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An Efficient GNSS-Simulator for Noisy Multipath Scenario

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Abstract

GNSS simulators for multipath scenarios use various approaches to increase the positioning accuracy. However, the efficiency of the algorithm remains a major challenge. A new software tool for simulation of a GNSS receiver in multipath scenarios is presented based on the calculation of the detection probability. A compact formula is derived, which leads to an efficient algorithm. In the receiver simulated, all the satellites can be used together or in a selection to give a weighted contribution to the determination of the position depending on the SNR. The software tool is evaluated using field measurements at a reflecting wall. The distribution of the simulation results shows a high degree of agreement with the real field measurements. The simulator takes into account various noise sources and reflections at walls with its influence on the correlation results of the receiver. It can be especially applied to improve receivers and antennas for optimized positioning accuracy in multipath scenarios.

1. Introduction

In recent years, the demand for precise global positioning has grown significantly, driven by emerging applications such as autonomous driving. The automotive industries in particular are increasingly focusing on the development of autonomous driving systems, which has underscored the need for reliable and highly accurate navigation solutions. Although advanced odometric techniques and terrestrial navigation systems offer some support, satellite-based navigation remains a fundamental technology in this domain [1]. Despite the growing constellation of navigation satellites in recent years, as well as the introduction of new frequency bands and advances in signal processing algorithms, significant challenges remain [2]. Positioning errors resulting from signal reflections continue to pose a particular problem, especially in dense urban environments [3]. To overcome these challenges, various analytical methods have been developed to assess and analyze positioning errors in urban scenarios. In [4] and [5] examples are given for methods to estimate multipath effects in GNSS receivers.

The challenge is to evaluate methods for precise positioning in terms of accuracy in a noisy multipath scenario with respect to the complete GNSS-system, containing the satellite positions and movements, the antennas and its amplifiers as well as the correlators in the receiver and the algorithm to find the position on base of the correlation values.

In this contribution we introduce a novel GNSS simulator which captures the behavior of such a GNSS system in the noisy scenario by means of a probability investigation. For each position to be found, a probability density function is derived to show the statistical behavior of the receiver. Using this simulator we investigate the effects influencing positioning accuracy in a reflection scenario. We present the corresponding mathematical derivations and furthermore, we perform simulations of a reflection scenario on a strongly reflecting wall of a building (see Fig. 1). Finally, we compare and analyze the simulation results with field measurements and give an outlook on future work.

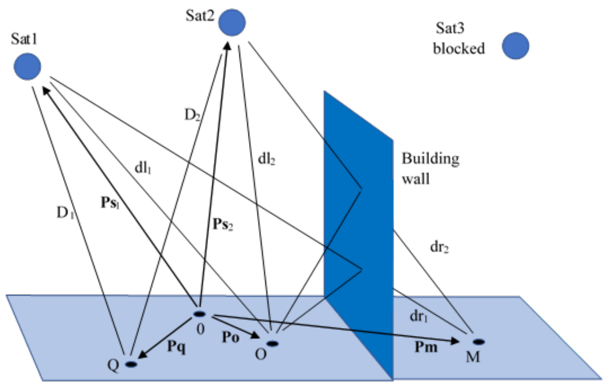


Figure 1. Satellite and position point constellation showing LOS and reflected rays to the actual object position $\mathbf{P_o}$ with the distances $dl_i = |\mathbf{Po_i} - \mathbf{Ps_i}|$ and dr_i , respectively, the rays to the considered position $\mathbf{P_q}$ with the distances D_i , the mirrored object position $\mathbf{P_m}$ and the positions of the satellites $\mathbf{P_{Si}}$.

2. The Simulation Tool

The simulation tool is designed to enable a flexible and user-friendly investigation of various scenarios. The approach follows the principle of estimating the quality of the positioning of a GNSS receiver in various reception scenarios in a simulation environment based on the probability of detection. Figure 1 shows the reception scenario with the actual object position point O of the receiver and the arbitrarily chosen considered position point Q. In the following, the probability that the receiver obtains the considered position point as its positioning result instead of the object position is determined. For each of the considered position points an explicit equation can be used to calculate this probability easily. In this way, a probability density function can be derived in the area around the object position by sampling this area for a lot of different considered position points with low computational effort.

In the following the structure of the algorithm is explained. The first step of the algorithm determines whether there is a direct line of sight between the antenna and the satellite or if the satellite is blocked or reflected by the building wall. We calculate the complex wave amplitudes $\underline{S}_i$ of the incident waves from each satellite, as if they were received at the considered point Q via LOS path. The levels of $\underline{S}_i$ and their phase depend on the complex antenna pattern, the direction of the transmission path, path length and path loss and the transmission power of satellite number i. In analogous way, we calculate the complex wave amplitudes $\underline{Sr}_i$ of the reflected waves for each satellite, as if they would be received at Q via the reflection path over the building wall. The mirrored point M is used for this purpose. The signal to noise ratio SNR_i after correlation is calculated from the amplitudes of each satellite signal and the noise power N taking into account the external noise, the noise figure of the antenna amplifier and the correlation gain as well as the integration time.

