High-Sensitivity GPS
– an Availability, Reliability and Accuracy Test

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Key words: GPS, High-Sensitivity GPS, Low Cost Techniques

SUMMARY

High-Sensitivity GPS receivers shall deliver positions in shadowed areas as well as inside buildings due to their sensitivity with respect to GPS signals with a power ratio below -150 dBm. The paper shows a comparison for three high-sensitivity GPS receivers used in static mode regarding availability, reliability and accuracy in areas with free horizon, in shadowed areas as well as indoor. The investigations show that the availability rate indicates more than 90 % for shadowed areas. Inside buildings with low attenuation and in rooms with windows the availability ranges between more than 70 % and 18 % depending on the receicer type.

For free horizon conditions the reproducability standard deviation shows values between 3.75 m and 7.33 m. Inside buildings the respective standard deviation is degraded to more than 80 m. More inside the building, e.g. in a windowless room or a cellar, no GPS signals are received.

Additionally kinematic measurements were carried through too. Here the availability reaches values of around 97 % for the track including shadowed areas and even tunnels. The reproducability standard deviation indicates values between 4.92 m and 12.22 m. Obviously the kinematic results are more accurate than static results, due to a filter for the positions using a movement model.

ZUSAMMENFASSUNG

High-Sensitivity GPS-Empfänger sollen sowohl in abgeschatteten Bereichen als auch innerhalb von Gebäuden Positionen liefern, da sie GPS Signale mit einem Leistungsverhältnis kleiner als -150 dBm verarbeiten können. In diesem Beitrag werden drei High-Sensitivity Empfänger hinsichtlich Verfügbarkeit, Zuverlässigkeit und Genauigkeit für die Umgebungen: freier Horizont, starke Abschattungen und innerhalb von Gebäuden verglichen. Die Untersuchungen zeigen Verfügbarkeitsraten von mehr als 90 % für abgeschattete Bereiche. Innerhalb der Gebäude mit geringer Signaldämpfung und in Räumen mit Fenstern werden in Abhängigkeit vom Empfängertyp Verfügbarkeitsraten zwischen 70 % und 18 % erreicht.

Bei freiem Horizont ergeben sich Vergleichsstandardabweichungen zwischen 3,75 m und 7,33 m. Innerhalb der Gebäude verschlechtern sich diese Werte bis auf über 80 m. Geht man weiter in die Gebäude hinein, z.B. in fensterlose Räume oder Keller, so können keine GPS Signale mehr empfangen werden.

Zusätzlich wurden kinematische Messungen durchgeführt. Hier erreichte die Verfügbarkeit Werte von etwa 97 % für die Fahrt, die sowohl abgeschattete Bereiche als auch Tunnel umfasst. Die Vergleichstandardabweichungen ergeben Werte zwischen 4,92 und 12,22 m. Offensichtlich sind die kinematischen genauer als die statischen Ergebnisse. Dies liegt an einem Filter, das die Positionen mittels eines Bewegungsmodells glättet.

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1. MOTIVATION

Satellite-based positioning has been developed and is still developing towards a general tool for surveyors all over the globe. But still the restrictions have to be mentioned: free line-of-sight to minimum four satellites. For real time solutions requiring phase data even five satellites have to be tracked. The dream of each surveyor would be to avoid these problems and have something like indoor GPS or GNSS.

Since some years the so called High-Sensitivity (HS) GPS receivers are on the market. They show a higher sensitivity with respect to weak GPS signals. In general the possibility to track signals inside forests, cars and even buildings is given. But this ability is restricted to the use of non-line-of-sight signals that may be reflected and attenuated. Thus leading to decrease of accuracy and reliability. In this paper the author has investigated the availability, the reliability and the accuracy of three HS GPS receivers in static and kinematic scenarios. An insight into the possibilities to use the technology for indoor positioning as well as for trajectory determination for vehicles in urban canyons is given. Positioning for surveying tasks that require mm to dm accuracy level will not be treated in this paper.

2. HIGH-SENSITVITY GPS

2.1 Basics

The GPS Interface Control Document (ARINC, 2000) defines the minimum GPS signal strength for a user on the earth surface. For C/A-code this is defined with -130 dBm. This value may be reached only, if no attenuation occurs. In reality the GPS signals are attenuated e.g. by the atmosphere, trees, buildings.

