# Multipath Mitigation Techniques Suitable For Low Cost GNSS Receivers

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## ABSTRACT

Today, Global Navigation Satellite Systems (GNSS) have become available to civilian population. Because of that, the market of low cost GNSS receivers is very active.

There are several limitations to the use of GNSS receivers: signal delays in the ionosphere, receiver's clock bias, multipath, etc. Nevertheless, the effect of multipath is very significant, specially in urban environments, where there are many and large building surfaces that can reflect GNSS signals. So, it is required low cost receivers that are capable to mitigate the multipath effect in difficult situations, like urban navigation. Thereby, it is necessary to find multipath mitigation techniques, suitable for use in low cost GNSS receivers.

In the search for techniques capable of meeting those requirements, several techniques were found: the Narrow Correlator, the High Resolution Correlator (HRC), several Code Correlation Reference Waveforms (CCRWs) and a Teager Kaiser operator based technique. The different techniques were initially analysed using the multipath error envelopes and the steady-state noise. For more representative results, it was developed a GNSS receiver simulator, using *Simulink* and *GRANADA FCM Blockset*.

From the tested techniques, it is one of the CCRWs that is considered the more suitable for implementation in low cost receiver.

## INTRODUCTION

Global Navigation Satellite System (GNSS) is defined as satellite navigation systems (SNS) capable of providing position, speed and time (PVT) with global coverage. The original motivations behind GNSS were military applications (e.g. precise location of forces on the field, weaponry guidance, etc.). However, today, GNSS cover a wider range of applications, like transportation systems, agriculture and fisheries, several sciences or leisure applications.

Currently, the location of persons and vehicles has become more and more important and a large number of GNSS receivers were made available for that purpose. However, GNSS application in urban scenarios is limited by low satellites' visibility, signal interference and multipath. In fact, today, multipath is one of the dominant error sources in GNSS applications [1]. Thereby, it is necessary to search for suitable techniques capable of mitigating the multipath effect.

### Research Objectives

This thesis investigates the multipath mitigation techniques for urban scenarios, which are suitable for low cost GNSS receivers. Specifically, the main objectives are to study the GNSS principles, some navigation signals available for civilian use, typical GNSS receiver architecture and the effect of multipath; to investigate different multipath mitigation techniques: special attention will be given to the correlation based techniques; to evaluate several multipath mitigation techniques: this analysis will be done comparing simulation results obtaining for several multipath scenarios; to identify the multipath mitigation techniques suitable for low cost GNSS receivers.

## BASIC CONCEPTS

### Principles Of GNSS

The primary goal of a GNSS receiver is the determination of Position, Velocity and Time (PVT). The basic principle behind the determination of position and velocity is trilateration. The receiver needs to solve the so called Navigation Equation for, at least four satellites:

$$\rho_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} - b \quad (1)$$

where $\rho_i$ is the pseudorange between the receiver and the $i$th satellite, $[x \quad y \quad z]$ is the receiver position, $[x_i \quad y_i \quad z_i]$ is the $i$th satellite position and $b$ depends on the user receiver clock bias.

The receiver measurements are called pseudorange because they include the clock offset. The pseudorange, $\rho$, between the receiver and a satellite is directly proportional to the signal propagation time:

$$\rho = c.\Delta t - b, \quad (2)$$

where $c$ is the speed of light and $\Delta t = t_{t_x} - t_{r_x}$ is the propagation time defined by the difference between the time of transmission and the time of reception. The range measured by the receiver is affected by several error sources: receiver's clock errors, ionosphere delays, multipath,etc. [2].

## Signals

A navigation signal, $s(t)$, can be given as

$$s(t) = A(t)D(t)C(t)x(t)\cos(\omega t + \theta_0), \quad (3)$$

where $A(t)$ is the signal amplitude, $D(t)$ is the navigation message, $C(t)$ is the spreading code, $x(t)$ is the sub-carrier, $\cos(\omega t + \theta_0)$ is the carrier, a Radio Frequency (RF) sinusoidal with a known frequency $\omega$ and initial carrier phase $\theta_0$.