Now we consider the correlation of the received signals of each satellite with the corresponding PRN-code in the receiver. In all those correlators of the receiver, which are assigned to satellites where their signals are also received via reflection, the correlation function of the reflected signal with its path length d_r superposes the correlation function of the LOS signal with its LOS path length d_l. In most cases of a strong reflected signal, the reflector is close to the object with a distance of several meters. Thus, the differences between d_l and d_r are much less than half the base width of the triangular correlation function $|d_l - d_r| << c_o \Delta t$, where the product of the PRN-code-chip duration Δt and the velocity of light c_o is around 300m. In this case the triangular correlation peaks of the LOS signal and the reflected signal are strongly superposed. Even in a noisy scenario, with highest probability, the resulting correlation peak maximum is found at a certain distance d, which depends on phase and level of the LOS signal and the reflected signal. From the superposition of the complex correlation functions of the LOS part and the reflected part of the antenna signal with their maximum values $\underline{S}_l$ at the distance d_l for LOS and $\underline{S}_r$ at the distance d_r for the reflected part we individually obtain for each satellite i:

$$d_i = d_{li} \, \mathrm{Re}\{\underline{S}_{li}/(\underline{S}_{li}+\underline{S}_{ri})\} + d_{ri} \, \mathrm{Re}\{\underline{S}_{ri}/(\underline{S}_{li}+\underline{S}_{ri})\} \qquad (1)$$

For satellites with pure LOS-reception d_i is equal to d_{li}. In a noisy scenario the variance of the correlation peak value according to the SNR_i of the satellite signal can be mapped onto a variance σ_i of the detected distance of the correlation peak maximum by a linear transformation. Hence we derive for each satellite a probability function for all possible detected distances l of the correlation peak, which is a gaussian function $G((l-d_i),\sigma_i)$ with a maximum at the distance d_i where σ_i^2 is proportional to SNR_i. This gives the probability of a detected correlation maximum for all possible length values d_{li} in all cases of LOS and NLOS reception.

Now, on base of the correlation results and their probability functions for all visible satellites, we derive a three-dimensional probability density function. This probability function gives the probability of each considered point in the near range of the object to be chosen by the GNSS receiver as the detected position. In case of pure LOS conditions, a function which is similar to a 3D gaussian function will occur with its maximum at the real position of the object. In case of reflections, the maximum will occur at other positions. This probability function is derived as follows.

In the receiver, only the difference between the times of arrival of the signals of the different satellites is detected, while the duration of the signal transfer along the path length is unknown. Thus, we calculate the difference Δ between the LOS signal paths from the satellites to each considered point in the range around the object point. We select one well visible satellite nr. k close to zenith to serve for time reference and obtain the path differences Δ_{ik} with $\Delta_{ik}=D_i-D_k$ for i=1,2,3,… and $\Delta_{kk}=0$.

Now, we derive the probability $\mathcal{P}(\mathbf{Pq})$ of the considered point Q to be called the position of the object by the receiver. As can be seen above, this is also the probability of its respective combination of differences in distance $\Delta_{1k}, \Delta_{2k}, \Delta_{3k}, \ldots$ to be detected as a correlation maximum for every single satellite i=1,2,3,… This gives the Gaussian distribution $G((l-d_i),\sigma_i)$ with the expected value d and the variance σ^2. Finally, the probability $\mathcal{P}(\Delta_{1k}, \Delta_{2k}, \Delta_{3k}, \ldots)$ of the combination of the distances $\Delta_{1k}, \Delta_{2k}, \Delta_{3k}, \ldots$ to come true is computed by multiplying the respectively shifted Gaussian probability functions of the single satellites. We obtain

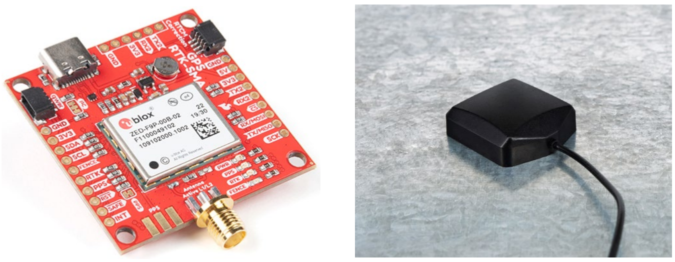
$$\mathcal{P}(\mathbf{Pq}) = \mathcal{P}(\Delta_{1k}, \Delta_{2k}, \Delta_{3k}, \ldots) = \qquad (2)$$
$$= \int_{-\infty}^{\infty} \Pi \, (G(l-d_i-\Delta_{ik} , \sigma_i)) \, dl$$

