HIGH-SENSITIVITY GNSS: THE TRADE-OFF BETWEEN AVAILABILITY AND ACCURACY

Andreas Wieser
Engineering Geodesy and Measurement Systems (IGMS)
Graz University of Technology
Email: andreas.wieser@TUGraz.at

Abstract: High-sensitivity (HS) GPS receivers can acquire and track signals 20–25 dB below the threshold of a conventional receiver. This allows GPS positioning in environments where other receivers might not provide enough observations. There are also applications like GIS data collection, mapping, or traffic guidance and control, where both types of receivers might be applicable, and the question is which one is the better choice?

Using data from a dedicated experiment we show that indeed an HS receiver can provide significantly more observations than a conventional GPS receiver, because it also tracks satellites behind an obstruction. Here, this results in a positioning availability of nearly 100% for the HS receiver, whereas the conventional receiver gives a controlled position solution only 50% of the time. However, the accuracy of the observations additionally provided by the HS receiver may be a factor 10–100 worse than that of the line-of-sight observations. This difference in quality needs to be taken into account properly when computing position, velocity, and time. Failure to do so may result in position errors of several hundred meters. We show that positioning accuracies of 5–20 m are attainable even in harsh environment when using an optimum variance model and a sophisticated quality control kernel in the positioning algorithm. These components help to balance increased availability and desired accuracy by reducing the influence of poor observations. Using such algorithms, there is a clear advantage of using HS receivers instead of conventional receivers in applications requiring meter level accuracies with moderate antenna dynamics.

1. Introduction

Buildings, trees, and topography are potential obstacles in the line-of-sight between satellites and receiver. They attenuate GNSS signals by typically more than 10–20 dB, [13]. Conventional receivers cannot acquire and track heavily attenuated signals, meaning that line-of-sight obstacles actually may block signals and reduce the availability of GNSS in terrestrial applications.

Recently, high-sensitivity (HS) GPS receivers have become available, see [10,3,4,11]. They can typically acquire and track signals 20–25 dB below the threshold of conventional receivers. So, HS receivers increase the number of satellite observations available and thus allow GNSS positioning in environments like urban canyons, forests, or even inside buildings.

However, exceptionally weak signals are usually not only attenuated but also delayed. They arrive at the receiving antenna indirectly e.g. by reflection or diffraction, rather than along the line-of-sight. The associated range errors are significantly larger than the typical errors of line-of-sight observations, as we will show below. So, the signals additionally provided by an HS receiver are usually less accurate than those which can also be tracked with a conventional GPS receiver.

This difference in quality needs to be taken into account properly when computing position, velocity, and time. Failure to do so may result in position errors of several hundred meters, whereas positioning accuracies within the GPS SPS specification may be attainable even in harsh environment when using an optimum variance model and a sophisticated quality control kernel in the positioning algorithm. This is also demonstrated using experimental data.

2. Signal strength and obstructions

GPS satellites transmit the L1 C/A code with a power of about 27W [1] in order to comply with the specification given in the *GPS Interface Control Document* [2]. This document states that the received signal power near the surface of the earth must be at least –160 dBW.[1] The majority of the power reduction of 17 orders of magnitude is due to free-space loss as a function of the satellite-to-receiver distance. See e.g. [12] and [9, pp.183] for a discussion of the power link budget.

The critical parameter in terms of signal acquisition and tracking performance is not the absolute signal strength but the signal-to-noise ratio (SNR) and more specifically the SNR in a 1 Hz bandwidth i.e., the carrier-to-noise power density ratio (C/N_0). However, the noise power is largely determined by the equipment used (mainly by the gain and noise figure of the first amplifier between antenna element and receiver) and thus constant for a given equipment. So, the C/N_0 can also be seen as a measure of signal-strength and will be used as such below. Typically, a signal strength of –160 dBW corresponds to a C/N_0 of about 41–44 dBHz.

Obstacles in the line-of-sight between satellite and receiver attenuate the signals and thus reduce the C/N_0 values. Fig. 1 shows typical C/N_0 values in various environments and compares them to the tracking capability of different types of GPS receivers. Conventional GPS receivers have been designed to acquire and track signals with a C/N_0 above 33–35 dBHz. This means that line-of-sight observations can be tracked by such receivers, but signals behind an obstruction usually cannot, see Fig. 1.