Tab. 1: Attenuation for different building material for 1 500 MHz (Eissfeller et al. 2006*)*

material	**attenuation [dB]**
dry wall	1
plywood	1 - 3
glass	1 - 4
shaded glass	10
construction timber	2 - 9
steel fabric mats	2 - 11
brick	5 - 31
concrete	12 - 43
reinforced concrete	29 - 33

According to WIESER & HARTINGER (2006) the attenuation may reach values about 5 dB in cars, up to 20 dB in buildings and more that 25 dB in subterranean garages. EISSFELLER et al. (2006) indicate attenuation values for building materials (see table 1). They complement the ones given before. These attenuation values lead to the problems occuring with the acquisition of GPS signals inside buildings. “Normal” GPS receivers, especially GPS receivers for geodetic applications, do not work indoor, because the sensitivity is not sufficient to track signals with low dBm values. The HS GPS receivers acquire signals below -150 dBm assured by a longer integration time, non-coherent integration and a high number of parallelly working correlators. Further information may be found e.g. in WIESER & HARTINGER (2006).

2.2 Exemplary Receivers

In 2006 the Institute for Applications of Geodesy to Engineering (IAGB) has procured three HS GPS receivers reflecting the latest technologic developments: u-blox LEA-4T, SiRFstarIII and Fastrax iTrax03-S. These receivers showed the highest sensitivity at the time of purchase. Table 2 shows the different characteristics of the three receivers and figure 1 presents the hardware including receiver, antenna, cables and boxes indicating that the investigations have been made with the evaluation kit delivered by the respective companies. The table has been compiled using information of the producers (U-BLOX 2007, SIRF 2007, FASTRAX 2007). The values for the sensitivity differ between -159 dBm for the SirFstarIII and 156 dBm for the Fastrax iTrax03-S. All receivers use the phase observable L1 and the C/A code for real time positioning. The u-blox receiver has two advantages: the number of channels allowing to track more satellites simultaneously, and the possibility to store the phase data on a computer, a PDA or even a data logger. The second feature is important for the post-processing precise positioning task (e.g. SCHWIEGER, WANNINGER 2006) currently investigated at IAGB. This research is beyond the scope of this paper.

Tab. 2: Characteristics of investigated HS GPS receivers

Receiver	**u-blox LEA-4T**	**SiRFstarIII**	**Fastrax iTrax03-S**
Tracking-Sensitivity	-158 dBm	-159 dBm	-156 dBm
Signals	L1, C/A Code	L1, C/A Code	L1, C/A Code
Cold Start	34 s	35 s	40 s
Warm Start	34 s	15 s	33 s
Hot Start	< 3.5 s	< 1 s	4 s
Number of channels	16	12	12
Output of phase data	yes	only with special agreement of SiRF	no
Protocoll	NMEA, UBX Binary, RTCM	NMEA, SiRF Binary	NMEA, iTalk Binary

Intermediate results for real time navigation solutions for these receivers regarding static code measurements were presented in SCHWIEGER (2006). In this paper results of static as well as kinematic measurements are reported. Since the procurement of the three receivers the technologic development has been gone further; e.g. the company u-blox has developed u-blox 5 chips having a sensitivity of 160 dBm, so that a further improvement of availability is expected (U-BLOX 2008). Nevertheless the comparison of the three receivers will give a good insight into the performance of HS GPS.

Fig. 1: Investigated high-sensitivity GPS receivers (top down: u-blox, SiRF, Fastrax)

As to be seen in table 2 all receivers support the output format NMEA developed by the National Marine Electronics Association. This is the standard for navigation applications. Additionally proprietary formats of the producers are supported. For the investigations the NMEA strings (NMEA 2007) are used for SiRF and u-blox. The coordinates are extracted of the GPGGA string. This string includes e.g. information regarding the sort of the solution (not valid, GPS or DGPS), and the accuracy criteria “Horizontal Dilution of Precision” (HDOP) as well as the number of satellites in view, if a free horizon is assumed. These additional information may be used to analyse the solutions and find e.g. reasons for outliers or bad quality data in general. Additionally the GPGSA and the GPGSV strings are stored. The first delivers information about the satellites really used for the determination of the coordinates. The excluded satellites may be shadowed by obstructions like buildings, or the quality of the data is so bad that the internal algorithms eliminate the data. The second string provides for each satellite the azimuths and elevations as well as the signal-to-noise-ratios (SNR) as a second quality criteria. For the Fastrax receiver the propriety format is used and the required information is extracted by matlab-files provided by the producer.

3. STATIC POSITIONG

3.1 Measurement Concept and Realisation

Main topic of the investigation is the determination of the availability of the HS GPS receivers in shadowed and strong multipath areas as well as indoor environments. The study of reliability and accuracy of the coordinates is of importance too. For this reason sites were chosen to cover different attenuation values and different shadowing effects. Figure 2 shows the location of the sites outdoor and indoor. The building sketched in figure 2 is built using concrete leading to attenuation values of 12 to 43 dB (compare table 1).
Figure 3 presents the adapter used for the measurements, and figures 4 to 6 show the different environments. The adapter guaranties that the receivers may measure simultaneously almost at the same place. The position difference is at the 10 cm level and therefore negligible for the accuracy levels discussed in this paper.