And by solving this integral we derive

$$\mathcal{P}(\mathbf{Pq}) = [2\pi^2 \, \Pi(\sigma_i^2) \, (\Sigma(\sigma_i^{-2}))^{1/2}]^{-1} \cdot \qquad (3)$$
$$\cdot \exp[-\tfrac{1}{2} \, \{\Sigma(\Delta_{ik}^2\sigma_i^{-2}) - (\Sigma(\Delta_{ik}\sigma_i^{-2}))^2/\Sigma(\sigma_i^{-2})\}]$$

where Σ, Π are sum and product over all satellites i=1,2,…, satellite k serves for the time reference and the Δ_{ik} are computed from the distances to the satellites. The compact formula (3) is the beautiful result containing no integrals and just one exponential function to evaluate. It is not necessary to compute any intersections of hyperboloid or the like. — The maximum of the probability function (3) is where the receiver detects the position of the object with highest probability. In the case of reflections, this position will differ from the real position of the object. In cases with low SNR eq. (3) shows that the variance of the maximum will be wide. In our simulator we can choose different cases of strategy for positioning. Alternatively, all satellites can be used to contribute to the result as well as a selection of those with the best SNR. The inclusion of more satellites in the simulation produces increased accuracy as our simulations confirm.

3. Test scenario and results



a) b)

Figure 2. a) SparkFun GPS-RTK2 Board. **2b)** Multi-Band GNSS Patch Antenna

The hardware used for the measurements consists of the high quality GNSS receiver shown in Figure 2a. It should be emphasized that no corrections via Real-Time Kinematics (RTK) were applied during the subsequent measurements. A patch antenna, illustrated in Figure 2b, was employed for the reception of GNSS signals.

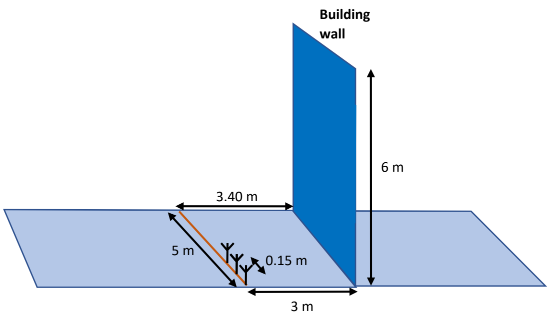


Figure 3. Sketched representation of the investigated reflection scenario on a building wall

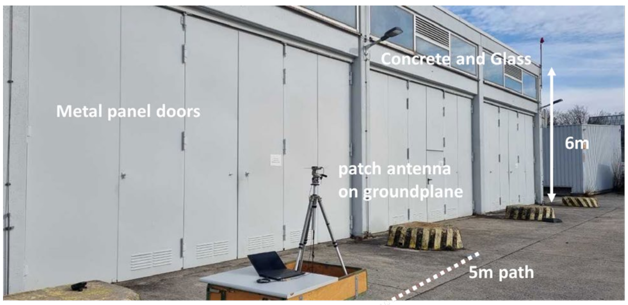
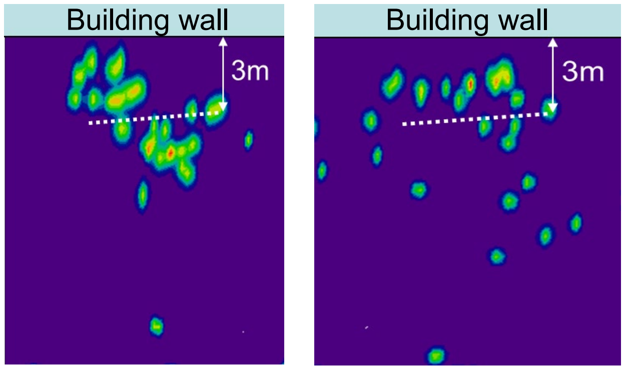


Figure 4. Experimental setup of the investigated scenario

The measurement setup in Figures 3 and 4 illustrates the test scenario. The GNSS antenna is mounted on a tripod with a height of 1.60 m above ground level. To create a defined and electrically conductive base, the antenna was mounted on a metal plate. A building with a height of 6 m is located at a distance of 3 m from the antenna. The structure of the building consists of about 75% metal panels, while the remaining 25% is made of concrete and glass. The antenna is moved away from the building step by step during the series of measurements. The movement takes place at regular intervals of 15 cm along a total distance of 5 m. This results in a total of 33 measuring points. During the measurement series, the antenna is gradually repositioned away from the building. After a displacement of 5 meters, the total distance between the antenna and the building amounts to 3.40 meters. A hot start was carried out before each measurement point to prevent filtering effects caused by the receiver during the antenna position changeover. The measuring frequency of the GNSS receiver is 5 Hz, which means that 50 data entries are recorded and saved for each individual measuring point after 10 seconds.

