Indoor Positioning Using GPS Revisited

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Abstract. It has been considered a fact that GPS performs too poorly inside buildings to provide usable indoor positioning. We analyze results of a measurement campaign to improve on the understanding of indoor GPS reception characteristics. The results show that using state-of-the-art receivers GPS availability is good in many buildings with standard material walls and roofs. The measured root mean squared 2D positioning error was below five meters in wooden buildings and below ten meters in most of the investigated brick and concrete buildings. Lower accuracies, where observed, can be linked to either low signal-to-noise ratios, multipath phenomena or bad satellite constellation geometry. We have also measured the indoor performance of embedded GPS receivers in mobile phones which provided lower availability and accuracy than state-of-the-art ones. Finally, we consider how the GPS performance within a given building is dependent on local properties like close-by building elements and materials, number of walls, number of overlaying stories and surrounding buildings.

1 Introduction

Applying the visions of ubiquitous computing to a variety of domains requires positioning with (i) pervasive coverage and (ii) independence from local infrastructures. Examples of such domains are fire fighting [1], search and rescue, health care and policing. Furthermore, also many other position-based applications would benefit from positioning technologies that fulfill both requirements [9]. One technology fulfilling (ii) is positioning by GPS. However, it has been considered as a fact that GPS positioning does not work indoors and therefore does not fulfill the coverage requirement (i). Due to recent technological advances, e.g, high-sensitivity receivers and the promise of an increase in the number of global navigation satellites, this situation is changing.

In 2005, LaMarca *et al.* [11] studied GPS availability with an off-the-shelf receiver for tracking the daily tasks of an immunologist, a home maker and a retail clerk. For the three studied persons, the availability was on average only 4.5% and the average gap between fixes was 105 minutes. To address these shortcomings they proposed fingerprinting-based positioning [8] as a solution. However, for the previously mentioned domains fingerprinting-based solutions are less suitable, given the requirement of fingerprinting collection, the vulnerability to hacking, that e.g. fires might alter the building and the unknown factor of whether or not fingerprinted base stations are taken out, e.g. by a fire.

P. Floréen, A. Krüger, and M. Spasojevic (Eds.): Pervasive 2010, LNCS 6030, pp. 38–56, 2010.

We have conducted a measurement campaign at several indoor sites, including wooden and brick houses, a public school, a warehouse, a shopping mall and a tower block, to determine to what extent GPS is usable indoors and which performance to expect from it. Furthermore, we intended to link the measured performance to the type of errors affecting GPS as well as to local properties of the buildings like dominating materials and proximity to external walls and windows or surrounding buildings.

In this paper we argue that—when using state-of-the-art receivers GPS— GPS indoor performance is better than suggested in earlier literature. The results of our measurement campaign, which is to our knowledge the most comprehensive of its kind, show good GPS availability in many buildings except for larger ones with thick roofs or walls. The horizontal RMS error in our measurements was below five meters in wooden and below ten meters in most of the brick and concrete buildings investigated. Lower accuracies could be linked to low signal-to-noise ratios, multipath phenomena or bad satellite constellation geometry. We also considered GPS receivers embedded in mobile phones which provided lower availability and accuracy than dedicated receivers.

The rest of this paper is structured as follows: In Section 2 we give a brief introduction and overview of research on GPS and satellite based navigation with a focus on indoor usage. In Section 3 we present our measuring methodology. In Section 4 we present our analysis of the measurement campaign. Finally, Section 5 concludes the paper and provides directions for future work.

2 GPS Primer

GPS satellites send signals for civilian use at the L1 frequency at 1.575 GHz; these signals are modulated with a *Pseudo-Random Noise (PRN)* code unique to each satellite. A GPS receiver tries to *acquire* each GPS satellite's signal by correlating the signal spectrum it receives at L1 with a local copy of the satellite's PRN code. An acquisition is successful, once the local copy is in sync with the received signal, which requires shifting the copy appropriately both in time and in frequency. The latter shift is due to the Doppler effect caused by the satellite's and the user's relative motion. Once a satellite's signal has been acquired, the receiver *tracks* it, that is, the receiver continuously checks the validity of the shift parameters above and updates them if necessary.

Each satellite's signal is modulated not only with its PRN code but additionally with a navigation message, which contains almanac data (for easier acquisition of further satellites) as well as its precise *ephemeris data*, that is the satellite's predicted trajectory as a function of time, allowing GPS receivers to estimate the current position of the satellite. Finally, to achieve precise 3D positioning with a standard GPS receiver via trilateration, the positions of and distances to at least 4 satellites have to be known; those distances can be computed from the time shift maintained while tracking the respective satellites. As a general rule, the more satellites can be tracked, and the wider they are spread over the sky as seen by the user, the more precise the positioning – due to the additional distance data and a satellite geometry resulting in less error-prone lateration.

A popular enhancement of GPS positioning is given by *Assisted GPS (A-GPS)* [17]. A-GPS provides assistance data to GPS receivers via an additional communication channel e.g. a cellular network. This assisting data may consist of e.g. ephemerides and atmospheric corrections. Also, a cellular network provides means for a rough positioning of the GPS enabled device. A-GPS eases satellite acquisition and can therefore drastically reduce the time to first fix and the initial positioning imprecision of a receiver in *cold start* (i.e. when no initial information about satellite constellations is available): Essentially, A-GPS allows for a *hot start* (precise ephemerides for all satellites available), once the assisting data has been transmitted. Furthermore, A-GPS can improve positioning accuracy by eliminating systemic error sources [12, Chapter 13.4].

GPS performance degrades in terms of both coverage and accuracy when experiencing problematic signal conditions, e.g. in urban canyons and especially in indoor environments. The cause for this is termed signal *fading*, subsuming two fundamental signal processing obstacles: First, when GPS signals penetrate building materials, they are subjected to attenuation, resulting in lower *signal-to-noise ratio (SNR)*. Furthermore, the signal is subject to *multipath phenomena*: Reflection and refraction of the signal results in multiple echoes of the *line-of-sight (LOS)* signal arriving at the receiver. Low signal-to-noise ratios and multipath handicap both acquiring and tracking GPS signals and usually result in less reliable positioning due to less suitable satellite geometry and individual time shifts measurements being less accurate. *High-Sensitivity GPS (HSGPS)* [10] receivers are specifically designed for difficult signal conditions, i.e. to alleviate the above problems. HSGPS is claimed to allow tracking for received GPS signal strengths down to -190 dBW: three orders of magnitude less than to be expected in open-sky conditions [12]. These thresholds are constantly being improved using new processing techniques [17, Ch. 6]. Note, that for acquiring signals at cold start, a somewhat (around 15dBW) higher signal strength is usually necessary, as during acquisition reliable time and frequency shifts of the signal have not only to be maintained, but instead searched for in a wide spectrum.