3. High-sensitivity GPS receivers

There is a legal conditions in the US which states that a caller of the 911 emergency number needs to be located precisely, even when the call comes from a cell phone [6,7]. This, and market demands (location based services) have pushed the development of low-cost GPS receivers which should be able to operate in virtually any environment where also a cell phone works. This seemed feasible, because GPS signals exist in those environments. However, these signals may be extremely weak.

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[1] Power ratios are usually expressed in logarithmic units in order to simplify handling numbers across several orders of magnitude. The ratio P1:P2 can be expressed in dezi-Bel (dB) as $R_{dB}=10\times\log(P1/P2)$. Also absolute powers can be expressed in dB when referring to them as ratio with respect to 1W (then denoted dBW) or 1mW (dBm). A value of –160dBW thus corresponds to 10^{-16} W.

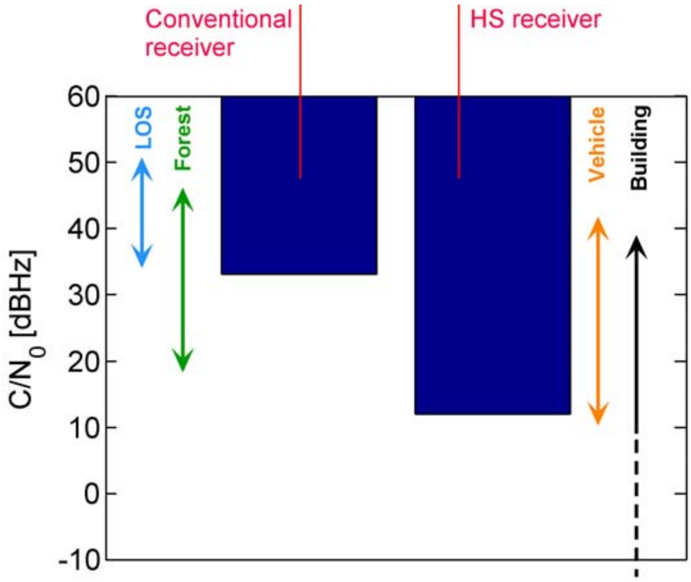

Fig. 1: Signal tracking capability of GPS receivers compared to GPS L1(C/A) C/N_0 levels typically encountered in different environments: line-of-sight (LOS) i.e. no obstruction, inside forest, inside a vehicle, inside a building.

Peterson et al. [10] demonstrated experimentally that GPS signals are indeed available even deeply inside a building and can be acquired there. They succeeded in acquiring signals 60 dB weaker than outdoors (this would correspond to a C/N_0 of about –10 to –20 dBHz) using special hardware. The key to enhancing the sensitivity of GPS receivers is to extend the signal integration time significantly beyond the typical 2–5 ms, see [10,3,4,11]. This required several modifications to the receiver design, which have recently been summarized e.g. in [5] and [13]. High-sensitivity (HS) GPS receivers are now commercially available at low cost from several manufacturers. State-of-the-art HS receivers can track and acquire signals with C/N_0 values as low as 12 dBHz and allow thus to collect measurement data of obstructed satellites beneath forest canopy, in urban canyons and even indoors, see Fig. 1.

4. Availability of observations

Fig. 2 shows the position of satellites tracked during a 15-hour static session using a u-blox TIM-LH high-sensitivity GPS receiver and a low-cost patch antenna placed on the desk inside an office. The grey shading represents the portions of the sky at which the line-of-sight is blocked by walls; the small area without shading represents the portion of the sky visible through a (closed) window. The majority of the signals are heavily attenuated with respect to the typical clear-sky values of 40 dBHz. A conventional receiver could not track enough signals for positioning in this environment. The u-blox HS receiver outputs pseudo-ranges of typically 5–6 satellites per epoch, and only 5% of the time it provides less than 4. So, GPS based positioning inside this office is possible about 95% of the time using the HS receiver.

The focus of this paper is not on indoor positioning but rather on applications like GIS data collection, mapping, or traffic guidance and control. In such applications it may often be possible to use either a conventional receiver or a high-sensitivity receiver, and the question is which one is the better choice? We will try to answer this question using data collected on the roof of a building of the Graz University of Technology (TUG), see Fig. 3.