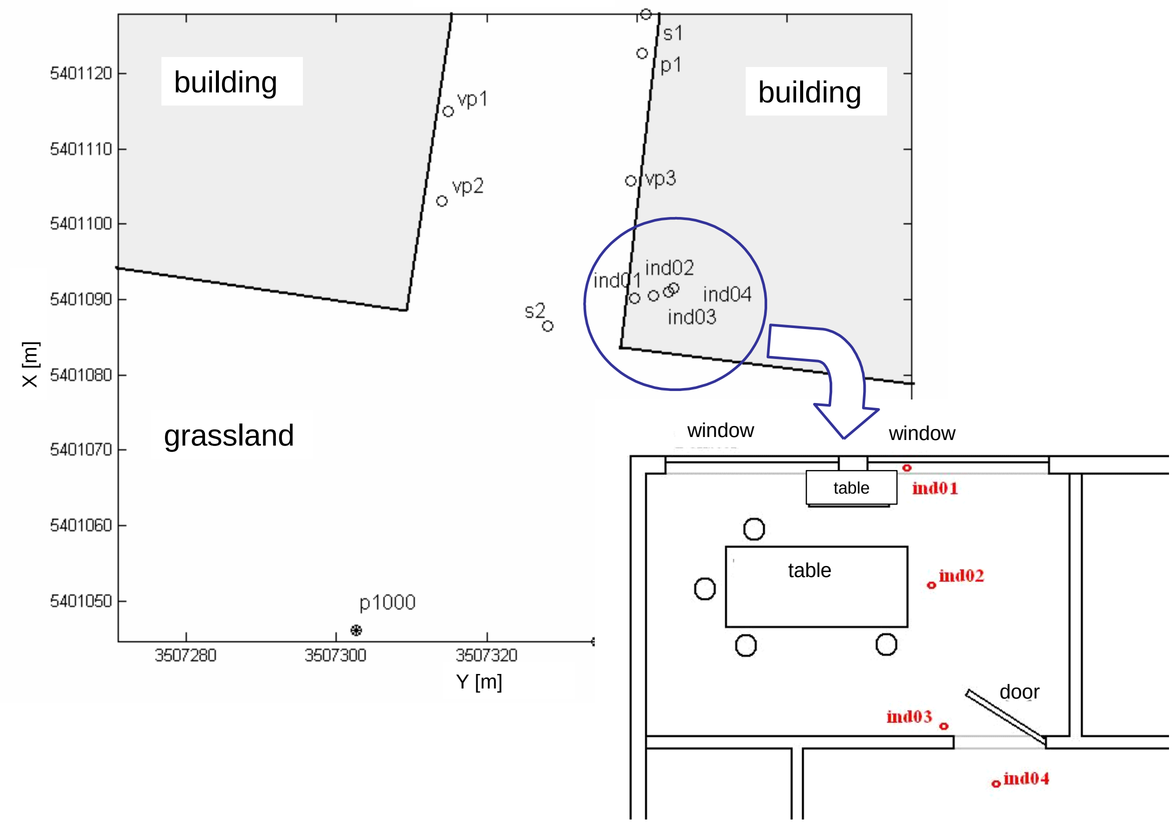

Fig. 2: Sketch of measurement sites

For reliability and accuracy analysis the coordinates of all measurement sites have to be known with superior accuracy. For this task all sites presented in figure 2 are measured using geodetic GPS receivers and a tachymeter. The accuracy is around the cm level (compare SCHWIEGER 2006). All site occupations were carried through in 30 minutes and were repeated a second time to get to an affordable extend independence from the satellite configuration. The sampling interval was set to 1 second.

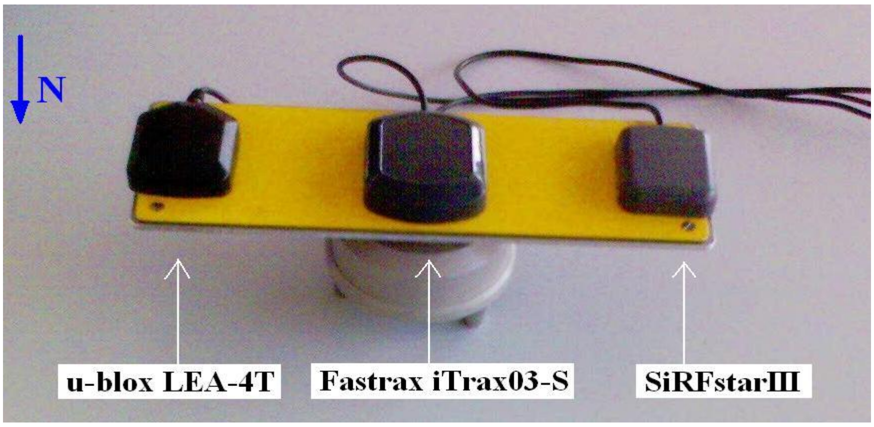

Fig. 3: Adapter for HS GPS receivers

Fig. 4: Site with free horizon (p1000 / left) and shadowed site (vp1 / right)

