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Multipath Mitigation Based on Deconvolution

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Abstract

There are many applications which require continuous positioning in combined outdoor urban and indoor environments. For a long time GNSS has been used in outdoor environments while indoor positioning is still a challenging task. One of the major degradations that GNSS receivers experience indoors is the presence of multipath. The current paper analyzes several available multipath mitigation techniques which would be suitable for indoor applications. Some of these techniques are described in more details. A few deconvolution based techniques such as the Projection Onto Convex Sets and the Deconvolution Approach are focused on and some tests are performed to show how they work. It is shown which advantages these techniques have over the conventional techniques. The wide range of tests show how these techniques work under ideal conditions, with simulated signals in different environments and in real world using data from high-end GNSS front-end.

Keywords: multipath mitigation, indoor positioning, deconvolution.

1. Introduction

Indoor positioning applications are becoming more and more popular. Some examples are: finding goods in a shopping mall, guiding blind pedestrians or even navigating firefighters in a burning house. However, today we do not have solutions which offer simple and seamless positioning outdoors and indoors without creating infrastructure or mapping the location beforehand (see Table 1). For example, most inertial sensors (accelerometers and gyros) or optical systems (lasers and cameras) offer accurate relative positioning. Such systems only work autonomously for a short period of time before they lose information about absolute position and must be readjusted. To perform the readjustment one needs either to establish some infrastructure or to use already available systems (e.g. mobile communication networks or GNSS). Wireless solutions such as WiFi, Bluetooth or RFID need infrastructure like any ultrawideband (UWB), ultrasound or pseudolite based techniques. Mobile communication networks are widely available, but accuracy is still insufficient for accurate outdoor and indoor positioning.

GNSS would be the best solution, because it offers absolute positioning everywhere in the world and it is already widely used in many smart phones and even watches. Unfortunately, GNSS was designed to operate in open sky conditions and thus, it works poorly in urban or indoor environments. In these harsh working conditions, GNSS need to be augmented by the use of assisted-GNSS (A-GNSS) [Monnerat 2008], high-sensitivity (HS) techniques [Seco-Granados et al. 2006] and other improvements such as differential positioning [Mautz 2009]. Nevertheless, even using the best techniques we cannot use GNSS indoors alone. The best method would be to combine GNSS with other techniques which can provide sufficient accuracy indoors, but which cannot determine absolute position on their own. For example, GNSS tightly integrated with inertial and/or optical sensors would allow us to seamlessly navigate indoors and outdoors.

Table 1: Indoor Positioning Technique Survey

Technology	Accuracy indoors	Accuracy outdoors	Absolute pos.	Relative pos.	Need infrastructure / price
GNSS	Poor	Good	Yes	Yes	No / low
Mobile communication networks (GSM, CDMA)	Poor	Poor	Yes	Yes	No / low
Wireless RF based systems (WiFi, Bluetooth, RFID)	Poor-good*	Poor-good*	No	Yes	Yes / high
GNSS pseudolites, Ultrawideband, Ultrasound	Good	Poor-good*	Yes/No*	Yes	Yes / high
Optical systems (lasers, cameras, IR)	Good	Poor-good*	No	Yes	* / low
Inertial sensors (accelerometers, gyros, magnetometers)	Good	Good	No	Yes	* / low

* Depends on environment and/or implementation

GNSS Errors

In this paper we look at how to improve GNSS performance indoors. Most GNSS related errors can be mitigated by using differential corrections, coming for instance from DGPS or SBAS system, but multipath is a local phenomenon and depends on the local environment. Multipath error is currently the largest error source in GNSS and it is widely studied, but the focus has almost always been put on outdoor cases. Therefore indoor GNSS is a rather new topic. The first high sensitivity hardware receivers were introduced on year 2000-2001 [van Diggelen 2009, van Diggelen & Abraham 2001], while availability of these receivers started to emerge only around the end of 2005 [Global Locate 2005].

The indoors multipath situation is different than outdoors and this must be taken into account. Most of the algorithms we looked at were designed for outdoor usage. For this scenario it is generally assumed that the line of sight (LOS) signal is always present and no more than three secondary paths exist in the channel. Indoors this situation is rare. There are more signal reflections/ diffractions and distances between objects are also smaller. Thus there will be more secondary paths present in the channel. There can be situations where even no LOS signal and only secondary paths exist. For example, LOS signal arriving through a concrete wall will be attenuated by 12-43 dB [van Diggelen 2009], while a secondary path reflected from some object and arriving through the window will be attenuated by only 1-4 dB. Therefore, in our study we assume that:

- LOS signal is not always present
- There may be more than three secondary paths
- The secondary paths may be close to each other

Multipath Mitigation Algorithms

We looked at many already available algorithms which could be useful for mitigating multipath indoors. Our search included algorithms that prevent multipath to enter the receiver, by using special antenna designs, as well as algorithms dealing directly with receiver measurements such as pseudoranges and carrier phases, and finally techniques based on special tracking loops.