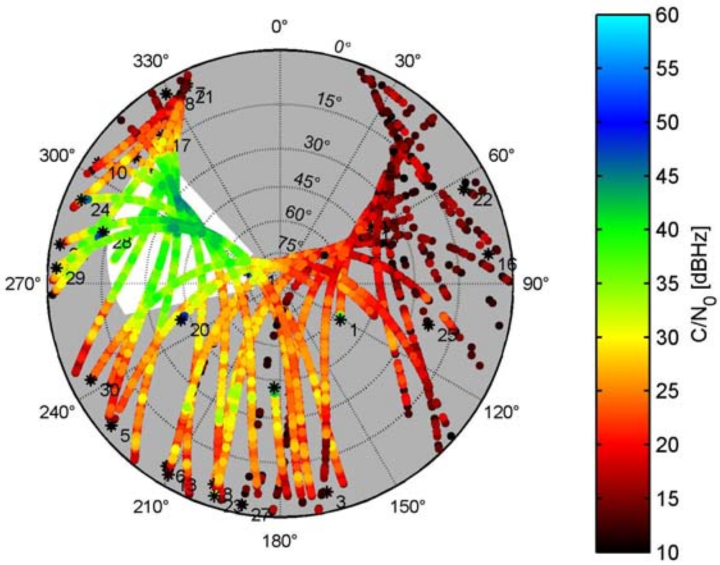

Fig. 2: Satellites tracked by a high-sensitivity receiver (u-blox TIM-LH) during 15 hours with static antenna inside an office; white area indicates approximate location of a window, shaded area indicates walls; colors represent the measured C/N_0 values.

A u-blox TIM-LH high-sensitivity GPS receiver and an Ashtech G12 single-frequency geodetic GPS receiver were connected to a single low-cost patch antenna, placed on the floor of the flat roof (location A, Fig. 3). About 0.3 m west of the antenna there was a wall which caused considerable obstruction. Raw measurement data of both receivers were recorded during 5 hours and analyzed in post-processing. The use of a signal splitter allowed feeding the same antenna output to both receivers. Thus differences in the raw measurement data and in the computed positions are due to differences between the receivers.

Fig. 3: Antenna location A on roof of TUG building during experiment.

Fig. 4 shows the satellites tracked by the respective receiver, along with the C/N_0 values stored in the raw data files. The plots show that the wall shades almost half the sky. Minor obstructions up to an elevation of 15 degrees can also be seen across the eastern hemisphere. They are caused by the enclosing wall (see Fig. 3) and by nearby buildings.

As expected, the HS receiver (Fig. 4b) tracks significantly more satellites than the conventional receiver (Fig. 4a). In fact, the HS receiver outputs 71% of the theoretically possible pseudo-range observations (*observation availability*), where 100% would represent one pseudo-range per satellite and epoch for all satellites above 0 degree elevation. On an epoch-by-epoch basis, the HS receiver here provides 6–7 pseudo-ranges per epoch on average, and never less than 4. As opposed to that, the conventional receiver achieves an observation availability of only 51%, corresponding to 4–5 pseudo-ranges per epoch.

Using data from various static and kinematic experiments in different environments, we found that HS receivers typically track 6 satellites per epoch in urban outdoor environment, and 8 beneath forest canopy. During these experiments, conventional receivers tracked up to 20% fewer observations[2] than HS receivers beneath forest canopy, and about 60% fewer in urban outdoor environment, see [13]. They were thus not useful for standalone positioning in such an environment.