With respect to future improvements towards satellite based indoor positioning, note also that the upcoming Galileo system is a *Global Navigation Satellite Systems(GNSS)*, like GPS, and will soon be interoperable with the latter, resulting in roughly a doubling of GNSS satellites available [12, Ch. 3]. Combined satellite constellations will yield, in effect, better geometries at the user position, improving positioning accuracy, especially indoors, where signals from only parts of the sky may be available. Other upcoming improvements for indoor GNSS are provided by the modernized public signal structures of GPS and Galileo, allowing improved tracking of weakened signals via pilot channels, and yielding additional protection against multipath-induced inaccuracies [2]. In the GNSS community indoor positioning and respective obstacles and improvements are being investigated, see, e.g., Teuber *et al.* [16], Paonni *et al.* [13], Lachapelle *et al.* [10], Watson *et al.* [18] and references therein. This paper adds to this line of work but from an application-oriented perspective using real-world measurements to investigate where and to what extent one can employ GPS for indoor positioning.

3 Measurement Campaign Methodology

In the following, we describe the measurement campaign, the equipment used, as well as methodology regarding measurement collection procedures and choice of in-building locations; for a more thorough justification of the chosen methodology see also [3].

3.1 Receiver Equipment Employed

Throughout our campaign, we employed a u-blox LEA-5H Evaluation Kit and a SiRF-Star III BU-353 USB GPS receiver as examples of dedicated receivers, and a Nokia N95 8GB driven by Texas Instruments' NaviLink 4.0 GPS5300 chip as an example for a currently used in-phone GPS receiver system. The u-blox receiver is specified to have a -190dBW (-175dBW) threshold for tracking (respectively, acquisition) and was connected to a 48x40x13mm u-blox ANN-MS patch antenna, providing 27dB gain and specified with a 1.5dB noise figure. We will focus on the measurements obtained with this dedicated receiver and note in passing, that the SiRF product performered equivalently, though slightly poorer which might be solely due to the u-blox's high quality external patch antenna. To obtain A-GPS assistance data [17], we connected the u-blox receiver to a N95 phone.

The two classes of receivers considered differ not only in performance but also in price, energy consumption and size: Whereas the larger and more power consuming dedicated receivers will be used in specific scenarios mentioned in the introduction, such as search and rescue operations, the Nokia N95 in-phone receiver represents typical hardware for the every-day consumer use of location based services. Furthermore, given the pace of development the chosen dedicated receiver allows an outlook on the performance of future in-phone GPS receivers used, e.g., for location-based services.[1]

3.2 Data Collection Procedures

During our campaign, we focused on static measurements at a number of locations per building, partially in order to eliminate effects from the receiver's recent history of measurements. Consequently, we reset the receivers prior to each measurement, thereby minimizing the effects of, e.g. Kalman filtering techniques, which exploit recent measurement history and therefore potentially pollute static measurements w.r.t. both locations and durations, see, e.g., Brown and Hwang [4].

To focus on and to fairly compare signal conditions at individual indoor locations, we also decided against an on-person receiver setup. Instead, each of the GPS enabled devices was mounted on the seat of a light-weight wooden chair, spaced 20 cm apart from the other receiver devices to remove the chance of any near-field interference. Note though, that the measurements carried out within the shopping mall, the warehouse and the tower block were conducted during business hours, providing realistic pedestrian traffic conditions, see also [14] for the impact of pedestrian traffic on GPS performance. The chair was then placed at the in-building measurement locations chosen and we collected GPS measurements using the following procedure:

After initializing the programs for logging GPS data at 1 Hz, we "hot started" the Nokia and the u-blox receivers. Note, that by hot start we refer to a initialization using A-GPS data. If the hot start of the u-blox receiver was successful, i.e., if it within 10 minutes produced a position fix, we subsequently logged the u-blox receivers' NMEA formatted data for 5 minutes; then we repeated as above, but this time cold starting the receivers without A-GPS. In case the hot start of the u-blox was not successful, we

[1] The generation 6 of the u-blox receiver has been improved over the version used here, specifically focusing on low energy consumption, allowing for more economic use in mobile gadgets.

produced a successful hot start at a nearby location and walked back to the measurement location. If the receiver still produced position fixes upon arrival, we logged the receivers' data for 5 minutes.

3.3 Choosing Measurement Locations

For choosing where to measure GPS reception within the buildings, we overlaid the larger buildings' floor plans with a regular grid, choosing measurement locations as the centers of the grid cells, where feasible, i.e. where these centers fall within the respective building. We chose this strategy to avoid biases induced by alternative approaches in which locations are picked so to reflect environmental conditions which are—by a priori hypotheses—associated with specific GPS signal reception conditions.

