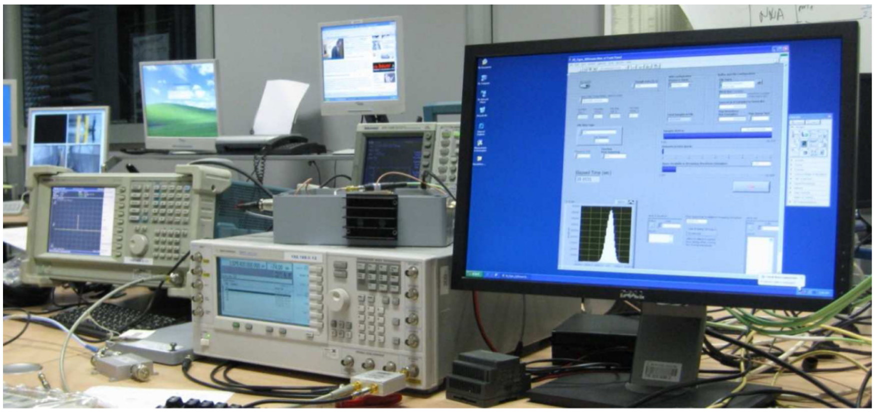
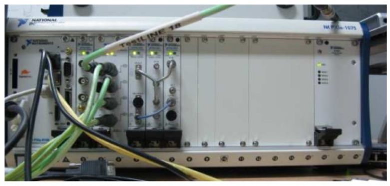
JRC Scientific and Technical Reports

Impact of Pseudolite Signals on Non-Participating GPS Receivers

Compatibility analysis for Commercial Receivers





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Executive Summary

Pseudolites or pseudo-satellites are an emerging technology that has the potential to extend the capability of Global Navigation Satellite Systems (GNSS) indoors and in harsh environments where GNSS services are denied. The European Commission (EC) with other entities including the European Telecommunications Standard Institute (ETSI) and industrial partners has started preliminary studies that could eventually lead to the standardization of pseudolite services.
Although pseudolites have the potential to bridge the gap between outdoor and indoor positioning, they could cause severe interference problems to non-participating receivers, i.e., GNSS receivers unable or not designed to use pseudolite signals. More specifically, most of the proposals for pseudolite signals suggest modulations that will occupy partially or completely bands already allocated for GNSS. Although this choice will minimize the hardware changes required to make current GNSS receivers capable of using pseudolite signals, it potentially implies interference problems with non-participating receivers. The pseudolite interference problem has to be quantified and addressed as a preliminary step before starting any standardization process. In this respect, the EC has mandated to the Electronic Communications Committee (ECC) within the European Conference of Postal and Telecommunications Administrations (CEPT) a preliminary study for assessing compatibility issues between pseudolites and GNSS services. This has led to the ECC Report 128 [1] where a Monte Carlo approach has been used to determine the impact of pseudolite signals on non-participating receivers. In the first version of [1] some important aspects, such as the cross-correlation between GNSS and pseudolite signals, were neglected and a second revision of the report is currently under preparation.

At the same time, the EC and in particular the Directorate-General for Enterprise and Industry (DG ENTR) has promoted a series of meetings for investigating the impact of pseudolite signals on non-participating receivers. The Institute for the Protection and Security of the Citizen of the EC Joint Research Centre (IPSC-JRC) has been invited to participate at the meetings and provide technical support for the analysis promoted by the EC.

In this report, preliminary results obtained by the IPSC-JRC on the impact of pseudolite signals on commercial non-participating receivers are presented. More specifically, a methodology involving the collection of real GPS data and the addition of a synthetic pseudolite signal have been developed. The final results are data sets containing both real GPS L1 C/A signals and synthetic pseudolite components. The analysis has been carried out as a function of the Carrier-to-Noise density power (C/N_0) of the synthetic pseudolite signals and two different scenarios have been considered. In the first case, the pseudolite signal was modulated using the same structure adopted by GPS L1 C/A signals. The same centre frequency and the same modulation parameters as those of real GPS L1 C/A signals were used and the pseudolite signal was modulated by the Pseudo-Random Noise (PRN) of a satellite signal not in view during the experiment. This represents the worst-case scenario since no countermeasure at the transmitter side is implemented to reduce the impact of pseudolite signals.
In the second case, the pseudolite signal was pulsed according to the scheme proposed by [2] with a 10 % duty-cycle. In this way, the pseudolite signal is transmitted only in allocated time slots significantly reducing the impact on non-participating receivers. The tests have been repeated for two different commercial receivers.

From the analysis, it emerges that in the case of a continuous pseudolite modulation (the first case considered), the performance of the non-participating receiver is already significantly degraded when the pseudolite signal is about 10 times stronger than the average signal power. More specifically, a 3 dB loss is introduced in the estimated C/N_0 of the useful GPS signals. The non-participating receivers under test were able to operate and provide a position solution for pseudolite C/N_0 levels approximately 20 dB stronger than the useful signal components. Above this limit (pseudolite $C/N_0 = 64/67$ dB-Hz) the receivers are unable to provide a position solution. It is noted that the main effect, preventing the receiver to operate correctly, seems to be the presence of secondary cross-correlation peaks that significantly bias the measurements estimated from the useful GPS signal components.
The use of a pulsing scheme significantly mitigates the impact of pseudolite signals and the receiver is

able to maintain lock and provide a position solution for all the tested pseudolite C/N_0 values ([55-85] dB-Hz range). Further investigations are required to determine if higher pseudolite signal powers could affect more severely a non-participating receiver.

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1 Introduction

Pseudolites or pseudo-satellites are an emerging technology with the potential of bridging the gap between outdoor and indoor navigation. Services based on Global Navigation Satellite Systems (GNSS) are widely used in several situations becoming part of citizen daily life. The wide-spread of GNSS services is further promoted by the integration of Global Positioning System (GPS) receivers in mobile phone and Personal Digital Assistant (PDA) that makes GNSS technology easily available to a large number of users. GNSS perform well outdoors where a clear view of the satellite signals, used for computing the user position and velocity, is available. Satellite signals are usually strongly degraded or obstructed indoors and the use of GNSS services is limited by the satellite visibility. A solution is the installation of fix transmitters that broadcast signals similar to those used by GNSS satellites. Indoors, these transmitters can play a similar role as GNSS satellites outdoors and for this reason have been named pseudo-satellites or pseudolites[3].

The European Commission (EC) is in the process of developing its own GNSS, Galileo, and at the same time it has expressed interest in regulating the pseudolite technology. The EC with other entities including the European Telecommunications Standard Institute (ETSI) and industrial partners has started preliminary studies that could eventually lead to the standardization of pseudolite services. Specific focus has been devoted to interference problems that pseudolite technology could cause, most of all with respect to non-participating receivers, i.e., GNSS receivers unable or not designed to use pseudolite signals. Most of the proposals for pseudolite signals suggest modulations that will occupy partially or completely bands already allocated for GNSS. Although this choice will minimize the hardware changes required for making current GNSS receivers capable of using pseudolite signals, it potentially implies interference problems with non-participating receivers. The pseudolite interference problem has to be quantified and addressed as a preliminary step before starting any standardization process. In this respect, the EC has mandated to the Electronic Communications Committee (ECC) within the European Conference of Postal and Telecommunications Administrations (CEPT) a preliminary study for assessing compatibility issues between pseudolites and GNSS services. This has lead to the ECC Report 128 [1] where a Monte Carlo approach has been used to determine the impact of pseudolite signals on non-participating receivers. In the first version of [1] some important aspects such as the cross-correlation between GNSS and pseudolite signals were neglected and a second revision of the report is currently under preparation.

At the same time, the EC and in particular the Directorate-General for Enterprise and Industry (DG ENTR) has promoted a series of meetings for investigating the impact of pseudolite signals on non-participating receivers. The Institute for the Protection and Security of the Citizen of the EC Joint Research Centre (IPSC-JRC) has been invited to participate at the meetings and provide technical support for the analysis promoted by the EC. For this reason, the IPSC-JRC has started instrumenting a laboratory testbed and developing a methodology for assessing the impact of pseudolite signals on non-participating receivers. In this report, preliminary results obtained by the IPSC-JRC on the impact of pseudolite signals on commercial non-participating receivers are presented. More specifically, a methodology involving the collection of real GPS data and the addition of a synthetic pseudolite signal have been developed. The final results are data sets containing both real GPS L1 C/A signals and synthetic pesudolite components. The analysis has been carried out as a function of the Carrier-to-Noise density power (C/N_0) of the synthetic pseudolite signal and two different scenarios have been considered. In the first case, the pseudolite signal was modulated using the same structure adopted by GPS L1 C/A signals. The same centre frequency and the same modulation parameters as those of real GPS L1 C/A signals were used and the pseudolite signal was modulated by the Pseudo-Random Noise (PRN) of a satellite signal not in view during the experiment. This represents the worst-case scenario since no countermeasure is adopted to reduce the impact of pseudolite signals.
In the second case, the pseudolite signal was pulsed according to the scheme proposed by [2] with a 10% duty-cycle. In this way, the pseudolite signal is transmitted only in allocated time slots significantly reducing the impact on non-participating receivers. The tests have been repeated for two different commercial receivers.

This report is organized as follows. In Section 2, the general approach developed for testing the impact of pseudolite signals on non-participating receivers is described. This includes a description of the different hardware components used for collecting real GPS data and re-broadcast them with an additional pseudolite signal. The modulation parameters and the software developed for the generation of the pseudolite signal are also detailed. The results obtained in term of useful signal degradation are presented in Section 3. More specifically, the presence of a pseudolite signal reduces the C/N_0 of useful GPS components perceived by the receiver. The C/N_0 estimated by the receiver is thus used as a metric reflecting the signal quality. It is shown that a continuous pseudolite signal can seriously degrade the receiver performance that for high pseudolite power levels is unable to operate and provide a position solution. The impact of the pseudolite signal in the position domain is studied in Section 4. The obtained results are in agreement with the findings of Section 3: the signal degradation is translated into a degradation of the position accuracy and when the pseudolite signal power is greater than a predefined threshold the receiver is unable to provide a position solution at all. It is noted that the two tested receivers, Receiver #1 and Receiver #2 , respond differently to the presence of the interfering pseudolite signal. This is likely due to the different front-ends employed by the two receivers. Different input dynamic ranges in the front-end, different Automatic Gain Controls (AGC) and different quantization strategies can lead to significantly different responses to the pseudolite signal [3]. Recommendations and possible follow-on activities are provided in Section 5.

2 Experimental Approach

In order to test the impact of a pseudolite signal on non-participating receivers a modified record and play back methodology has been developed. This methodology was required since, it is not possible, without a specific authorization, to broadcast pseudolite signals or other potential interference sources potentially degrading or denying GPS/GNSS services. The developed methodology allows conducted experiments where Radio Frequency (RF) signals are directly conveyed to the receiver under test through cables. Fig. 1 shows the general methodology adopted for the testing. Live L1 C/A GPS signals are at first collected and stored on a hard drive. GPS signals are downconverted to baseband and stored in an In-phase/Quadrature (I&Q) format. A Matlab signal generator has been developed to provide baseband pseudolite signals. GPS signals are synthetic pseudolite component are merged and a new data set is generated. This data set is then upconverted to the GPS L1 band (1575.42 MHz centre frequency) and sent to the receiver under test. The processing strategy adopted for the generation of baseband

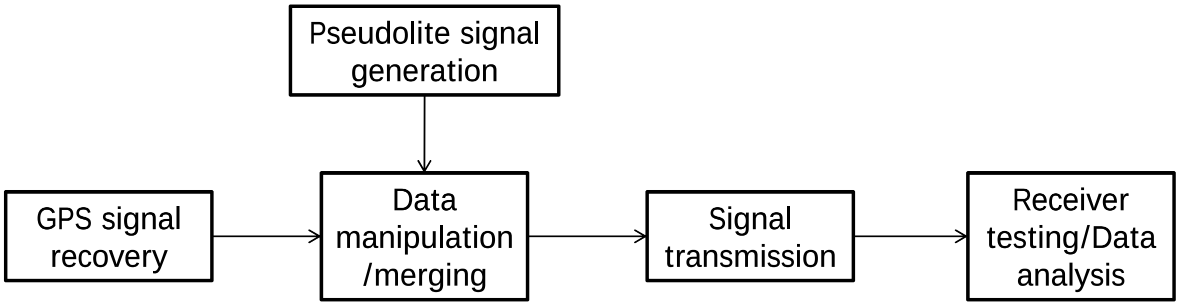

Figure 1: General methodology adopted for testing the impact of pseudolite signals on commercial GPS receivers. Live L1 C/A GPS signals are at first collected and stored on a hard drive. A synthetic pseudolite signal is generated and added to the collected GPS signals that are retransmitted at RF.

binary files containing GPS signals corrupted by a synthetic pseudolite component is detailed in Fig. 2. The collected GPS L1 C/A samples are at first pre-processed using a modified version of the software receiver developed by [4]. The software receiver is used to determine the time of the week of the collected samples and roughly synchronize the generation of the pseudolite signal. It is noted that since the pseudolite signal will not carry any useful information for the non-participating receiver, synchronization is not expected to play a significant role in the performed experiments. The raw GPS samples are also used to estimate the power spectral density, N_0, of the noise present in the recovered data set. N_0 along with an external text file containing a pseudolite C/N_0 profile are used to determine the amplitude of the simulated pseudolite signal. Raw GPS samples and the synthetic pseudolite signal are finally merged and a new binary file is generated.
Raw GPS samples have been collected using a National Instruments (NI) PXIe-5663 vector signal analyzer [5] using a sampling frequency $f_s = 2.5$ MHz. A complex I&Q sampling [6] was adopted.
In the following section the two modulation schemes adopted for the generation of pseudolite signals are detailed.