Fig. 5: Indoor sites (left: at window / ind01, right: windowless room / ind04)

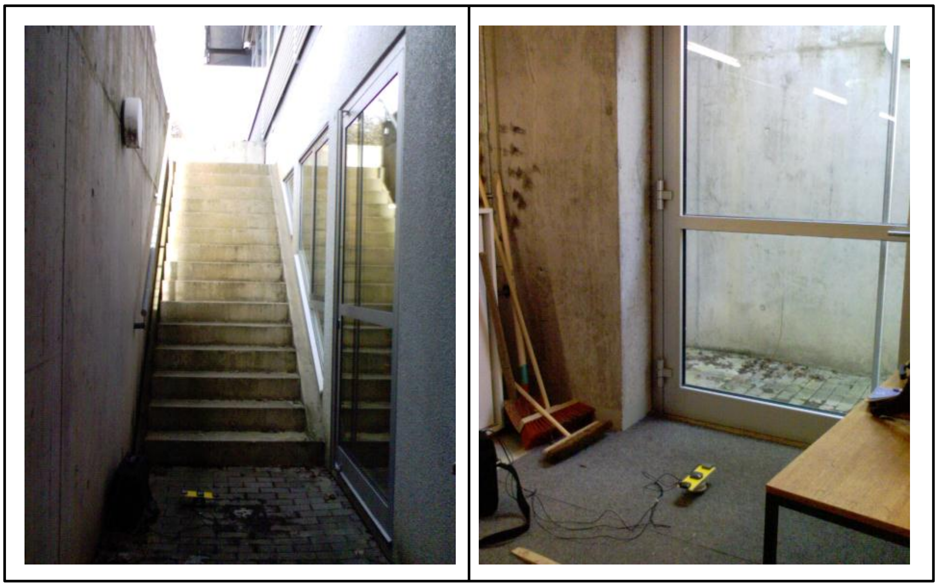

Fig. 6: Cellar sites (left: staircase point / s1, right: inside cellar / p1)

3.2 Quality Criteria and Parameters

In general the paper aims at the quality appraisal and comparison of the three different HS GPS receivers. The quality criteria relevant for geodetic and navigation issues are availability, reliability and accuracy. Reliability may be called correctness, too.
Availability is the probability or the measure that a system delivers a specified complete information at the right time. Here are the three dimensional coordinates delivered with a sampling rate of 1 second are this information. The availability quality parameter is the availability rate in percentage:

$$A[\%] = \frac{T_t - T_n}{T_t} \cdot 100, \qquad (1)$$

with T_t total measurement time,
T_n measurement time without coordinates.

Correctness or reliability describes the ability of a system to deliver information corresponding to the reality. Here the deviations between measured and given coordinates should not exceed a limit specified to three times the standard deviation. The reliability quality parameter is the reliability rate in percentage, whereby the percentage value is referred to the number of available measurements n_a taken within the time $T_a = T_t - T_n$:

$$R[\%] = \frac{n_{3\sigma}}{n_a} \cdot 100, \qquad (2)$$

with $n_{3\sigma}$ number of observations within the $3 \cdot \sigma$ limit.

Accuracy describes the random difference between measured and given values. Here the standard deviation of the measured coordinates is determined. The repeatability standard deviation s_{in} is related to the average, and the reproducibility standard deviation s_{ou} is related to the given true coordinates. Thus the latter includes systematic (described by the reliability too) and random errors (described by the repeatability standard deviation too). Both parameters are computed using $n_{3\sigma}$ measurements and are given in the following equations:

$$s_{in} = \sqrt{\frac{1}{n_{3\sigma}-1} \cdot \sum_{i=1}^{n_{3\sigma}} (x_i - \bar{x})^2}, \qquad (3)$$

$$s_{ou} = \sqrt{\frac{1}{n_{3\sigma}} \cdot \sum_{i=1}^{n_{3\sigma}} (x_i - \mu_x)^2}, \qquad (4)$$

with
- x_i single measurement value (here: coordinate),
- $\bar{x}$ average,
- μ_x expexted value of observation.