The spreading code of a signals is a unique Pseudo Random Noise (PRN) assigned to one only satellite. It is named spreading code because of the wider bandwidth occupied by the signal after modulation by the high-rate PRN waveform [3]. There are several modulations, however here it will be covered only three types:

- Binary Offset Carrier (BOC) - the (sine-shaped) BOC(m,n) modulation consists of multiplying the spreading code waveform, $C(t)$, by the square-wave subcarrier, $B(t) = sign[\sin(2\pi f_s t)]$ to obtain $X_{BOC}(t) = B(t)C(t)$. The chip rate and the subcarrier frequency are given, respectively, by $f_c = 1/T_c = nf_g$ and $f_s = mf_g$, where $m$ and $n$ are two positive integers and $f_g = 1.023\,\text{MHz}$ [4].
- Binary Phase Shift Keying (BPSK) - similar to BOC but the subcarrier is always $B(t) = 0$ [3].
- Multiplexed Binary Offset Carrier (MBOC) - a MBOC signal results from adding or multiplexing BOC signals. For instance, MBOC(6,1,1/11) is the result of a wideband BOC(6,1) signal multiplexed with a narrow-band BOC(1,1) signal, with 1/11 of the signal power allocated on the BOC(6,1) component [5]. Complex BOC and Time Multiplexed BOC are examples of MBOC modulations.

Fig. 1 shows the auto-correlation function for BPSK, BOC(1,1) and CBOC(6,1,1/11).

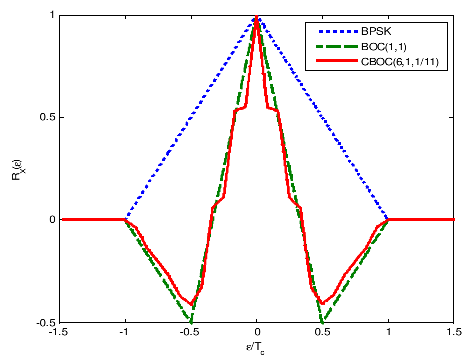


Fig. 1. Auto-correlation functions for unfiltered BPSK, BOC(1,1) and CBOC(6,1,1/11) signals.

## RECEIVER

The basic functions of a GNSS receiver are to capture RF signals transmitted by the satellites spread out in the sky, to separate the signals from satellites in view, to perform measurements of signal transit time and Doppler shift, to decode the navigation message in order to determine the satellite position, velocity, and clock parameters, and to estimate the user position, velocity, and time.

### Baseband Signal Processing

For better analysing the code delay and carrier tracking loops, it is useful to describe a GNSS receiver with the equivalent baseband receiver as sketched in Fig. 2 [6].

