ASSESSING THE ACCURACY OF A HIGH-SENSITIVITY GPS RECEIVER FOR LOCATION BASED SERVICES

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ABSTRACT

This contribution presents practical results with a High-Sensitivity GPS (HSGPS) receiver in Delft, the Netherlands. One outdoor experiment was carried out on a favourable location and acts as a reference. Next, two indoor experiments were carried out, each over a 24 hour period, in a residential and in an office location. Outdoor the 95% position error was 5-10 m. Indoor, in a top-floor apartment this was 10-20 m (including a few meter bias in the local Up component), and in the office location the 95% error reached hundreds of meters, with a bias of several tens of meters. Position availability was 100% outdoor and indoor residential, but only 26% for the indoor office location.

INTRODUCTION

Location Based Services require positioning in degraded signal environments such as urban canyons and inside buildings (indoor). Conventional GPS is not suitable within these environments because it requires direct line-of-sight signals, and these are not sufficiently available or too weak in attenuated signal environments. In addition, for emergency Location Based Services the acquisition times of the signals may be too long. With High-Sensitivity GPS (HSGPS) it has become practically possible to receive very weak GPS signals, thus offering possibilities for Location Based Services. In this paper we will present some practical examples of the performance of a mass-market state-of-the-art HSGPS receiver. Experiments are carried out both outdoor as well as indoor, in a residential and an office environment.

HIGH-SENSITIVITY GPS

A GPS receiver is traditionally designed for outdoor applications where sufficient (at least four) and clear line-of-sight signals are available. In addition, the signal-to-noise ratio of these signals should be high enough in order to be acquired and tracked by conventional receivers. The time to acquisition of the signals is usually rather long (up to few minutes). A High-Sensitivity GPS receiver uses large computing power and sophisticated signal processing to acquire and track weak signals, see e.g. [1] and [2]. The signals may be up to 1000 times weaker than with conventional receivers. This means that with HSGPS it is possible to receive signals indoor. HSGPS results showing this have previously been presented e.g. in [3], which reports about tests carried out in 2001. The noise of HSGPS measurements can be large, dependent on the signal attenuation [4]. In addition, the signals may get contaminated by large errors as due to reflections to walls, glass, concrete and obstacles (multipath).

In this contribution we will examine the accuracy of the TomTom SiRF III Bluetooth GPS receiver. This cheap HSGPS receiver has 20 channels and outputs position and status information at 1 Hz (in NMEA messages). For the acquisition of the signals the receiver has the possibility of aiding by GSM (Assisted GPS), but in our tests this option has not been used (we used the receiver in unaided, stand-alone mode). Instead, acquisition is conducted outdoor before going indoor (warm start). The kernel of the receiver is the SiRFstarIII chipset, which contains (the equivalent of) 200,000 correlators, which allows for a quick search of the frequency-code delay space [5].

HSGPS PERFORMANCE IN RESIDENTIAL AND OFFICE ENVIRONMENTS

In this section we present results of HSGPS experiments, carried out in Delft, the Netherlands. In the first experiment the TomTom SiRF III Bluetooth GPS receiver was put outside at the roof of a 4-storey apartment building and logged data for 24 hours. Because of the rather 'ideal' circumstances (direct line-of-sights to the satellites), this experiment acts as a reference for the two other experiments, in which the HSGPS receiver was placed indoor, also logging data for 24 hours.

In the first indoor experiment the receiver is tested in a residential environment, while in the second experiment HSGPS was tested in an office environment. For all three positions of the HSGPS receiver ground-truth coordinates had been determined (with 10 cm accuracy). In the following, when we present position errors, the ground-truth positions correspond to the origin of the local North-East-Up frames.

	number of epochs	satellites in view	satellites tracked	satellites used for position computation	3 satellites used for position computation
residential outdoor	86502	**100%** of time mean: 9.2 sat.	**100%** of time mean: 9.1 sat.	**100%** of time mean: 9.0 sat.	0% of time a position is computed.
residential indoor	86558	**100%** of time mean: 9.1 sat.	**100%** of time mean: 8.5 sat.	**100%** of time mean: 7.6 sat.	0.002% of time a position is computed.
office indoor	90022	**100%** of time mean: 9.5 sat.	**100%** of time mean: 6.1 sat.	**26%** of time mean: 3.8 sat.	36% of time a position is computed.

Table 1. Statistics of satellites in view, tracked and used in position computation in the three experiments.