3.3 Results of Investigations

The three quality criteria are separated with respect to three categories: free horizon, shadowing and indoor (compare table 3). The results of the single points are averaged to get an overall picture of the investigations. The cellar sites shown in figure 6 could not be measured due to high attenuation values. They are not included in the following analysis.

Tab. 3: Environment categories and allocated point numbers for static measurements

category	point numbers	remarks
free horizon	p1000, p1001	p1001 not visible in figure 2
shadowed area	s1, p1, vp1, vp2	includes almost shadowed points as well as multipath environments
indoor	ind01, ind02, ind03, ind04	ascending point numbers with longer distances from window

Tab. 4: Availability rates for static measurements

availability rate [%]	SiRF	u-blox	Fastrax
free horizon	100	100	99.5
shadowed area	99.6	92.6	93.6
indoor	71.6	42.2	18.1

Table 4 shows the availability rate for three dimensional coordinates. For the two dimensional case a slight increase of the rate is obtained (MAO 2007), but the general statements of the analysis are not different, so that these results are not presented here. The availability rate shows values of more or less 100 % for free horizon and higher than 90 % for shadowed areas. For the second environment the SiRF receiver outclasses the two other ones. This is even more valid for the indoor case. The SiRF receiver performs much better than the other two: more than 70 % availability in relation to around 40 % or even 16 % for the Fastrax receiver.

Table 5 shows that the reliability rate, with other words the ability to protect against outliers, is excellent even under bad GPS conditions. For all scenarios the values are larger than 98.7 %, meaning that 98.7 % of all measurements are within a sphere around the reference point coordinates. The differences among the receivers are negligible.

Tab. 5: Reliability rates for static measurements

reliability rate [%]	SiRF	u-blox	Fastrax
free horizon	100	99	99.8
shadowed area	100	100	99.9
indoor	99.4	99.5	98.7

Tab. 6: Repeatability and reproducibility standard deviations for exemplary sites

standard deviations [m]	SiRF		u-blox		Fastrax	
	repeat	reproduce	repeat	reproduce	repeat	reproduce
free horizon	2.74	7.33	2.65	5.17	1.70	3.75
shadowed area	7.41	34.69	17.42	36.69	16.80	36.78
indoor near window	18.37	41.36	36.54	48.30	33.49	51.86
indoor room middle	54.54	88.11	37.21	60.90	-	-

Table 6 presents the repeatability and reproducibility standard deviations for selected sites p1000, vp02, ind01, ind02. Due to the fact that the repeatability standard deviations contain random effects only and therefore are too optimistic, the reproducibility standard deviations will be discussed here only. In any case the general trend is the same. The standard deviations for free horizon environment are between 3.75 m and 7.33 m. They correspond to the values given in literature for HS GPS receivers (WIESER et al. 2005) as well as for "normal" navigation receivers (e.g. RAMM, SCHWIEGER 2004). The Fastrax receiver delivers the best results, due to the low sensitivity preserving him from tracking signals of low strength and, probable, low quality. In contradiction the SiRF receiver tracks signal of low strength. This increases the availability (see table 4), but degrades the accuracy due to low quality signals used for positioning. If shadowed areas or even indoor environments are investigated, the standard deviations rapidly decrease to values of 30 m up to more than 80 m. These standard deviation are better than the ones reported by Collin et al. (2003), but they are approximately at the same level. Figure 7 shows typical positions (blue) around the given reference coordinate (red cross) for the point vp2, shadowed and disturbed by multipath effects. Obviously the position average does not coincide with the true value indicated by the red cross. The Fastrax receiver do not track any satellite inside the room. The only indoor position was determined near the window.

Due to the fact that reliability and accuracy dependent on each other, the very good values for the reliability rates do not need to attach importance. The bad standard deviations are one reason for the good reliability rates.

No reproducible influence of the HDOP value, the number of tracked satellites, or the minimum elevation of the tracked satellites on the position quality can be shown. But a low minimum SNR results in a low position quality for most of considered cases. More details may be found in MAO (2007).

Altogether it may be summarized that obviously positioning near or inside buildings is possible but not with a high accuracy. Room-accurate positioning by GPS is impossible using current technology.