2.1 Continuous Pseudolite Signal

In the first experiment, pseudolite signals were generated according to the same modulation adopted for GPS L1 C/A signals [7]. More specifically, the same spreading codes and the same centre frequency (1575.42 MHz) where used. Also the data message was simulated in order to mimic the structure of the navigation data defined in [7] for the L1 C/A signal. More specifically, the data message of the pseudolite signal was structured in five subframes containing telemetry and handover words as defined in [7]; the synchronization preamble and the parity bits of each word where also computed. The only difference is that, although the structure of the message respects the definition of [7], the content is random. Only the health bits were set to false to indicate to the non-participating receiver not to use the information

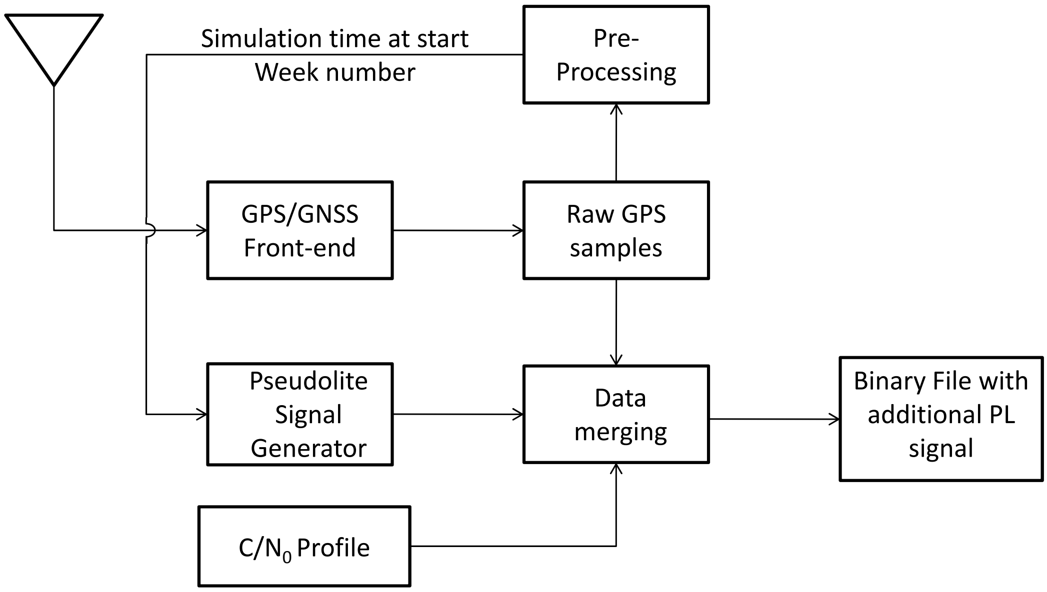

Figure 2: Processing strategy adopted for the generation of baseband binary files containing GPS signals corrupted by a synthetic pseudolite component.

extracted from the pseudolite signal.
The pseudolite signal was modulated using a code of a satellite not in view during the experiment. Moreover, the Doppler effect on the pseudolite signal has been neglected. This choice is justified by the fact that a pseudolite will be always static and the dynamics introduced by a pedestrian user is usually negligible.

2.2 Pulsed Pseudolite Signal

The use of a continuous signal adopting the same modulation used by GPS signals does not provide any protection for the non-participating receiver. For this reason, several solutions have been suggested for reducing the impact of pseudolite signals on non-participating receivers. These solutions includes [8]:

- **Code Division Multiple Access (CDMA)**: a different spreading code is used to broadcast the pseudolite signal. Although several spreading codes have been suggested, a possible solution is the use of 1023 chips long Gold codes from the same family of the GPS L1 C/A codes. This reduces the number of hardware modifications to be implemented in the participating receivers and avoids the problem of occupying processing channels in non-participating receivers;

- **Frequency Division Multiple Access (FDMA)**: the pseudolite signal is transmitted in a different band or its central frequency is offset with respect to the central frequency of GPS signals. If pseudolite signals were transmitted in a different band, the interference problem would be solved. This would however entail the implementation of a different front-end, dedicated to the pseudolite signal, in participating receivers. In addition to the required hardware complexity, hardware relative delays between GPS and pseudolite signals could be introduced. Thus, the beneficial impact of new measurements from pseudolite signals could be wasted without proper hardware calibration.

- **Time Division Multiple Access (TDMA)**: a pulsing scheme is adopted and the transmission of pseudolite signals occurs only in allocated time slots. It has been shown that pulsing reduces significantly the interference problem that can be further mitigated by adopting pulse blanking at the receiver side. If the receiver front-end is using a single bit for quantizing the input analog signal then the interference impact should not depend on the pseudolite signal power (the GPS signal

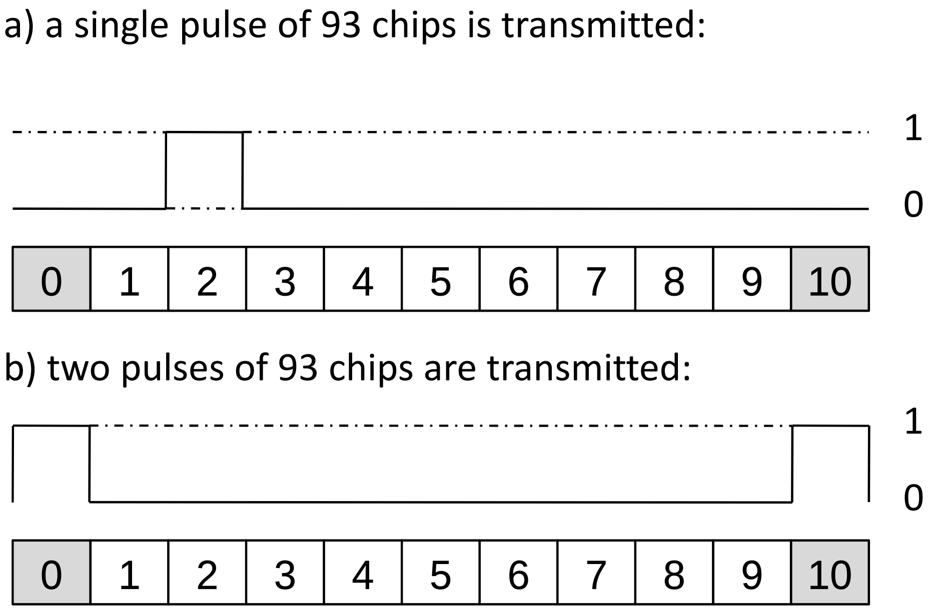

Figure 3: RTCM SC-104 pulsing scheme [2].

will be simply not available during a pseudolite pulse) whereas receivers using multi-bit ADCs and AGC could be still seriously impacted (depends on the AGC/ADC characteristics).

Among the different solutions proposed for reducing the impact of pseudolite signals on non-participating receivers, the TDMA approach has been chosen for the analysis developed in this research work. More specifically, the pulsing scheme suggested by the RTCM SC-104 working group [2] has been adopted. In the RTCM SC-104 pulsing scheme, a 1023 chip long Gold code is divided in 11 slots of 93 chips. At each millisecond epoch only a specific subset of slots is transmitted. More specifically, either a single slot is transmitted (slots from 1 to 9) or two slots are sent at the same time (slots 0 and 10). The transmission order is chosen in order to send all data slots each 10 milliseconds. In this way, a 10% duty cycle is obtained. The pulsing scheme suggested by the RTCM SC-104 standard is depicted in Fig. 3. This scheme has been implemented in the pseudolite signal generator and used for the second type of tests. All the other properties of the signal modulation are kept unchanged with respect to the description provided in Subsection 2.1.

2.3 Signal Playback

After generating a binary file containing the baseband I&Q samples with the GPS signals and the synthetic pseudolite component, a signal generator is used to up-convert and retransmit the signal. The experimental setup adopted for the transmission of GPS signals corrupted by a synthetic pseudolite component is shown in Fig. 4. The binary samples are read from disc and digital-to-analog converted by a National Instruments PXI-e 5450 I&Q signal generator [9] that produces differential baseband waveforms. An Agilent E8267D PSG vector signal generator [10] is used for the signal up-conversion. The generated analog signal is then split between the receiver under test and a spectrum analyzer used for visually verify the correct functioning of the setup.

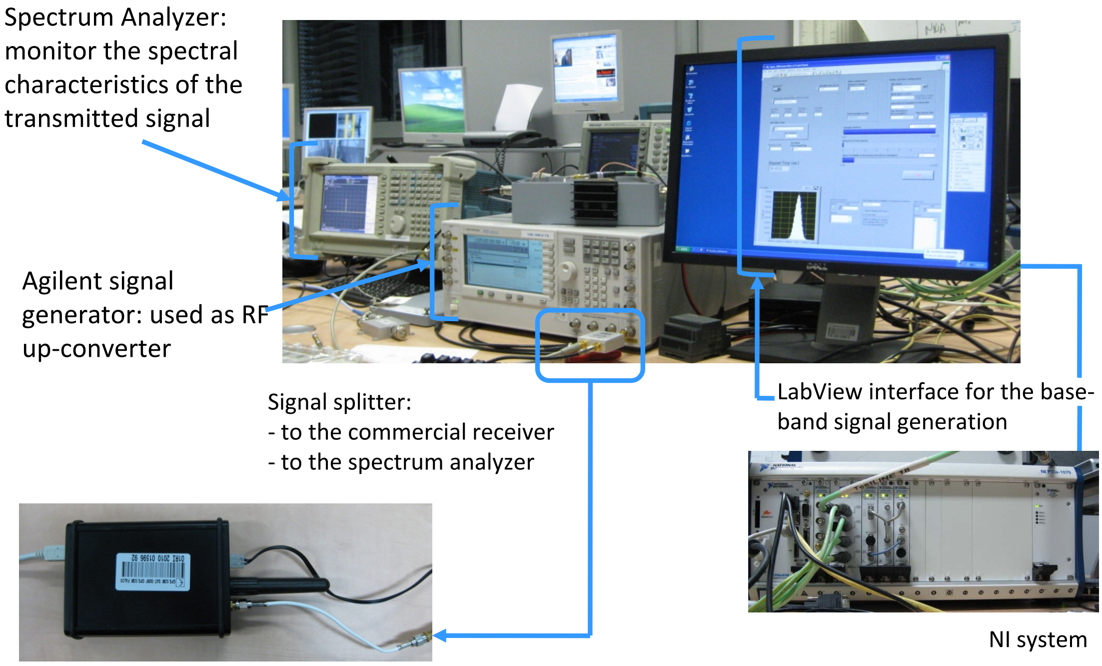

Figure 4: Experimental setup adopted for the transmission of GPS signals corrupted by a synthetic pseudolite component.

3 Signal Level Analysis

In this section, the results obtained in terms of useful signal degradation are shown. More specifically, the C/N_0 estimated by the receiver for the useful signal components is used as a metric for assessing the impact of the pseudolite interfering signal. Several tests have been performed for different pseudolite C/N_0 values. As the C/N_0 of the disturbing signal increases, the C/N_0 of the useful GPS signal components decreases and after a certain limit, depending on the receiver under test, it is not possible to acquire/track any useful signals. The two cases, continuous and pulsed pseudolite signals, are described below.

3.1 Continuous Pseudolite Signal

In the following, the case of a continuous pseudolite signal is considered. In all the performed test, the considered receiver was forced to a cold start, removing all previous information that could be used for speed up the acquisition and tracking process. In this way, the receiver was forced to search for all the satellite signals including for the PRN used for simulating the pseudolite signal.

3.1.1 Pseudolite signal tracking

Before analyzing the impact of the pseudolite signal, tests have been performed to verify that the synthetic pseudolite component was correctly generated. In this case PRN 10 was used for the pseudolite signal. Receiver #1 and Receiver #2 were able to correctly acquire the pseudolite signal, however since its navigation message did not contain any useful information it was not used for the computation of the navigation solution. Although it was expected that the two considered receivers would discard the signal after reading the health bits transmitted in the pseudolite navigation message, both receivers continued to process the interfering signal that was occupying a processing channel. If a significant number of pseudolite signals were present, then several processing channels could be used for processing these components limiting the resources available for the useful GPS signal components. For this reason it is strongly suggested to used PRNs not allocated for GNSS services.
The C/N_0 estimated by Receiver #1 for the pseudolite signal is shown in Fig. 5 as a function of time and for different simulated pseudolite C/N_0 values. It is noted that for moderate simulated C/N_0 values, the receiver estimates correctly the pseudolite C/N_0. For higher pseudolite powers, the receiver is unable to maintain lock and the estimated C/N_0 is underestimated.
For a pseudolite C/N_0 greater than 67 dB-Hz, Receiver #1 was unable to provide measurements indicating that a too strong interfering power prevented the receiver to operate correctly.

