Field trial on GPS Accuracy in a medium size city: The influence of built-up

Marko Modsching, Ronny Kramer, Klaus ten Hagen

University of Applied Sciences Zittau/Görlitz, Germany
{MModsching, RKramer,K.tenHagen)@HS-ZiGr.de

Based on the success of automotive navigation systems pedestrian navigation systems have been introduced for mobile devices. They have much higher accuracy requirements, since movements are less constrained in open places, and alternatives like alleys in an old town centre are in closer proximity. Location-based tourism information systems like tour guides are designed to provide context-driven interpretation of sights situated in the immediate vicinity. Current pedestrian navigation systems exclusively rely on GPS assisted by a map for localization. Hard to reproduce anecdotal evidence suggests that pedestrian navigators have difficulty to provide accurate navigational guidance. This paper examines the actual accuracy of positioning for various GPS receivers in areas of the city of Görlitz relevant to a tourist. These measurements are based on a comparison between a dense network of reference points of known locations and the estimated positions provided by the GPS receivers. The error of GPS localization is largely determined by the interaction of the current constellation of GPS satellites and the built-up in the immediate proximity. Since the constellation changes constantly the localization error of the same position varies significantly over time. A fraction of the error is reproducible and can therefore be used to correct the position estimate. The error along the street or alley is much smaller than the orthogonal error. This is of strategic importance for the design of mobile information systems targeting a tourist with interpretive information.

1 Introduction

Nowadays most people already have an internet enabled mobile device like a smart phone. This stimulates the demand for mobile agents and location aware services. The quality of location-based services is highly depended on the accuracy of the presumed position of the user. Positioning based on GPS is very attractive, since PDAs and mobile phones that have an integrated GPS receiver are on or coming on the market. Therefore the actual accuracy of GPS positioning is of strategic importance for the design of location-based services. As Meurer et. al. (2005) pointed out localization becomes unsatisfactory in multipath scenarios because of the large delay spreads leading to non line of sight propagation paths of the signal – which is very often the case in the so called urban canyons. But actually there is no clear description how to define an urban canyon concerning the height of the houses in the surrounding. In contrast to that a group of researches led by Eisenfeller (2005) showed that an exact positioning in urban areas is no problem and even possible indoor.

This paper will show the design, the execution and some results of several field trials performed in the city of Görlitz. The mediaeval town centre has some narrow alleys, but most of the city is dominated by buildings with 3-4 stories and streets laid out at the end of the 19th century. This is rather typical for many medium size cities of Europe. The positions are measured with four different GPS receivers based on two hardware platforms (Fortuna and Holux, SIRF II and SIRF III) with and without external antenna. The measured position data is compared with a dense network of reference points provided by the land surveying office to assess the accuracy itself and to identify the major factors on GPS positioning in an environment like Görlitz.

2 Related work

Shoval and Isaacson (2005) compared localization systems like GPS to land-based tracking systems; these are units sending signals to antenna stations that calculate the position, by measuring the movement of pedestrians. The main advantages of GPS are the worldwide ability, little costs and exacter positions, whereas land-based tracking systems have the advantages of being unaffected by the weather and work also well in urban regions and indoors.
Eisenfeller et. al. (2005) showed that the possibility in indoor positioning using GPS technology is highly depended on the materials of the walls around the room. The walls cause a noise which makes it hard for the receiver to filter the useful signals, leading to much longer calibration times. They pointed out that an assisted approach with the mobile network would be useful to shorten that calibration time.
Rempel and Rodgers (1997) researched the effectiveness of differential correction and the influence of well-spaced satellite configurations. They found out that it is possible to reduce the GPS error from 65 meters to lower than 10 meters by increasing the proportion of positions based on 4 rather than 3 satellites (3-dimensional mode). The error reduction is done by sending out correction information from fixed earth stations.
Nayak et. al. (2000) analyzed the occurrence of multipath propagation by mounting 4 GPS antennas onto a vehicle and driving through a city. The collected data was compared to an accurate digital road map to determine the position accuracy. They analyzed the correlation of the data from one antenna to the other and showed rapid decorrelation of multipath among antennas. They also pointed out that the success of an accuracy improvement depends on successful identification and subsequent elimination of the multipath corrupted measurement.

