous positioning is not possible. The solution for the ambiguities is the main task for precise positioning (see e.g. SEEBER 2003). The relative position may be determined with an accuracy of some cm up to the mm level, if the observations last some hours. These accuracies are attainable also for continental dimensions. If the precise positioning is carried through in realtime using corrections the accuracy may be estimated around 1 – 5 cm for static positioning. For a moving receiver (in other words: kinematic positioning) the accuracy is specified by approximately 10 cm due to problems in ambiguity fixing and due to the fact that one has only one position for each epoch at his disposal. Independent of the kinematic or static modus this technique is called precise differential GPS (PDGPS) or Realtime Kinematic (RTK). Generally this relative positioning using the phase signal is referred to as precise positioning, independently of the realtime or post-processed availability of the solution.

| | **absolute** | **relative** | |
|---|---|---|---|
| | | **Realtime** | **post-processing** |
| **code signal** | 10 m | 1 – 10 m | 1 – 5 m |
| **carrier signal** | - | static: 0,01 – 0,05 m<br>kinematic: 0,1 m | static: 0,001 – 0, 02 m<br>kinematic: 0,01 – 0,1 m |

**Table 1:** Accuracy potential of different GPS positioning modes

Different application scenarios and different accuracy levels require different receiver classes. They are separable by their technical possibilities, their accuracy level and their fields of application. Table 2 gives an overview about typical receiver classes. For more detailed information about GPS one is referred to textbooks like SEEBER (2003) or HOFMANN-WELLENHOF et.al. (1997).

| Receiver class | used signal | accuracy / realtime | special features | application |
|---|---|---|---|---|
| **Handheld** | code or phase-smoothed code, 1 frequency | 1 to 10 m / yes | navigation features | mass market, navigation, tourism |
| **GIS** | phase-smoothed code, 1 frequency | 0,5 to 3 m / yes | attribution of geometric data during field work | geo data acquisition for GIS |
| **Geodetic** | code and phase, in general 2 frequencies | 0,001 to 0,1 m / partly | post-processing software for high accuracies | surveying, precise kinematic positioning |

**Table 2**: Receiver classes and their characteristics

### 2.2 Post-processed Positioning Using Handheld GPS Receivers

As elaborated in the last chapter handheld GPS receivers are normally not suited to perform precise positioning because of the lack of carrier phase information. For some handheld receivers like e.g. the Garmin eTrex series the carrier phase is used to smooth the code observations. This means that the code and phase observations are available within the receiver in realtime but the raw data is not stored like in geodetic receivers. For Garmin receivers the raw data may be addressed through the serial interface of the receiver using the digital Garmin-specific format. A group of researchers at the Institute of Engineering Surveying and Space Geodesy of University Nottingham has decoded this Garmin-specific format. They developed a software called GRINGO (GPS RINEX Generator) that reads and decodes the data in realtime and writes the code and phase data in a RINEX formatted file To start the RINEX file generation the Garmin receiver has to be connected to a laptop or any other computer using the RS232 interface; at the receiver the GARMIN-specific output format has to be chosen and the GRINGO software has to be started on the laptop (SEMMELMANN 2003). Figure 1 shows a typical configuration including the shielding against multipath effects (see chapter 3.1).

**Figure 1:** GARMIN eTrex Vista, laptop and shielding against multipath effects

All commercial and scientific GPS post-processing software packages have the possibility to import and post-process RINEX files. This means that with the help of GRINGO phase observations of handheld GPS receivers are usable for precise positioning. Within this paper two post-processing software packages basing on double differenced observations were used: SKI-Pro (Version 2.5) of the Leica company, that is a standard commercial software package, and P4 (Pseudorange & Phase Post-Processor), that is developed of the University Nottingham to process Garmin data. The University Nottingham has made a lot of test measurements using two Garmin receivers for relative positioning. This paper focuses on the evaluation of Garmin data together with survey data of geodetic receivers.