Special antenna designs (choke-ring, and multi-array antenna) are only useful for outdoor multipath mitigation, primarily because we need to have the LOS signal. An interesting technique suggests using two antennas where one is right hand circularly polarized (RHCP) and the other is left hand circularly polarized (LHCP) [Manandhar & Shibasaki 2004]. The RHCP antenna is needed if we want to receive the LOS signal, but if the signal is reflected once, its polarization changes and only LHCP antenna will be able to receive that signal. When the secondary path is received in conventional (RHCP) antenna, it is already reflected at least twice. It would be beneficial to use both antennas for indoor applications.

In the measurement domain it is difficult to do anything with multipath, because most of the information you need to extract is already lost. The most famous technique is probably the Receiver Autonomous Integrity Monitoring (RAIM) system. It cannot mitigate multipath, but it can prevent the user from using satellites whose LOS signal is not available and secondary paths may have too large delays to be useful for the position computation. This is also one of the methods used today in indoor GNSS receivers to fight multipath [van Diggelen 2009].

Table 2: Tracking Loop Based Multipath Mitigation Techniques

Narrow Correlator [Garin 2005, Sahmoudi & Amin 2006, Irsigler and Eissfeller 2003, Lohan et al. 2006]	**Early/Late Slope Technique (ELS) & Multipath Elimination Technique (MET)** [Irsiger & Eissfeller 2003, Chang & Juang 2008, Fenton & Jones 2005, Sahmoudi & Amin 2006]
Double Delta Correlator [Irsigler & Eissfeller 2003]	**Fast Iterative Maximum-Likelihood Algorithm (FIMLA)** [Sahmodi & Amin 2006]
Feedforward Delay Estimation [Lohan et al. 2006]	**Phase Multipath Mitigation Window (PMMW)** [Lohan et al. 2006]
Edge Correlator [Garin & Rousseau 1997, Sleewaegen & Boon 2001, Chang & Juang 2008]	**Multipath Mitigating Technique (MMT)** [Fenton & Jones 2005, Sahmodi & Amin 2006]
Pulse Aperture Correlator (PAC) [Fenton & Jones 2005, Hurskainen et al. 2008]	**Modified RAKE DLL (MRDLL)** [Sleewaegen & Boon 2001, Chang & Juang 2008, Lohan et al. 2006]
Enhanced Strobe Correlator [Garin & Rousseau 1997, Garin 2005]	**High Resolution Correlator (HRC)** [Sleewaegen & Boon 2001, Lohan et al. 2006, Hurskainen et al. 2008, Irsiger & Eissfeller 2003]
Space-Alternating Generalized Expectation Maximization (SAGE) [Antreich et al. 2005]	**Multipath Estimating Delay Lock Loop (MEDLL)** [Sleewaegen & Boon 2001, Chang & Juang 2008, Fenton & Jones 2005, Sahmodi & Amin 2006]
Double-Double Delta Correlator [Garin 2005]	**Code Correlation Reference Waveforms (CCRW)** [Garin 2005]
Adaptive Multipath Estimator [Chang & Juang 2008]	**Multiple Gate Delay (MGD)** [Hurskainen et al. 2008]
Early1-Early2 Tracker [Irsigler & Eissfeller 2003]	**A-Posteriori Multipath Estimation (APME)** [Sleewaegen & Boon 2001]
Shaping Correlator [Garin 2005]	**Vision Correlator (VC)** [Fenton & Jones 2005, Sahmodi & Amin 2006]
Wavelet Transformation [de Souza 2004]	**Deconvolution Approach** [Kumar & Ahmad 2004, Kumar & Lau 1996]
Multi-correlator technique [Chang & Juang 2008]	**Multipath Invariant Approach** [Kumar & Ahmad 2004]
Projection Onto Convex Sets (POCS) [Lohan et al. 2006, Kostic et al. 1992, Lohan et al. 2009]	**Strobe Correlator** [Garin & Rousseau 1997, Garin 2005, Sleewaegen & Boon 2001, Chang & Juang 2008]
Teager-Kaiser (TK) [Lohan et al. 2006]	**Frequency Domain** [Yang & Porter 2005a, Yang & Porter 2005b]

The tracking loop based techniques are the most popular and this is where we focus. We have looked at more than 30 state-of-the-art multipath mitigation algorithms (refer to Table 2) and concluded that most algorithms are developed more than five years ago and do not support indoor environments. As we have already mentioned most algorithms require that a LOS signal is present at all times and that there is up to three secondary paths in the channel. We found only a few algorithms which could deal with this situation indoors. The first algorithm we want to mention was proposed by Chun Yang et al. It transforms all the processing of the GNSS receiver from the time domain to the frequency domain [Yang & Porter 2005a, Yang & Porter 2005b]. For signal detection and delay estimation it uses the impulse response rather than the correlation function. The conclusion is that the presence of multipath components has no effects on the timing of the direct signal, because they are isolated in time. Each secondary path can be identified from the channel impulse response provided that the signal bandwidth and sampling frequency are high enough. This would yield an impulse response with sufficient resolution to distinguish closely spaced signal replicas.

Similarly to frequency domain techniques, deconvolution based techniques use impulse response estimation to separate all secondary paths in the channel. For many years deconvolution type algorithms were used in other fields where closely separated paths were of interest (ocean acoustics and processing of seismic signals). According to [Kostic et al. 1992] the main advantages of deconvolution based techniques are 1) very good resolution in multipath component separation, 2) exact estimation of multipath arrival times, and 3) accurate estimates of attenuation factors.