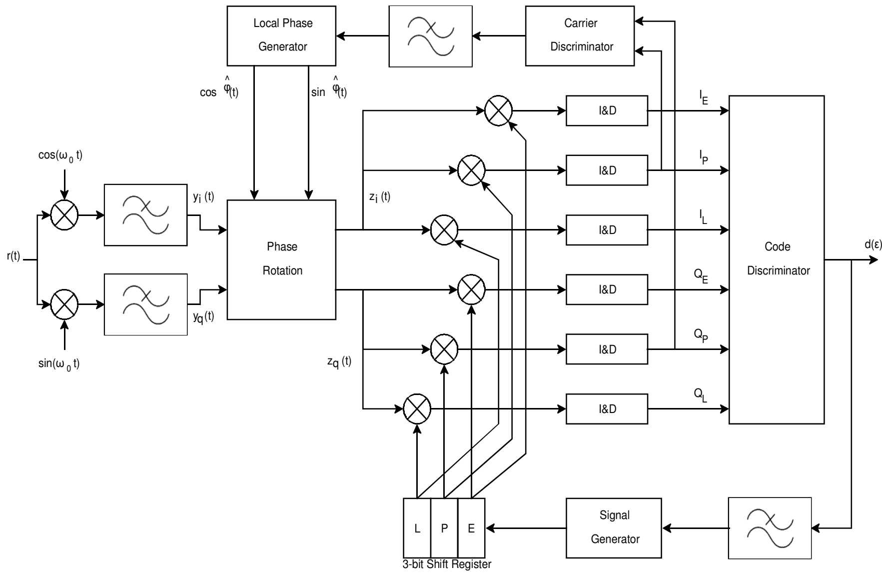


Fig. 2. Typical diagram of the receiver code and carrier loops.

It is assumed that the received signal is given by $r(t) = s(t) + n(t)$, where $n(t)$ is Gaussian noise and $s(t)$ is the navigation signal given by

$$s(t) = A\tilde{X}(t)D(t)\cos[(\omega_0 + \omega_d)t + \theta_0], \tag{4}$$

where $A$ depends on the power $s(t)$, $\tilde{X}(t)$ is the filtered spread sequence, $D(t)$ is the navigation data, $\omega_0$ is the nominal carrier frequency, $\omega_d$ is an offset frequency due to the Doppler effect and oscillators misalignments and $\theta_0$ is the initial phase. The filtered spread sequence can be defined as $\tilde{X}(t) = X(t) * h(t)$, where $h(t)$ is the impulse response of the receiver's input filter. Considering a raised-cosine filter with bandwidth $B_W$ and roll-off factor $0 \le \xi \le 1$, the impulse response is [7]:

$$h(t) = \text{sinc}(2B_W t)\left[\frac{\cos(2\pi\xi B_W t)}{1 - 16\xi^2 B_W^2 t^2}\right] \tag{5}$$

The in-phase and quadrature components of the received signal are given by

$$\begin{bmatrix} y_i(t) \\ y_q(t) \end{bmatrix} = A\tilde{X}(t)D(t)\begin{bmatrix} \cos\varphi(t) \\ \sin\varphi(t) \end{bmatrix} + \begin{bmatrix} n_i(t) \\ n_q(t) \end{bmatrix}, \tag{6}$$

with $\varphi(t) = \omega_d t + \theta_0$ and where $n_i(t)$ and $n_q(t)$ are the in-phase and quadrature noise components. The signals $z_i(t)$ and $z_q(t)$ results from rotating $[y_i(t) \quad y_q(t)]^T$ by the phase estimate $\hat{\varphi}(t)$ provided by the Phase-Lock Loop (PLL):

$$\begin{bmatrix} z_i(t) \\ z_q(t) \end{bmatrix} = \begin{bmatrix} \cos\hat{\varphi}(t) & \sin\hat{\varphi}(t) \\ \sin\hat{\varphi}(t) & \cos\hat{\varphi}(t) \end{bmatrix} \begin{bmatrix} y_i(t) \\ y_q(t) \end{bmatrix}. \tag{7}$$

Assuming that the phase error in the integration interval $[0,T]$ may be written as $\varphi_e(t) \equiv \varphi(t) - \hat{\varphi}(t) = \omega_e t + \theta_e$, where $\omega_e = 2\pi f_e$ is the frequency error and $\theta_e$ is the initial phase error, leads to

$$\begin{bmatrix} z_i(t) \\ z_q(t) \end{bmatrix} = A\tilde{X}(t)D(t) \begin{bmatrix} \cos\varphi_e(t) \\ \sin\varphi_e(t) \end{bmatrix} + \begin{bmatrix} n_i'(t) \\ n_q'(t) \end{bmatrix}, \tag{8}$$

where $D(t)$ is the navigation data in the integration, and $n_i'(t)$ and $n_q'(t)$ are the noise components after phase rotation.