At the Institute for Applications of Geodesy to Engineering (IAGB) at the University Stuttgart one Garmin eTrex Vista is at disposal. The Garmin receiver is the high-end handheld receiver of the eTrex series providing map display, barometer and compass. The phase and code data quality should be identical for all receivers of the eTrex series. The Garmin data is post-processed together with the data of Leica SR 530 receivers.
A specialty of the Garmin data is the occurrence of half cycle slips. SKI-Pro software is not feasible to detect these cycle slips, because it is optimized for Leica receivers that do not produce such kind of cycle slips. Consequently SKI-Pro delivers better results if it does not solve for ambiguities and cycle slips and a so-called float solution is estimated. P4 solves for half cycle slips, since it is optimized for Garmin data. Nevertheless the procedure to find and

correct for cycle slips is rather costly, but gives a fine insight into the algorithms of GPS positioning. For an inexperienced user the handling of the cycle slip correction in P4 is not practicable. SKI-Pro corrects automatically for cycle slips if requested (SEMMELMANN 2003).

**Figure 2**: Garmin eTrex Vista and adapter for tribrack

Due to the fact that handheld GPS receivers are not constructed for precise positioning the Garmin eTrex Vista cannot be fixed on a tribrack and therefore the exact definition of the antenna phase center is not available. That's why the workshop of the IAGB has constructed an adapter (see figure 2) that guarantees a reproducibility of 1 mm yielding the basis for precise positioning in general and for the antenna calibration in particular.

## 3. QUALITY INVESTIGATIONS

### 3.1 Accuracy Comparison

To have a first insight into the quality of the data tracked with the Garmin eTrex Vista receiver two measurement sessions were carried through. The first was realized on top of the IAGB building (see figure 1) lasting approximately 2 hours. The respective environment is well known for severe multipath effects, but the measurement was carried through using a simple aluminum shielding (see figure 1). At this place it should be noticed that further measurements on the institute roof without the shielding were carried through. Because of the bad quality of the positioning results, the aluminum shielding was constructed, that increases the quality of the Garmin data for multipath-rich environments. It should be kept in mind that the internal antenna and the internal software of the Garmin eTrex Vista is very sensible to multipath effects.

The second measurement was realized above grassland outside of Stuttgart (see figure 4) lasting approximately 50 minutes. Multipath effects are neglectable for this region. All Observations are tracked with a data rate of one second; the elevation mask was set to 10 degrees in post-processing. A Leica receiver was placed in the vicinity of the Garmin receiver for both sessions. The Leica receivers are placed on sites with known coordinates.
The two data sets are splitted into 5 minute blocks to evaluate accuracy and the reliability of the positioning results. To have general information the position is post-processed by three GPS positioning methods using the same data sets:

- absolute GPS using code data,
- relative GPS using code data,
- relative GPS using phase data (precise positioning).

The data was post-processed by P4 and SKI-Pro using these calculation methods. Tables 3 and 4 summarize the standard deviations that were estimated from the deviations to the given coordinates.

| | Latitude | | longitude | | height | |
|---|---|---|---|---|---|---|
| | SKI-Pro | P4 | SKI-Pro | P4 | SKI-Pro | P4 |
| Code | 7.54 | 3.43 | 4.58 | 2.26 | 7.05 | 18.50 |
| Rel. Code | 2.50 | 2.38 | 2.64 | 2.54 | 7.05 | 7.63 |
| Rel. Phase | 0.29 | 0.63 | 0.86 | 2.15 | 0.42 | 0.79 |

**Table 3:** Standard deviations for IAGB roof

| | Latitude | | longitude | | height | |
|---|---|---|---|---|---|---|
| | SKI-Pro | P4 | SKI-Pro | P4 | SKI-Pro | P4 |
| Code | 6.52 | 3.88 | 5.38 | 2.88 | 13.34 | 13.98 |
| Rel. Code | 1.44 | 1.65 | 0.75 | 1.23 | 1.16 | 1.64 |
| Rel. Phase | 0.41 | 1.59 | 2.48 | 8.95 | 0.56 | 2.89 |

**Table 4:** Standard deviations for grassland

The tables show that in general the accuracy increases from code to relative code and further on to relative phase data. Besides no obvious difference between the two measurement sessions occur showing the positive impact of the aluminum shielding. Obviously the P4 processing delivers better results than the SKI-Pro processing for code data and for most of the relative code positions. For precise positioning using relative phase data SKI-Pro is predominated. P4 has big problems to deliver high quality solutions. In any case the results do not provide accuracies one expects using geodetic receivers. The reason is the short observation time (5 minutes) of the Garmin receivers for each block. The ambiguities could not be solved correctly. Without solving the ambiguities the SKI-Pro software has the better algorithms to provide ”some-dm-accuracy”. Nevertheless the results are not reliable (e.g. SKI-Pro and P4 results for longitude on grassland). For the cases with better accuracies outliers exist nevertheless (SEMMELMANN 2003).