3.1.2 Useful signal power degradation

In order to determine the signal power degradation, the C/N_0 of each useful GPS signal component has been measured using the receiver under test. The power degradation have been obtained as:

$$L|_{\text{dB}} = \left.\frac{C}{N_0}\right|_{\text{no pl, dB}} - \left.\frac{C}{N_0}\right|_{\text{with pl, dB}} \tag{1}$$

that is the difference between the useful signal C/N_0 estimated in the absence of pseudolite signal, $\left(\left.\frac{C}{N_0}\right|_{\text{no pl, dB}}\right)$, and the C/N_0 estimated in the presence of a disturbing pseudolite component, $\left(\left.\frac{C}{N_0}\right|_{\text{with pl, dB}}\right)$. Different pseudolite C/N_0 values have been tested and the loss (1) has been determined as a function of this parameter. Sample results obtained for PRN 3 using Receiver #1 are shown in Fig. 6. Similar results have been obtained for the different PRNs and are not reported here to avoid the repetition of similar findings. PRN 3 is a strong signal characterized by an estimated C/N_0 equal to 46 dB-Hz in the absence of pseudolite signal. In this case, the receiver is able to maintain lock for a pseudolite C/N_0 equal to 67 dB-Hz. A loss of more than 10 dB is however observed. The presence

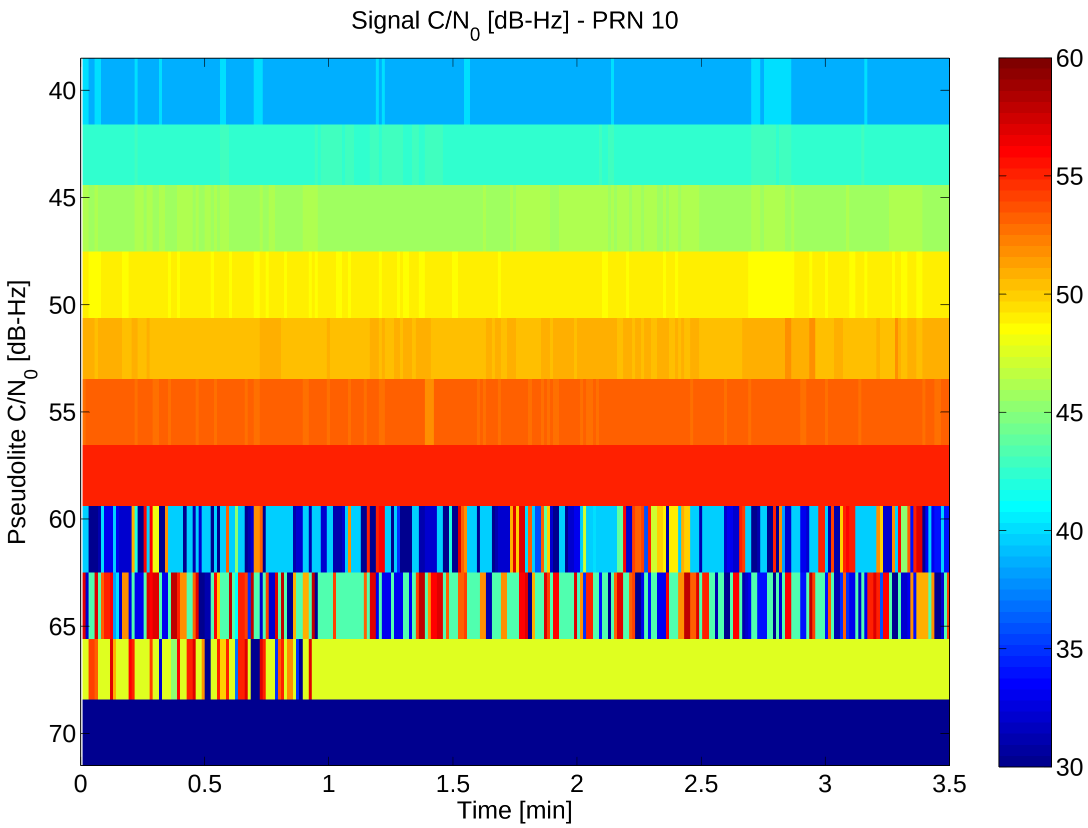

Figure 5: C/N_0 estimated by Receiver #1 for the pseudolite interfering signal as a function of time and for different simulated C/N_0 values. For low values of simulated pseudolite C/N_0, the receiver correctly estimates the pseudolite C/N_0. For higher C/N_0 values the receiver is unable to maintain lock and the estimated C/N_0 is underestimated. Continuous case.

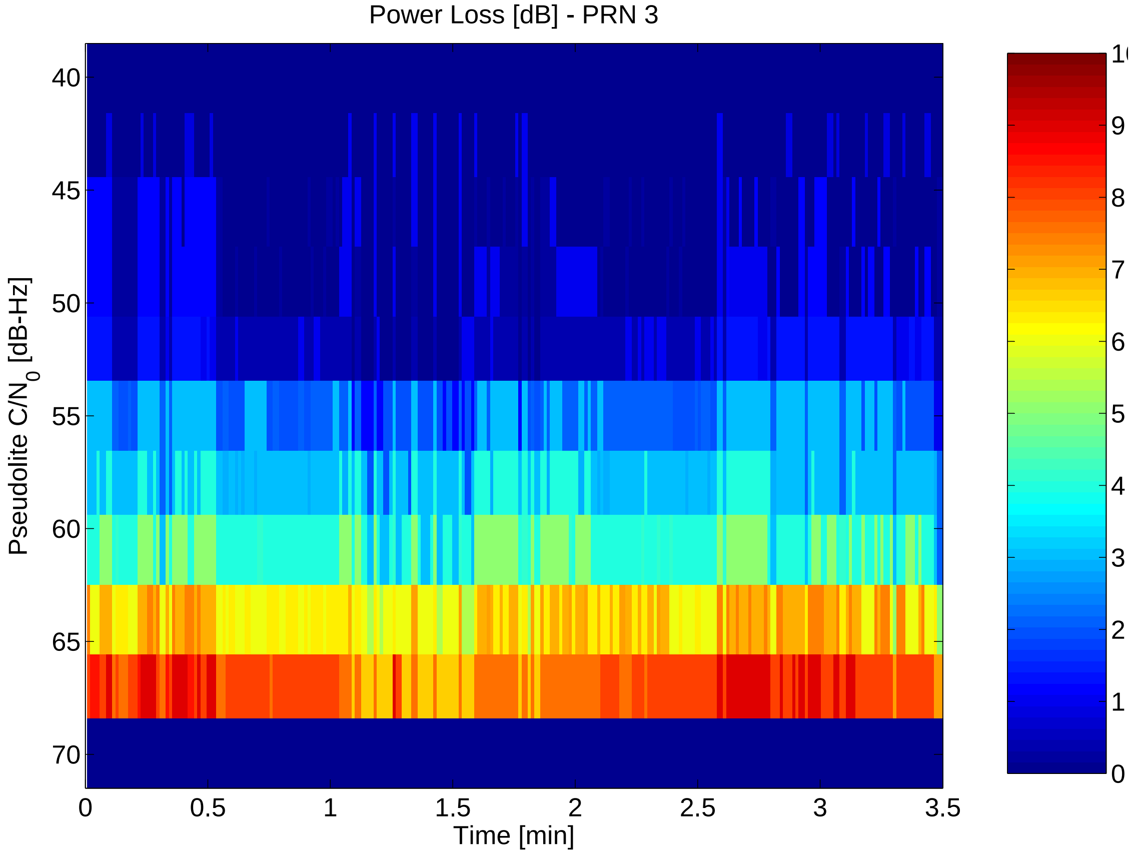

Figure 6: C/N_0 degradation estimated by Receiver #1 for the useful GPS signal PRN 3. The loss is depicted as a function of time and pseudolite C/N_0.

of the pseudolite signal causes a significant power degradation even when its power is only 10 times stronger than the useful signal. Receiver #1 is unable to operate for a pseudolite C/N_0 greater than 67 dB-Hz.

The behavior of Receiver #1 is further investigated in Fig. 7 where the interface of its control software is shown for two different pseudolite C/N_0 values, 40 and 70 dB-Hz, respectively. In the first case, i.e., 40 dB-Hz, the receiver is able to operate normally. A green indicator means that the corresponding GPS signal is tracked correctly and used for computing the navigation solution. In the 40 dB-Hz case, 10 useful signals are processed. A blue indicator implies that the corresponding signal is tracked/acquired but that the receiver is unable to extract its navigation message or cannot use the signal for the computation of the position solution. This is the case of the pseudolite signal that is correctly tracked but it is not used for the position computation. The receiver is also processing signals from EGNOS, the European augmentation systems, that are processed in the channels with PRNs 120 and 124.

In the 70 dB-Hz case, the receiver is unable to provide a position solution. Although several signals are tracked, the receiver is unable to use them. This may indicate that the receiver is either unable to extract the navigation message or that the ranging measurements are rejected. This can be due to the presence of strong cross-correlation peaks induced by the pseudolite signal. Strong cross-correlation peaks may significantly increase the bit error rate and make the receiver unable to extract the navigation message. In addition to this, significant biases in the pseudoranges can be introduced. This aspect is further investigated in Section 4. From Fig. 7, it also clearly emerges that some of the signals are tracked in a discontinuous way. More specifically, light gray indicators, implying that loss of lock occurred, are present in the right part of Fig. 7.

The average power loss experienced by Receiver #1 as a function of the Interference-to-Signal power ratio (J/S) is shown in Fig. 8. The J/S has been computed as

$$\left.\frac{J}{S}\right|_{\text{dB}} = \left.\frac{C}{N_0}\right|_{\text{pl, dB}} - \left.\frac{C}{N_0}\right|_{\text{no pl, dB}} \qquad (2)$$

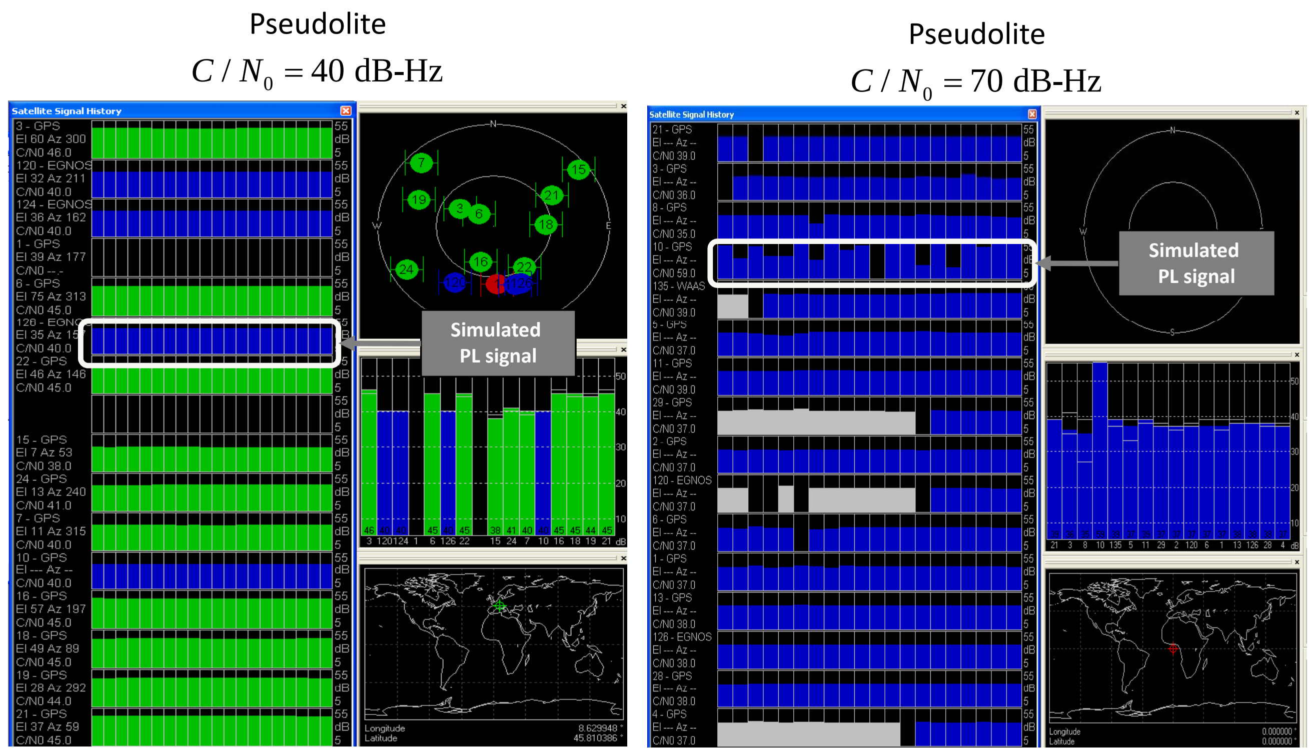

Figure 7: Software interface of Receiver #1 showing the different receiver performance for a pseudolite C/N_0 equal to 40 and 70 dB-Hz.