3 Research topics and design of experiment

To gain insight into the error of GPS localization the estimated coordinates provided by a GPS receiver are compared to reference points with well known positions. To make the error analysis representative a dense network of points was constructed for the city of Görlitz. That network was divided into a set of roughly equal length tours to facilitate the data gathering. Close collaboration with the Land Surveying Office (LSO) was necessary to determine the exact positions of visible reference points e.g. street lights, manhole covers, traffic signs, parking automata, inspection chambers, holes for flag poles, trees, drains or traffic lights.
According to the LSO the coordinates of these items are known with an accuracy of a few centimetres. In Germany the LSO stores all positions in the Gauss-Krüger format. Since the GPS receivers are delivering the position data in a format called WGS 84 (NMEA standard), the reference data had to be converted to WGS84. In order to enable the visualization of the referenced and measured positions, both of them were linearly interpolated.
The tours were plotted on a map and handed out to teams of two students each. The first student uses the map to determine the next reference point and walks to this point in a straight line. The second student follows with constant walking speed and indicates to a mobile device that the reference point has been reached. While walking the GPS estimates were constantly logged onto the mobile device in close relation to the exactly known positions to enable a comparison afterwards. Evaluating the logged data the following research questions should be answered:

Q1: What is the actual GPS error in various areas?
Q2: Which influence does the internal chip of the receiver have?
Q3: Is there a correlation between the error estimates of the device and the real errors?
Q4: Which other factors determine the accuracy of GPS localization?
Q5: How do the buildings in the close proximity influence the GPS accuracy?
Q6: How large is the reproducible fraction of the error?
Q7: Are there possibilities to correct the localization error?

3.1 Execution

In order to minimize the human error through distractions, the students with the role "map carrier" had to learn the points of their tour in advance. Insights into reproducibility of errors and the influences of the device configurations could be gained by executing each tour with each device configuration several times. The following configurations were available for the field study:

GPS receiver	chip set	External antenna
Fortuna clip-on	SIRF II	Yes
Holux GR 231	SIRF II	Yes
Fortuna Slim	SIRF III	
Holux GR236	SIRF III	

Table 1 GPS configurations during field trial

As Table 1 shows, the two latest generations of GPS receivers were available for the field trial. Additionally the two receivers of the older generations offered the possibility to plug in an external antenna. All together four tours with reference points in all areas relevant for tourism were modeled for the field trial. The tours had an average number of 181 exact measured reference points from the LSO. The following picture shows the distribution of the collected reference points in the areas relevant for a tourist.

Fig. 1 Field of View

The color of the grids in Fig. 1 visualizes the mean error per grid whereas the scale ranges from red indicating a low localization accuracy to green where positioning error was smaller when the measurements were taken. The students with the role "device carrier" were asked to carry the GPS device within their trouser pockets in order to determine the error in a realistic scenario for a location-aware application.

3.2 Tracking and evaluation software

The mobile tracking of the position data was done by an application for a mobile device, since the user had to select a reference point and click a button when it was reached.

mobile application	evaluation application
	

	Nr.:	Beschreibung:
✓	1	Leuchte
✓	2	Gullideckel
✓	3	Straßenabfluss
✓	4	Einstiegsschacht
●	5	Einstiegsschacht
	6	Leuchte
	7	Wasserschieber
	8	Leuchte
	9	Leuchte
	10	Leuchte
	11	Leuchte

Table 2 Screenshots of experiment software

The screenshot on the left column of Table 2 shows the main screen of the mobile application with a list of reference points which are linked to points in the map by numbers. The green check indicates that the point was already visited and the red dot marks the current reference point which has to be visited next.