The analysis of the measurements show, that Garmin data blocks of 5 minutes are not suited for precise positioning. For code measurements the P4 software has to be preferred due to the use of phase-smoothed code data and the evaluation of phase observations should be done using SKI-Pro due to higher accuracy and reliability.

### 3.2 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. In reality there is only a need for the difference to the antenna offset to the reference antenna, if the antenna offset of the reference antenna is known. For the experiment carried through at the University Stuttgart the antenna offset of the Leica AT502 antenna was known and the respective one of the Garmin eTrex Vista has to be determined. For the correct determination of the offset the adapter (figure 2) has to be used and oriented correctly.
For the calibration measurements we choose an environment with little multipath effects. The Leica AT502 antenna and the Garmin receiver were installed on pillars that have known coordinates on the mm level (pillars 5 and 6 in figure 4). Both antennas were oriented to north and the receivers logged data for 2 hours 20 minutes. Thereafter the antennas were changed, oriented and again the receivers observe for 2 hours 20 minutes. The observation configuration allows two different ways to determine the antenna offset of the Garmin receiver:

- using given coordinates and
- antenna swap procedure.

First the given coordinates were used for calibration. Due to the results presented in chapter 3.1 SKI-Pro software was used for post-processing. The results of the computations for the two sessions are presented in figure 3.
The differences for the two estimations are in the mm level for the horizontal coordinates and around 1 cm for the vertical component, the height. The consistency between the two determinations is sufficient taking into account the first quality investigations of chapter 3.1. Two have a more reliable result the calibration computations are carried through using the antenna swap procedure. The results are identical within the 0.1-mm-level by the way assuring the quality of the given relative coordinates of the used pillars.

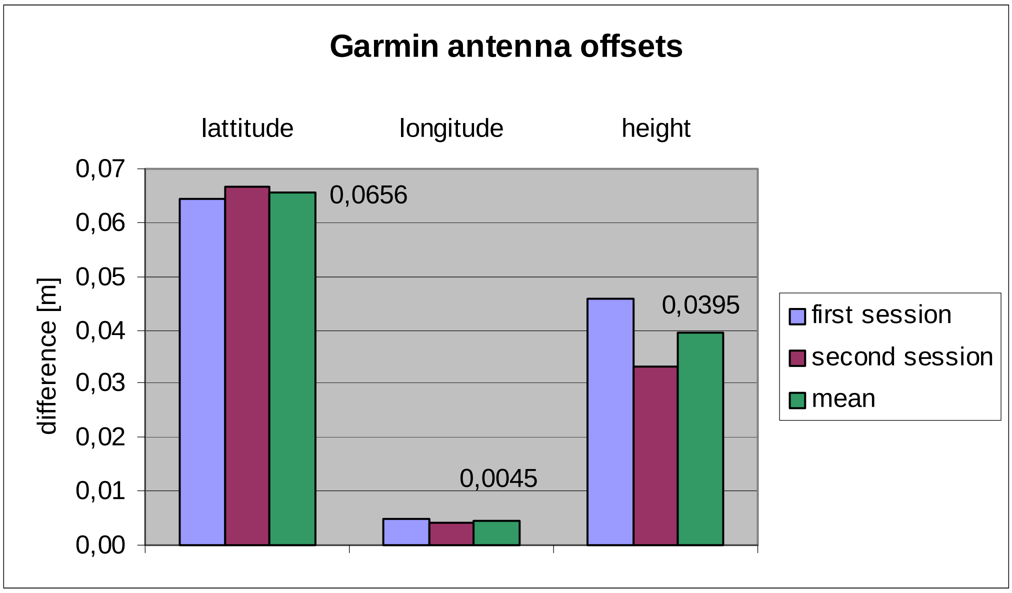



**Figure 3:** Results of antenna calibration

The estimated antenna offsets are valid if the constructed adapter is used. They may be extracted from figure 3 and are used for correction of all phase related evaluations (precise positioning), because the neglect is not allowed with respect to the magnitude of the offsets. For P4 the problem occurs that the horizontal offsets could not be considered by the software. This makes the software inconvenient for further phase related investigations.
By the way the result of this calibration show that cm-accuracies may be achieved, if the receivers observe longer than minutes. Further investigations have to prove this fact. Some are presented in the following chapter.