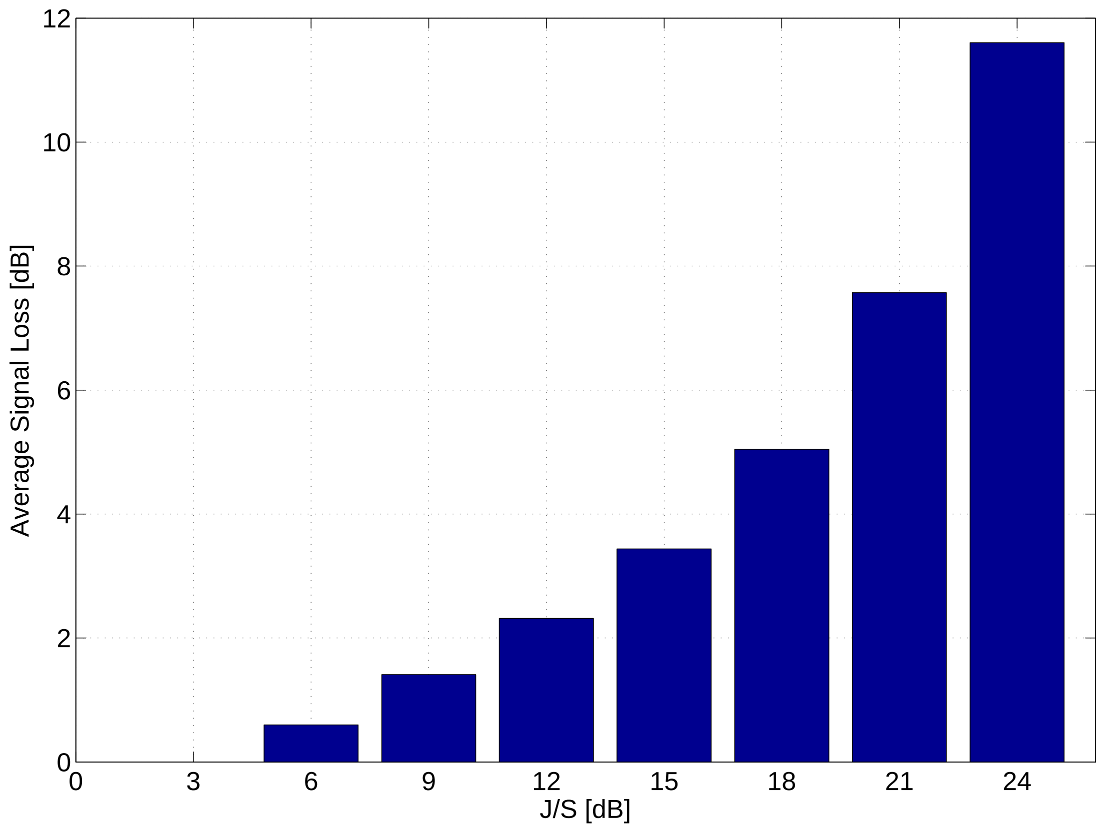

Figure 8: Average power loss measured by Receiver #1 as a function of the J/S. Continuous case.

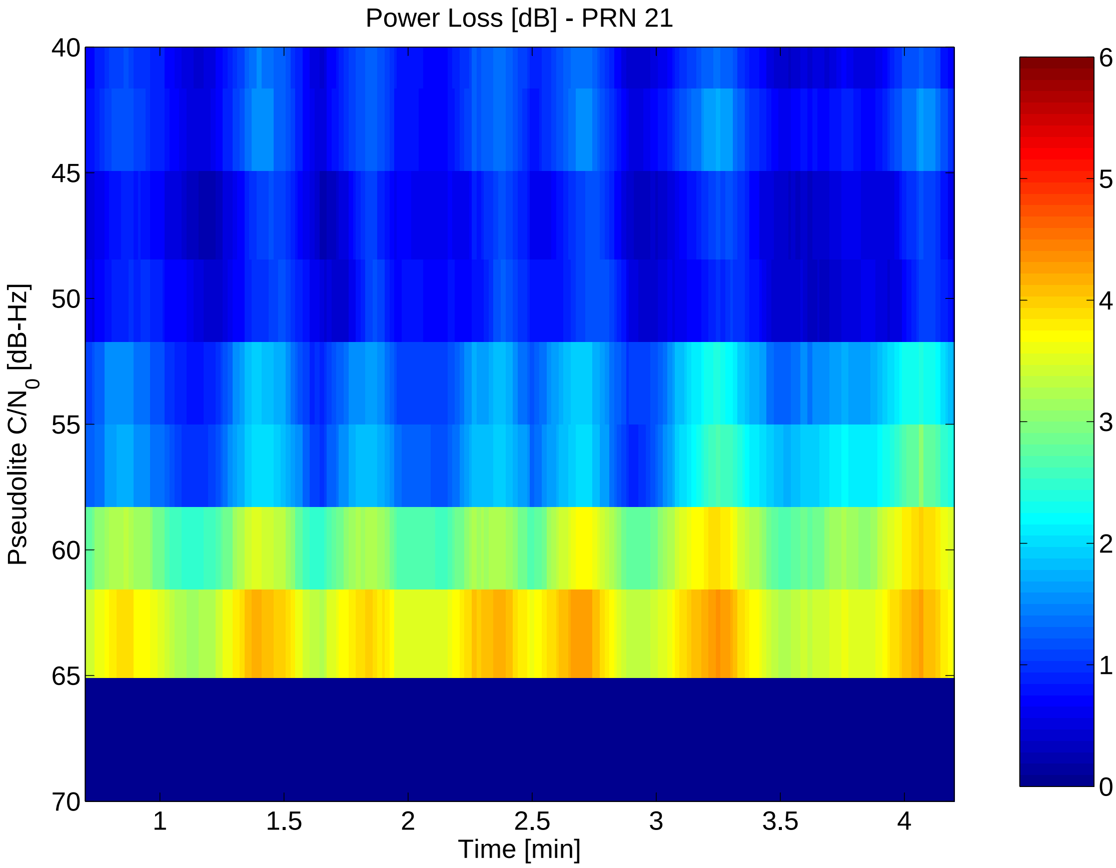

Figure 9: C/N_0 degradation estimated by Receiver #2 for the useful GPS signal PRN 21. The loss is depicted as a function of time and pseudolite C/N_0.

where $\left.\frac{C}{N_0}\right|_{\text{pl, dB}}$ is the C/N_0 of the simulated pseudolite signal. Since each useful GPS signal component has a different C/N_0, different J/S values were obtained. Thus, power losses were first interpolated and computed on the same J/S scale. Interpolated losses were then averaged using measurements from all the satellites. Thus, the results shown in Fig. 8 are averaged over the all duration of the test and for all the satellites. Fig. 8 shows that Receiver #1 can operate with a J/S as high as 24 dB-Hz, although significant power losses are observed.

Results obtained using Receiver #2 are shown in Figs. 9 and 10. In Fig. 10, the C/N_0 degradation estimated by Receiver #2 for the useful GPS signal PRN 21 is shown. In this case, a lower loss than in the case of Receiver #1 is observed, however the receiver loses lock for a 3 dB lower pseudolite C/N_0. This behavior is consistent among all the PRNs present in the dataset: although lower C/N_0 losses are observed, loss of lock usually occurs 3 dB earlier than in the case of Receiver #1 . These differences could be due to the different front-ends adopted by the two receivers. Without knowing the details of implementation of the two receivers, it is however not possible to draw definitive conclusions. This result is supported by Fig. 10 that shows the average power loss measured by Receiver #2 as a function of the J/S. Lower losses are measured although the receiver is not able to sustain a J/S higher than 21 dB-Hz.

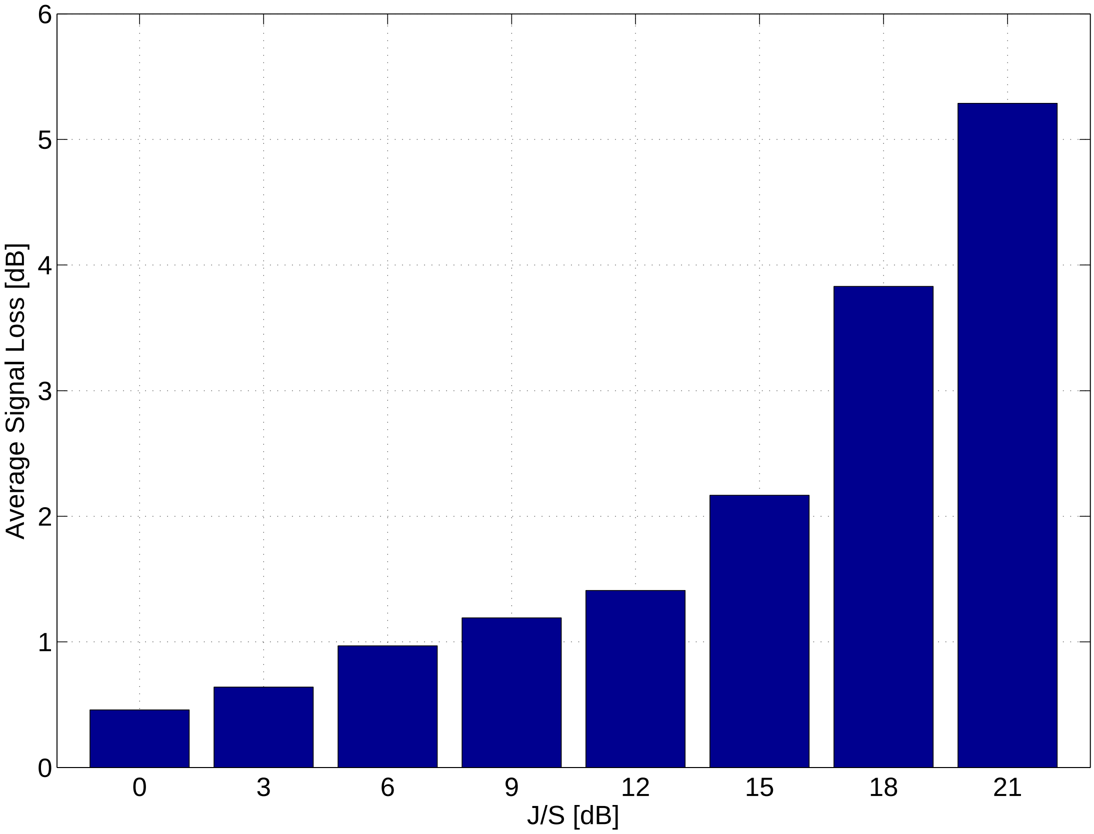

Figure 10: Average power loss measured by Receiver #2 as a function of the J/S. Continuous case.

3.2 Pulsed Pseudolite Signal

Results obtained in the presence of a pulsed pseudolite signal are reported in the following. The results are shown as a function of the pseudolite C/N_0 that is computed without considering the effect of pulsing. More specifically, the amplitude of the pseudolite signal is determined assuming a continuous signals. Pulsing with a 10 % duty cycle reduces the signal amplitude integrated on a single millisecond by a factor 10. Thus, the received pseudolite signal power is reduced by a factor 100 or equivalently -20 dB. Since in a non-participating receiver the signal is integrated over a full millisecond (or multiples), the collected noise power remains unchanged. In this way, without considering saturation phenomena, the pseudolite C/N_0 estimated by the receiver should be degraded by 20 dB. In a participating receiver, the pseudolite signal can be integrated only over the active time slot leading to 10 dB noise reduction. In this case, the C/N_0 would be degraded only by a factor 10.
It is noted that in the case of a pulsed signal, both Receiver #1 and Receiver #2 were able to process the different useful signals and provide a navigation solution for all the tested pseudolite C/N_0 values ($[40-85]$ dB-Hz range). For a pseudolite C/N_0 lower than 55 dB-Hz, the receivers are unable to detect and process the pseudolite signal.

3.2.1 Pseudolite signal tracking

The pseudolite C/N_0 estimated by Receiver #1 in the pulsed case is shown in Fig. 11 as a function of the simulated pseudolite C/N_0. It is noted that for low to moderate pseudolite C/N_0, the receiver estimates a C/N_0 that is approximately 20 dB lower than the simulated one. This phenomenon was expected as explained above. The red diagonal line in Fig. 11 corresponds to the relationship

$$\left.\frac{\hat{C}}{N_0}\right|_{\text{pl,pulsed}} = \left.\frac{C}{N_0}\right|_{\text{pl,sim}} - 20 \text{ dB} \quad (3)$$

where $\left.\frac{C}{N_0}\right|_{\text{pl,sim}}$ is the simulated pseudolite C/N_0 and $\left.\frac{\hat{C}}{N_0}\right|_{\text{pl,pulsed}}$ is the C/N_0 estimated by the receiver in the pulsed case. A good agreement between empirical and theoretical findings is obtained. For pseudolite C/N_0 higher than 64 dB-Hz, the estimated pseudolite C/N_0 starts saturating around a value close to 44 dB. This saturation effect is probably due to the receiver front-end. When the amplitude of the input signal passes a certain threshold, it is clipped by the front-end and saved by the receiver ADC to the maximum value representable by the front-end arithmetic.The performance of a GNSS receiver depends on the type of AGC and adopted by the receiver [3]. It was not possible to conduct a similar analysis for Receiver #2 since the receiver was providing information about PRN 10, the simulated pseudolite signal, in a discontinuous way.