Multipath is dynamic indoors and the situation may change quickly depending on the environment. The new secondary paths may appear and the old ones disappear as the time goes on. The only thing which is not changing as quickly is the LOS signal. If we could find the LOS signal and to lock on it, then even when it is much weaker than the other paths in the channel we could use it for better time of arrival estimation.

In indoor applications there may be several secondary paths and they may be closely spaced in time. Using deconvolution based techniques we could extract each path. In this case we could select the first available path as our LOS signal regardless if it is the actual LOS or the first arrived secondary path. In many situations of indoor usage, the LOS may not be available and thus the first arrived secondary path would be the closest guess. Many conventional algorithms that work with correlator output may fail in these cases. The typical estimate using those techniques is to find the highest magnitude in correlator output or to look at the shape of it. This may lead to the larger estimation error than using deconvolution based techniques, because the first arrived path may not be the strongest one.

To know more about multipath indoors we selected deconvolution based techniques for the further study. We looked at two deconvolution based algorithms the Projection Onto Convex Sets (POCS) [Lohan et al. 2009] and the Deconvolution Approach (DA) [Kumar & Ahmad 2004, Kumar & Lau 1996].

2. POCS

We define the incoming signal

$$s(t) = \sum_{k=1}^{N} \alpha_k u(t - t_k) + n(t) \qquad (1)$$

where N is the number of paths, α_k is the path attenuation factors ($0 \le \alpha_k \le 1$), $u(t)$ is the original transmitted signal, t_k is the k-th path delay (or signal arrival time), and $n(t)$ is the additive noise usually assumed to be zero-mean white Gaussian..

Our model of the multipath channel and its relation to channel impulse response is

$$y(t) = \sum_{k=1}^{N} g(t - t_k) h_k + n(t) \qquad (2)$$

where $y(t)$ is the matched filter or correlator output, h_k is the channel impulse response, and $g(t)$ is the autocorrelation function of PRN code.

To estimate the channel impulse response we rewrite (2) as a vector-matrix equation

$$\mathbf{y} = \mathbf{G}\mathbf{h} + \mathbf{n} \qquad (3)$$

where $\mathbf{G}$ is the matrix where each row is the autocorrelation function $g(t)$ shifted by k steps for $k = 1{:}N$, $\mathbf{h}$ is a vector of length N.

We use the following equation to estimate the impulse response

$$\hat{\mathbf{h}} = (\hat{\sigma}^2 \mathbf{I} + \mathbf{G}^T \mathbf{G})^{-1} \mathbf{G}^T \mathbf{y} \qquad (4)$$

Here $\mathbf{I}$ is the identity matrix, $\hat{\sigma}^2$ is the estimated noise variance.

The typically solution is found by iteration.

$$\hat{\mathbf{h}}_{i+1} = \hat{\mathbf{h}}_i + \left(\hat{\sigma}^2 \mathbf{I} + \mathbf{G}^T \mathbf{G}\right)^{-1} \mathbf{G}^T (\mathbf{y} - \mathbf{G}\hat{\mathbf{h}}_i) \qquad (5)$$

where i is the iteration number and $\hat{\mathbf{h}}_0$ is initialized by taking appropriate values from $\mathbf{y}$, depending on the chosen area to investigate multipath. At the end the difference between $\mathbf{y}$ and $\mathbf{G\hat{h}}$ is minimized.

The estimation of multipath channel impulse response is a typical example of signal deconvolution, however the POCS algorithm goes further by estimating the multipath components in a channel by introducing constraints. Generally, the constraints are a priori information about the environment, signal properties or any other parameter which can help us to minimize the estimation error. The constraint is formed as a set with the condition that the actual estimate is a member of that set. The constraint set is projected onto the initial estimate to improve it. There can be many constraints projected to the estimate, but all constraint sets should form a new set, which is basically the intersection of all constraint sets and the actual estimate. Any member of this new set then can become a solution to the problem which will satisfy all defined constraints.

Some examples of constraints could be simpler such as the range of possible delays (e.g. we limit the results to be looked at only in a window around the position of estimate with the maximum magnitude), threshold for the minimum allowed estimate magnitude [Lohan et al. 2009], or there can be more complicated constraints such as a real-valued constraint [Kostic et al. 1992].

We show an example how to apply a constraint to limit the range of possible delays. If we call the constraint P_1, then we can write it like this:

$$P_1: \quad \hat{h}_m = \begin{cases} \hat{h}_m, & m \in [\tau - \tau_{max}, \ \tau + \tau_{max}] \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

where $\hat{h}_m$ is the m-th element of an estimate $\mathbf{\hat{h}}$, τ is the estimate position where it has maximum magnitude, and τ_{max} is the maximum distance from τ we want to limit our solution to.

Now we have to project the estimate to the constraint after each iteration:

$$\mathbf{\hat{h}}_{i+1} = P_1\{\mathbf{\hat{h}}_i\} \tag{7}$$

After this operation $\mathbf{\hat{h}}_{i+1}$ will be zeroed in all positions which fall outside of selected range.

A typical issue in GNSS is to estimate the LOS signal. In this case the solution would be to find the value in $\mathbf{\hat{h}}$ with the highest magnitude. Using POCS it is also possible to estimate the other paths, their attenuation factors and delays, but then the constraints have to be specified properly.