## 4. FURTER TEST MEASUREMENTS

### 4.1 Static Measurements

To prove respectively disprove the possibility to provide precise positioning results in static mode with Garmin data a geodetic network is observed using Leica SR 530 receivers. We choose an environment with poor multipath effects. The network is presented in figure 4. In each session one changing observation site is observed with the Garmin eTrex Vista, four other sites were observed using the Leica receivers. Pillars one, four, five, six and ten were observed within this campaign. The Garmin receiver rotates from pillar to pillar omitting pillar ten due to the continuous observation with a Leica receiver. Pillars one, four and five were observed 30 minutes, pillar six 60 minutes. Both receiving systems operate with a data rate of one second and an elevation mask of 0 degrees. The post-processing was realized by Ski-Pro using the carrier phase observations and considering the specific features described in chapter 2.2. The known respectively estimated offsets were introduced for the Leica antennas as well as for the internal Garmin antenna and the data was evaluated with an elevation mask of 15 respectively 20 degrees depending on the site environment.

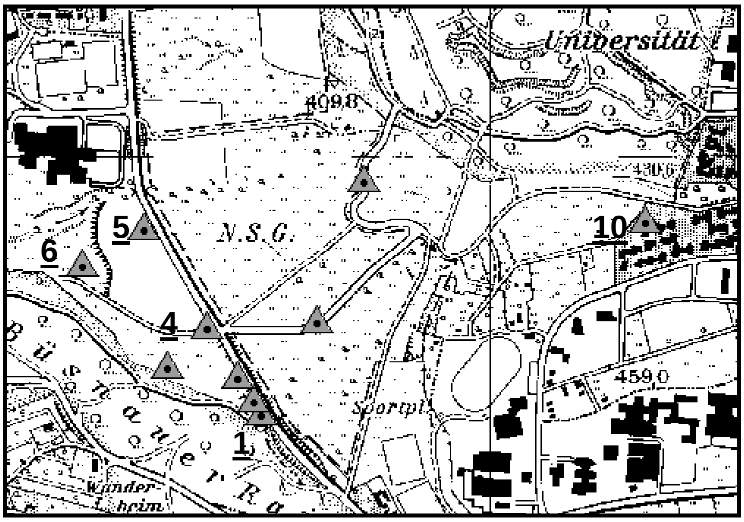



**Figure 4:** Static network with pillars, map of LVA (2003)

Figure 5 presents the deviation of the coordinates determined by the Garmin receiver to the known coordinates given with mm-accuracy. For pillar one an outlier of around 25 cm for the longitude component is observable. The reason for this problem may be seen in the vicinity to the forest area (compare figure 4), because handheld receivers track all data that it may get and, in contradiction to geodetic receivers, do not perform any quality check. Due to this reason the positioning is biased by signals that do not find the direct path from the satellite to the receiver because of their pass e.g. through leaves of trees. This effect is called diffraction.
Excluding the outlier all deviations are within a 7 cm range. This result shows that Garmin receivers may be used in a network with geodetic receivers obtaining accuracies below 10 cm in rapid static mode (observation time below 30 minutes). This result corresponds with the accuracy obtained by HILL et.al. (2001). The problem is that one have to take care about multipath (compare chapter 3.1) and diffraction. The future concept will be to choose the site accordingly or to develop own quality check algorithms using the RINEX files.