The components $z_i(t)$ and $z_q(t)$ are then multiplied by Early (E) and Late (L) version of the locally generated $X(t)$, respectively $X(t+\Delta/2)$ and $X(1-\Delta/2)$, where $\Delta$ is the E-L spacing (with $\Delta \le T_c$). By integrating in the interval $[0,T]$, leads to

$$I_E(\varepsilon) = \frac{1}{T}\int_0^T z_i(t) X(t-\varepsilon+\Delta/2)dt = ADR_{\tilde{X}X}\left(\varepsilon - \frac{\Delta}{2}\right)\text{sinc}(f_e T)\cos(\pi f_e T + \theta_e) + N_{i,E} \tag{9}$$

where the cross-correlation function between $X(t)$ and $\tilde{X}(t)$ can be defined as $R_{\tilde{X}X}(\varepsilon) = \int_0^T X(\varepsilon)X(t-\varepsilon)dt = R_X(\varepsilon) * h(\varepsilon)$, $\Delta$ is the early-late spacing, and $N_{i,E}$ is the noise component.

The output of the Code Discriminator block depends on the selected discriminator. Three common discriminators are: non-coherent dot-product, $d(\varepsilon) = [I_E(\varepsilon) - I_L(\varepsilon)]I_P(\varepsilon) + [Q_E(\varepsilon) - Q_L(\varepsilon)]Q_P(\varepsilon)$, non-coherent Early-minus-Late Power, $d(\varepsilon) = [I_E^2(\varepsilon) - I_L^2(\varepsilon)] + [Q_E^2(\varepsilon) - Q_L^2(\varepsilon)]$, Early-minus-Late coherent, $d(\varepsilon) = I_E(\varepsilon) - I_L(\varepsilon)$. The three code discriminator functions are plotted in Fig. 3. These three functions, as all the discriminator functions, present a zero crossing for a tracking error $\varepsilon = 0$ and a linear or near linear behaviour in the neighbour region, where the code discriminator output will be proportional to the code tracking error. Thereby the output of the code discriminator is used as a estimation of the code tracking error to feed back the signal generated (see Fig. 2). In this way, the receiver can keep the locally generated signal synchronized with the received signal.

The output of the Carrier Discriminator depends on the carrier discriminator function. One example is the arc tangent discriminator, that is insensitive to the phase transition of the navigation data bit transitions [3]:

$$d_{PLL}(\varphi_e) = \arctan\left(\frac{I_P(\varphi_e)}{Q_P(\varphi_e)}\right) \tag{10}$$

The discriminator for the carrier loop is showed in Fig. 3, and, similar to the code discriminator, it is used to give a phase tracking error estimate to feed back the Local Phase Generator.

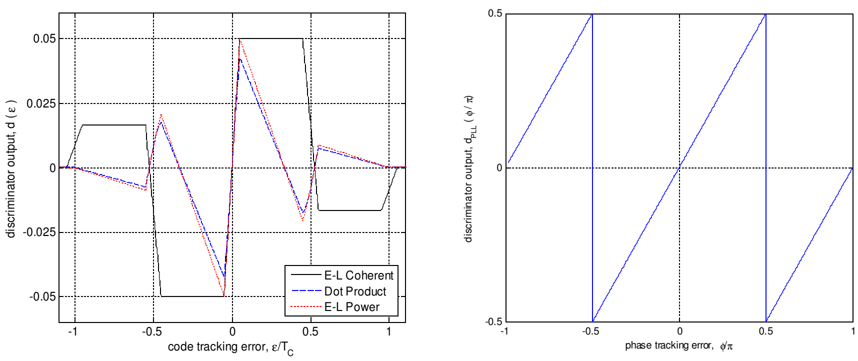


Fig. 3. Code discriminator outputs for BOC(1,1) with unlimited pre-correlation bandwidth (right). Carrier discriminator output for the arc tangent discriminator (left).

## MULTIPATH EFFECT

Multipath is defined as the propagation of a wave from one point to another by more than one path. By that means, the received signal will be the result of the sum of a first path plus one or several reflected echoes. Fig. 4 shows a possible multipath situation, where three rays reach the receiver: line of sight (LOS) ray, a ray reflected on a building and another ray reflected on the ground.