The screenshot in the right column visualize the desktop application for analyzing the tracked GPS data. It shows a blue line on the map which symbolizes the interpolated points of the reference tour given by the LSO and a red line announces the estimates of the GPS device. In order to enable the evaluation of the error in a user-defined area the user can draw a rectangle in the map. To get insight into the error values of several points a vector lens can be used to connect the exact points with the estimated ones. This lens is shown on the upper right of the map whereas the little number aside shows the mean error of all points covered by the lens in meter. This makes the error visible even if the red and blue line overlap and the error arises along the path. Finally it is important to get insight into the constellation of the satellites for several geographical points. Therefore the application provides a satellite lens for showing the fixed satellites at the focused position and a satellite tool window for visualizing the signal to noise ratio (S/N ratio) which is indicated by the colour of the satellites within the tool window. Starting with a high S/N ratio the scale goes from green to yellow, orange, pink and red.

Both applications are based on the currently dominating NMEA 0183 standard to enable other analysts to evaluate GPS data from external measurements or to compare the evaluation with other tools on the market too.

4 Results

The land surveying office provided 706 references points organized in four tours. On average the GPS devices were estimating 4149 positions per tour. The mean error of all runs is 24.5 meter with significant variations for different areas.

Tour	#Points	#Runs	Ø GPS estimates
1	142	4	3578
2	163	1	3540
3	224	3	3960
4	177	7	5521
All	706	15	Ø 4149

Table 3 Experiment statistics

The 4th tour was walked several times with different GPS receivers of the generations SIRF II and SIRF III to find out whether there are improvements due to the revised hardware equipment. While the Fortuna Slim device showed an average error of 12 meter within tour 4, the Holux GR 236 reached much worse results with a mean error of 18 meter. This proves that a more sensitive hardware of a newer generation doesn't necessarily lead to better measurement results.

4.1 Estimation of positional error

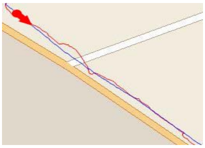
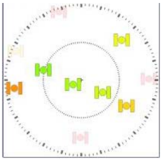
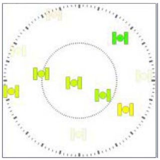
The standard data transmitted by most commonly available GPS receivers offers a record called *GSA* which contains an internal assessment about the quality of the signals. A linear correlation of this data to the actual errors would enable a mobile application to estimate its own precision dynamically at runtime and react in different manners according to the current precision. The Pearson correlation coefficient was used to verify the correlation of the two lists. According to Gravetter (2000) the following formula was applied:

$$Corr(X,Y) = \frac{Cov(X,Y)}{\sqrt{Var(X)} * \sqrt{Var(Y)}} \qquad (1)$$

The covariance of two samples divided by the product of their squares of variances returns a value between -1 meaning a reverse correlation and 1 approving a clear correlation within the two item lists. The outcome of this is a correlation of ***0.13*** meaning that the device assessments are inapplicable to predict the current localization error.

4.2 Influence of built-up

As mentioned earlier in this paper the localization error depends on the area. Table 4 shows a comparison between two locations. The first row visualizes the topography of the localities with red arrows in the map to show the positions and directions of view where the pictures in the last row were taken. The main difference between the two locations is the built-up in close proximity. While the train station street is a broader street with just a few high houses at distance, the 43 feet high houses on the hospital street are at close quarters. The map and the satellite view in the second row are aligned to make it easier to show the visible GPS satellites and the S/N ratio of the received signal.

	Area #1 (Hospital street)	Area #2 (train station street)
Map		
Satellite constellation		

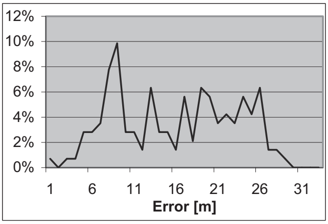
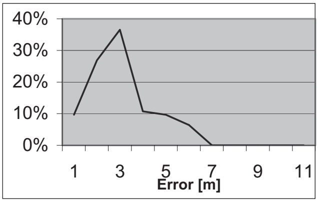
Distribution of error		
Mean error	15.43m	2.52m
Local photo		

Table 4 Comparison of different area types

The error distributions in the third row and the average error underneath show that the error is highly depended on the built-up in the area the measurement was taken. The houses at the Hospital Street prevent the device to get a direct signal from satellites in directions orthogonal to the rows of houses on both sides. A mean error of about 15 meter forces a context aware mobile application to use other information to remove positioning uncertainty, e.g. request the help of the user for the final navigation to the sight on this street.