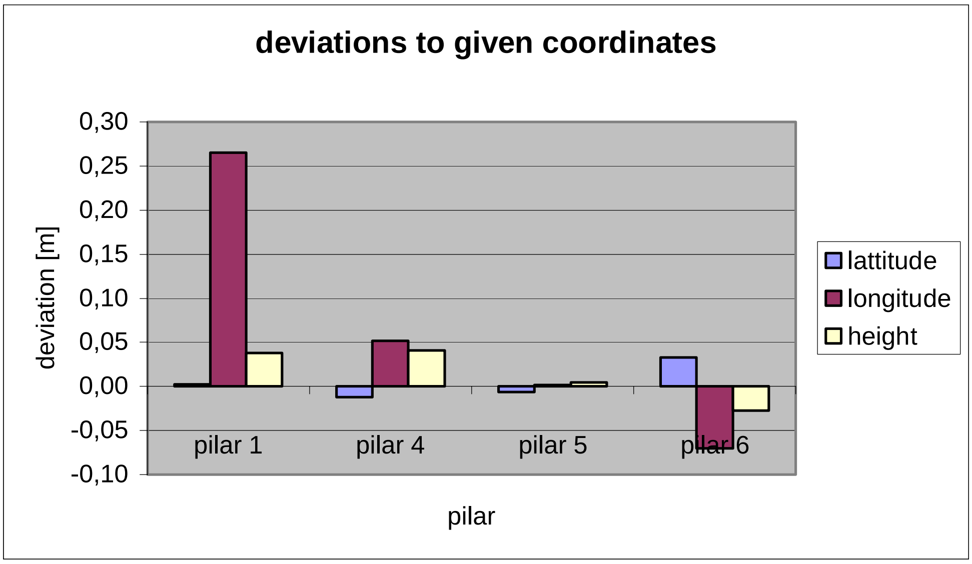



**Figure 5:** Comparison of given and Garmin based coordinates

### 4.2 Kinematic Measurements

Chapter 4.1 has shown the usability of handheld GPS receivers for static geodetic positioning. In this case accuracy and reliability is increased by the measurement period of half or one hour. In the kinematic case we have to deal with one observation at each site, since the antenna is moving.

For these investigations we fix the Garmin eTrex Vista on top of the measurement vehicle of our institute using the adapter shown in figure 2. Relative positioning was realized by computing baselines to a Leica receiver mounted on top of the IAGB building. The epoch wise baseline solution delivers the Garmin trajectory for the moving vehicle. To get a reference trajectory a Leica receiver tracks data in the vehicle too and its antenna was mounted on top of the measurement vehicle.

The data was post-processed with P4 as well as with SKI-Pro. The first allowing relative code-solution only, the latter providing phase solution if available and code solution in the other cases.

The presented test drive covers different environments like urban canyons in downtown Stuttgart, hillsides and wine yards as well as open country. Figure 6 presents the test area and the Garmin trajectory post-processed by SKI-Pro. The blue spot illustrates the location of the reference receiver.