In Fig. 1 we demonstrate the difference between POCS without any constraints and with one delay range constraint as it was shown in (6) with $\tau_{max} = 0.25$ (chip).

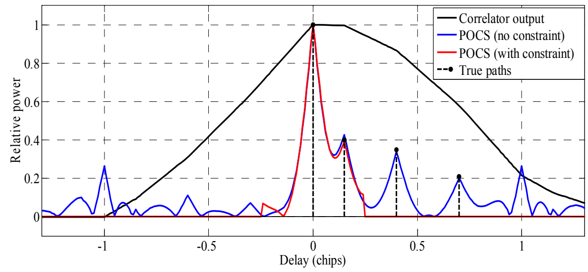

Figure 1: POCS output comparison with one constraint (delay range ±0.25 chip) and without

Furthermore, we look at the benefits by using POCS algorithm compared to a traditional matched filter approach. Fig 2. shows the situation where some signals are 180° phase-shifted and are causing destructive interference to the matched filter. POCS, however, is able to distinguish separate paths and estimate LOS signal.

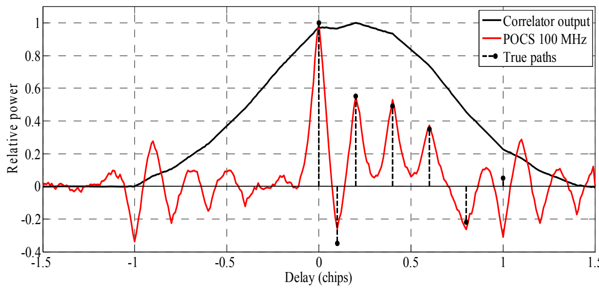

Figure 2: Destructive multipath (fading) does not influence POCS performance

In case of indoor multipath it was important to see if POCS can distinguish between closely spaced paths. One of the main parameters here is the signal sampling frequency Fig. 3 shows POCS output using different sampling frequency values. In this test we have a LOS signal and 10 secondary paths, each spaced 0.1 chip. This test shows that only with sampling frequency equal to or greater than 100 MHz, the LOS was successfully identified.

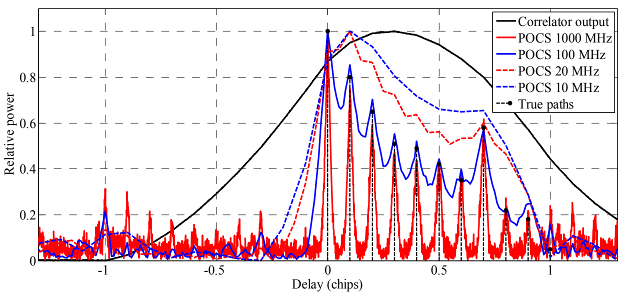

Figure 3: Sampling frequency influence

In Fig. 4 we try to show how far POCS can go by using 1.5 GHz sampling frequency and in this case we could distinguish between 2 paths which are only 0.025 chip away (corresponding to a distance of approximately 7 meters).

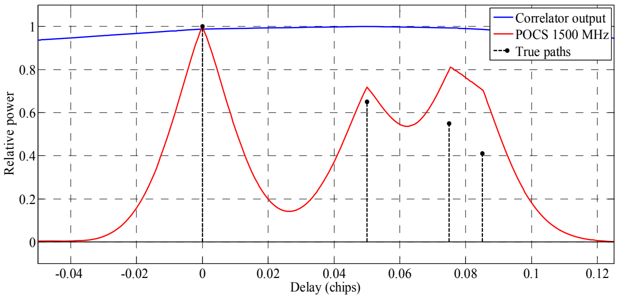

Figure 4: POCS test to see how far it can go in distinguishing separate paths

3. Deconvolution Approach

The underlying idea of Deconvolution Approach algorithm is similar to POCS, but the implementation differs. POCS algorithm is more universal and one may adjust it to suit different situations while the DA is defined with one purpose – to estimate LOS. For example, with POCS separate paths can be estimated by applying custom constraint sets.

In this paper we concentrate more on deconvolution itself rather than on specific algorithm, so here we will not show how the DA is implemented, but will show only the algorithm to see the difference from POCS algorithm. We have detailed the implementation of DA algorithm before in our previous papers [Dragūnas 2010, Dragūnas & Borre 2010]. Also refere to DA author papers [Kumar & Ahmad 2004, Kumar & Lau 1996, Kumar & Lau 1999].

Below is the algorithm for DA [Kumar & Lau 1999]:

1. Get measurements from correlation process
2. Compute multiple channel impulse responses in the area of interest
3. Find the best channel impulse response which matches the measurements
4. Compute deconvolution filter coefficients
5. Remove the multipath by convolving the measurements with deconvolution filter coefficients
6. Find the code and carrier phase estimates and correct it in the tracking loop to obtain new measurements
7. Repeat the process until the correct LOS estimate is found

4. Simulations

This section presents simulation results. We already presented the concept of how deconvolution based techniques work by using ideal signals with no noise. Now we are presenting more realistic simulation using GPS signals.

The POCS and the DA algorithms estimate the channel impulse response which is the main step for both algorithms. If channel impulse response is estimated uncorrectly we will not achieve good results. Our simulation shows channel impulse response estimation using different signal parameters.