4.3 Influence of constellation

The interaction of the built-up and the actual constellation determines the localization error. Fundamentally the "visible" constellation can either be advantageous for the positioning if the satellites are spread out in all directions of the sky, whereas if the satellites are concentrated in one area the localization error will be much higher. However the GPS System was designed with the intention to maximize the convenient constellations around the world (Dixon, 1991). Unfortunately the built-up of different urban locations seems to shade the reception of the satellites most suitable for an accurate positioning.

In order to analyze the impact of the interaction between built-up and constellation two points with different positional error were selected for a deeper analysis. Pictures of the locations were taken and merged to a 360 degree panorama. The camera has an aperture angle of 40° in landscape mode. It was elevated 30° upwards, thus taking a panorama with 10 degrees above the horizon up to 50 degree. The position and satellite data was tracked constantly over a period of three hours. To visualize the positions of the satellites the successive positions and the S/N ratio were projected into the 360° panorama picture as shown in the following pictures.

Fig. 2 Hospital street

Fig. 3 Elisabeth square

At the Elisabeth's square it is much more likely that an advantageous satellite constellation becomes visible than at the Hospital Street where many satellites are shaded by the houses preventing a direct reception of the signal. In that case the GPS receiver has to balance between using satellites with a less suitable signal and using satellites with a low S/N ratio. A low S/N ratio might indicate one or multiple reflections. Even wide streets like the hospital street with houses of 3-4 stories surprisingly seem to match the definition of "urban canyon". Because of this interaction between built-up and time varying satellite constellation the error for the same position varies significantly in amount and direction over time as indicated in Table 5.

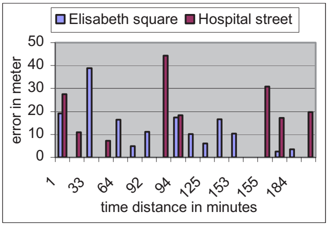
Error variation over time	Time varying error at Elisabeth square
	

Table 5 Error variation

The diagram on the left shows the positional error for the same position but at different times and confirms that the error can differ up to 34 meters. Even the Elisabeth square which has a wider and more unobstructed view to the sky shows significant variations of the localisation error over time. Of course the mean error is much smaller there but still any estimate of the positional error has to be based on the built-up and the time varying constellation of the GPS satellites. This might explain the puzzling conflict between reports of participants in our field trial in the summer of 2005. Some reported misleading navigational instructions, whereas others moving through the same area a little bit later didn't experience any problems.

5 Correction strategies

Context-aware applications cannot allocate a timely and adequate service without an exact knowledge about the current position. This kind of ambient intelligence might turn into ambient hell for the user if the information doesn't fit to the local context (e.g. wrong navigational instructions). That's why finding additional ways for improving the original signal is absolutely necessary. This section discusses several methodologies of correcting and evaluates its effectiveness.

5.1 Prediction of reflection using a 3D model

The reflection of satellite signals seems to have a tremendous impact on the accuracy of a GPS receiver. Fig. 2 sketches a reflection of a signal in an "urban canyon" and the position estimated by a GPS receiver. The satellite signal is reflected at the facades. The reflections cause an increase of the time of arrival value. Since this value is the basis for calculating the distance to the satellite the receiver sets the position further aside. Fig. 2 shows a signal which is reflected 3 times before reaching the receiver. The delay of the signal is extended by the length of *t* which is the sum of all additional paths the signal takes due to reflection. Because the GPS receiver isn't aware of the built-up in its environment it would determine its own position to *Pos*($_{GPS}$) – at the opposite side of the building.