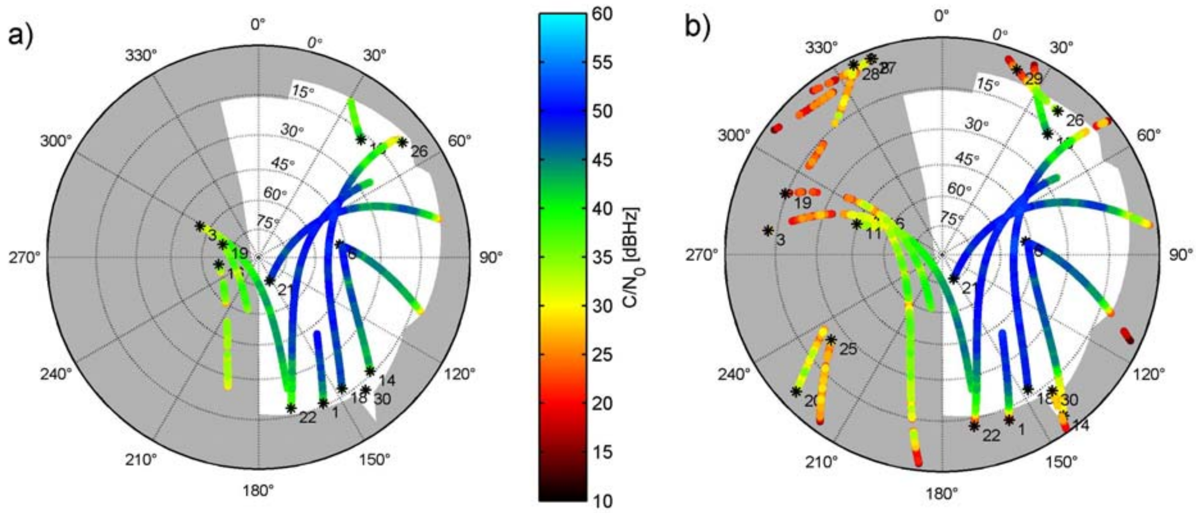

Fig. 4: Stereographic diagram of antenna site A with satellites tracked by Ashtech G12 receiver (a), and u-blox TIM-LH receiver (b); shaded area represents visually obstructed portions of sky, colors indicate signal strength (C/N0).

5. Accuracy of pseudo-range observations

The ITRF 2000 coordinates of the antenna location A (Fig. 3) are known with an accuracy of a few cm. These coordinates can be used as ground truth to analyze the error of the estimated coordinates. However, they can also be fixed when processing the pseudo-range data collected during the experiment. In this case, only a receiver clock bias needs to be estimated per epoch, and thus the residuals of this adjustment closely resemble the pseudo-range errors.

For the purpose of studying the accuracy of the pseudo-range observations, such a post-processing was performed using a MATLAB Kalman Filter program[3], precise CODE[4] orbit

[2] The percentage refers to the number of observations output by the HS receiver, not to the theoretically available number of observations.
[3] This MATLAB package was developed at IGMS.
[4] Center for Orbit Determination in Europe, University of Bern, Switzerland, http://www.aiub.unibe.ch/igs.html

and satellite clock data, the Saastamoinen tropospheric model along with a standard atmosphere model, and the Klobuchar ionospheric model along with CODE model parameters were used. The post-update residuals of this processing represent the combined effect of remaining ionospheric and tropospheric errors, multipath, diffraction, and random noise. They will be referred to as *pseudo-range errors* below. Outliers detected by the quality control kernel of the program were not rejected but down-weighted so that they would still be assigned a residual and thus show up in the subsequent analysis, but their influence on the estimated clock bias and thus the other residuals would be negligible.

Fig. 5 shows again the satellites tracked during the above experiment. However, the colors now represent the magnitude of the pseudo-range errors and thus give an impression of the accuracy in the observation domain. Obviously, the signals of obstructed satellites have significantly larger errors (orange and red dots) than the line-of-sight observations.