HSGPS results outdoor: residential environment

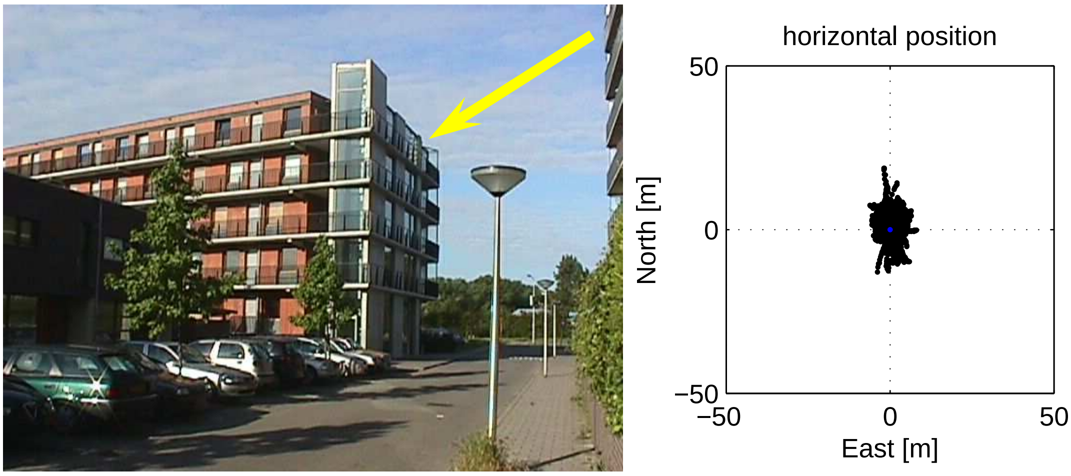

Fig. 1. Outdoor HSGPS in residential area (left) and horizontal position scatter (right).

For the outdoor experiment the HSGPS receiver was placed 10 cm above the roof, near the edge of the roof, upright attached to a small wooden lath, and wrapped in a plastic sandwich bag to protect it from rain. The site has good sky-visibility; there are no obstructions within several hundreds of meters, see Fig. 1, except for one apartment-building across the street which has two more layers, but lies in the local North-East direction (usually very few GPS satellites over there).

This experiment was conducted from 30 September 2006 17:00 UTC until 1 October 2006 17:01 UTC. Table 1 gives information on the number of epochs the receiver was able to 'view' satellites, the number of epochs the receiver could track satellites and the number of epochs the receiver was able to compute a position from the satellite observations. For the outdoor experiment this was in all three cases 100%: at every epoch of the day satellites were in view, tracked and used to compute a position. The receiver tracks nearly all available satellite and uses them in the position computation (on average 9.1 and 9.0 satellites, out of 9.2). The last column of Table 1 also provides information on the time only three satellites are used to compute a (horizontal) position, but because of sufficient satellites, this was never the case in the outdoor experiment. In Fig. 2 (second row, left) a graph of the number of satellites in view, tracked and used for positioning is given as function of the day. For the satellites used to compute positions also a graph of HDOP values (horizontal dilution of precision) is shown (second row, right). For the number of satellites in view and tracked histograms are given (third row). Since practically all satellites in view are also tracked by the receiver, both histograms are the same. In Fig. 2 also two graphs are given (on top) for the signal-to-noise ratio of the tracked signals, or more precisely, the carrier-to-noise density ratio C/N0 (different satellites have different colors). In the first graph this ratio is