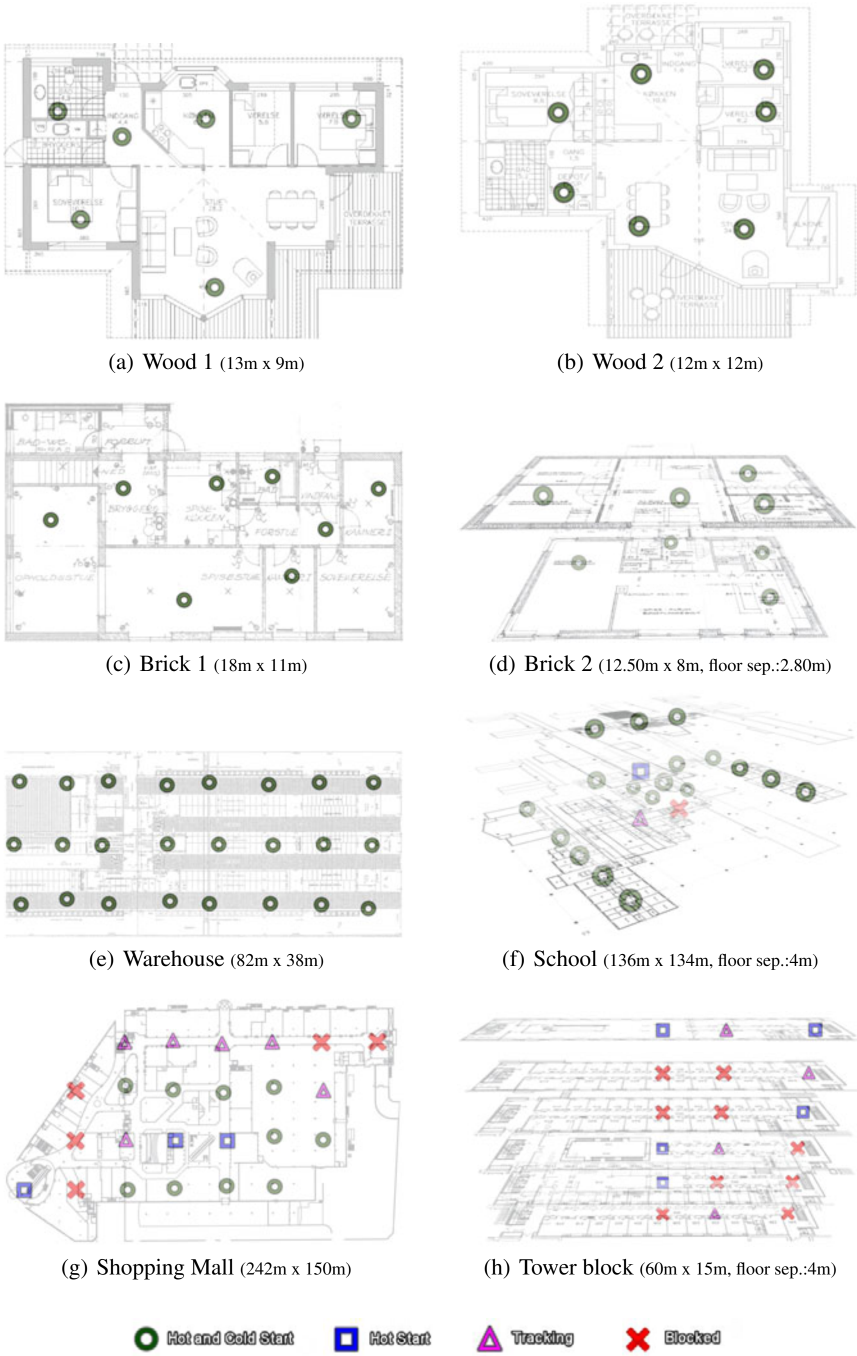
4 Results

Using the measurement procedures described above allows us to explore the performance of GPS positioning in various environments using state-of-the-art receiver technology. In section 4.1 we will introduce the environments investigated in our measurement campaign and characterize them with regards to availability, the most fundamental measure for GPS performance. Subsequently, we will cover further GPS performance measures, namely time-to-first-fix in Section 4.2 and positioning accuracy in Section 4.3. Throughout this section, we not only present performance measures for the individual measurement locations, but also elaborate on general rules which govern GPS indoor performance, as observable in the analysis of our measurement campaign. In Section 4.4 we give results for measurements using the Nokia N95 in-phone receiver, comparing them to the measurements obtained from dedicated receivers.

4.1 GPS Availability and Signal Strength

The GPS availability results for the eight environments chosen for our campaign are illustrated in Figure 1. The figure shows for each in-building measurement location whether and by which means we were able to acquire GPS fixes. As described by the figure legend, we categorize availability performance into 4 categories: (i) both *hot start* and *cold start* (indicated by a green circle) were successful; (ii) a *hot start* but no *cold start* (indicated by a blue square) was successful; (iii) neither hot or cold starts were successful, but *tracking* was, that is acquiring a GPS position at a location with high GPS availability and moving to the measurement location where GPS upon arrival continued to produce position fixes (indicated by a purple triangle); (iv) and finally *blocked* where no GPS position fixes could be established (indicated by a red cross).

A main factor impacting to which extent and quality one can get GPS fixes at specific in-building locations are the surrounding building structures and elements. Therefore, complementing Figure 1, we listed in Table 1 for the environments investigated the respective dominating materials used for external and internal building elements. The table also contains approximations, compiled from various sources [6,15,19], for



Note, that the distances between floors are modified in the figure in order for all grid points to become visible.

Fig. 1. Overview of GPS availability in various building types

Table 1. Building materials and their attenuation properties in the buildings investigated

Building Type	Walls				Roof	dB
	External	dB	Internal	dB		
Wood 1	Wood	2.40	Wood	2.40	Tiles	5.19
Wood 2	Wood	2.40	Wood	2.40	Tiles	5.19
Brick 1	Double Brick	10.38	Brick	5.19	Fiber Cement	N/A
Brick 2	Double Brick	10.38	Brick	5.19	Tiles	5.19
School main building + right wing annex + left wing	 Double Brick Brick and Concrete	 10.38 14.76	 Brick Concrete	 5.19 9.57	 Tiles Tiles	 5.19 5.19
Warehouse	Fiber Cement and Curtains/Openings	N/A N/A	Equipment	N/A	Fiber Cement	N/A
Shopping Mall	Reinforced Concrete Tinted Glass Glass	16.70 24.44 2.43	Brick	5.19	Flagstone Sand Felt roofing Concrete	N/A 2 N/A 9.57
Tower block	Double Brick around Concrete	19.95	Brick	5.19	Tiles	5.19

the attenuation (w.r.t. GPS L1 frequency signals and assuming an incident angle of 0 degree) caused by the respective building materials (assuming common respective thicknesses).[2] The attenuation values listed directly impact the signal-to-noise-ratio of GPS signals indoors, since, as a rule of thumb, a penetrated material's attenuation value is to be subtracted from the received signal-to-noise-ratio as experienced outside the given building. For signals penetrating multiple layers of building materials, attenuation can be considered at least additive. The average signal-to-noise-ratio over time for the 4 satellites with the strongest received SNR is shown in Figure 2 for all measurements, grouped by building, see, e.g., Misra and Enge [12] for relating signal-to-noise-ratios and GPS signal power. Differences in the SNR figures within one building are naturally due to properties of the individual in-building locations. Such properties include the number and distances to building elements such as walls and roofs: For example, Teuber *et al.* [16] concluded from their measurements, that the power of received GNSS signals does not only depend on the building materials penetrated, but also further decreases with the distance traveled after the respective penetrations. In general, our measurements confirmed that observation.

Per-case availability analysis. When looking at Figure 1 the GPS availability seems promising for both the two wooden houses 1(b) and 1(a) as well as for the two brick houses 1(c) and 1(d), of which only the last one is a multi-story building. However, in the other buildings GPS is only partially available, and in order to understand these variations we will go deeper into the analysis of these particular buildings.

The larger 82m x 38m warehouse 1(e) is a relatively open environment, with just cloth curtains between roof and lowered outer walls, and four 50cm wide skylights

[2] For GNSS frequencies lower than L1, e.g., L2 and L5, the attenuation for most of the listed materials is somewhat lower, see, e.g., [6, Table 3]. For further studies on the strength of GPS frequency signals in indoor environments see also [5, Ch. 9.4.2] and references therein.