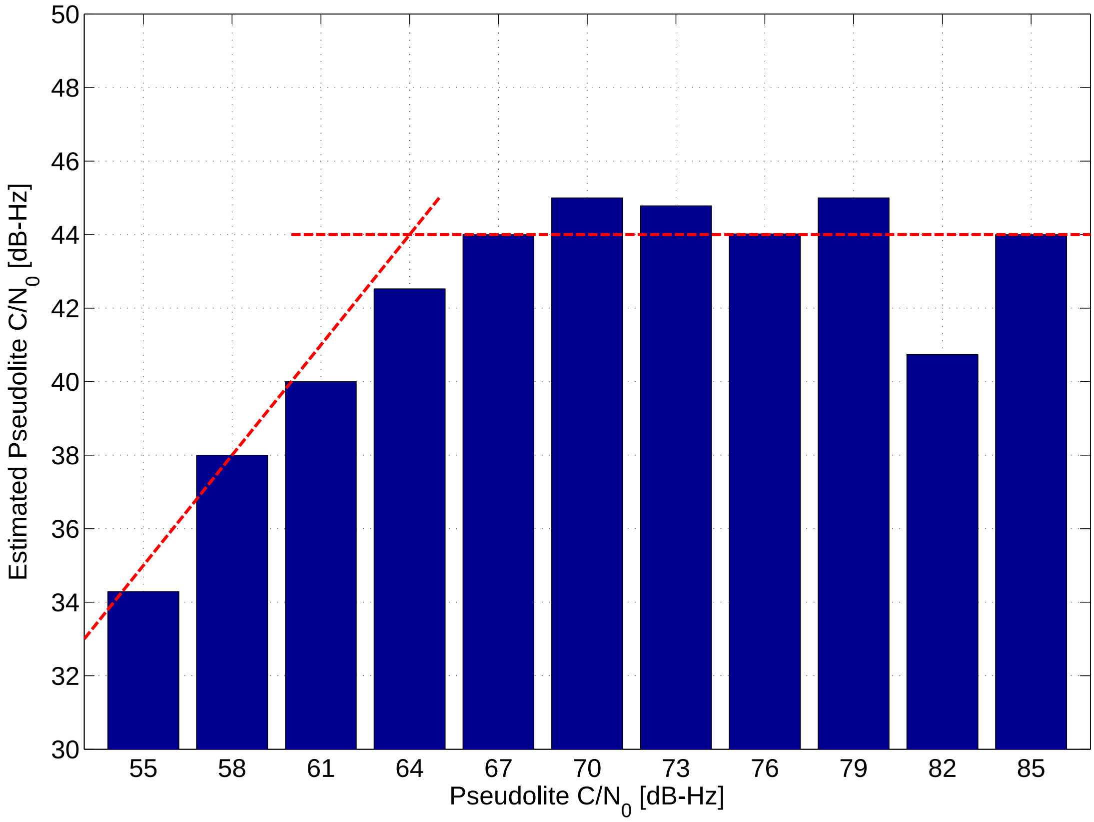

Figure 11: Average pseudolite C/N_0 estimated by Receiver #1 as a function of the simulated C/N_0. Pulsed pseudolite signals.

3.2.2 Useful signal degradation

The degradation caused by a pulsed pseudolite signal is analyzed in the following. In Fig. 12, sample results obtained from Receiver #1 are shown. More specifically, the C/N_0 degradation estimated by Receiver #1 for the signal PRN 22 is shown as a function of time and pseudolite C/N_0. It is noted that a phenomenon complementary to the one observed in Fig. 11 occurs. More specifically, the C/N_0 degradation increases until a saturation level is reached. This saturation is the same phenomenon observed for the C/N_0 of the pseudolite signal. When the pseudolite signal is completely saturated then also the loss on the useful signal reaches its maximum. It is also noted that the impact of the pseudolite signal is limited to a loss lower than 3 dB. These findings are supported by the results shown in Fig. 13 where the average C/N_0 loss is shown as a function of the J/S. The introduced loss is always lower than 3 dB and Receiver #1 is able to operate for all the considered pseudolite C/N_0 levels.

Results obtained for Receiver #2 are summarized in Fig. 14 that shows the average C/N_0 loss experienced by Receiver #2 as a function of the J/S. Although the receiver is able to operate for all the considered pseudolite C/N_0 values, a higher loss with respect to Receiver #1 is experienced. More

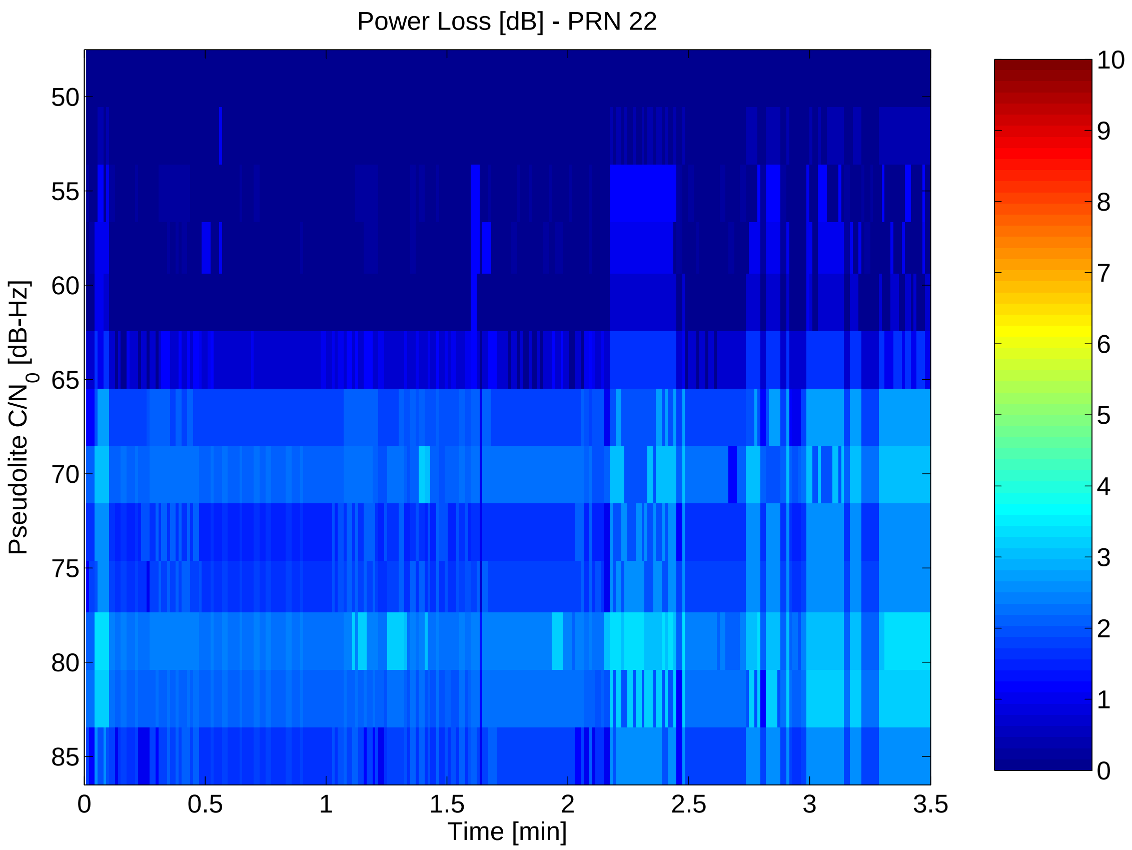

Figure 12: C/N_0 degradation estimated by Receiver #1 for the useful GPS signal PRN 22. The loss is depicted as a function of time and pseudolite C/N_0.

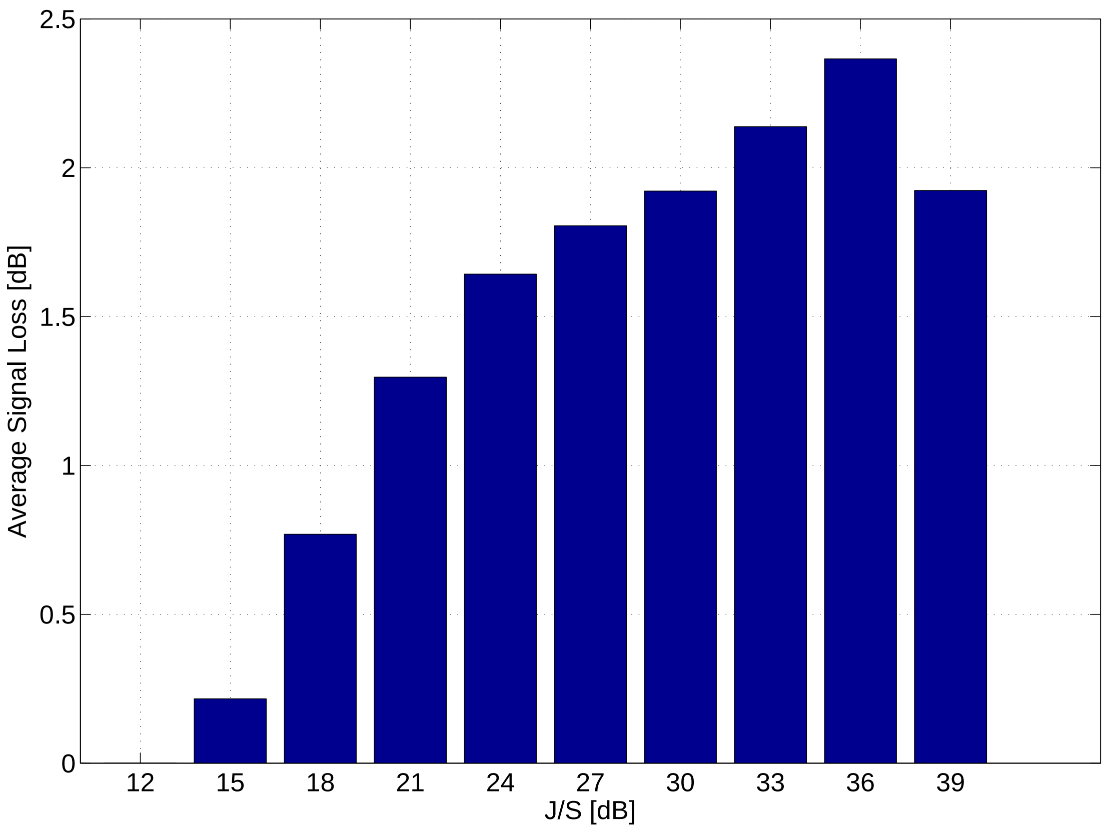

Figure 13: Average power loss measured by Receiver #1 as a function of the J/S. Pulsed pseudolite signal.

specifically, an average loss equal to 4.5 dB is experienced for a J/S equal to $36/39$ dB. Also in this case, a saturation phenomenon is observed for high J/S level.

The differences between Receiver #1 and Receiver #2 are, as already mentioned, due to the different

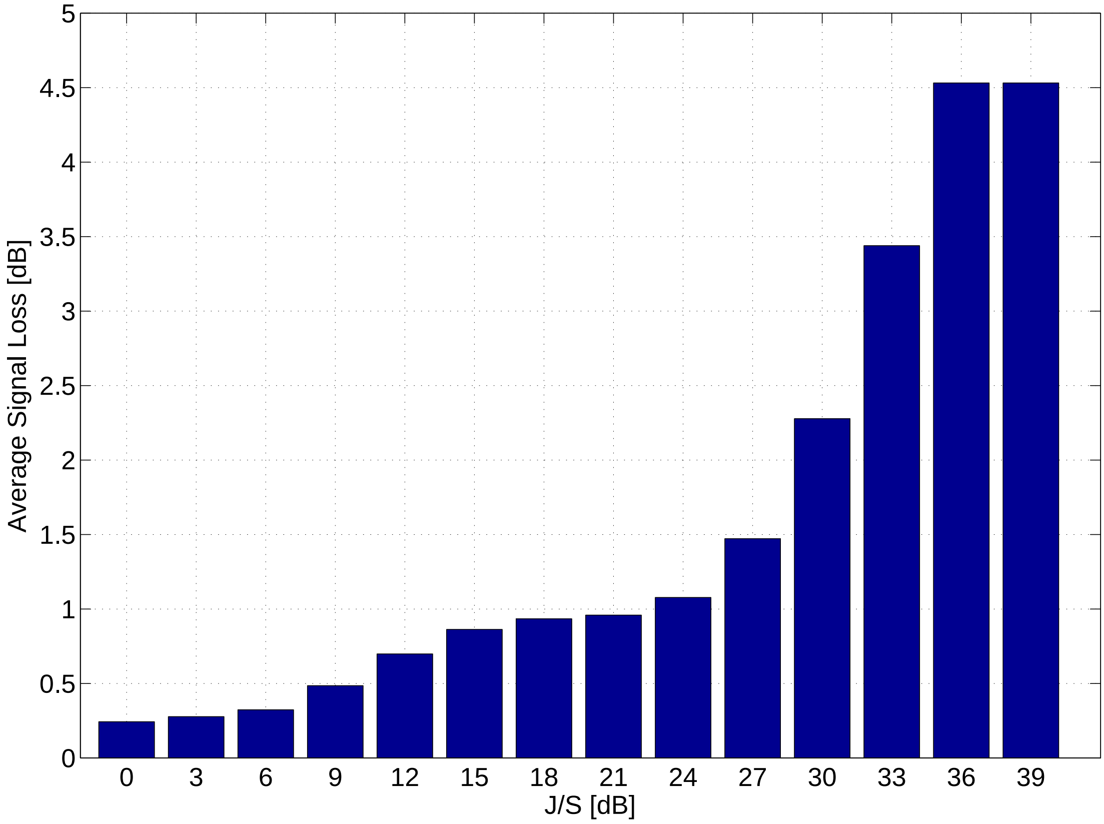

Figure 14: Average power loss measured by Receiver #2 as a function of the J/S. Pulsed pseudolite signal.

front-ends used for the signal conditioning/digital representations. In both Receiver #1 and Receiver #2 cases, additional measurements are required for establishing if higher pseudolite power levels can further degrade the receiver performance.