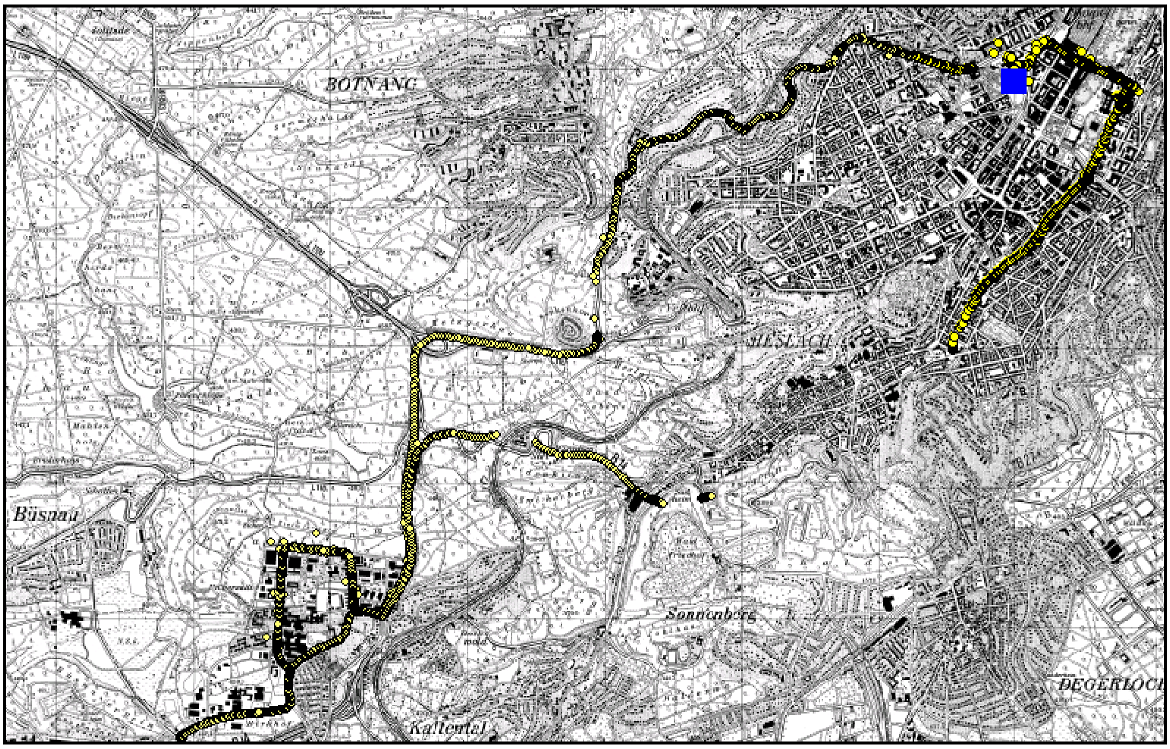



**Figure 6**: Kinematic test area and SKI-Pro-processed trajectory; map of LVA (2003)

A first visual inspection shows that most of the trajectory points are located on the streets and roads shown on the topographic map. Obviously only a few outliers occur; this is valid for the urban canyons too.

Exemplary figure 7 shows in detail the behavior of the two post-processed solutions for a motorway access. The measurement vehicle has passed the access point two times. The blue point show the reference trajectory, the left figure presents the SKI-Pro evaluation in yellow points and the right figure presents the P4 evaluation in orange points. The visual inspection shows a quite homogeneous course of the trajectories. In comparison to the reference trajectory the SKI-Pro evaluation shows less deviations.

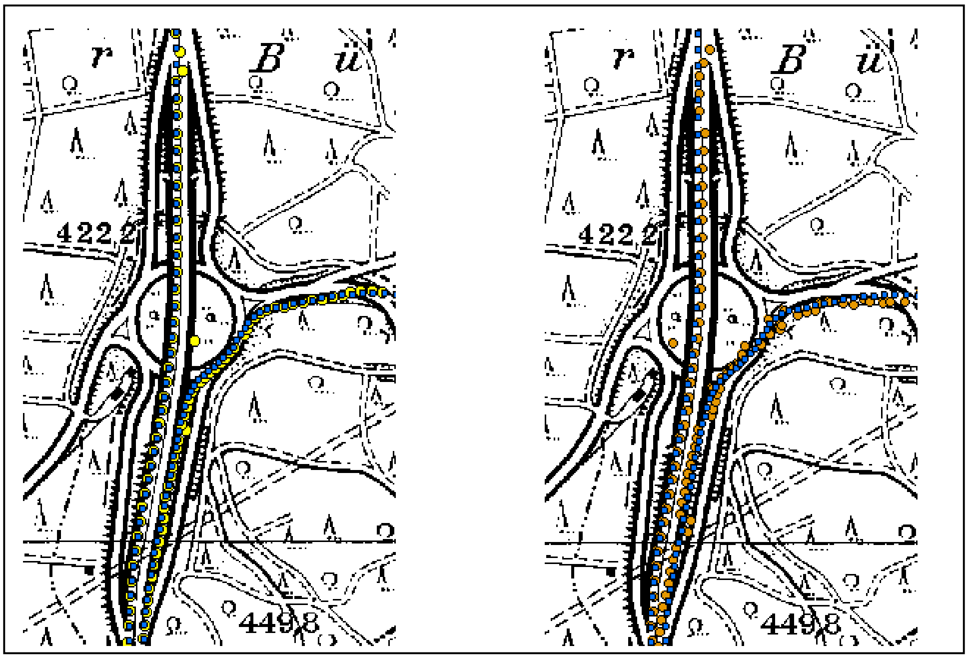



**Figure 7:** Deviation between reference trajectory and SKI-Pro processed (left) and P4 processed (right) Garmin trajectory; map of LVA (2003)