The performance uses GPS L1 signal with wideband precorrelation bandwidth (20.46 MHz) and all signals are sampled at 100 MHz. All tests use three paths: one direct path (LOS) and two secondary paths. Secondary paths are delayed by 0.4 and 0.8 chip and have power ratio of 0.7 and 0.4 as compared to the direct path. The results shown in Figures 5-8 were acquired using uncoherently integrating matched filter output for 12 ms.

We present three different signals in three test cases. The details are shown in Table 3.

Table 3: Simulation cases

Case 1 – perfect conditions outdoors	
Signal strength	-150 dBW (-120 dBm, ~54 dB-Hz)
SNR	34.8 dB
Case 2 – typical conditions outdoors	
Signal strength	-160 dBW (-130 dBm, ~44 dB-Hz)
SNR	30.9 dB
Case 3 – light indoors	
Signal strength	-170 dBW (-140 dBm, ~34 dB-Hz)
SNR	16.0 dB

The Case 1 scenario is shown in Fig. 5. This case represents an ideal situation which one can obtain outdoors. Fig. 5 demonstrates that the channel impulse response is close to the ideal one.

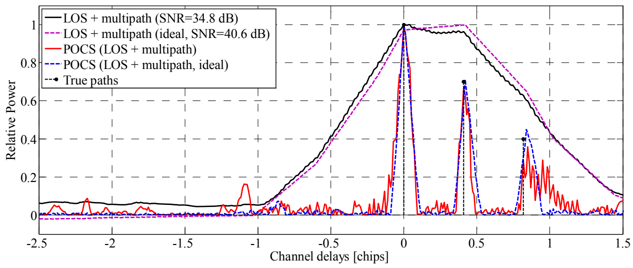

Figure 5: Case 1 – perfect conditions outdoors

The Case 2 scenario is shown in Fig. 6. This case represents a typical realistic situation outdoors. The situation is worse than previous case with a few additional peaks which should not be there, but the LOS can still be estimated without any problem.

The Case 3 scenario is shown in Fig. 7. This case represents a situation typically obtainable in light indoor conditions. The situation is much worse than in the two previous cases. There are plenty of additional peaks which have significantly large magnitude and can be misdetected as actual paths. The LOS signal is also deformed and if one would search for the peak with maximum magnitude, one would find a wrong one. Looking at more tests with similar SNR shows that even more inconsistency in detecting the actual paths in the channel.

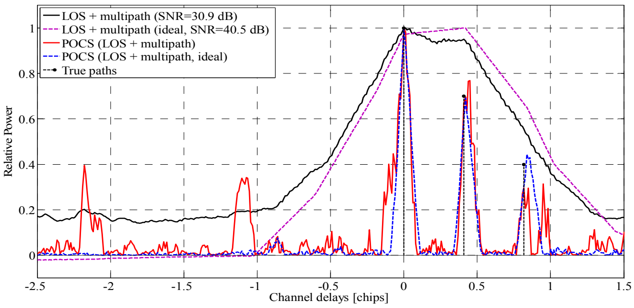

Figure 6: Case 2 – typical conditions outdoors

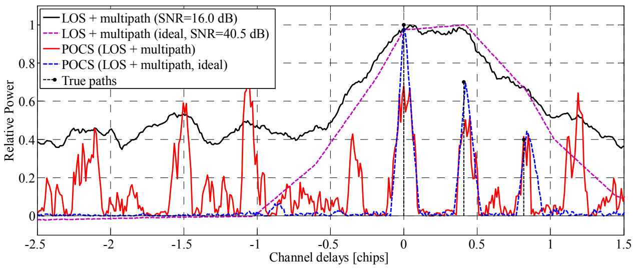

Figure 7: Case 3 – light indoors

However, if we know an approximate LOS estimate and apply constraints (e.g. range constraint in this case) we can get a rather good LOS estimate as it is shown in Fig. 8.

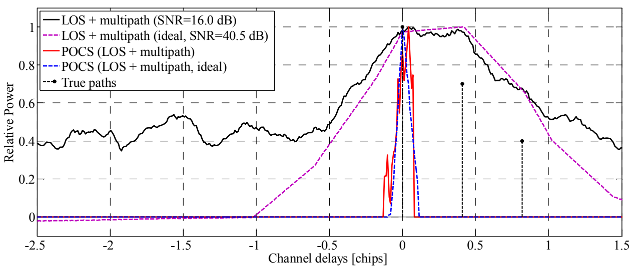

Figure 8: Case 3 – light indoors, with constraints

5. Tests with real world data

In order to verify simulation results we looked for a possibility to record real world data. We had access to two low-end front-ends:

- NordNav-R25 software GNSS receiver with L1 front-end
- SiGe GN3S Sampler

Both front-ends have 2 MHz bandwidth and up to 16 MHz sampling frequency. In the previous test under ideal conditions we showed that POCS capabilities strongly depend on sampling frequency (refer to Fig. 3). Our previous simulations also relied on unlimited bandwidth, so before doing any real world tests we have to run a simulation to see what we can expect from our front-ends. In this simulation we used the same parameters as in our previous Case 3 simulation, just instead of 100 MHz sampling frequency we use 16 MHz, and instead of unlimited bandwidth we use 2 MHz prefiltering. The results are shown in Fig. 9 where we compare two signals. One is ideal signal with no noise and unlimited bandwidth (blue and magenta lines) while the other signal is showing what we would expect to get using our front-ends. Both signals are simulated using the same sampling frequency.