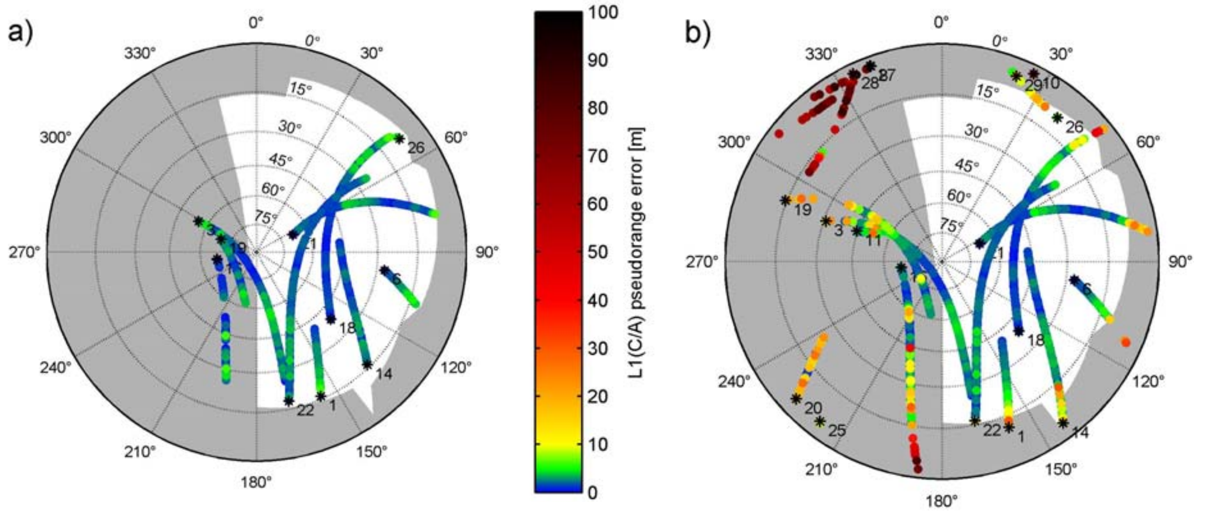

Fig. 5: Stereographic diagram of antenna site A with satellites tracked by Ashtech G12 receiver (a), and u-blox TIM-LH receiver (b); shaded area represents visually obstructed portions of sky, colors indicate magnitude of L1(C/A) pseudo-range error.

This difference in accuracy between line-of-sight observations and obstructed observations has been investigated numerically by analyzing the empirical distribution of the pseudo-range errors separately for both groups and both receivers. The distribution functions are shown in Fig. 6 for the u-blox HS receiver, and the results of the analysis of both receivers are summarized in Tab. 1.

Using the Ashtech G12, there is little difference between both groups, which exhibit a pseudo-range accuracy of about 3.6 m (95% of the errors do not exceed this magnitude). The reason is that this receiver only tracks few signals of satellites behind the obstruction mask, and those few signals arrive at the antenna by diffraction around the edge of the wall. Using the local geometry it can be shown that there is no significant multipath signal for these satellites, and that the additional path length due to diffraction is on the order of a few cm only, i.e. well hidden within the random noise.

The u-blox HS receiver provides slightly more line-of-sight observations than the Ashtech receiver, and these observations are slightly less accurate in terms of the 95th percentile (4.8 m) which reflects the different tracking loop design and quality of the receiver hardware components (including the clock). However, about 40% of the total observations output by the HS receiver are from obstructed satellites at both high and low elevations. These signals arrive at the antenna by diffraction and by multipath, the latter causing large pseudo-range errors. The accuracy of these observations is only 70 m (95th percentile) and their maximum error is 178 m, during this experiment.

We have found such a difference in quality between line-of-sight observations and obstructed observations in a variety of tests involving HS receivers. Often, the maximum errors were even larger than here, reaching almost 1 km in some cases.

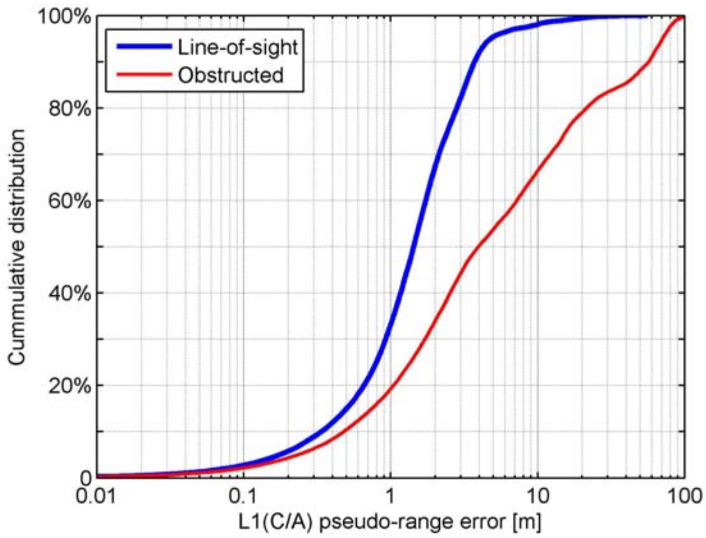

Fig. 6: Empirical distribution function of L1(C/A) pseudo-range errors of u-blox TIM-LH receiver, computed separately for line-of-sight observations (no obstacle between satellite and antenna) and obstructed observations.

Tab. 1: Statistical properties of L1 pseudo-range observations (C/A code) collected at the site STGR during the 5-hour experiment, computed separately for obstructed satellites and satellites with clear line-of-sight.