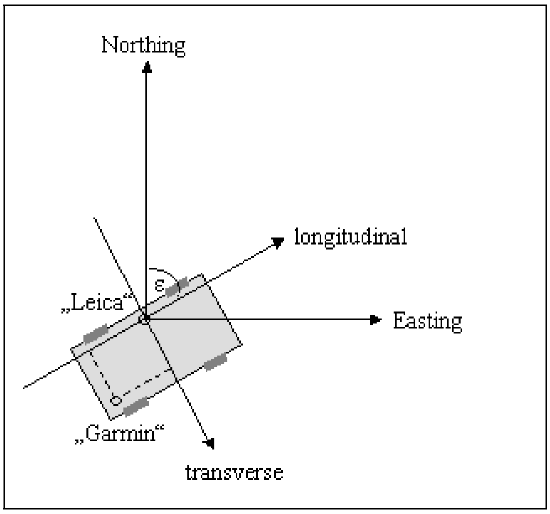
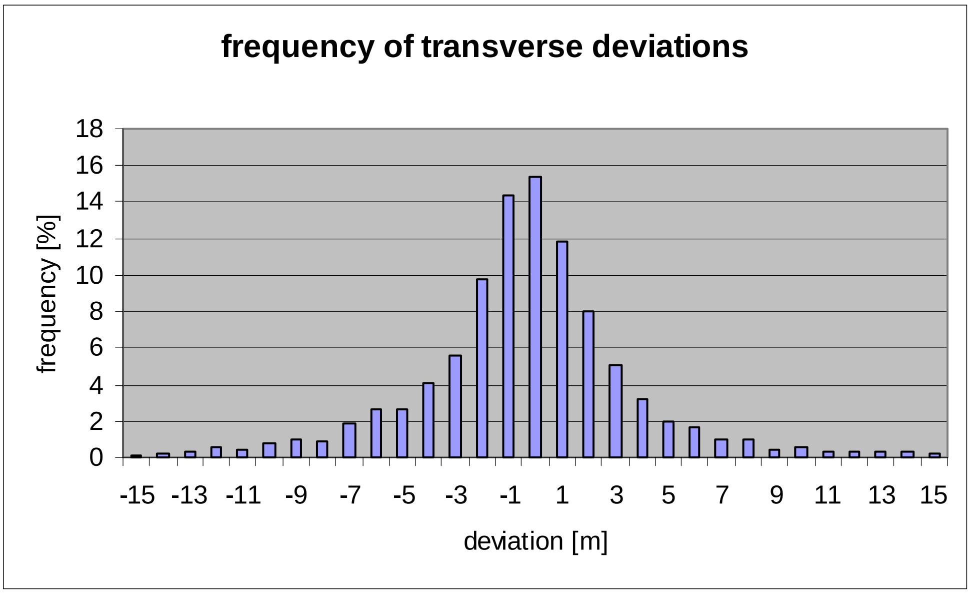



**Figure 8:** Local horizontal and vehicle coordinate system

These visual inspections have to be verified numerically. For this aim the coordinates of the reference as well as of the Garmin trajectory has to transformed into two-dimensional horizontal coordinates (Northing and Easting). After computing the orientation of the vehicle in the two-dimensional horizontal coordinate system using the grid bearing ε determined from the reference trajectory the coordinates are rotated into the vehicle coordinate system (coordinate axes: longitudinal and transverse; see figure 8). The Garmin trajectory is corrected by the known offset between the Leica and the Garmin receiver. Hereafter the deviations are computable for each epoch in the vehicle coordinate system as well as in the horizontal coordinate system.

In general the computed deviations in transverse and longitudinal direction are within the 15 m range for around 97 % of the available epochs. As expected the height component has a poorer frequency distribution. As the height is less important for most kinematic purposes, it will be not shown here. Figure 9 gives an example for the deviations in the vehicle coordinate system based on the SKI-Pro solution of the Garmin trajectory.