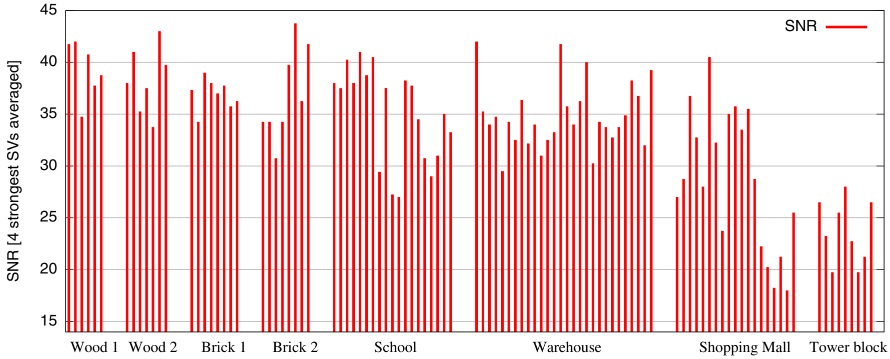


Fig. 2. Averaged signal-to-noise ratio at individual measurement locations

along the roof. Consequently, it allows for proper GPS fixes. Further analysis shows that reception was difficult and SNR low for signals which had to penetrate interior elements of the warehouse—whereas signals entering close to or through skylights were received much stronger. That GPS signals are received strongly only from certain parts of the sky is observable in the skyplots [7] in Figure 3 for two exemplary measurement locations close to exterior walls of the warehouse. In the skyplots, the 3 concentric circles represent 0, 30, and 60 degrees elevation, respectively. Depicted are the location of the satellites, tracked by the receiver during the respective hot start measurement period. Individual satellites are identified by the id of the PRN code, they are sending, respectively. The individual positions over time of each shown satellite are depicted by "+" symbols, where the symbol's color indicates signal-to-noise ratio, as experienced by the u-blox receiver at the respective measurement location and according to the color scale given in the figure. A green arrow trailing the orbit of a satellite signals its direction of movement. The pseudorange error for each satellite and for each individual time instance of reception during the measurement period are sketched in blue color, according to the scale given in the figure, and—for presentation purposes—perpendicular to the respective satellite's direction of movement.[3]

The school building at Figure 1(f) forms an H with two single-story wings and one three-story middle section and finally a single-story annex. First, due to the skylight windows signals have easy access to locations in the two wings. In the annex and also in the middle section on the second floor strong signals were present. Second, the first floor allowed for receivable but weaker signals, in particular at the location at the center of the middle section. Here a cold start was not successful, possibly due to the attenuation caused by the top floor, and due to the location being in a wide part of the building. Third, in the basement the signals are attenuated by the two top floors and only due to the relatively open area at the center were we able to track the signal there. At another basement location no GPS fixed were achieved at all.

[3] Note that while a GPS receiver can only output pseudorange errors w.r.t. the estimated position, they can be transformed into pseudorange errors w.r.t. the actual receiver position, given properly surveyed ground truth by means of, e.g., satellite imagery, building floor plans and laser ranging, as done by the authors, see also [3, Ch.3].

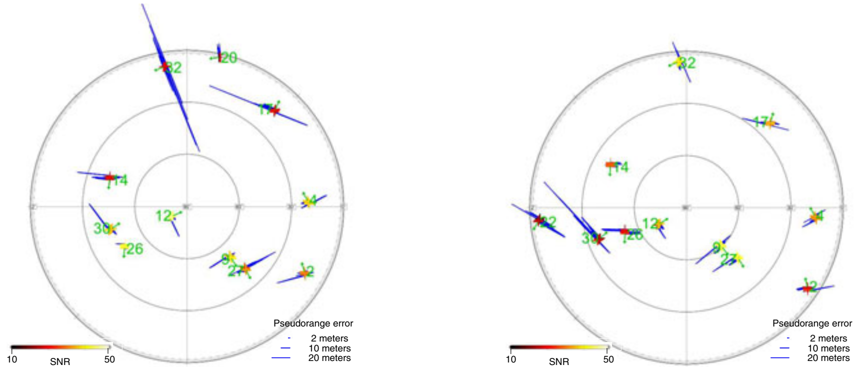


Fig. 3. Skyplots of measurements at two locations inside the warehouse

Figure 1(g) depicts the middle floor a three-story shopping mall. The grid points will be refereed to by coordinate tuples, where the bottom left corner would be (1,4), and the upper right would be (8,1),which is consistent with Figure 9, which will be discussed in Section 4.3 and which depicts most of the mall's middle floor plan, overlaid with skyplots. The center (3-5,3) of the middle floor is covered by a top floor of smaller size, and some other locations (2,2-4), (3-8,1), (7,1-3) are not only covered by a roof, but also by a parking deck. As a first observation, the grid points where both a cold and a hot start was possible are located in the single-story part of the building where only a top felt roof attenuates the GPS signals, with the exception of one grid point at the bottom of the second most right row (7,3), which is covered by the parking deck. Second, the signal could at least be tracked at all grid points that are covered by the second story, which consists of shops, offices and an atrium-like opening from the top floor roof down to the basement. Third, hot starts could also be performed at the grid points (4,3) and (5,3)—most likely due to the closeness to the glass atrium covering all floors. This hypothesis is supported by the relatively high SNR values experienced at these two locations (as compared with other measurement locations beneath the same heavy roof structure). Third, grid point (1,4), located in another atrium, presumably depicts the highly attenuating effect of tinted glass, see Table 1, resulting in comparatively low SNR values and allowing only for a hot, but not for a cold start. Fourth, all 5 blocked locations are among the 11 grid points covered by the top floor parking lot, where the separation to the middle floor consists of layers of steel-reinforced concrete, sand and flagstones. With the exception of point (7,3) only tracking is possible at the remaining 6 points, implying that GPS reception is still difficult. Note also, that, though not depicted in Figure 1(g), measurements were performed also in the basement, which provided position fixes only near exits and near the atriums spanning all floors.

Figure 1(h) shows all stories except the ground floor of a seven-story office building built in a tower block fashion. Averaged over the in-building measurement locations, this building showed the highest signal attenuations experienced in any of the explored buildings. This is only partially due to the outer double-brick and concrete walls. Additionally, our measurements showed that SNR was significantly impacted by the inner walls or ceilings, the respective signals had to penetrate. Fittingly, all blocked locations,

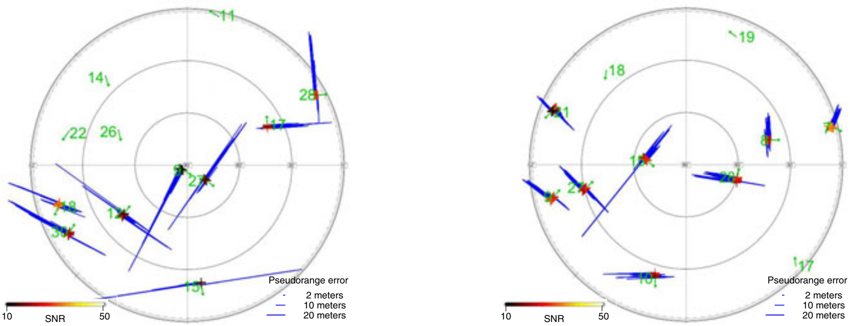


Fig. 4. Skyplots of measurements on 2nd (left) and 7th (right) floor of a tower block

apart from those residing on the staircase, are in narrow aisles surrounded by small offices. Furthermore, the two measurement locations at the 2nd and 3rd floor where hot starts were possible are both located adjacent to a two story library which means that GPS signals from lower elevation satellites have to penetrate only the external walls. Similarly, reception was possible at all three locations on the top floor, where signals can pass with less attenuation, not being obstructed by multiple inner building elements.