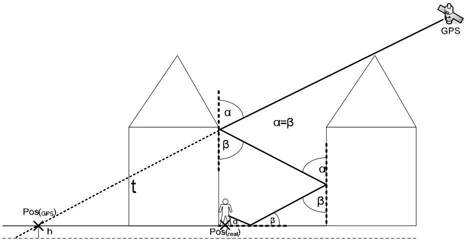


Fig. 4 Reflection

The above described situation leads to the assumption that the correctness of the positioning could be greatly improved if a prediction of the reflection was possible. The standard NMEA protocol which is supported by almost all GPS devices delivers a sentence called *GSV* containing the satellite information azimuth, elevation and S/N ratio for all tracked satellites. This information in combination with a city's 3D model should enable a mobile application to predict the number and length of signal reflections for any tracked satellite. Unfortunately the exact position of the receiver within the 3D model is an important precondition for this mathematical model. Since the delivered position is only estimated, the projection into the 3D model is kind of vague and makes the reflection predication ambiguous. However a 3D model should enable a GPS receiver to exclude signals w/ a low S/N ratio from satellites, which are at this point in time shaded by the built-up.

5.2 Map based correction

A closer look at the errors in conjunction with the course of the streets reveals an interesting fact: The error in direction of the street seems to be much smaller than the error orthogonal to the street. Fig. 5 illustrates this situation at an exemplary street whereas DistX is much smaller than DistY.

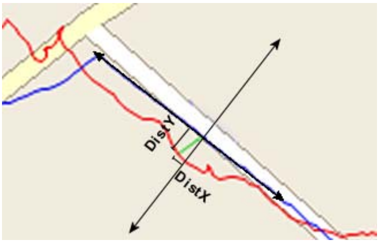


Fig. 5 Error along and orthogonal to a street

This constellation is pretty much the same at most other measured positions. This effect seems to be due to reflections on the facades. Satellites along the street are visible directly and thus their signals are received without any reflection, whereas satellites on the left and right of the street are shaded behind houses. This fact provides the opportunity to correct a GPS signal with the help of street maps. However, this methodology has a weakness in areas of crossroads where the position of the nearest street isn't clear at any place. But in such areas the GPS signal very often becomes more accurate anyhow since more satellites can be received directly due to a much larger view of the sky. Another difficulty appears if only crossing streets but not the square itself is saved within the underlying map. This leads to the problem that the position of a tourist staying in the middle of a square and requesting information about a central attraction, like a statue, is always set onto the adjacent street by the correction process. A solution to that problem will require an adaptation of the map material.

5.3 Effectiveness of map based correction

In order to evaluate the chances of the map based approach the methodology was applied to correct the data collected in the field study. Fig. 6 shows the error in meter before and after the correction methodology was applied.

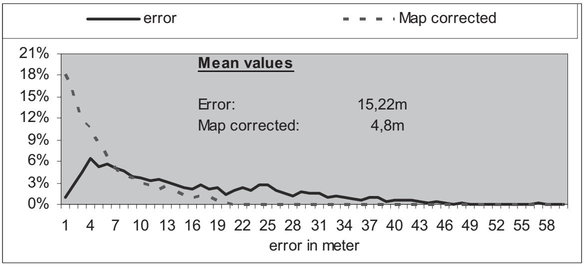


Fig. 6 Comparison of correction methods

This chart gives a first impression that the map based approach is very effective one since the mean error after adapting the values is lower than 5 meters. This is a significant improvement to the raw data of about 15 meters.

However, to avoid ambient intelligence bothering the user with wrongly timed information it is important for the mobile application to know how credible the positioning within the mobile context is. Dependent on this value the application will react differently according to the assumed mobile context (e.g. “somewhere in front of you is a church: Turn to your right afterwards.” instead of “Turn to your right now!”) in order to involve the user to resolve positional ambiguities.