	Ashtech G12		u-blox TIM-LH	
	Obstructed	Line-of-sight	Obstructed	Line-of-sight
Number of observations	14500	55400	38800	59000
Standard deviation (robust) [m]	1.6	1.9	6.2	2.3
Error (95%) [m]	3.6	3.7	70.6	4.8
Maximum error [m]	7	10	178	56
Percentage of outliers (>3STD)[5]	1.0%	0.6%	21.7%	2.9%

6. Variance modeling

In order to compute accurate and reliable coordinates using HS GPS observations, the potentially different accuracy of the observations needs to be taken into account. We have investi-

[5] These percentages depend on the assumption of identical variance of all observations among the respective group. If the SIGMA-ε variance model (see sec. 6) is used, the percentages are significantly lower.

gated different variance models for use with HS GPS pseudo-range observations, see [14]. In this investigation it turned out that the C/N_0 based SIGMA-ε variance model, originally developed for use with high-precision carrier phase observations by Hartinger and Brunner [8], can predict the precision of the pseudo-range observations very well: in favorable environment (majority of observations obtained along line-of-sight) about 99% of the observations were found to follow a normal distribution with the predicted variance. In harsh environment (majority of observations obtained from obstructed satellites), the percentage was still 80% or better.

For the subsequent analysis we used two different variance models in order to highlight the impact of variance modeling on the accuracy in the position domain: identical variances (ID), and SIGMA-ε variances (EPS). The respective model parameters are given in Tab. 2 for both receivers. The values have been determined using appropriate training data sets.

Tab. 2: Numerical values of scale parameters used with identical variance model (σ) and SIGMA-ε variance model (C) for data processing in this paper.

Receiver	Antenna	σ [m]	C [m^2Hz]
Ashtech G12	Active low cost antenna	2.0	0.6×10^5
u-blox TIM-LH*	Active low cost antenna	7.2	1.2×10^5

)* *Super Sense evaluation kit, firmware version 3.10 TLH 1.0*

7. Accuracy in the position domain

In order to study the accuracy in the position domain, the pseudo-range observations collected by the two receivers during the above experiment have been processed again using the MATLAB Kalman Filter program. The same auxiliary data as above were used. Outliers were now rejected by the quality control kernel such as to avoid any influence on the estimated coordinates. The coordinates were set-up as random walk processes with a spectral noise density of 10^4 m^2Hz in North, East, and Height. This means that the Kalman Filter hardly *filtered* the observations and that the results closely resemble an epoch-by-epoch least squares estimation[6], unless there are not enough observations available within an epoch. In that case, the filter output is partially or largely based on the assumption of constant coordinates and constant clock drift.

Fig. 7 shows the deviation of the estimated coordinates from ground truth as computed from the Ashtech data using identical variances for all pseudo-range observations. Only 49% of the time a fully controlled solution was obtained (overall model test (LOM) passed, and at least 5 observations still used within this epoch after quality control kernel had eliminated all identified outliers). 37% of the time a solution can be computed using the observations of the respective epoch (4 observations available) but the solution cannot be controlled (no redundancy) using the data of this epoch alone.[7] 13% of the time, the solution uses less than 4 observations and should be used with care.

[6] The MATLAB based Kalman Filter package offers a variety of processing options and data mining tools and was thus chosen for this analysis.

[7] Of course, in the scope of the Kalman Filter, the model test is possible even if there is only 1 observation. However, the test is then largely based on the assumed system model which may only be an approximation in a real world application. So, this scenario is not taken into account here.

Tab. 3 summarizes the results numerically. The point error ($\sqrt{\hat{\sigma}_N^2 + \hat{\sigma}_E^2}$) is computed using the empirical variance of the estimated North and East coordinates and represents the horizontal positioning precision. The positioning accuracy is expressed in terms of bias (computed from median of North, East, and Height coordinates), and 95th percentile of the 2d radial error and the absolute height error.