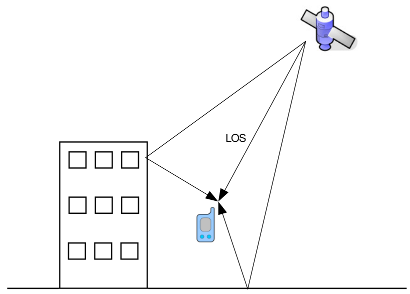


Fig. 4. Possible multipath situation.

The effects of multipath in the receiver tracking loops will depend on: the amplitudes of the reflected signals relative to the LOS; the delays of the reflected signals relative to the LOS; the phases of the reflected signals relative to the LOS; the rate of change of the relative phases; and the number of echoes.

In the presence of multipath, the correlator outputs can be viewed as a superposition of shifted and distorted versions of undisturbed output. As the output of the correlators is distorted in the presence of multipath, the zero-crossing of the discriminator function will be shifted from the correct position. This leads to an error in the code delay measurement between the received signal code and the local generated code.

## MULTIPATH MITIGATION

Several techniques have been studied in the past to mitigate the multipath tracking error. These different techniques can be classified into three main categories:

1) Pre-processing techniques: These techniques are applied before the satellite signals enters the receiver's processing chain. In this category it is possible to find the Choke-Ring antenna [8] and methods that assume repeatability of the multipath from one day to another.
2) Receiver signal processing techniques: Signal processing techniques occur within the code and frequency tracking loops. Examples are the Narrow Correlator [9], Code Correlation Reference Waveforms [10], Kalman Filtering, Multipath Estimating DLL, Pulse Subtraction, Least Squares, Subspace-based algorithms and Quadratic Optimization Methods [11].
3) Post-processing techniques: Post-processing techniques are applied after the pseudo-range measurements have been produced, like Receiver Autonomous Integrity Monitoring.

However, not all the mitigation techniques are suitable for implementation in low cost GNSS receivers. Low cost receivers can not afford to use high performance processor and expensive hardware. These receivers have limited computational capabilities. Thereby, the techniques suitable for such type of receiver must minimize the computing load. In this category, it can be found: the Narrow Correlator, the CCRWs and the Teager-Kaiser operator.

### Narrow Correlator

The structure of the Narrow Correlator's receiver is sketched in Fig. 2. Historically, the first generation of GPS receivers used large E-L spacings (e.g. $\Delta = 1T_c$ ). The main concept behind the Narrow Correlator is narrowing the E-L correlator spacing. This has the advantage of reducing the tracking errors in the presence of both noise and multipath [9]. In this work was considered the Narrow Early-Late Power (NELP) discriminator given by:

$$d(\varepsilon)=\left[I_E^2(\varepsilon)-I_L^2(\varepsilon)\right]+\left[Q_E^2(\varepsilon)-Q_L^2(\varepsilon)\right]. \quad (11)$$

**High Resolution Correlator**

The High Resolution Correlator (HRC) was introduced in [12] for BPSK signals. The HRC uses multiple correlator outputs, from a conventional GNSS receiver (Fig. 2), to yield an approximation to W1 Code Correlation Reference Waveform. The structure of the HRC receiver is similar to the one illustrated in Fig. 2, but with the difference that the HRC receiver requires eight correlators: Very-Early-in-phase $I_{VE}$, Early-in-phase $I_E$, Late-in-phase $I_L$, Very-Late-in-phase $I_{VL}$, Very-Early-quadrature $Q_{VE}$, Early-quadrature $Q_E$, Late-quadrature $Q_L$, Very-Late-quadrature $Q_{VL}$. The response of the HRC discriminator is given by

$$d(\lambda,\varepsilon)=\lambda\left[(I_E-I_L)+(Q_E-Q_L)\right]-\left[(I_{VE}-I_{VL})+(Q_{VE}-Q_{VL})\right]. \quad (12)$$