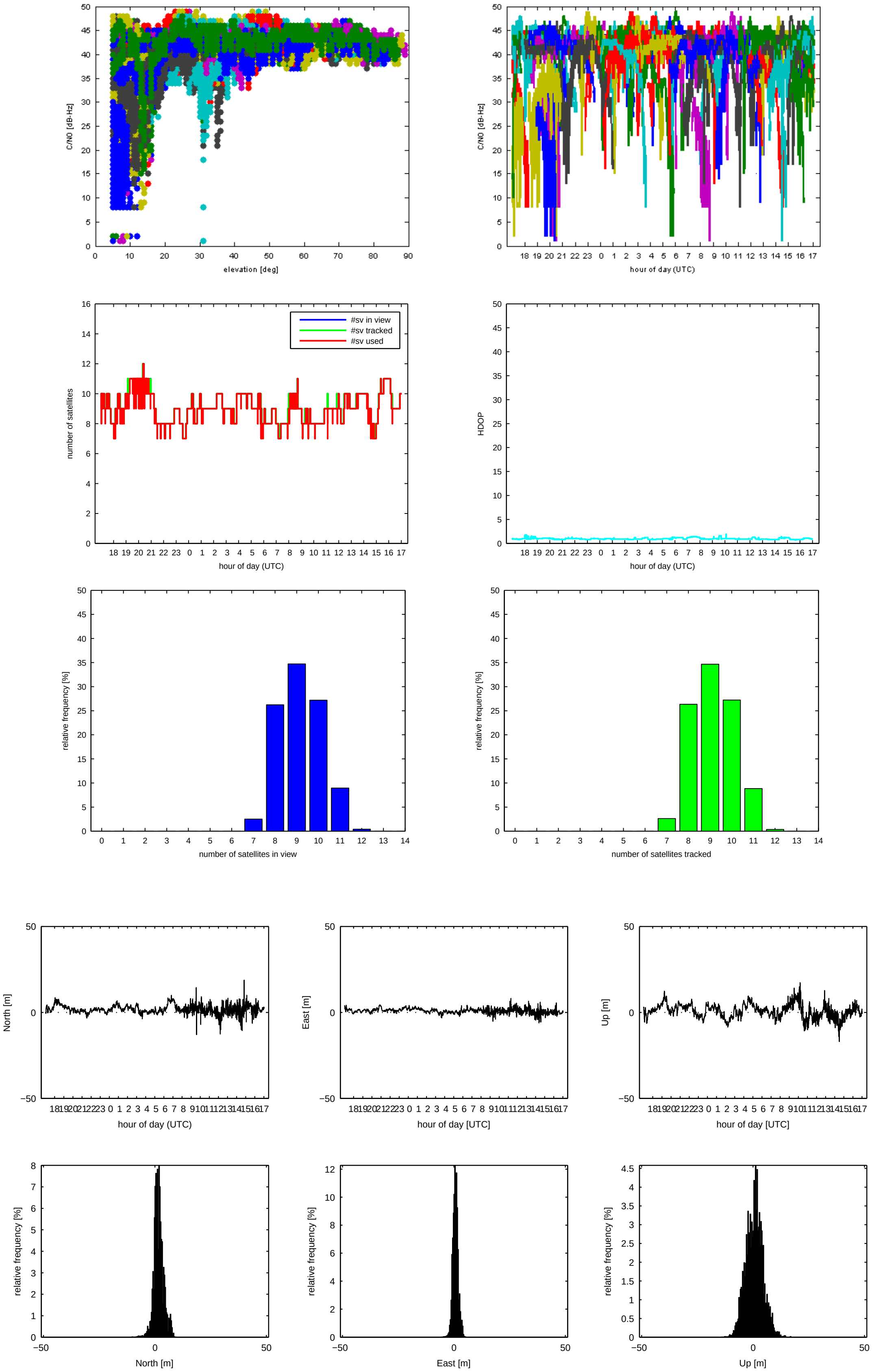

Fig. 2. HSGPS results outdoor in a residential environment.

plotted as function of the satellite elevation. It can be clearly seen that the signals of satellites at high elevation are generally stronger than those at lower elevations. This is what we expect, because of the antenna gain pattern, and since the lower the elevation the longer the signal's path through the atmosphere becomes, affecting its strength.

The computed positions are depicted as horizontal scatter in Fig. 1 at right, while in Fig. 2 time series of the North, East and Up coordinates can be found (one-but-last row). Table 2 gives statistics (mean, standard deviation, 95% position error) of the computed positions during the day. As can be seen, the spread in the positions is very small. Also the standard deviations with respect to the mean coordinates and the reference coordinates sufficiently agree, which indicates that the mean of the computed positions corresponds to the ground-truth position. The 95% position error falls within 5-10 m. Fig. 2 finally shows histograms of the three coordinate components and from these it seems that the observations are more or less normally distributed.

	mean [m]	standard deviation (w.r.t. mean) [m]	standard deviation (w.r.t. ref. pos) [m]	95% position error [m]
North	1.9	2.2	2.9	6.4
East	0.9	1.2	1.5	
Up	0.7	3.9	4.0	7.7