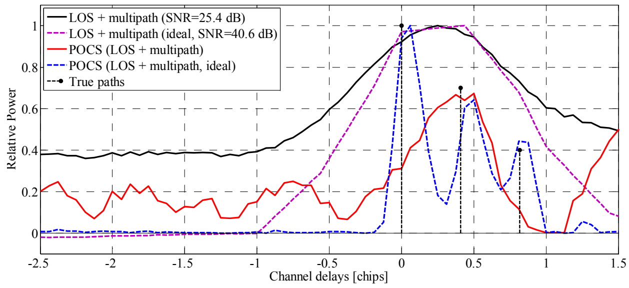

Figure 9: Low-end front-end expected results simulation

The results are not good. POCS could not find the LOS signal correctly, nor separate any of the two secondary paths. Even though the ideal example shows that sampling frequency is not an issue in this case, but bandwidth limitation is. By prefiltering the signal we have got a smoothed matched filter output and also delayed the signal. POCS depends on the shape of correlator output and thus it had a hard time trying to estimate impulse response under these conditions.

Because of these poor results we decided to perform real world tests using a front-end with wider bandwidth. The one we found was made by Jordi Marin Garcia et al. at Universitat Autònoma de Barcelona (UAB) as a student project [García et al. 2009]. The receiver specifications are given in Table 4.

Table 4: UAB front-end specifications

Bands	E1/L1 and E5/L5
Sampling frequency	Up to 500 MHz
Intermediate frequency	~192 MHz
Bandwidth	~51 MHz E5 ~32 MHz E1

To see what we can expect from this front-end we have run the same simulation again (Case 3 – light indoors). This time we used unfiltered signal with 500 MHz sampling frequency. The results are shown in Fig. 10.

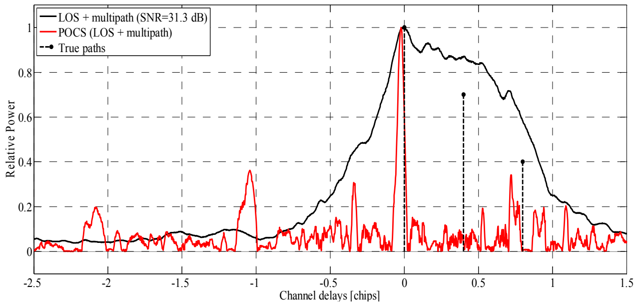

Figure 10: UAB front-end expected results simulation

The results were better. The POCS have found the LOS signal, but it had problems finding the secondary paths. So far we have not found the reason and will need to do more simulations in the future.

The data collection with UAB front-end was done by the students who made it [García et al 2009] and we got their data only after actual process. We could not alter data collection process so we used the data as is.

The front-end is shown in Fig. 11. During data collection it was connected to the antenna which was placed approximately 1 meter outside the window on the third floor. The test environment is shown in Fig. 12.

This test shows POCS performance on 2 signals. One signal is from satellite PRN 11 and the other one is from satellite PRN 20. These satellites were chosen, because satellite PRN 11 has a direct view, while the PRN 20 doesn't, see Fig. 12. Satellite PRN 20 is blocked by the building and the signal is significantly weaker than that one from satellite PRN 11. The results are shown in Fig. 13 (PRN 11) and Fig. 14 (PRN 20). As with simulation examples we use 12 ms incoherent integration.

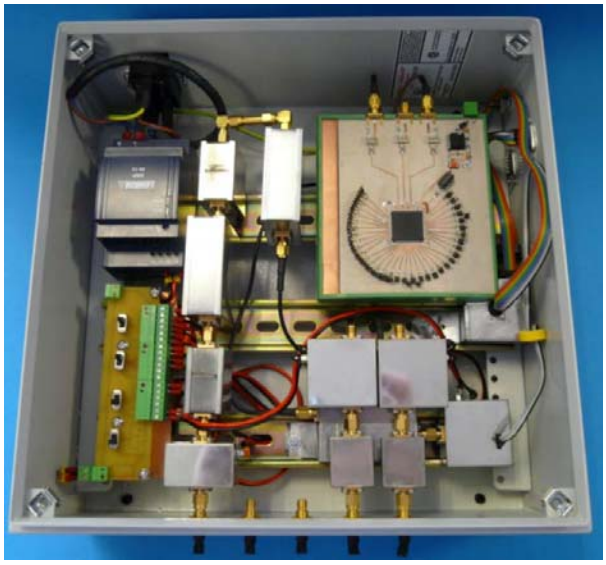

Figure 11: UAB front-end [García et al. 2009]