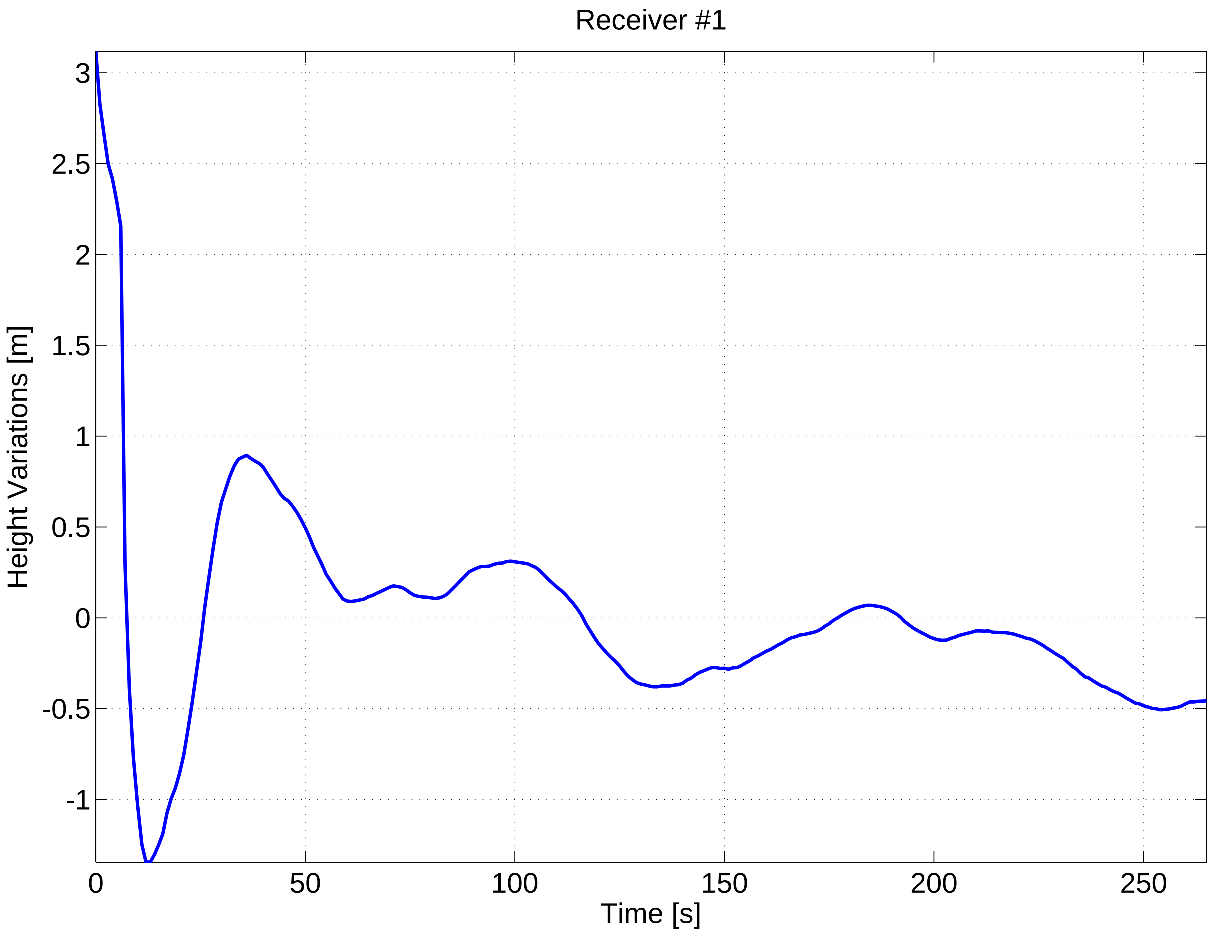

Figure 15: Height variations estimated by Receiver #1 . The height has been obtained directly from the messages sent by the receiver to the host PC and the variations have been computed with respect to the mean height (279.54 m) estimated by Receiver #1 . Absence of interfering pseudolite signal.

4 Position Domain Analysis

In this section, the performance of Receiver #1 and Receiver #2 are assessed in the position domain. More specifically, the variance of the position estimates, the number of satellites available and other parameters are analyzed as a function of the C/N_0 of the interfering pseudolite signal. Both continuous and pulsed modulations are considered.
It is noted that both Receiver #1 and Receiver #2 use a Kalman filter for the computation of the position solution. More specifically, the receiver assumes a dynamic model that is used to smooth the position solution among different epochs. This phenomenon is shown in Fig. 15 where the variations in the estimated height are shown with respect to the mean estimated height (279.54 m). The variations in the estimated height progressively decrease because of the progressive smoothing provided by the Kalman filter. The Kalman filter used for the computation of the navigation solution can mask the effect of the interfering pseudolite signal and should be thus disabled. A Least Squares (LS) approach, where the navigation solution is computed epoch by epoch in an independent way, should be adopted. The interface software provided by the receiver manufacturer allows one to set different Kalman filter parameters corresponding to different dynamic conditions (from static to high dynamic) but not the use of LS. For this reason, position was computed starting from the raw pseudorange measurements provided by the receiver using the LS algorithms. Broadcast ephemerides were downloaded and used for the computation. In the following, all the results have been obtained using the LS approach.

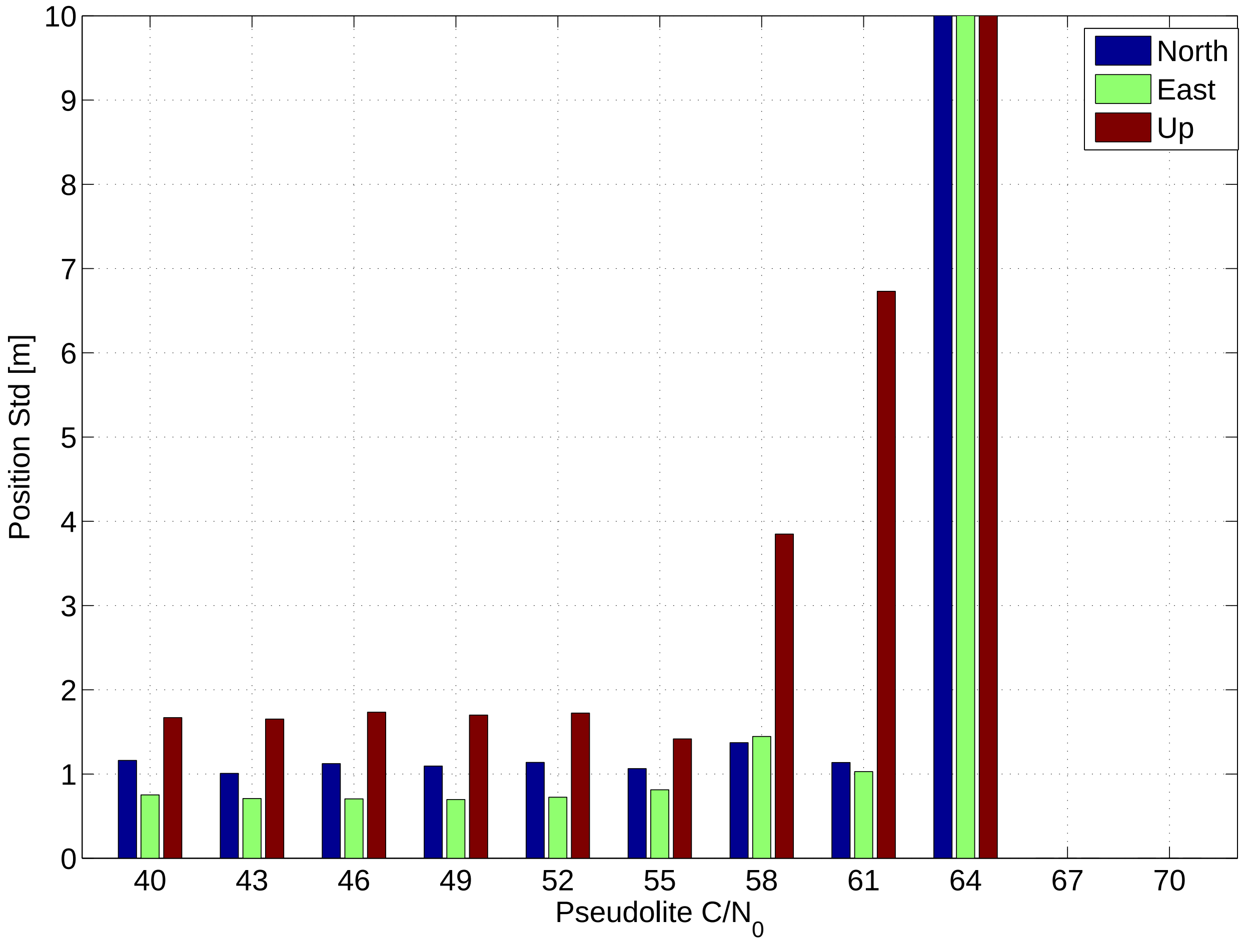

Figure 16: Position accuracy obtained using Receiver #1 as a function of the C/N_0 of the interfering pseudolite signal. Continuous signal.

4.1 Continuous Pseudolite Signal

Results obtained when considering a continuous pseudolite signal are shown in this section.

In Fig. 16 the standard deviation of the position estimates obtained using Receiver #1 are shown as a function of the C/N_0 of the interfering pseudolite signal. The position solution has been at first expressed in the local frame and the standard deviation of the East, North and Up components computed. In general the standard deviation of the different position components increases as the C/N_0 of the pseudolite signal increases. This behavior is expected and is in agreement with the findings provided in Section 3. Deviations from this trend are likely due to the limited number of runs used for estimating the quality of the position solution (5 minutes of data, approximately 280 position fixes). It is noted that Receiver #1 is unable to provide a position solution when the pseudolite C/N_0 reaches a value of about 67 dB-Hz. At 64 dB-Hz the position solution is discontinuous and several outliers are present. This makes the standard deviation of the position estimates become quite significant and outlier removal techniques should be adopted for the standard deviation estimation. The 64 dB-Hz case is better analyzed in Fig. 17 where the time evolution of the North, East and Up components is shown. The number of satellite observations used for the computation of the navigation solution is also shown. The position solution is highly discontinuous and, in certain cases (for example in the $[100 - 150$ s$]$ time interval), highly biased estimates are obtained. From Fig. 17 it emerges that the main problem is not the lack of available measurements, the number of observations is always greater than 4, but their quality. More specifically, it is noted that the position solution significantly degrades when the number of satellites jumps to 8. This has motivated further analysis and it has been found that the additional measurement included in the navigation solution is the one obtained from PRN 15. The signal from this satellite is strongly biased

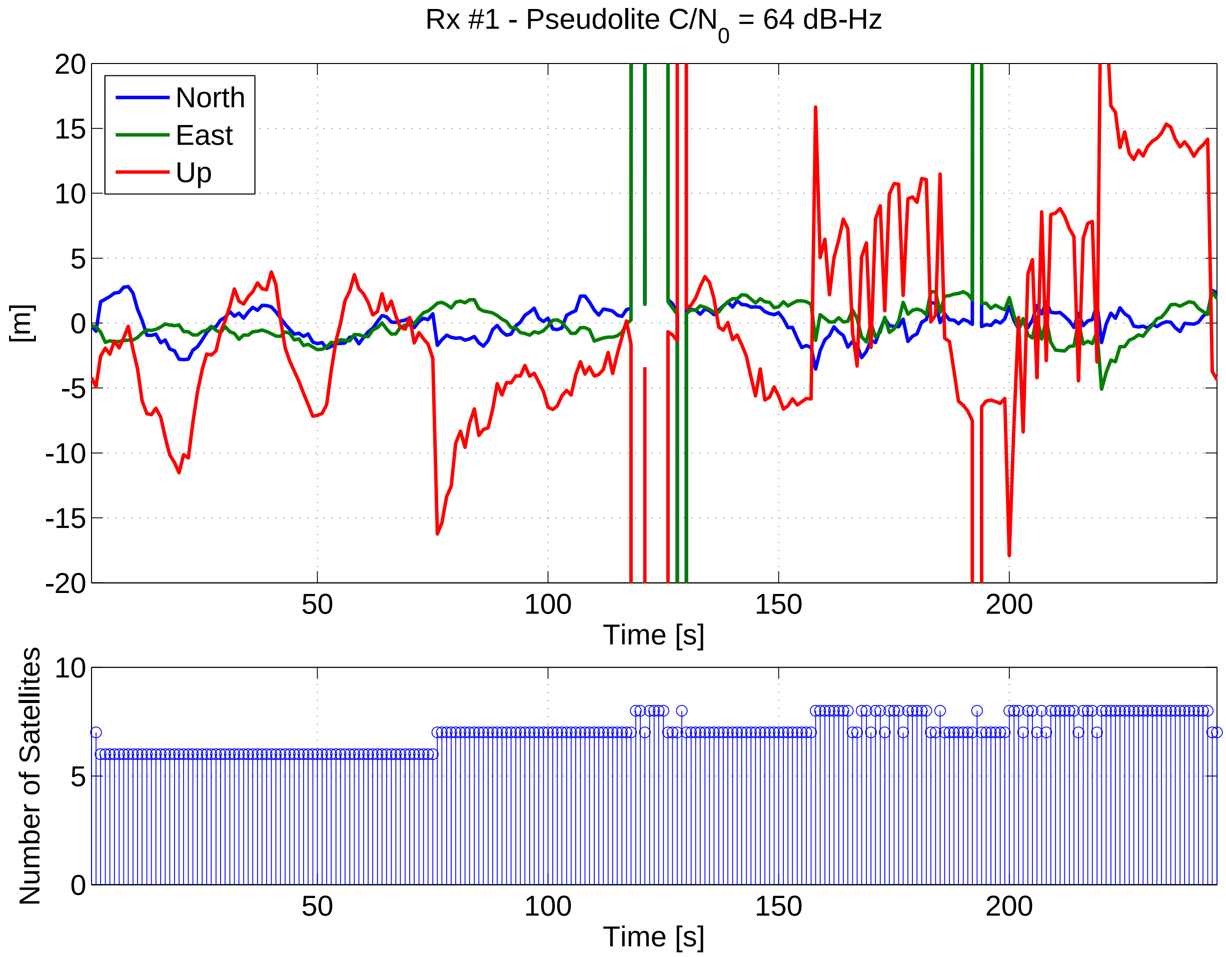

Figure 17: Upper part: North, East and Up components estimated by Receiver #1 as a function of time. Lower part: number of satellites used for the computation of the navigation solution.