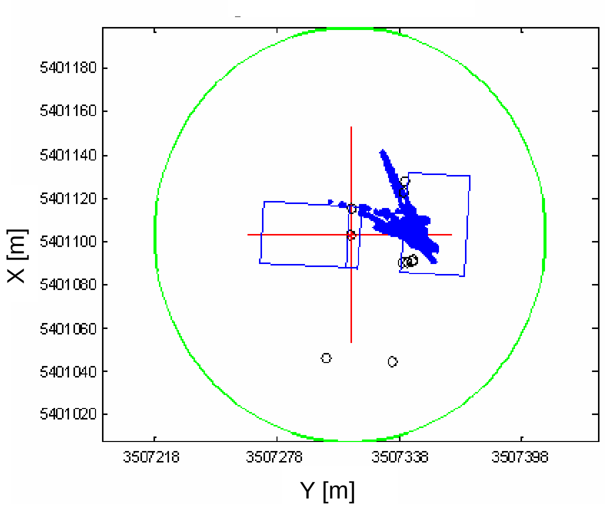

Fig. 7: Measured positions (blue) and true position (red) for point vp2 in shadowed area

4. KINEMATIC POSITIONING

4.1 Measurement Concept and Realisation

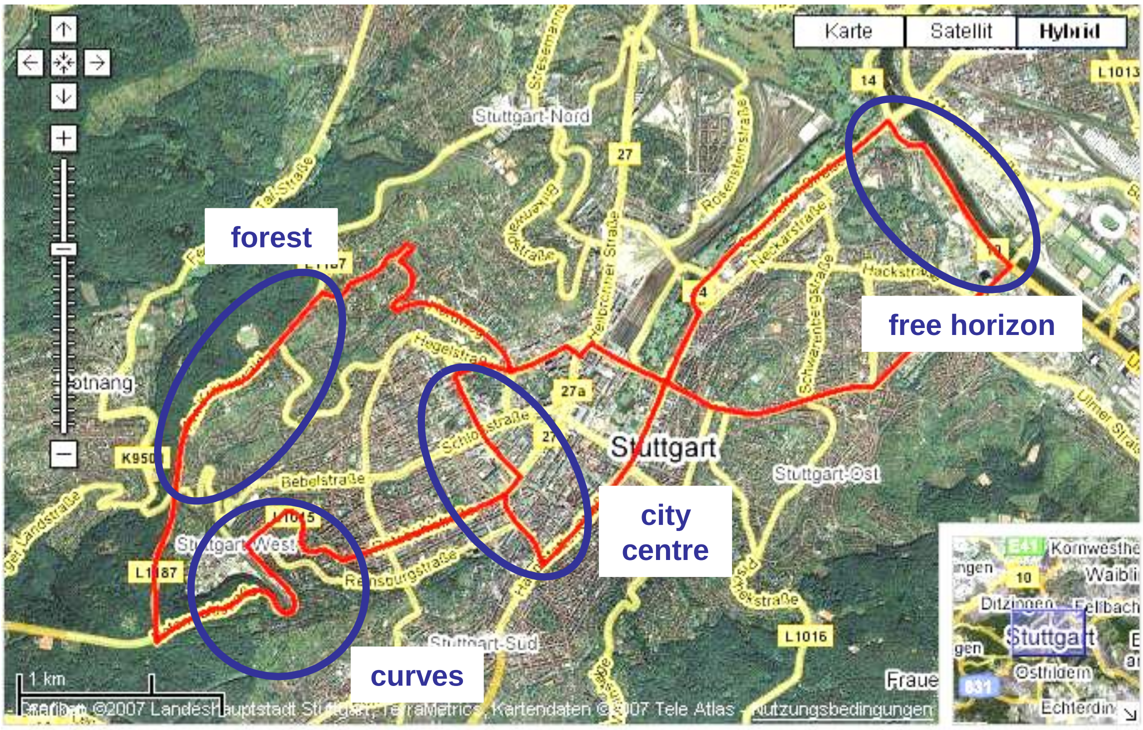

Fig. 8: Kinematic track and different environments

In a second step the quality of moving receivers should be investigated. For this purpose the three HS GPS receivers are mounted on the IAGB measurement vehicle, a Mercedes Sprinter. The sampling rate was chosen to 1 second again. Additionally a Leica SR530 receiver was mounted on the top of the vehicle. The geometric differences between the four receivers are of no importance for the determination of the quality parameters. The Leica receiver was used for determining the reference trajectories, if available. The availability of the Leica solution is strongly reduced, since phase signals of high quality are required. Therefore two different standard deviations have to be determined (see section 4.2) for evaluating the accuracy.

The investigation scenarios cover different environments typical for kinematic drives: free horizon, city centre (urban canyons), forest, narrow curves, underpasses and tunnels. Figure 8 shows the whole track and the most important environments.

4.2 Quality Criteria and Parameters

The availability and the reliability rates are determined as described in section 3.2, equations (1) and (2). For the reliability one has to take into account that reference trajectories are available for a part of the total time only (for concrete value see table 7).