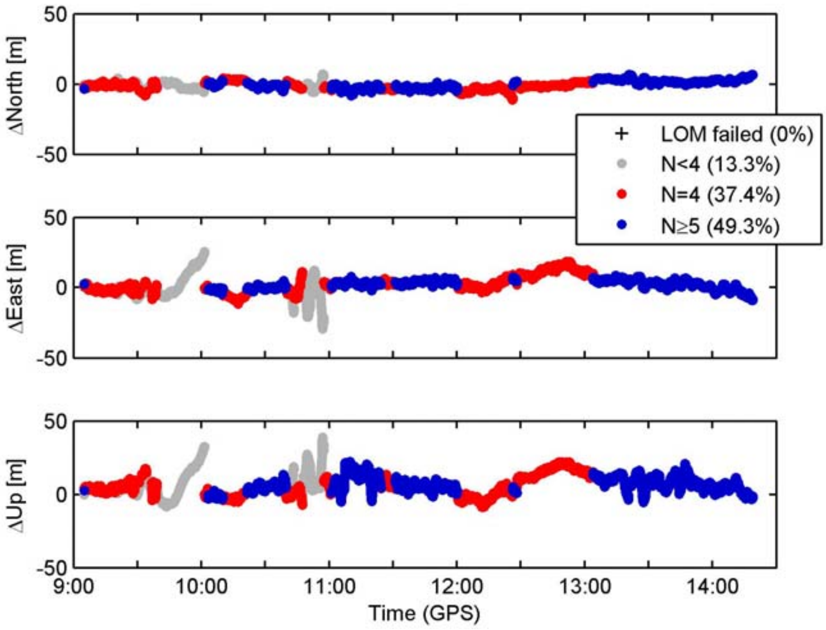

Fig. 7: Ahstech G12, deviation of estimated coordinates from ground truth (Kalman Filter, identical variance model; see text for further settings), blue dots represent controlled solutions.

Tab. 3: Statistical summary of coordinate results obtained using two different variance models: identical variances (ID) and SIGMA-ε (EPS); see text for discussion of processing scheme and definition of terms.

	Ashtech G12		u-blox TIM-LH	
	ID	EPS	ID	EPS
Availability	49%	49%	98%	98%
Precision				
2d point error [m]	4.2	5.1	15.9	7.7
Height STD [m]	5.1	5.2	27.5	8.4
Accuracy				
Position bias [m]	2.5	2.7	3.9	3.0
Height bias [m]	-6.2	-5.6	-14.0	-8.9
Position error (95%) [m]	7.5	8.5	35.8	17.2
Height error (95%) [m]	15.8	13.7	75.2	23.1

The values in Tab. 3 indicate that there is apparently little impact of the variance model when using the Ashtech receiver. The precision is 4 to 5 m for both horizontal position and height, the accuracy (95%) is better than 9 m horizontally and 16 m vertically in both cases. The reason for the unexpected result (little difference, EPS worse than ID) is the combination of the high raw data quality of the geodetic receiver and the considerable obstruction which causes relatively poor geometry but coincidentally few range errors. The SIGMA-ε variance model reduces the impact of weak signals (which have unusually small errors here) on the solution. However, this deteriorates the geometry further and makes the solution more susceptible to small errors of the strong signals (e.g. random errors and minor multipath effects).

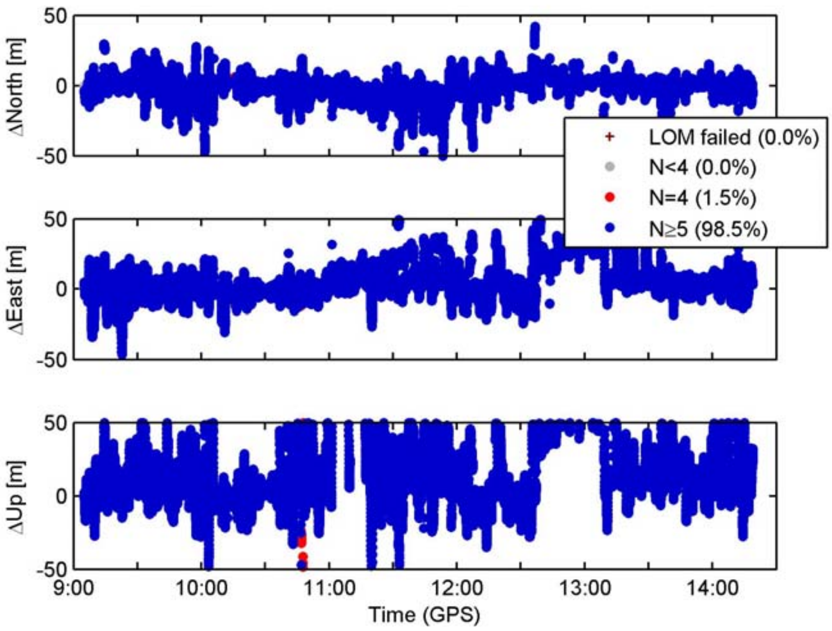

Fig. 8: Identical variances assumed—deviation of estimated coordinates from ground truth (u-blox TIM-LH, Kalman Filter; see text for further settings), blue dots represent controlled solutions.