Table 2: Statistics of computed positions in the HSGPS outdoor experiment

HSGPS results indoor: residential environment

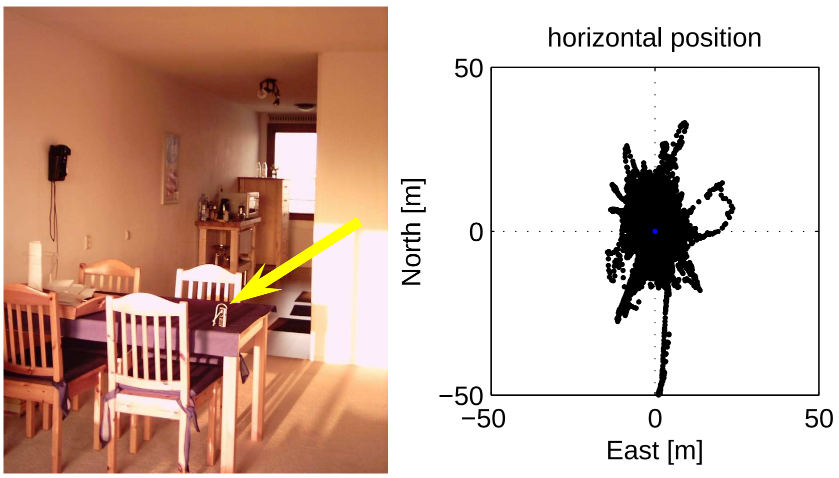

Fig. 3. Indoor HSGPS in residential area (left) and horizontal position scatter (right).

The HSGPS receiver was also tested in a residential *indoor* location, namely in the top-floor apartment of the same building as where the outdoor experiment was conducted. The building is constructed from solid concrete (walls, floors, and roof). The receiver was placed (after a few minutes warm-up on the balcony) on the table in the living room, and powered through the adapter. The receiver was about 4.5 m from the balcony-window (which was the nearest window) and about 8.5 m from the kitchen window, see Fig. 3 (left).

This indoor experiment was conducted from 29 September 2006 16:46 UTC until 30 September 2006 16:49 UTC and in Table 1 information can be found on the number of satellites in view, tracked and used for positioning. While in the outdoor experiment these numbers were very similar, indoor the receiver still has about 9 satellites in view and these are also tracked, but 7.6 (on average) are used for the position computation. Probably the receiver leaves out signals of satellites that are too weak for instance (to extract the navigation message). In Fig. 4 similar graphs can be found as those in Fig. 2 for outdoor HSGPS. From the C/N0 graphs it can be seen that the signals tracked indoor have a carrier-to-noise ratio lower than 35 dB-Hz, while outdoor they may be up to 50 dB-Hz. This illustrates signal attenuation and presence of multipath indoor. In the graph depicting the number of satellites it can be seen that at a few epochs the receiver uses only 3 satellites to compute a (horizontal) position. Consequently, this shows up as large values in the HDOP graph in Fig. 4.