Simulation results

The simulation results are based on the theoretical foundations outlined in Section 2. The selected simulation scenario has been designed to correspond to the measurement setup described earlier.



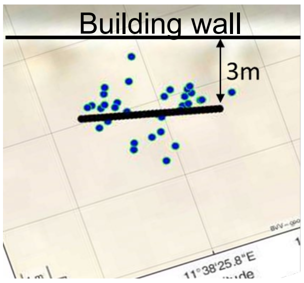
a) b)

Figure 5. 2D-Representation of the simulation results. The line of expected positions is shown as white dashed line. **a)** and **b)** show the simulation results for different satellite constellations.

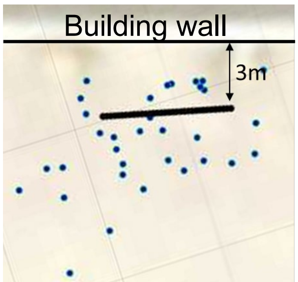
The positions calculated by the simulation program are shown in Figure 5 with the building wall at the top. The calculated positions of the individual measuring points are represented by dots in the color spectrum from yellow to red. This represents the superimposed quasi-Gaussian distributions. The more the color of the dots changes to red, the more frequently this position is calculated. The reflection factor by which the LOS signal is reflected at the building wall was assumed to be 0.9. The two subfigures 5a) and b) show the simulation results for different satellite constellations. Many of the calculated points are spread between the building and the desired position. In these cases, the deviation to the target positions is roughly around 1.5 meters. Many other points are spread on the other side of the driving path where larger deviations up to 10 meters occur. Position and shapes of the distribution of the calculated position points depend on the constellation and the paths of the satellites.

Experimental results

The experimental results use the same measurement setup as the simulation environment. In addition to the following measurements, LOS measurements were conducted, showing minimal deviations with a standard deviation of 0.1 m.



a)



b)

Figure 6a) and b): Field measurement results for various satellite constellations.

The satellite image section of the measurement scenario and the measured values are shown in Figure 6 with the building wall at the top again. The black line represents the target positions, while the blue-green dots indicate the measured positions. For each measurement position, the most frequent value was selected from 50 individual measurements and shown in the illustration. For each measuring point, the receiver uses around 25 satellites to determine the position. Satellites in the north area are not considered due to shadowing by the building. The characteristic behavior of the positioning is remarkably similar to the simulation results. The distributions of the simulation results in Figures 5a) and 5b) show a high degree of agreement with the real field measurements in Figures 6a) and 6b). The average deviations of positioning points in figures 5a) and 5b) are 2.76 m and 3.54 m while those of the measured examples in figures 6a) and 6b) are 2.71 m and 3.99 m. The shape of the point distributions is strongly depending on the satellite constellation, but for all examples considered we observe an average deviation between the actual position and the calculated or measured position of around 3 to 4 meters, both in the simulation and in the field measurements. These strong deviations can be prevented potentially by cancelling the reflected signals via an efficient antenna diversity system. This will be shown in a future contribution.

While in the case of a strong reflection scenario, we observe deviations in the range of several meters, for cases of pure LOS transmission we obtain a low average deviation in the order of magnitude of only 0.1m around the points along the driving path. This is also confirmed by our simulation results as well as field measurements. Not all physical effects are taken into account in the current version of the simulation, in particular, the surface properties of the reflective material and diffraction effects on building structures. These factors can influence the accuracy of the position determination. Work is in progress to integrate these effects also into the software.

4. Conclusions

In this work, a novel GNSS simulator based on the detection probability has been presented. The performance of the simulation software is evaluated by comparison with field measurements in a strong reflection scenario. The characteristic features of the simulation results show a high degree of agreement with the measured scenarios. The influence of the satellite constellation has a major impact on the positions and their distributions. In both, simulation and measured results, average deviations between 3 and 4 m occur along a path that is close to a building in a distance of 3-3.4 m. Even for highest performance receivers, the detected position points are spread in all directions around the driving path in a strong reflection scenario, if filtering algorithms are switched off. Work is in progress to prevent this effect by using an efficient antenna diversity system. In pure LOS-conditions on the other hand, simulations and measurements show the typical positioning accuracy with deviations in the range of only 0.1m.

References

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