Figure 12: UAB test location

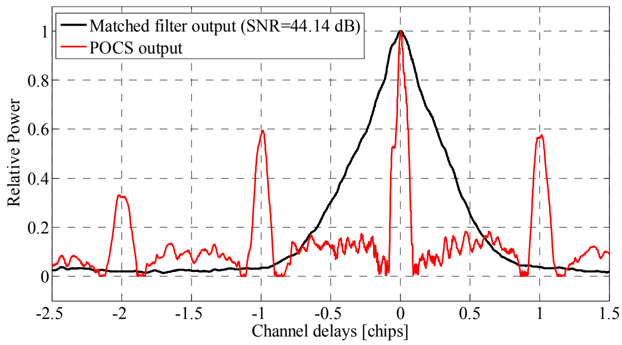

Figure 13: PRN 11 – LOS signal

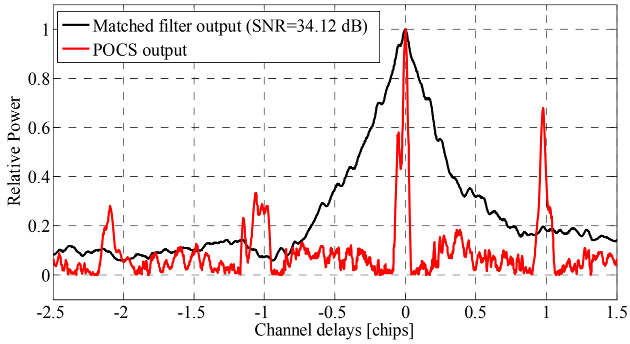

Figure 14: PRN 20 – obstructed signal

We expected to see some reflected signals from the walls and other nearby objects, but POCS have not found any signals, which would show any obvious signs of multipath being present. From satellite PRN 20 matched filter output we can see a slight curve deformation at the right side of the peak which starts at approximately 0.5 chip, but POCS failed to detect any secondary paths like in the simulation case.

We show one more figure where we simulated how UAB front-end would work if there were no multipath present. The simulation used the same conditions as in the previous simulation shown in Fig. 10. The results are shown in Fig. 15.

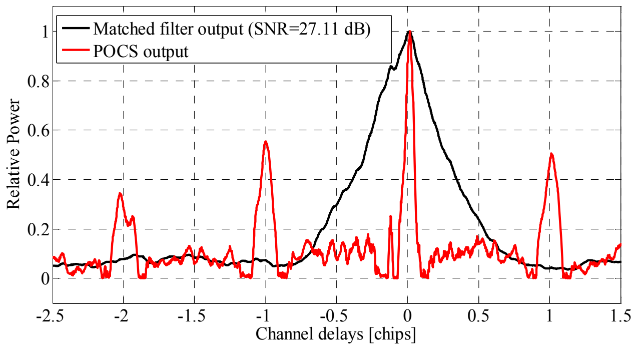

Figure 15: PRN 20 – obstructed signal

6. Conclusions and Future Work

We demonstrated two deconvolution based techniques which may provide a better way to fight multipath than was possible using conventional techniques. Our simulations also demonstrated that deconvolution based techniques have a potential to distinguish some of the secondary paths, even if they are close to each other. For real world data this feature was not functioning as expected, and we will have to work more to understand why.

For deconvolution based algorithms to work well it is neccessary that they satisfy some conditions. In our simulations we saw that simple front-end with narrow bandwidth is not suitable for such application. It is also important to use the highest possible sampling frequency to achieve better resolution in secondary path separation. However, we have experienced many situations where higher samling frequency does not help to achieve better results. This only works well under ideal conditions which we do not have in the real world.

Tests with simulated and real world data showed that deconvolution based techniques work well in outdoor conditions. Even though there were no secondary paths detected in real world test within a weak signal, the LOS signal was detected corectly in all signals we tested.

For indoor environments we have similar problems as using conventional techniques. In order to achieve something we need to have strong enough signal. Deconvolution based techniques strongly depend on the quality of matched filter output and to achieve that we need to use wide bandwidth (to avoid smoothing) and get good SNR. In many cases to achieve good SNR indoors the task is more chalanging than mitigating multipath. In our tests we integrate matched filter output for a few milliseconds to achieve better SNR values, but in real conditions this may not be enough.

Further, our future work will concentrate on deconvolution based techniques. We are also interested in testing deconvolution algorithms with real world signals obtainable indoors and to have controled setup test where we know more about what to expect from the data. Finally we want to test deconvolution based techniques on Galileo signals and compare to GPS results.

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References

Antreich F., Esbri-Rodriguez O., Nossek J. A., and Utschick W. (2005), ***Estimation of Synchronization Parameters Using SAGE in a GNSS Receiver***, in Proceedings of the 18th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2005), Long Beach, CA, pp. 2124–2131.

Chang C. and Juang J. (2008), ***An Adaptive Multipath Mitigation Filter for GNSS Applications***, EURASIP Journal on Advances in Signal Processing, p. 10.

de Souza E. M. (2004), ***Multipath Reduction from GPS Double Differences using Wavelets: How far can we go?*** in Proceedings of the 17th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2004), Long Beach, CA, pp. 2563–2571.

Dragūnas K. (2010), ***Indoor Multipath Mitigation***, Indoor Positioning and Indoor Navigation (IPIN) 2010, pp.1-7, doi: 10.1109/IPIN.2010.5647613

Dragūnas K., Borre K. (2010), ***Indoor Multipath Mitigation***, Ubiquitous Positioning Indoor Navigation and Location Based Service (UPINLBS) 2010, pp.1-8, doi: 10.1109/UPINLBS.2010.5653939.