The poor reception on the lower floors can also be attributed to an additional shielding effect caused by two adjacent four-story buildings. These are placed in the same major direction as the building depicted and in immediate continuation and on opposite sides of what is depicted as the rightmost end of the building. The signal attenuation by these two buildings are contributing to the GPS unavailability on the second, third and fourth floor in the staircase to the right, additional to the attenuation caused by the concrete-built staircase as well as building elements further above. Consistent with this explanation, on the same staircase, but on the highest three level (clear from the shielding buildings), tracking, and for the 5th and 7th even hot starts, were successful.

To illustrate exemplary the effects of attenuation by multiple building stories, Figure 4 shows skyplots [7] for the middle location in Figure 1(h) on the 2nd and 7th floor, respectively. The observed SNR values are generally, and especially around the zenith, higher at the location on the highest floor, since the latter is separated from open sky by less elements of its own (as well as of the neighboring) building(s). Noteworthy, the low SNR values around the zenith are typical for the measurements we carried out at lower levels of multi-story buildings, but stand in contrast to the outdoor situation where SNR values generally increase with the satellites' elevation w.r.t. the receiver position. Both skyplots depict also the positive effect of the tower block's windows in east and west direction, adding to the proper signal reception from low elevation satellites.

Summary. We have found that both signal-to-noise-ratios as well as, in result, the availability of GPS indoors—using today's receiver technology—is generally more promising than suggested by earlier positioning literature. Furthermore, covering many different building types, we found, mostly in confirmation with empirical studies for different individual environments, that GPS availability is negatively impacted by: the number of overlaying stories, the roof material, e.g. reinforced steel, in contrast to more favorable materials such as felt roofing or fiber-cement, as well as wall materials and the number of walls, the distance to the walls separating the receiver from the outside and the closeness to surrounding buildings.

4.2 Time To First Fix

The time to first position fix is prolonged, where acquisition of weaker and refracted signals is necessary, in particular indoors. Figure 5 plots on a logarithmic scale time to first fix in seconds for hot and cold starts of the u-blox receiver in three environments.

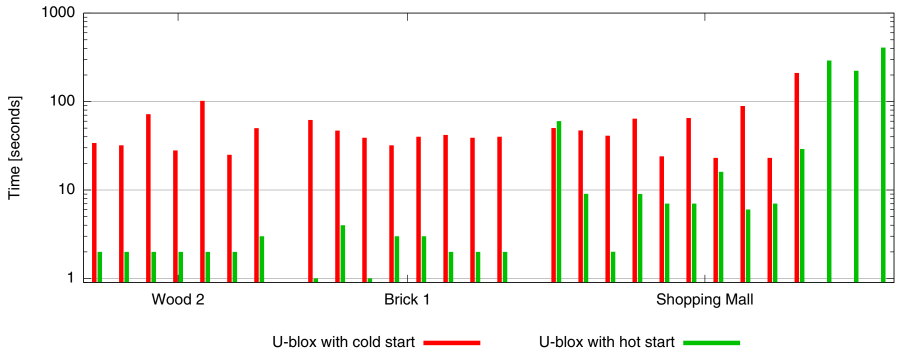


Fig. 5. Time to first fix for three measurement sites

Inside both buildings 'wood 2' and 'brick 1' the u-blox receiver shows a fast hot acquisition of less than four seconds. As expected, the cold starts take longer, around 40 seconds on average, with some faster at half a minute and some slower. In comparison, for outdoor use the technical specification of the u-blox receiver states that hot starts take less than one second and cold starts take about 29 seconds. In the shopping mall the hot starts take around ten seconds on average but at three locations the time increases to several minutes. Comparing SNR and time to first fix for each measurement location, one can observe a strong dependency between the weakness of signals and the time it takes to acquire the signals. This implies that in locations with weak signals one can expect high values for time to first fix. For cold starts the average time-to-first-fix is around 60 seconds but at the three last locations cold start were not even possible within the 10 minute time limit.

4.3 Accuracy

To study the GPS positioning accuracy in the environments investigated using a dedicated receiver we have compared the u-blox receiver's GPS position fixes with manually surveyed ground truth positions. Figure 6 shows for each measurement location,which allowed for a hot start or tracking the root mean squared 2D and 3D positioning errors, averaged over the five minutes of data gathered. Figure 7 shows per building the cumulative 2D error distribution, averaged over all position fixes gathered at in-building

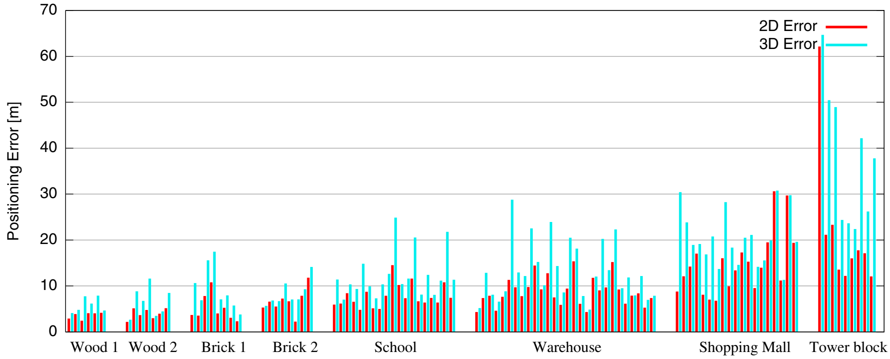


Fig. 6. RMS positioning error in 2 and 3 dimensions

measurement locations. These CDFs yield popular comparative measures of GPS quality, implying an order on the investigated buildings—which is noticeably invariant for most of the popular confidence intervals, e.g., 50th, 67th (i.e. RMS), and 95th percentile. Note, that u-blox claims to allow for a horizontal RMS position error of 3m or less, a claim which holds for outdoor measurements we carried out in open-sky surroundings. The accuracy achieved for cold starts (not shown) averaged over 5 minutes is as expected lower due to the usually small number of satellite ephemerides known and the resulting poor DOP values, when achieving first position fixes without assistance data. The accuracy, though, usually converges over time to the one for hot starts, as more parts of the almanac and precise ephemerides for newly acquired satellites can be decoded. For the remainder, when referring to or visualizing measurement details, we implicitly refer to 'hot start' measurements where successful and to 'tracking' ones, where not.