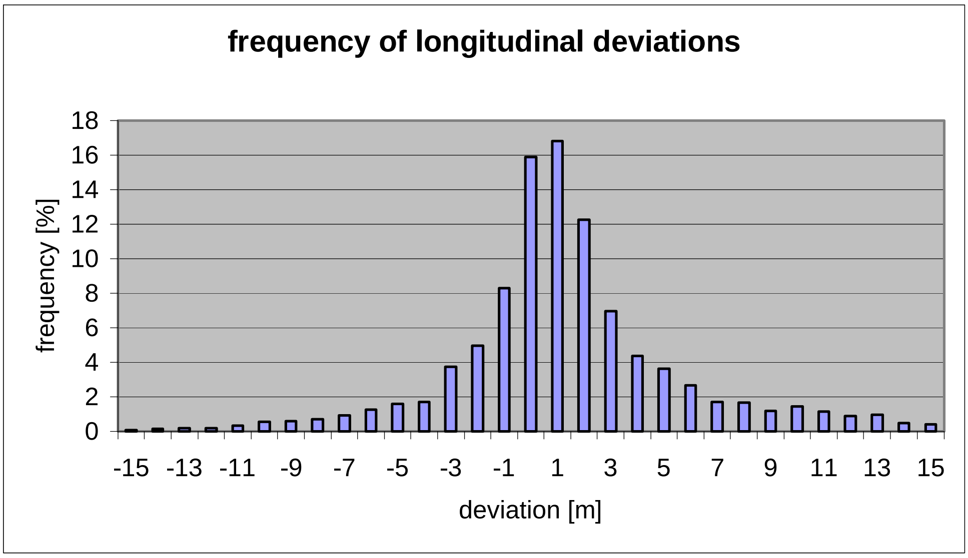




**Figure 9:** Frequency of deviations in vehicle coordinate system

Table 5 summarizes the results in terms of standard deviations. The table shows at first the determined standard deviations including all observed positions. No apparent differences are visible between the two post-processed solutions.

If we start from the assumption that we use filter algorithms to find outliers in the data the computation of the standard deviations have to be repeated excluding these outliers. It is assumed that the filter algorithm would identify an outlier larger than 15 m. After excluding all values above 15 m deviation to the reference trajectory the corrected standard deviation are presented in the second part of table 3 (indicated by corr.). In this case the SKI-Pro processed solution shows slightly better results. The availability column indicates the availability of the Garmin trajectory with respect to the Leica reference trajectory. If all deviations are included into the computation of the standard deviation, the availability has to be 100 %. If the deviations larger 15 m are excluded, the number of excepted solutions is reduced to 97.2 % for SKI-Pro and to 95.2 % for P4. This result means that accuracy and availability is reduced using the P4 evaluation, SKI-Pro has to be preferred.

| Standard Deviation [m] | Transverse | Longitudinal | Northing | Easting | Availability |
|---|---|---|---|---|---|
| SKI-Pro | 9.33 | 8.99 | 9.43 | 9.01 | 100 % |
| P4 | 9.46 | 8.78 | 9.07 | 9.18 | 100 % |
| corr. SKI-Pro | 4.02 | 4.22 | 4.64 | 3.95 | 97.2 % |
| **corr. P4** | **5.02** | **5.05** | **5.42** | **4.74** | **95.2 %** |

**Table 5:** Standard deviations and availabilities for different solutions

Generally the kinematic accuracy does not reach the precise position level. The phase information does not help to reach this accuracy. It seems to be that post-processing does not show better results than realtime kinematic positioning with handheld receivers. The obtained accuracies correspond with the accuracies of HILL et.al. (1999) and MOORE et.al. (2002) obtained using only Garmin receivers for kinematic positioning for slow movements.

## 5. CONCLUSION

The GRINGO and the P4 software packages function without problems. P4 is well suited for post-processing code data in absolute and relative mode. The SKI-Pro software deliver better results for phase observations, although fixing of ambiguities is not possible due to the occurrence of half cycle slips in the Garmin data.
The aim to use handheld GPS receivers for precise positioning together with geodetic receivers could be reached only for the static case. If obstructed sites and multipath and diffraction effects are avoided, accuracies of geodetic receivers are attainable using the phase signal for post-processing. If the conditions are fulfilled accuracies below 10 cm can be ensured. If the conditions are less comfortable accuracies around 1 m may be obtained. This makes this handheld GPS receiver a perfect tool for the acquisition of data for Geo-Information systems using the static mode.

The kinematic post-processed positions are restricted to accuracies of the DGPS level to around 5 m. The phase information does not help to estimate more accurate solutions. GIS data acquisition is possible for limited accuracies only.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**BIOGRAPHICAL NOTES**

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| 1991 – 2000 | Scientific associate at Geodetic Institute, University Hannover |
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