Fenton P. C. and Jones J. (2005), ***The Theory and Performance of NovAtel Inc.'s Vision Correlator***, in Proceedings of the 18th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2005), Long Beach, CA, pp. 2178–2186.

García J. M. et al. (2009), ***Diseño e implementación de un receptor GNSS multifrecuencia y multiconstelación***, Universitat Autònoma de Barcelona.

Garin L. and Rousseau J. (1997), ***Enhanced Strobe Correlator Multipath Rejection for Code & Carrier***, in Proceedings of the 10th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 1997), Sunnyvale, CA, pp. 559–568.

Garin L. J. (2005), ***The "Shaping Correlator", Novel Multipath Mitigation Technique Applicable to Galileo BOC(1,1) Modulation Waveforms in High Volume Markets***, in The European Navigation Conference – GNSS 2005. University of Calgary / SiRF Technology, Inc.

Global Locate (2005), ***Global Locate A-GPS Technology on Board HP iPAQ hw6500 Mobile Messenger***, http://www.marketwire.com/press-release/Global-Locate-A-GPS-Technology-on-Board-HP-iPAQ-hw6500-Mobile-Messenger-670159.htm.

Hurskainen H., E. Lohan S., Hu X., Raasakka J., and Nurmi J. (2008), ***Multiple Gate Delay Tracking Structures for GNSS Signals and Their Evaluation with Simulink, SystemC, and VHDL***, International Journal of Navigation and Observation, vol. 2008, p. 17.

Irsigler M. and Eissfeller B. (2003), ***Comparison of Multipath Mitigation Techniques with Consideration of Future Signal Structures***, in Proceedings of the 16th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS/GNSS 2003), Portland, pp. 2584–2592.

Kostic Z., Sezan M., and Titlebaum E. (1992), ***Estimation of the parameters of a multipath channel using set-theoretic deconvolution***, IEEE Transactions on Communications, vol. 40, pp. 1006-1011.

Kumar R. and Ahmad M. M. (2004), ***Comparison of Multipath Error Elimination Techniques under Relatively Severe Multipath Environments***, ION GNSS 17th International Technical Meeting of the Satellite Division, Long Beach, CA.

Kumar R. and Lau K. (1996), ***Deconvolution Approach to Carrier and Code Multipath Error Elimination in High Precision GPS***, Proceedings of the 1996 National Technical Meeting of The Institute of Navigation, Santa Monica, CA, pp. 729-737.

Kumar R. and Lau K. (1999), ***Method and apparatus for reducing multipath signal error using deconvolution***, U.S. Patent 5,919,161, June 29.

Lohan E. S., Lakhzouri A., and Renfors M. (2006), ***Feedforward Delay Estimators in Adverse Multipath Propagation for Galileo and Modernized GPS Signals***, in EURASIP Journal on Applied Signal Processing, vol. 2006, Finland, Tampere, pp. 1–19.

Lohan S., Skournetou D., and Sayed A. H. (2009), ***A deconvolution algorithm for estimating jointly the Line-Of-Sight code delay and carrier phase of GNSS signals***, ENC-GNSS, Naples, Italy.

Manandhar D. and Shibasaki R. (2004), ***Possibility Analysis of Polarization Diversity Scheme for Multipath Mitigation in GPS Receivers***, GNSS Sydney 2004, Sydney, Australia.

Mautz R. (2009), ***The challenges of indoor environments and specification on some alternative positioning systems***, 2009 6th Workshop on Positioning, Navigation and Communication, Hannover, Germany, pp. 29-36.

Monnerat M. (2008), ***AGNSS Standardization. The Path to Success in Location-Based Services***, Inside GNSS, pp. 22-23.

Sahmoudi M. and Amin M. (2006), ***Fast Iterative Maximum-Likelihood Algorithm (FIMLA) for Multipath Mitigation in Next Generation of GNSS Receivers***, in ACSSC '06. IEEE, pp. 579–584.

Seco-Granados G., Jiménez-Baños D., López-Risueño G., Blanco-Delgado N., and Garcia-Rodríguez A. (2006), ***Innovative Techniques for GPS Indoor Positioning Using a Snapshot Receiver***, Proceedings of the 19th International Technical Meeting of the Satellite Division of The Institute of Navigation, Fort Worth, TX.

Sleewaegen J. M. and Boon F. (2001), ***Mitigating Short-Delay Multipath: a Promising New Technique***, in Proceedings of the 14th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 2001), Salt Lake City, UT, pp. 204–213.

van Diggelen F. (2009), ***A-GPS: Assisted GPS, GNSS, and SBAS***, Artech House.

van Diggelen F. and Abraham C. (2001), ***Indoor GPS technology***, CTIA Wireless-Agenda, Dallas.

Yang C. and Porter A. (2005a), ***Frequency-Domain Characterization of GPS Multipath for Estimation and Mitigation***, ION GNSS 18th International Technical Meeting of the Satellite Division, Long Beach, California.

Yang D. C. and Porter L. A. (2005b), ***Multipath-Desensitized Delay Estimation with GPS Signal Channel Transfer Function Filtering***, ION 61st Anual Meeting, Cambridge, MA.

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