Similar to the performances measures of availability and time to first fix, also accuracy is impaired by signal attenuation. This is mainly due to the following two reasons: First, signal attenuation may lead to fewer satellites being tracked and therefore to less favorable satellite constellation geometries. Second, low signal-to-noise-ratio of

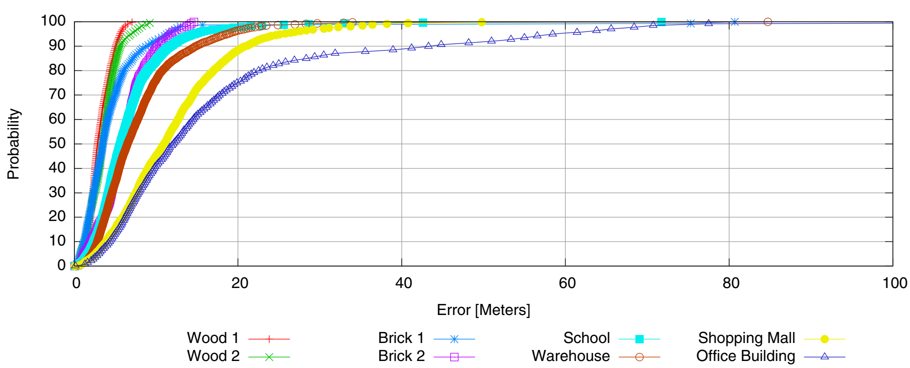


Fig. 7. Cumulative distribution functions (CDFs) of 2D positioning errors per building

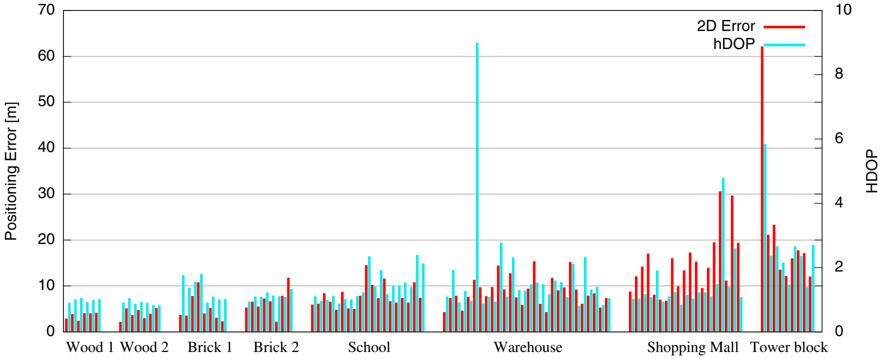


Fig. 8. RMS 2D positioning error and respective horizontal DOP

received signals may result in less precise tracking of the signal, and therefore in less accurate measurements of the distance to the satellite. Figure 8 shows both the RMS 2D error as well as the horizontal DOP value, as an indicator for the negative impact of the satellite geometry with values below 1 being considered ideal. In an outdoor setting, a linear dependency of DOP value and positioning inaccuracy should be observable, and so it is also, to a large extent, in our measurements. Deviations from this linear dependency are mostly constituted by the second main reason for GPS inaccuracy indoors: multipath phenomena. In the following, we will discuss both positioning accuracy and the impact of multipath phenomena in a per-environment analysis, relying foremost on analysing skyplot visualizations yielding SNR and the pseudorange errors for individual satellites received at the measurement locations. Note, that within a GPS receiver the measured pseudoranges are the main basis for the subsequent positioning computation via lateration.

For the wooden buildings (see Figure 1(a) and Figure 1(b), respectively) positioning accuracy is close to outdoor levels, at 3.6m and 4.0m, respectively, for the average over the RMS 2D positioning errors shown in Figure 6. The good accuracy is partially due to the low attenuation of wooden building materials. Additionally, the small size of the building means closeness to outer walls and few or none obstructing inner building elements. Finally, multipath phenomena are weak, because the line-of-sight signal is as expected strong, and because the time-of-arrival difference between line-of-sight signal and echoes is small, since reflecting buildings elements are generally close by. For the two brick houses the positioning errors were on average, at 5.0m and 6.7m, respectively, only slightly larger than the smaller houses built from less attenuating wood. Together with the results from the recent sections, this suggests that modern dedicated receivers can cope well with the indoor challenges within small houses.

Within the school depicted in Figure 1(f) the 2D positioning errors are significantly larger for locations buried deep inside the building, i.e., in the center and especially in the basement of the building, increasing the average error to 7.8m, whereas for other locations the error is on the same level as for the brick houses.

The measurements in the warehouse (Figure 1(e)) showed an average 2D error of 8.8m and the average HDOP of 1.7 was considerably higher than for the buildings

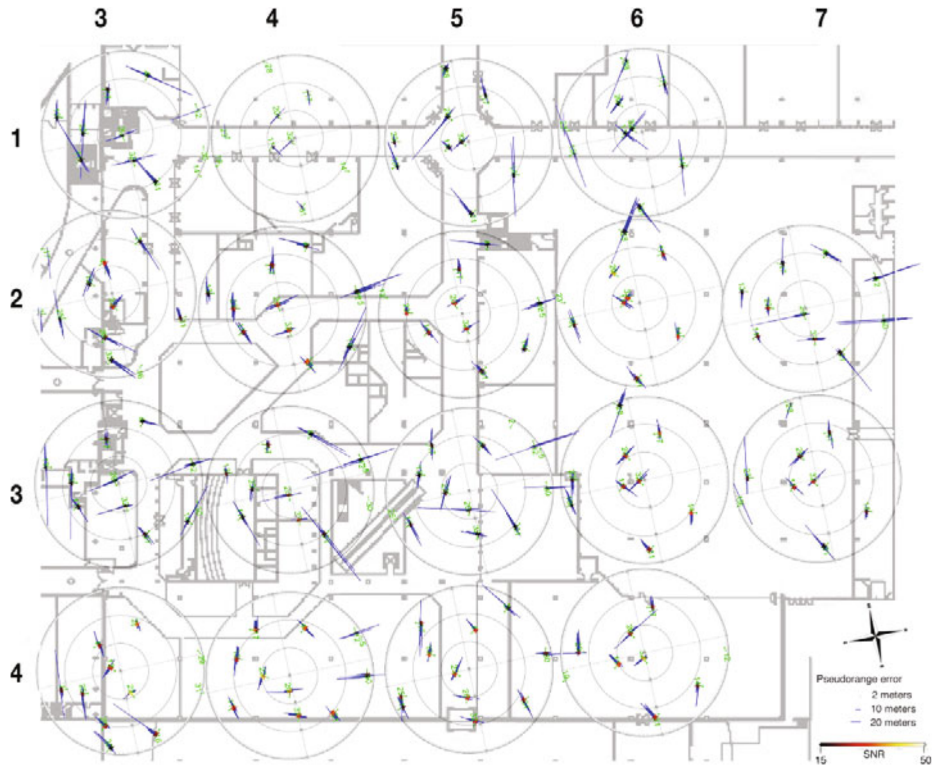


Fig. 9. Measurement locations in the shopping mall, overlaid with skyplots showing SNR and pseudorange error, as observed by the u-blox receiver

mentioned above, suggesting that the large window and skylight areas allow for easy access for GPS signals, but only from certain parts of the sky, as visible in Figure 3.