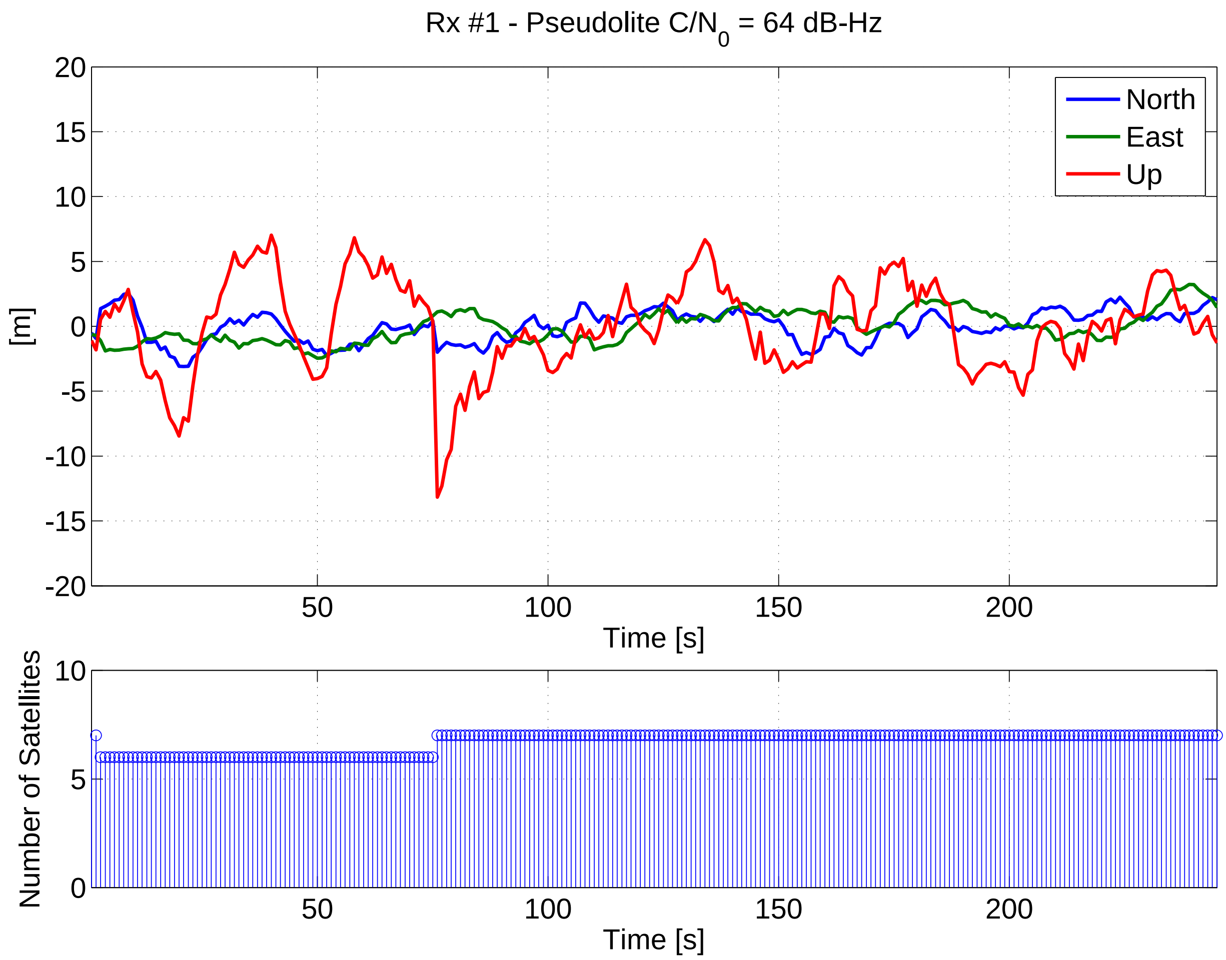

Figure 18: Upper part: North, East and Up components estimated by Receiver #1 as a function of time. Lower part: number of satellites used for the computation of the navigation solution. In this case, the measurement from PRN 15 has been removed from the navigation solution.

by the pseudolite interferer and its inclusion in the navigation solution produces extremely significant errors. This hypothesis is supported by the results shown in Fig. 18 where the measurement from PRN 15 has been excluded from the navigation solution. In this case, the variations of the North, East and Up components remain limited and the standard deviations reported in Table 1 are obtained. It is noted that the obtained standard deviations are of the same order of magnitude as those obtained for the pseudolite signal C/N_0 equal to 58 dB-Hz. This suggests that the performance degradation observed for a pseudolite C/N_0 equal to 61 dB-Hz is also due to the measurements from PRN 15. For this reason, observations from PRN 15 has been removed and the position has been recomputed also for a pseudolite $C/N_0 = 61$ dB-Hz. As for the previous case, the standard deviation of the obtained navigation solution drops providing results similar to those obtained with a lower pseudolite signal C/N_0. The estimated standard deviations are reported in Table 1 and in Fig. 19. In Fig. 19, the standard deviation of the position components has been computed by removing the measurements from PRN 15. For low pseudolite signal C/N_0 a performance degradation is observed due to the reduced geometry.
From these results it emerges that pseudolite signals have a twofold effect on the navigation solution of non-participating receivers:

- the standard deviation of the estimated position solution increases as the power of the pseudolite interfering signal increases;
- some of the measurements can be significantly biased by the presence of the interfering signal. These biases can corrupt the navigation solution resulting in degraded performance.

In addition to this, it is clear that after a certain pseudolite power level (in this case corresponding to a C/N_0 greater than 64 dB), the receiver is unable to provide a navigation solution.

Table 1: Standard deviation of the position solution obtained by removing the measurements from PRN 15.

Component	Standard Deviation
North (61 dB-Hz)	1.19 m
East (61 dB-Hz)	1.17 m
Up (61 dB-Hz)	3.11 m
North (64 dB-Hz)	1.21 m
East (64 dB-Hz)	1.26 m
Up (64 dB-Hz)	3.55 m

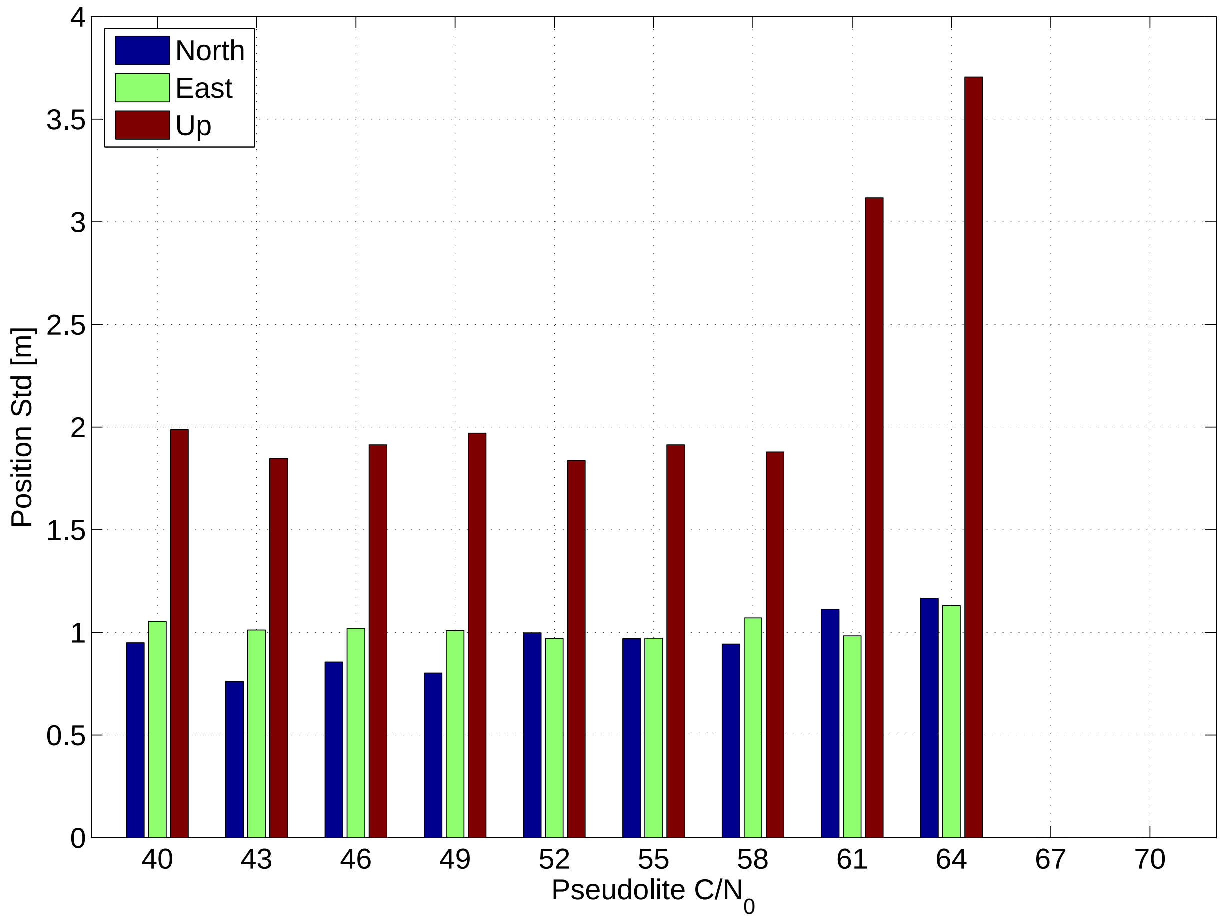

Figure 19: Position accuracy obtained using Receiver #1 as a function of the C/N_0 of the interfering pseudolite signal. Continuous signal. In this case, pseudoranges from PRN 15 have been removed.

It is noted that many GPS receivers are equipped with outlier detection algorithms that allows the removal of bad measurements. This can be done for example by checking the values in the residuals of the LS solution. This implies that the bad measurement from PRN 15 would have been likely detected and discarded.

In the case of Receiver #2 , it was not possible to repeat an analysis similar to the one provided for Receiver #1 . This is essentially due to the fact that the pseudorange measurements were carrier-smoothed. This introduces time correlation among diffent measurements and the smoothing hides the degradations caused by the pseudolite signal. This phenomenon is clearly shown in Fig. 20 where the hight estimated from the measurements provided by Receiver #2 is shown as a function of time and for different pseudolite C/N_0 values. The height has been considered since it is usually the position component estimated with lower accuracy. It is noted that for all the considered pseudolite levels similar height estimates have been obtained. The estimated heights follows a clear trend confirming the presence of time correlation in the measurements. In Fig. 20, the height provided directly by Receiver #2 is also shown along with the height obtained in the absence of pseudolite signal using LS. All the estimates are within 4 meters and thus it is possible to conclude that measurement smoothing and Kalman filtering at the navigation solution level can effectively mash the degradation introduced by the pseudolite signal. It is important to note that in Fig. 20, the height estimates (and the navigation solution) start becoming

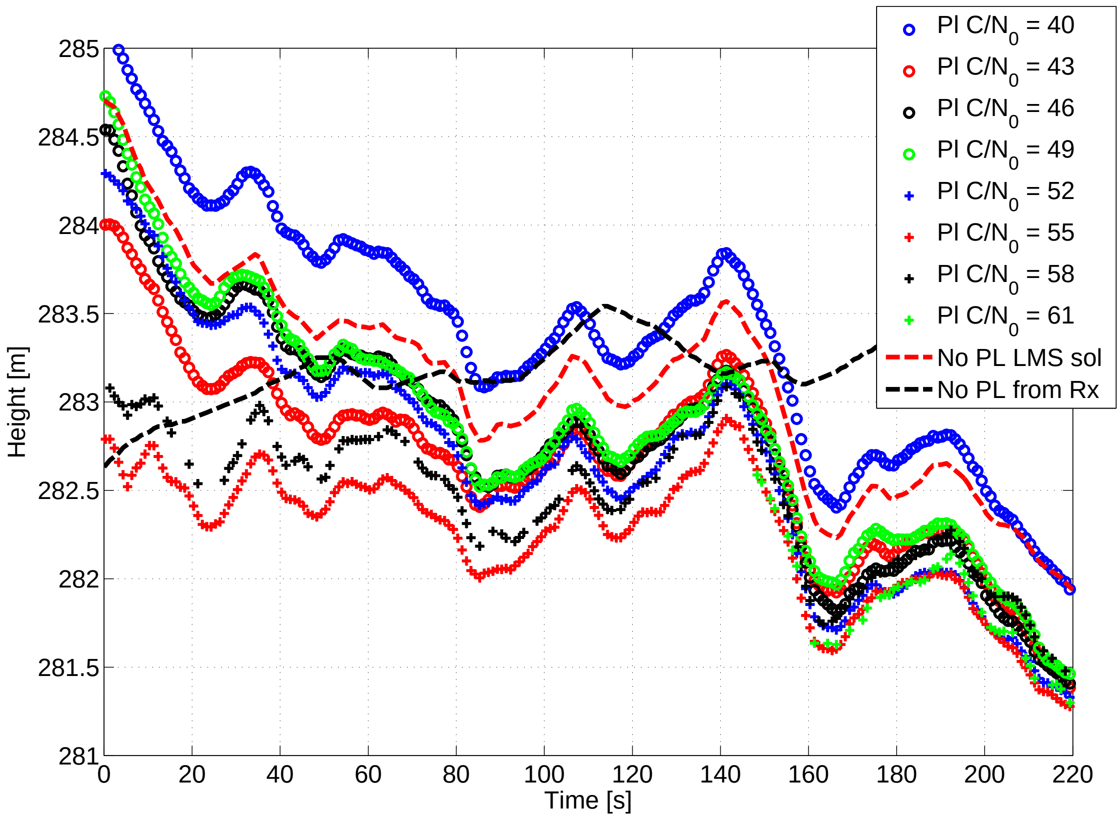

Figure 20: Comparison of the heights estimated from the measurements provided by Receiver #2 as a function of time and for different pseudolite C/N_0 values.

discontinuous for pseudolite C/N_0 values equal to 58 and 61 dB-Hz. This is due to the fact that for high C/N_0 values the receiver have difficulties in locking on the signals and loss of lock occurs frequently. Discontinuous measurements lead to a discontinuous position solutions as shown in Fig. 20. For a pseudolite C/N_0 equal to 64 dB-Hz, Receiver #2 is unable to provide a position solution in agreement with the results discussed in Section 3.