Reference area	Error [m]					
	Without map correction		With map correction		Improvement	
	95%	99%	95%	99%	95%	99%
Elisabeth Square	47m	61m	26m	34m	45%	44%
Hospital Street	31m	33m	10m	12m	68%	64%
City	43m	84m	28m	76m	35%	10%

Table 7 Cumulative localization error for different localities

Table 7 shows the error an application has to expect in different localities for 95% and 99% of all cases. The table also shows that the map based correction approach could improve the accuracy in all areas. A pretty interesting result is that the best enhancements could be achieved in the hospital street having no adjacent street in close proximity which might “distract” the map-based correction. This confirms the great impact of the built-up to the location precision.

6 Conclusion

This paper has shown the design and the execution of several field studies executed in Görlitz to capture the localization error of commercially available GPS receivers targeting the consumer. The error of the GPS position is mainly determined by the interaction of the time varying constellation of the satellites and the built-up in the close vicinity. The average position error ranges from 2 meters on an open square to 15 meters even in wide streets with four story houses on both sides. The built-up shades the satellites especially suitable for a positioning. The constellation of the satellites is periodic and the built-up constant, therefore a rudimentary database was used to reduce the positioning error by ~10%. Most location-based services targeting the tourist need a higher accuracy along the street than orthogonal to it. Fortunately the built-up shades the satellites to the left and right, but not along the street. Hence the error along the street was by a factor of 3 times smaller than the total error. All-in-all a location-based application has to assume a positional error along the street of 28 meters for 95% of the time. Therefore navigation instructions and context driven interpretation have to include the tourist her/himself to resolve positional ambiguity.

Acknowledgements

This project is part of VESUV (http://www.vesuv-projekt.de) in cooperation with Siemens AG, Microsoft's European Innovation Center (EMIC) and Fraunhofer Institute IGD. VESUV is supported by the Federal Ministry for Economics and Labour (BMWA). This analysis was mainly supported by the work of the students Stefan Hofman, Maik Herrmann and Michael Brandt. Students from the Augustum-Annen-Gymnasium under the guidance of Margitta Kandler contributed to this paper.

7 References

[1] Dixon, T. H. (1991): "An introduction to the global positioning system and some geological applications", Journal Reviews of Geophysics (ISSN 8755-1209), vol. 29, May 1991, p. 249-276;

[2] Eissfeller Bernd, Teuber Andreas (2005): Universität der Bundeswehr München, "Untersuchungen zum GPS-Satellitenempfang in Gebäuden"

[3] Gravetter Frederick J., Wallnau Larry B., (2000); Statistics for the Behavioral Sciences,

[4] Meurer M., Heilmann S., Reddy D., Weber T., Baier P.W. (2005): „A signature based localization technique relying on covariance matrices of channel impulse responses", Workshop on Positioning, Navigation and Communication (WPNC'05), University of Hannover

[5] MapPoint (2005): http://www.microsoft.com /mappoint

[6] Navigon (2005): http://www.navigon.de

[7] Nayak R. A., Cannon M. E., Wilson C., Zhang G. (2000): "Analysis of Multiple GPS Antennas for Multipath Mitigation in Vehicular Navigation", Institute of Navigation National Technical Meeting/Anaheim, CA/January 26-28,2000

[8] Rempel, RS; Rodgers, AR (1997): "Effects of differential correction on accuracy of a GPS animal location system", Journal of Wildlife Management [J. WILDL. MANAGE.]. Vol. 61, no. 2, pp. 525-530. Apr 1997

[9] Shoval, Noam; Isaacson, Michal (2005): "The Application of Tracking Technologies to the Study of Pedestrian Spatial Behaviour" The Professional Geographer

[10] Klaus ten Hagen, Marko Modsching and Ronny Kramer, „A location-aware mobile tourist guide selecting and interpreting sights and services by context matching" in 2nd Annual International Conference on Mobile and Ubiquitous Systems: Networking and Services (Mobiquitous 2005), San Diego, California, July 17-21 2005