Within the main floor of the shopping mall, depicted in Figure 1(g), the RMS positioning errors, averaging at 14.8m in the plane, deviated more than in any of the building mentioned above; this observation correlates with the heterogeneity of both architecture and building materials used in the mall. To support the discussion of the different signal conditions and resulting accuracies observable, Figure 9 shows skyplots, as introduced in Section 4.1, for all measurement locations in the center part of the mall's main floor. All locations in the top row and and rightmost column lie beneath the mall's parking lot—causing low SNR values. Interestingly, the pseudorange errors for satellites around the zenith are not necessarily large. Notably, though, location (7,2) shows different data: Mostly in the sky part below which windows lie, reflections through these windows seem to be stronger than the line-of-sight signals, resulting in large multipath-induced errors.[4] The biased pseudorange measurements lead to strongly biased positioning,

[4] Note, that multipath-induced errors can be con- or destructive: Depending on the relative phase of the incoming signal versions, they either lengthen or shorten the pseudorange measured.

resulting in the largest horizontal RMS error of all locations in the mall, except (4,1). At the latter location tracking was possible only for 4 satellites and for a short amount of time, leading to the within the mall by far largest horizontal DOP values of over 4.

Another area where accuracy is strongly impacted by multipath phenomena is under the atrium roof. The atrium located between locations (4,3) and (5,3) spans all three roof and provides signal echoes easy access especially to locations (3-5,3) which are otherwise covered by the mall's top floor. Consequently, the skyplots for (3,3) and (5,3) suffer from large pseudorange errors indicating that the echoes hinder precise tracking of the line-of-sight (versions of the) GPS signals, resulting in biased position fixes, deviating in particular directions from the true location. Such an effect does not occur and the pseudorange error is small, in case a satellite is received in direct line of sight through the atrium, as e.g., PRN 23 as received from (4,3).

When rerunning measurements at day-times yielding considerably different satellite constellations, we noted only minor changes in GPS performance measures. Exceptions occurred where SNR is rather good, but multipath phenomena impact the positioning strongly, depending on the current satellite constellation: Of all mall locations investigated, location (4,3) showed the largest deviation in 2D error, from an original 8.1m RMS to 17.2m for the rerun of the measurement, averaged over 5 minutes, respectively.

The tower block (Figure 1(h)) exhibits, averaging over measurement durations and locations, the by far poorest SNR (of 23), and the highest HDOP (of 2.7) and, consequently, also the largest horizontal errors (of 21.7m RMS) amongst all investigated environments. While the highest floor shows acceptable reception, SNR and pseudorange errors are worse on lower floors as shown for the 2nd floor in Figure 4. Consequently and consistent with the results obtained in the other investigated buildings, the attenuated and indirect signals yield here a much larger HDOP value of 5.8 and horizontal RMS error of 62.1m than on the top floor with 1.5 and 12.2m, respectively.

Summary. The accuracy in the four wooden and brick houses investigated was good using the dedicated u-blox receiver due to it being separated from the outside both by only few building elements and also only short distances, resulting in low signal attenuation and dispersion and in only small delays of multipath echoes. If more building elements get between the receiver and the outside, as in the basement of a school or a mall, under a roof parking lot or deep inside a tall building, signal attenuation impacts both availability and positioning accuracy, since only few satellites and only in restricted parts of the sky can be acquired leading to poor satellite constellation geometries.

Especially in environments of heterogeneous architecture like in the investigated mall, GPS accuracy varies considerably and can be strongly biased and impaired by multipath phenomena, e.g., when window areas allow for echoes being potentially stronger than the line-of-sight signal which may have to penetrate strongly attenuating building elements to be received directly.

4.4 Embedded GPS Receivers

Embedded GPS receivers in mobile phones are restricted both in terms of power consumption and antenna type and size. In result, such receivers are less sensitive than those

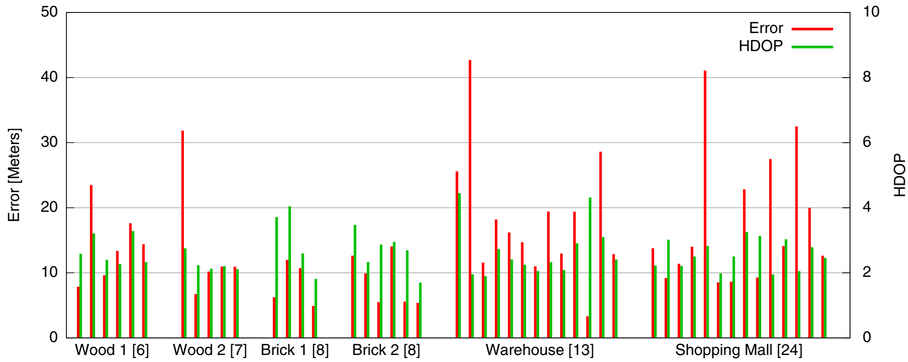


Fig. 10. Horizontal RMS errors and DOP values, using the N95 in-phone receiver

typically used for standalone receivers, implying less sensitive antennas and weaker amplification stages, see also [5, Ch. 9.4.2.1]. Therefore, it is relevant to consider how well an embedded GPS receiver performs compared to the state-of-the-art receiver we relied on in the previous sections. As mentioned in Section 3, we collected data with a Nokia N95 8GB phone which employs a Texas Instruments GPS chip launched in 2006.

Figure 10 shows the horizontal RMS error and the average horizontal DOP value for each measurement location in the six environments where we collected measurements using the N95 embedded receiver. The labellings at the bottom of the figure include the number of measurement locations for each environment. By comparing for each environment the latter number to the number of bars shown, one can comment on the availability for the N95. Generally, the N95 allows for GPS positioning in fewer locations than the u-blox receiver, except for the house 'wood 1' and the warehouse, where availability was equivalent.

The horizontal RMS errors measured in the four houses average around 10 meters, for the warehouse and the shopping mall even higher. Particularly for the four houses,

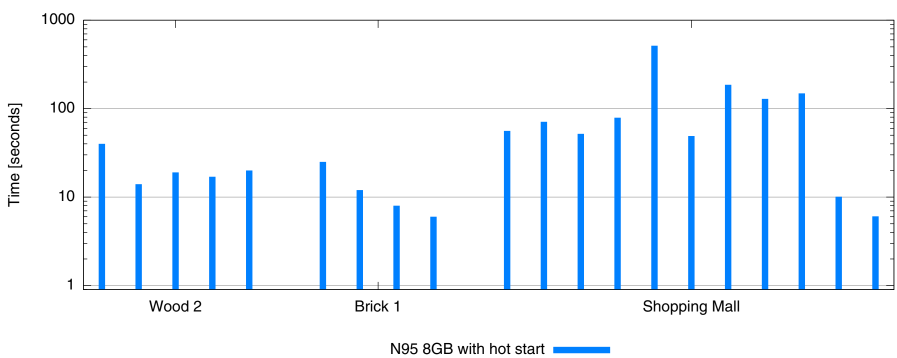


Fig. 11. Time to first fix for the N95 for hot starts

the RMS values are twice as bad as when using the u-blox receiver. Due to the N95 acquiring consistently fewer satellites than the more sensitive u-blox receiver, the HDOP results for the N95 are usually higher than 2 and twice as large as for the u-blox, which yields the main explanation for the lower positioning accuracy of the N95. The time to first fix for hot starts is shown on a logarithmic scale in Figure 11. For the 'wood 2' and 'brick 1' environments it is around 10 seconds, thus longer than the 1-3 seconds used by the u-blox receiver. For the shopping mall it averages around 90 seconds—much more than the on average 10 seconds used by the u-blox.