4.2 Pulsed Pseudolite Signal

In the case of pulsed signals, a lower impact of the pseudolite signal is found on the navigation solution. This is in agreement with the results discussed in Section 3 where it was shown that lower C/N_0 degradations are experience by the non-participating receiver. Results for Receiver #1 are shown in Fig. 21 where the standard deviation of the North, East and Up components are shown as a function of the C/N_0 of the interfering pseudolite signal.

In this case, it is not possible to observe a significant degradation in the accuracy of the estimated position solution. All the estimated standard deviations are lower than 2 meters. It is noted that these values are quite low most of all considering the fact that only pseudorange measurements are used. The good position estimates are likely due to the good geometry and high number of satellites in view during the data collection.

The specific case of a pseudolite signal C/N_0 equal to 82 dB-Hz is considered in Fig. 22. In this case,

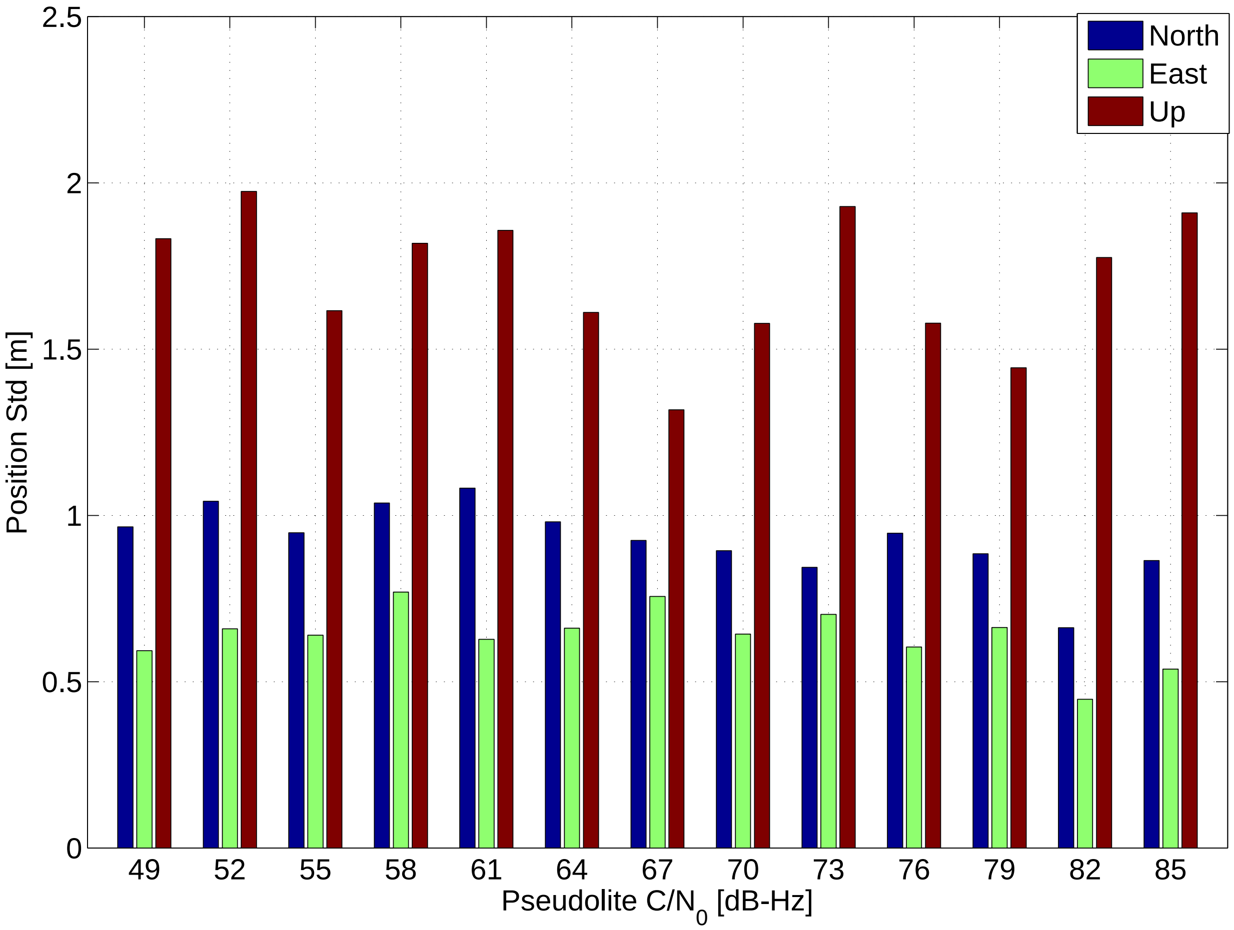

Figure 21: Position accuracy obtained using Receiver #1 as a function of the C/N_0 of the interfering pseudolite signal. Pulsed signal.

the receiver was able to process and obtain measurements from 10 satellites. For this reason and due to the absence of biases in the pseudoranges used in the navigation solution, the North, East and Up component are affected by variations lower than ± 2 meters. It is noted that the signal with PRN 1 (SV 49) was present during the data collection. This signal is currently declared unhealthy and should not be used in the navigation solution. The exclusion of this signal however impacts only marginally the final navigation solution.

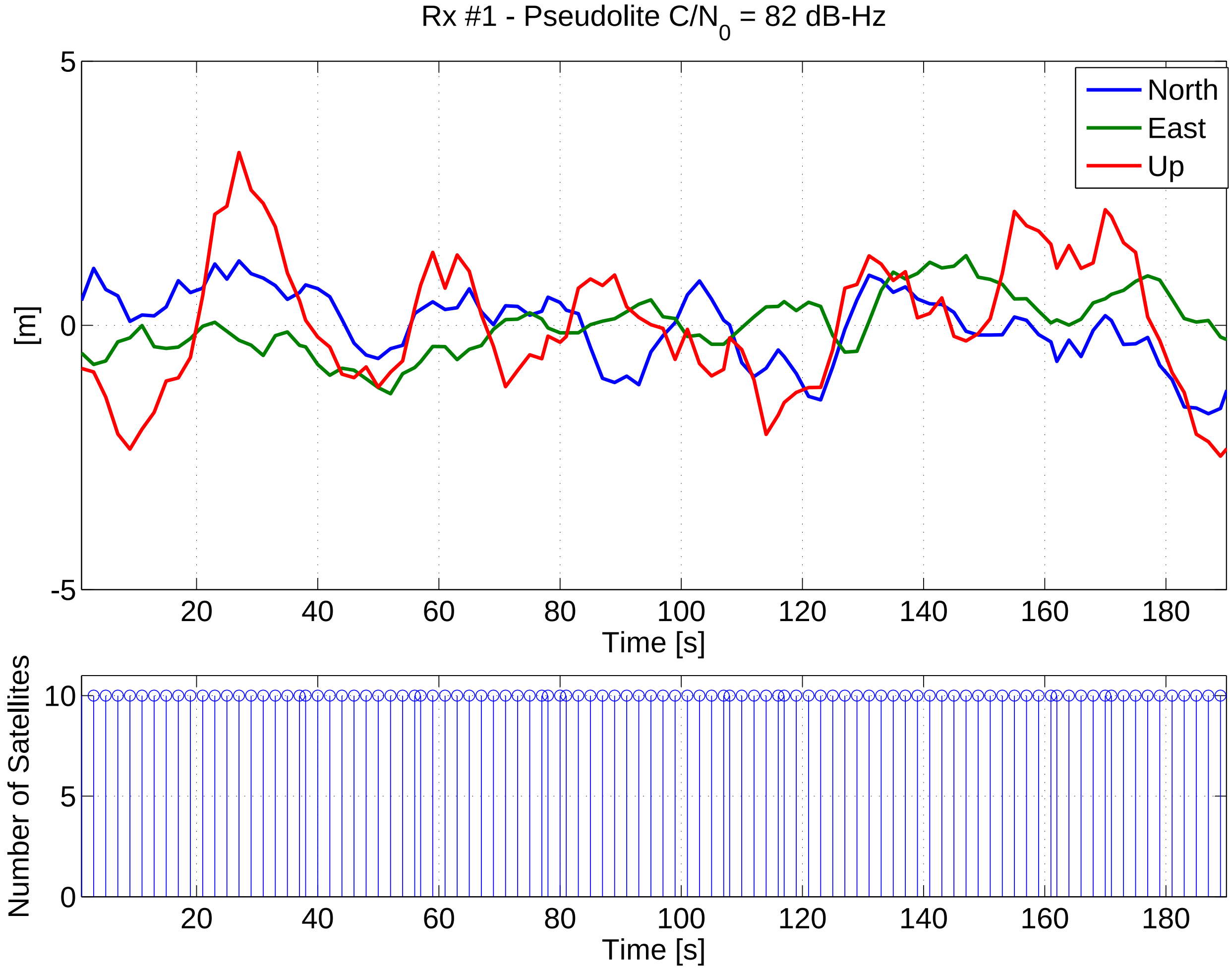

Figure 22: Upper part: North, East and Up components estimated by Receiver #1 as a function of time. Lower part: number of satellites used for the computation of the navigation solution. Pulsed pseudolite signal with a $C/N_0 = 82$ dB-Hz.

5 Recommendations and Possible Follow-on Activities

In this report, preliminary results obtained by testing the impact of a pesudolite signal on a non-participating receiver have been provided. A modified record and playback methodology has been developed and used to test commercial GPS receivers. The provided results support the effectiveness of the developed methodology and show the capabilities of the IPSC-JRC for the analysis of electromagnetic coexistence issues in the GNSS bands.
From the preliminary results provided in this documents, the following conclusions/recommendations can be drawn

- pseudolite signals should be modulated using non-existing PRN codes. This will avoid the occupation of a processing channel in a non-participating receiver;
- the use of continuous signals in the same frequency band of existing GNSS modulations, should be avoided. Commercial receivers may be prevented to operate for J/S levels as low as 20 dB;
- although, codes with good correlation properties with respect to existing GNSS signals provide better interference margin at the correlator output, i.e., the interfering signal is strongly attenuated after correlation, the input signal power should be also considered as a critical parameter. More specifically, strong input interfering signals can saturate the receiver front-end. Pulsing can be an effective way to reduce this effect, allowing a GNSS receiver to operate normally during time slots not affect by pseudolite signals;
- GNSS receivers respond differently to the presence of pseudolite signals depending on the type of front-end adopted. In this respect, the number of bits used by the ADC and the strategy implemented by the AGC play a significant role and further studies should be devoted to those aspects.

The analysis detailed in this report is preliminary and the following aspects should be further investigated:

- extension of the analysis to higher pseudolite power levels to determine the limits of pulsing as a protection strategy for non-participating receivers;
- analysis of the impact of several pseudolite signals with different synchronization algorithms for avoiding the collision of pulses from different transmitters;
- consideration of more complex scenarios (indoor environments, in the presence of multipath, ...) where GPS/GNSS signals are partially obstructed and the number of visible satellites is limited. In the current study, GPS signals were collected in an open-sky environment and the receiver has a sufficient number of measurements to be able to cope with the signal degradations induced by the pseudolite signal;
- development of a test methodology in which GNSS and pseudolite signals are radiated. The deployment of a such a lab testbed is possible at the IPSC-JRC that has at its disposal a unique anechoic chamber that is currently being equipped for GNSS compatibility analysis;
- tests should be carried out using a software redefined radio GNSS receiver providing a higher flexibility than commercial receivers allowing the full control of the different components of the receiver chain. The software receiver could be used in conjunction with a high fidelity signal vector analyzer the dynamic range of which allows one to separate the effects due to the receiver AGC/ADC from other phenomena.

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Abstract

Pseudolites or pseudo-satellites are an emerging technology that has the potential to extend the capability of Global Navigation Satellite Systems (GNSS) indoors and in harsh environments where GNSS services are denied. Although their potential, pseudolites could cause severe interference problems to non-participating receivers, i.e., GNSS receivers unable or not designed to use pseudolite signals. In this report, preliminary results obtained by the IPSC-JRC on the impact of pseudolite signals on commercial non-participating receivers are presented. The analysis considered two pseudolite modulations. In the fist case, the pseudolite signal has same structure adopted by GPS L1 C/A signals whereas in the second scenario a pulsing scheme has been adopted to reduce the interference problem.

From the analysis, it emerges that in the case of a continuous pseudolite modulation, the performance of the non-participating receiver is already significantly degraded when the pseudolite signal is about 10 times stronger than the average signal power. More specifically, a 3 dB loss is introduced in the estimated C/N_0 of the useful GPS signals. The use of a pulsing scheme significantly mitigates the impact of pseudolite signals and the receiver is able to maintain lock and provide a position solution for all the tested pseudolite power levels. Further investigations are required to determine if higher pseudolite signal powers could affect more severely a non-participating receiver.

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