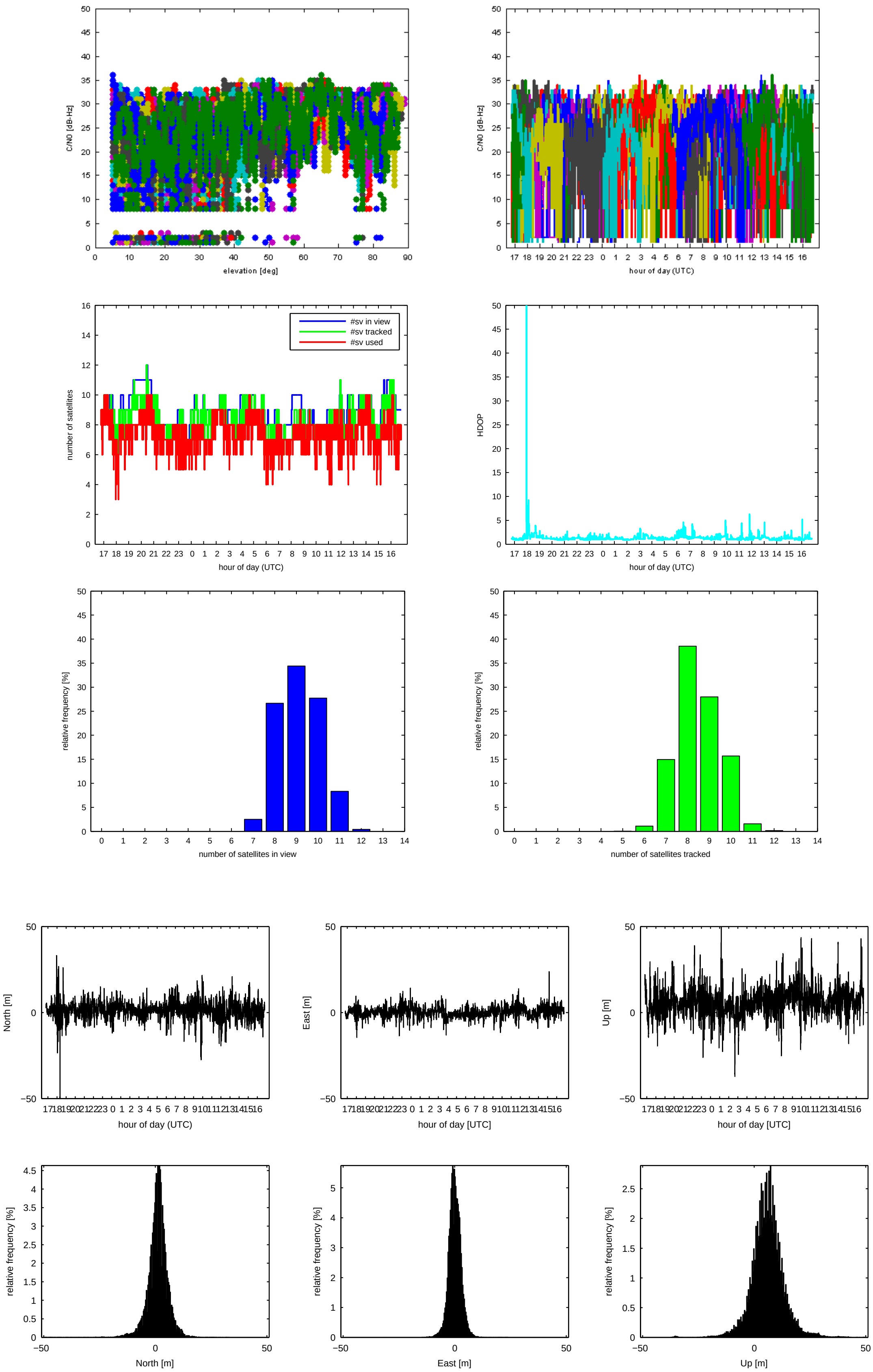

Fig. 4. HSGPS results indoor in a residential environment.

The positioning results can be found in Fig. 3 (right) and in Fig. 4. The larger spread in positions indoor compared to outdoor can be seen immediately and also outliers of more than 50 m show up. Despite this, the standard deviations of the horizontal components with respect to the mean nicely agree with the standard deviations with respect to the ground-truth position, see Table 3. The Up component however shows a (positive) bias of several meters. The 95% position error now falls within 10-20 m; a factor 2 worse than outdoor.

	mean [m]	standard deviation (w.r.t. mean) [m]	standard deviation (w.r.t. ref. pos) [m]	95% position error [m]
North	1.3	4.6	4.8	10.1
East	0.3	2.7	2.7	
Up	6.2	7.2	9.5	17.9

Table 3: Statistics of computed positions in the HSGPS indoor experiment

HSGPS results indoor: office environment

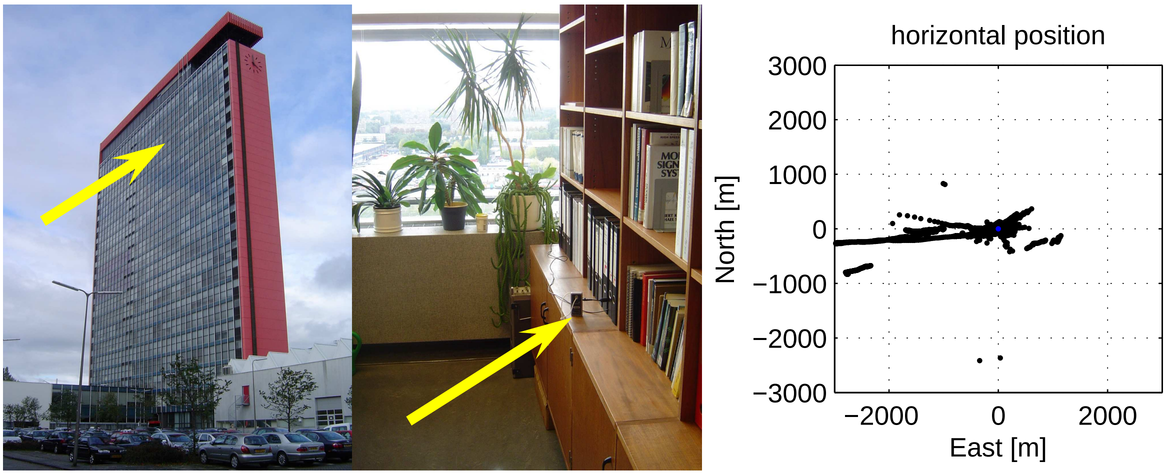

Fig. 5. Faculty of Electrical Engineering : indoor HSGPS in office area (left) and horizontal position scatter (right).