The repeatability accuracy according to section 3.2 cannot be computed, since averages cannot be determined. Regarding reproducibility accuracy equation (4) is used for time periods where the reference trajectory is available. For time periods without reference trajectories, which is clearly more than half of the time, a standard deviation is computed using double differences:

$$s = \sqrt{\frac{1}{2n} \cdot \sum_{i=1}^{n} (x_i^1 - x_i^2)^2}, \qquad (5)$$

with
n number of measurements,
x_i^1 single measurement of receiver 1,
x_i^2 single measurement of receiver 2,
both measurements simultanously.

Due to the fact that no reference values exist, a clear statement regarding repeatability or reproducibility conditions cannot be given, since it remains unknown, whether systematic errors are included in the accuracy measure. If the different HS GPS receivers have different systematic errors, the standard deviation would be a reproducibility value. If they show the same systematic effects, the result would be a repeatability standard deviation. In any case by this way standard deviation for three receiver combinations could be determined. This may give hints concerning best and worst receiver.

4.3 Results of Investigations

The track has been driven two times for all the scenarios. The information in the following tables is based on an average of the respective two drives. The table showing the availability rate is enlarged by the values for the Leica reference receiver thus indicating the large difference between a geodetic GPS receiver and a HS GPS receiver. The GPS reference receiver shows an availability rate of around 20 % for the total track. In contradiction all HS GPS receivers deliver values better than 97 %. These values include tunnel and underpasses, so that almost 100 % is reached for areas where GPS signals are receivable. The difference gets even larger, if the two curve drives are analysed. These drives are carried through in a shadowed area. The three different HS GPS receivers show no significant differences.

Tab. 7: Availability rates for kinematic measurements

availability rate [%]	**Leica**	**SiRF**	**u-blox**	**Fastrax**
total track	20.5	97.4	97.6	97.1
curves (slow drive)	10.2	100	100	100
curves (fast drive)	0	100	100	99.8

Tab. 8: Reliability rates for kinematic measurements

reliability rate in %	**SiRF**	**u-blox**	**Fastrax**
total track	100	100	99.5
curves (slow drive)	100	100	100

The reliability rate is again, as for the static case, excellent. Please keep in mind that these values are determined for the time periods, where the reference trajectory is available. This means that the quality of the signals is very good by this way allowing accurate and reliable code solutions of the HS GPS receivers too. Due to this reason the good results should not be overrated. For the fast curve drive reliability cannot be computed, since no reference trajectories are available (see table 7).

As written in 4.2 the author distinguishes between standard deviation calculated versus reference trajectory and using double differences. Due to the fact that the reference trajectory is estimated using phase observations, it shows an accuracy of cm to dm level. Therefore it may be used as reference. For these accuracy parameters the u-blox receiver obviously has the best accuracy and, if compared to 3.3 the standard deviations, are even better than for the static measurements. For this purpose two reasons are given in the following. One is that only time periods with good data quality are compared, since phase data solutions with Leica receivers are possible. On the other hand it can be assumed that kinematic measurements are supported by a filter algorithm working correctly only in the case of movement. This assumption can be exemplarily verified, if typical trajectories at an intersection including a stationary phase are presented. Figure 9 shows this behaviour exemplarily for the SiRF receiver. The same could be shown for the Fastrax and with less influence for the u-blox receiver. Additionally it is visible that the trajectories are very smooth. There is no shape difference with respect to the reference trajectory.

F**ab. 9:** Reproducibility stand. dev. for kinematic measurements (using reference trajectories)

standard deviation [m]	**SiRF**	**u-blox**	**Fastrax**
total track	7.85	4.92	6.31

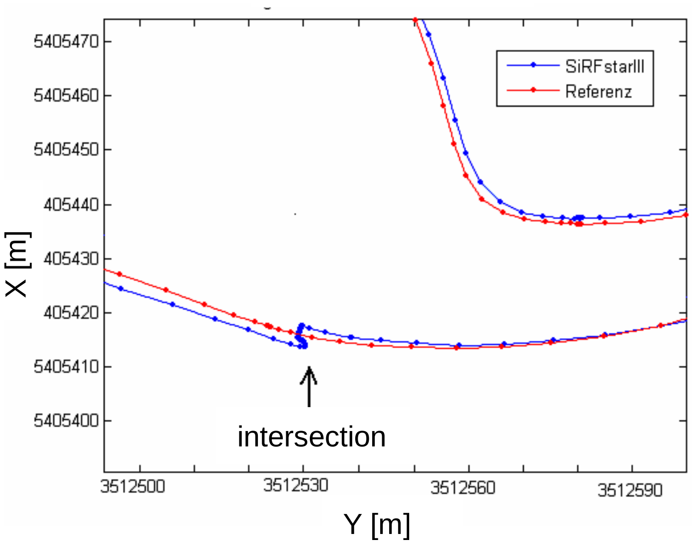

Fig. 9: Error at intersection for SiRF receiver

Tab 10: Standard deviations for kinematic measurements (using double differences)

standard deviation [m]	SiRF / u-blox	u-blox / Fastrax	Fastrax / SiRF
total track	10.67	10.83	12.22
curves (slow drive)	10.37	15.46	13.43
curves (fast drive)	13.93	19.34	25.10