In summary, the embedded N95 GPS receiver is able to provide positioning in considerably fewer indoor environments than the u-blox receiver. Furthermore, the time to first fix is considerably longer and positioning errors are twice as large.

5 Conclusions

In this paper we improve on the understanding of indoor GPS reception characteristics by analyzing results from a measurement campaign covering eight different buildings. We have found that both signal-to-noise-ratios as well as, in result, the availability of GPS indoors using state-of-the-art receiver technology is generally more promising than suggested in the positioning literature. Furthermore, covering many different building types, we found that GPS availability is negatively impacted by: the number of overlaying stories, the roof material, as well as wall materials and the number of walls and the closeness to surrounding buildings. Time to first fix with at hot starts, i.e. using A-GPS, generally took less than ten seconds. However, at some locations longer time was required, occasionally more than a minute. Especially for battery-powered devices this might be a drawback as longer time to first fix will consume extra power.The 2D root mean squared accuracy of the measurements was below 5 meters in the wooden and below 10 meters in most of the brick and concrete buildings. Low accuracies can be linked, depending on the environment's characteristics, to either low signal-to-noise ratios, multipath phenomena or poor satellite constellation geometries. We also carried out measurements using GPS receivers, embedded in mobile phones, which provided considerably lower availability, lower accuracy and longer time to first fix than the state-of-the-art receivers employed in the campaign.

Our results indicate for the application domains mentioned in the paper, that GPS can be used as a positioning technology to provide situational awareness at a building-part granularity, especially when A-GPS is available, yielding an accuracy level of tens of meters and a time to first fix in the range from a few seconds to minutes. GPS though, does not currently provide instantly available indoor positioning accurate to the meter as might be crucial for some indoor applications, e.g. fire fighters navigating in burning buildings. Therefore, another use of indoor GPS would be as a complementary indoor positioning technology, e.g., to help fighting the error growth over time of inertial positioning systems when available. The results are also indicative for the performance of future embedded GPS devices, as state-of-the-art receivers are being constantly miniaturized and power optimized.

The line of work presented in this paper naturally gives rise to further items of research, potentially inspiring or giving input to improved GPS positioning algorithms. It would be relevant to study systematically to which extents in-building position parameters like distance and angle to the closest wall, window or room corner affect signal strength and quality as measured at the receiver position. Whereas such dependencies were found and formulated already by Teuber *et al.* using data gathered in a single office building, a validation of such dependencies in other real-world indoor environments is yet to be done. Furthermore, it would be relevant to conduct new measurement campaigns to evaluate the impact on indoor GNSS performance of the new GPS and Galileo signals and satellites as they become available.

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References

1. Angermann, M., Khider, M., Robertson, P.: Towards operational systems for continuous navigation of rescue teams. In: Proc. Position, Location and Navigation Symposium (2008)
2. Avila-Rodriguez, J.-A., Hein, G., Wallner, S., Issler, J.-L., Ries, L., Lestarquit, L., de Latour, A., Godet, J., Bastide, F., Pratt, T., Owen, J.: The mboc modulation. a final touch for the galileo frequency and signal plan. Inside GNSS 2(6), 43–58 (2007)
3. Blunck, H., Kjærgaard, M.B., Godsk, T., Toftkjær, T., Christensen, D.L., Grønbæk, K.: Empirical analysis and characterization of indoor gps signal fading and multipath conditions. In: Proc. 22nd Intl. Techn. Meeting Satellite Division Inst. of Navigation, ION GNSS (2009)
4. Brown, R., Hwang, P.Y.C.: Introduction to random signals and applied Kalman filtering: with MATLAB exercises and solutions, 3rd edn. (1997)
5. Bullock, J., Floss, M., Geier, G., King, M.: Integration of gps with other sensors and network assistance. In: Kaplan, E.D., Hegarty, C. (eds.) Understanding GPS: Principles and Applications, ch. 9, 2nd edn. Artech House, Reading (2006)
6. Hein, G., Teuber, A., Thierfelder, H., Wolf, A.: Fighting the fading - part 2. Inside GNSS (2008)
7. Hilla, S.: Plotting pseudorange multipath with respect to satellite azimuth and elevation. GPS Solutions 8(1) (2004)
8. Kjærgaard, M.B.: A Taxonomy for Radio Location Fingerprinting. In: Proceedings of the Third International Symposium on Location and Context Awareness (2007)
9. Küpper, A.: Location-Based Services: Fundamentals and Operation, October 2005. Wiley, Chichester (2005)
10. Lachapelle, G., Kuusniemi, H., Dao, D., MacGougan, G., Cannon, M.: HSGPS signal analysis and performance under various indoor conditions. Navigation, Inst. of Navigation 51(1), 29–43 (2004)
11. LaMarca, A., Chawathe, Y., Consolvo, S., Hightower, J., Smith, I., Scott, J., Sohn, T., Howard, J., Hughes, J., Potter, F., Tabert, J., Powledge, P., Borriello, G., Schilit, B.: Place Lab: Device Positioning Using Radio Beacons in the Wild. In: Gellersen, H.-W., Want, R., Schmidt, A. (eds.) PERVASIVE 2005. LNCS, vol. 3468, pp. 116–133. Springer, Heidelberg (2005)
12. Misra, P., Enge, P.: Global Positioning System: Signals, Measurements, and Performance. In: Navtech, 2nd edn. (2006)

13. Paonni, M., Kropp, V., Teuber, A., Hein, G.: A new statistical model of the indoor propagation channel for satellite navigation. In: Proc. 21st Intl. Techn. Meeting Satellite Division Inst. of Navigation, ION GNSS (2008)
14. Sokolova, N., Forssell, B.: Moderate pedestrian traffic: Indoor hsgps receiver performance. European Journal of Navigation 5(3), 2–7 (2007)
15. Stone, W.: Electromagnetic signal attenuation in construction materials. NIST Construction Automation Program Report No. 3, National Inst. Standards and Technology, U.S. (1997)
16. Teuber, A., Paonni, M., Kropp, V., Hein, G.: Galileo signal fading in an indoor environment. In: Proc. 21st Intl. Techn. Meeting Satellite Division Inst. of Navigation, ION GNSS (2008)
17. van Diggelen, F.: A-GPS: Assisted GPS, GNSS, and SBAS. Artech House (2009)
18. Watson, R., Lachapelle, G., Klukas, R., Turunen, S., Pietil, S., Halivaara, I.: Investigating gps signals indoors with extreme high-sensitivity detection techniques. Navigation, Inst. of Navigation 52(4), 199–213 (2006)
19. Williams, K., Greeley, R.: Radar attenuation by sand: laboratory measurements of radar transmission. IEEE Transactions Geoscience and Remote Sensing 39(11), 2521–2526 (2001)