In the third experiment the HSGPS receiver was also tested indoor, but now in an office environment. The receiver was placed on an open book shelf, about 80 cm from the floor, about 3 meter from the outside window, in an office on the 19th floor (nearly in the middle) of the TU Delft building for Electrical Engineering, Mathematics and Computer Science. This tall building consists of 21 floors.

The experiment took place on 23 October 2006 13.00 UTC until 24 October 2006 14.00 UTC. In Table 1 we find that there are on average more than 9 satellites in view, but the receiver is able to track only 6 satellites on average. The building thus blocks a part of the GPS signals. The number of satellites tracked follows from counting the satellites with nonzero C/N0 as reported by the receiver. The carrier-to-noise density ratio of the tracked signals as function of the satellites, see Fig. 6, is clearly different from the graph in the residential indoor experiment, see Fig. 4. In the office the signals of satellites at high elevation have a much smaller carrier-to-noise density ratio than in the apartment building. Obviously these signals are only able to arrive at the receiver in the office as multipath after multiple reflections.

Even less signals than tracked are used by the receiver's positioning algorithm, since for only 26% of the epochs a position is computed. Obviously most of the tracked signals are too weak. In Fig. 6 it can be seen that for the period from about 17.00 UTC to 4.00 UTC the next day the receiver has not computed a position at all. For the epochs for which a position is computed, the average number of satellites is quite low, only 3.8 satellites on average, and for 36% of these epochs the receiver only used 3 satellites for a (horizontal) position computation. As a consequence of using 3 satellites the HDOP values can be very high (see Fig. 6). The horizontal position scatter is shown in Fig. 5 (right). It can be seen that compared to the residential experiment the position spread is very large; especially in local East direction there are biases of more than 3 km from the ground-truth position (Note that the graphs on position errors have a largely different scale than the corresponding ones of the two previous experiments!). This demonstrates the presence of multipath signals entering the office through the window, on the West side of the building. Table 4 presents the positioning statistics of this experiment. Despite the large standard deviation of East, the standard deviations with respect to mean and those with respect to the ground-truth position agree reasonably well, which indicates that the mean