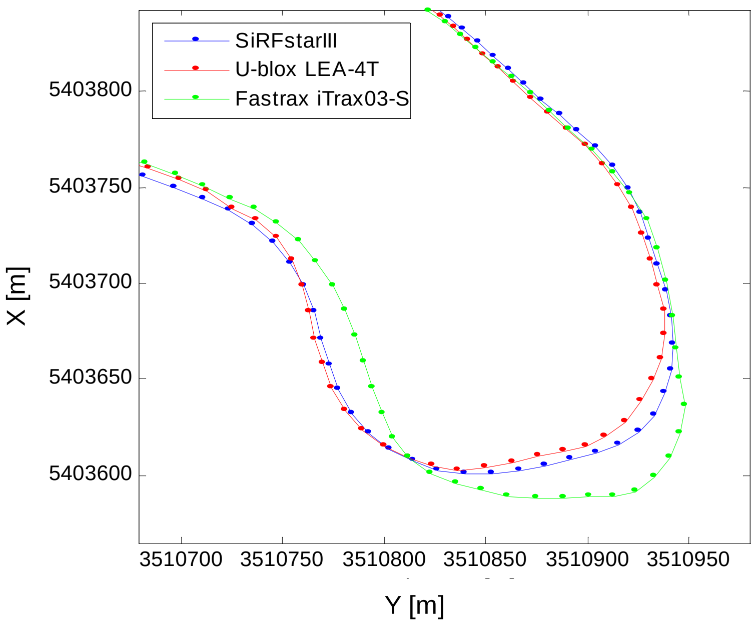

Fig. 10: Different movement models for curve drives

The standard deviations using double differences are worst than those using the reference trajectories. This is caused by the lower quality of the data showed up by the fact that no phase solutions for the Leica receivers were possible. Nevertheless the standard deviations are still better than in the shadowed static case (compare table 6). This is even true for the very shadowed drive through the curves.

The fast drive through the curves pruduces worst results caused again by different filter models for the motion. Figure 10 shows e.g. a curve where SiRF and u-blox receiver positions fit together and the Fastrax positions deviate obviously. But for the total track no obvious difference among the receivers can be outlined. This is valid for the curve tracks too.

The correlation of the position quality with possible input parameters like number of satellites, HDOP value, signal-to-noise ratio (SNR) do dot deliver any obvious result. The SNR is the only indicator: a low SNR will in a lot of, but not in all, cases lead to bad accuracy of the position. For further details the author refers to MAO (2007).

5. CONCLUSION

The paper clearly shows that the new generation of HS GPS receivers shows standard deviations from 3.75 m to 7.33 m in free horizon environment. The accuracy strongly decreases up to 88 m, if shadowed areas or even indoor measurements are analysed. This shows that room-accurate positioning is not possible for the time being. The author concludes that the way towards indoor positioning using GPS respectively GNSS is still a long one.

On the other hand it could be presented that for shadowed areas more than 92 % availability rates and reliability rates higher than 99.9 % are determined. The availability decreases for indoor measurements, but the SiRF receiver still tracks satellites. This receiver has a clear plus in static applications, especially regarding availability. Discussing the kinematic measurements the u-blox receiver outperforms the other two especially with respect to accuracy. Concerning reliability and availability the three receivers are comparable.

An important result of the analysis is the fact that the receivers are designed for kinematic applications. All three seem to include a movement model respective a filter algorithm as a black-box model not known to the user. This fact is not reported to the user, but could be shown by some examples as well as by an statistical overview showing that the kinematic standard deviations are smaller that the static ones for comparable environments.

Regarding precise positioning at the cm level a diploma thesis at IAGB is on the way to investigate the use of phase observations of the u-blox receiver. Due to the fact that the use of phase data falsified by multipath and attenuation effects for indoor positioning with geodetic accuracy is even not visible at the horizon, the research is restricted for non-indoor measurements under “normal” geodetic conditions. First results show encouraging accuracies.
For the future more field tests using the respective latest technology should be performed. The author encourage other research groups to contribute to these investigations.

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