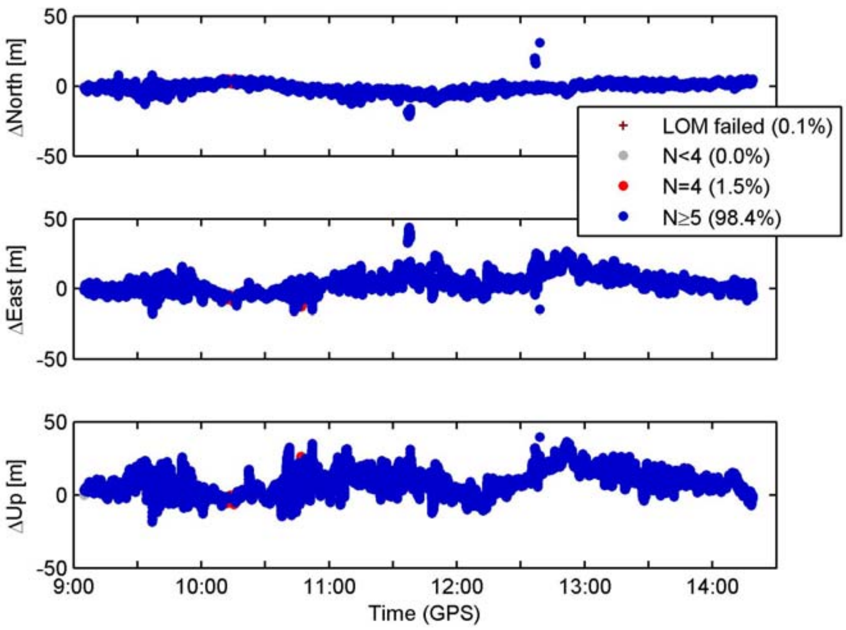

Fig. 9: SIGMA-ε variance model—deviation of estimated coordinates from ground truth (u-blox TIM-LH, Kalman Filter; see text for further settings), blue dots represent controlled solutions.

Fig. 8 shows the results obtained using the HS receiver's data. The HS receiver yields enough observations to compute a controlled solution 98.5% of the time. So, the positioning availability is more than twice that of the geodetic receiver, here. However, the precision and accuracy of the results is obviously considerably worse than that of the geodetic receiver, see values in Tab. 3. This is due to the fact that the identical variances do not properly reflect the different quality of the HS receiver's pseudo-range observations. The maximum horizontal and vertical errors are 80 m and 120 m, here (due to the chosen scaling of the plots, these values are not visible in Fig. 8).

When processing the data using the SIGMA-ε variance model, both the precision and the accuracy of the results are improved significantly, see Fig. 9 and Tab. 3, but they do still not reach the high levels obtained using the geodetic receiver. This is largely due to the exceptionally high quality of the geodetic receiver and not to the difference between HS and non-HS receiver.

In other experiments we have found that horizontal errors of several 100 m may occur when using HS GPS receivers, if the variance model is not properly selected, but that accuracies of 20 m or better can be achieved even in harsh environment using an HS receiver and the SIGMA-ε variance model.

8. Conclusion

We have shown that a commercial high-sensitivity receiver can track weaker GPS signals than a conventional GPS receiver. The difference of about 20–25 dB may be a significant advantage in applications where the line-of-sight between the receiver and the GPS satellites is obstructed and a conventional receiver does not provide enough observations for positioning, like in urban canyons, beneath forest canopy, or even inside buildings.

A dedicated experiment featuring an obstruction which affected about 50% of the sky was used to compare the quality of line-of-sight observations and obstructed observations. We showed that the accuracy of the line-of-sight observations can be 1–2 orders of magnitude better than the accuracy of the obstructed observations, which were found to exhibit errors of up to 178 m in the experiment discussed above.

This difference in quality needs to be taken into account properly when computing position, velocity, and time. We showed that failure to do so may result in poor positioning accuracy and errors of 100 m and more, whereas positioning accuracies of 5–20 m are attainable even in harsh environment when using an optimum variance model and a sophisticated quality control kernel in the positioning algorithm. These components help to balance increased availability and desired accuracy by reducing the influence of poor observations. Using such algorithms, there is a clear advantage of using HS receivers instead of conventional receivers in applications requiring meter level accuracies with moderate antenna dynamics.

Acknowledgement

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