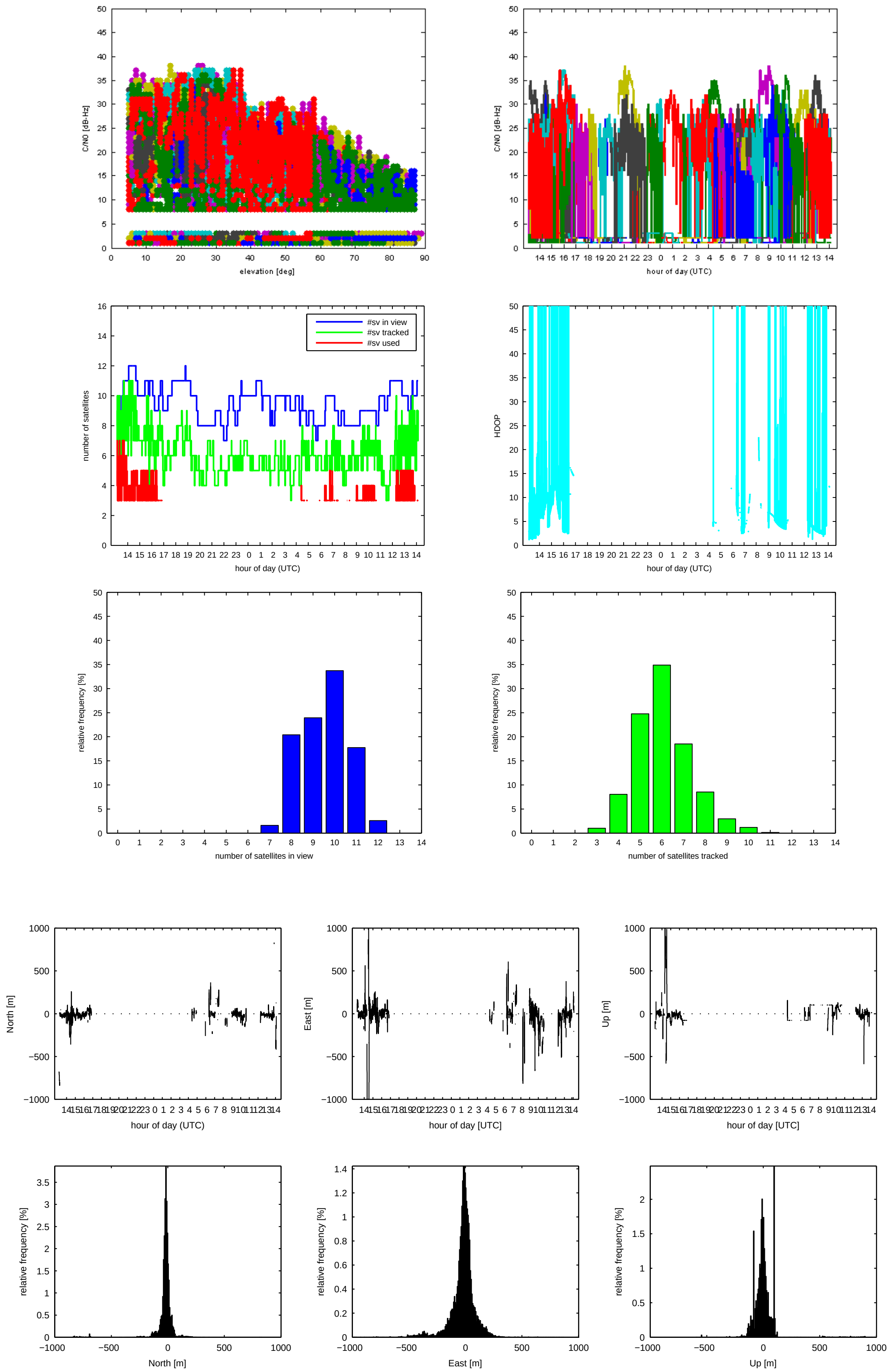

Fig. 6. HSGPS results indoor in an office environment.

of the positions more or less corresponds to this ground truth. The 95% horizontal position error is about 400 m; a factor 40 larger than in the residential indoor experiment.

	mean [m]	standard deviation (w.r.t. mean) [m]	standard deviation (w.r.t. ref. pos) [m]	95% position error [m]
North	-19.9	122.9	124.5	401.5
East	-70.2	397.5	403.6	
Up	52.2	369.0	372.7	131.4

Table 4: Statistics of computed positions in the HSGPS indoor office experiment

CONCLUDING REMARKS

In this paper we have assessed the performance of the TomTom SiRF III Bluetooth GPS receiver in two indoor environments, a residential house and an office. In addition, the HSGPS receiver was tested outdoor, as a reference. This performance was measured in receiver signal tracking as well as the accuracy of positioning, over 24 hours. For all three experiments the receiver was able to track satellites on every epoch of the day, although in the office on average just 6 satellites could be tracked, while on average more than 9 satellites were available. Of these tracked satellites, in the residential house still almost 8 satellites were used to compute positions, but in the office this was on average just 3.8. In addition, in the office environment for only 26% of the epochs the receiver had sufficiently strong signals in order to compute positions (in the residential environment positions could be computed for all epochs). Hence, the indoor positioning accuracy in the residential environment was very good: over 24 hours the 95% horizontal position error was 10 m (compare this with the 6 m horizontal position error for the outdoor experiment), while in the office environment this was more than 400 m. This large error is mainly felt in local East direction, which indicates that the signals only enter the office through the window (West side of the building) and that these signals are largely contaminated by multipath, caused by multiple reflections to obstacles. We should remark here that in some buildings entering of the signals through the window might not even be feasible at all, in case these windows are coated.

In these experiments the HSGPS receiver was positioned on a table or on a shelf. For Location Based Services it is however also relevant to assess the performance when the receiver is carried by, or close to a human body. Hence, more research has to be done with respect to this. In addition, one should realize that the performance depends, next to the environment, also on the equipment used. Hence, in further experiments one should use a representative set of HSGPS receivers simultaneously.

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