**Code Correlation Reference Waveform**

The concept of Code Correlation Reference Waveform (CCRW) was presented in [10] to describe different code correlation techniques used by some major GPS receiver manufacturers. These techniques had in common the fact that, they were specially designed to mitigate multipath, and instead of using a replica of the navigation signal, use a reference waveform, the CCRW. The receiver's performance will be strongly dependent of the selected CCRW. In the past several CCRW have been studied, as a way to improve the code tracking performance [10]. The CCRW studied and plotted in Fig. 5 can be partitioned in two sub-categories: transition-based, if a CCRW pulse appears only when a signal value transition occurs; or per-chip, if a CCRW pulse occurs for every chip code.

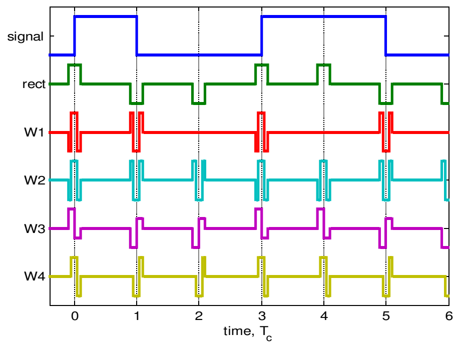


Fig. 5. CCRW waveforms for a BPSK signal.

The code discriminator considered for CCRW is given by

$$d(\varepsilon)=I_P(\varepsilon)I_W(\varepsilon)+Q_P(\varepsilon)Q_W(\varepsilon) \quad (13)$$

and the output of the correlators is given by

$$\begin{aligned} I_W(\varepsilon)&=AD\text{sinc}(f_eT)\left\{R_{\tilde{X}W}(\varepsilon)\cos(\pi f_eT+\theta_e)+\alpha R_{\tilde{X}W}(\varepsilon-\tau)\cos(\pi f_eT+\theta_e+\phi)\right\}+N_{i,W}\\ Q_W(\varepsilon)&=AD\text{sinc}(f_eT)\left\{R_{\tilde{X}W}(\varepsilon)\sin(\pi f_eT+\theta_e)+\alpha R_{\tilde{X}W}(\varepsilon-\tau)\sin(\pi f_eT+\theta_e+\phi)\right\}+N_{q,W}\end{aligned} \quad (14)$$

with $R_{\tilde{X}W}(\varepsilon)=R_{XW}(\varepsilon)*h(\varepsilon)$, where $R_{XW}(\varepsilon)=E\{X(t)W(t-\varepsilon)\}$ is the cross-correlation between $X(t)$ and the CCRW $W(t)$.

**Teager-Kaiser Operator**

The non-linear quadratic TK operator was first introduced for measuring the real physical energy of a system. The discrete-time TK operator for a complex valued signal $x[n]$ is given by [13]

$$\psi(x[n]) = x[n]x^*[n] - \frac{1}{2}\left(x[n-1]x^*[n+1] + x[n+1]x^*[n-1]\right) . \tag{15}$$

If this operator is applied to the ACF of a signal, the TK energy of the function will exhibit a peak at zero lag. Fig. 6 shows the behaviour of the TK output for different signals using a sample time $T_s = 0.04T_c$ .

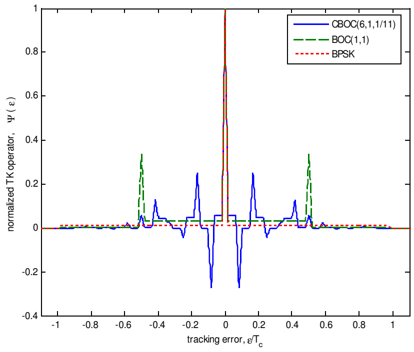


Fig. 6. TK operator output for BPSK, BOC(1,1) and CBOC(6,1,1/11) signals.

To keep the complexity as low as possible, the TK operator can be used to replace the Early and Late correlators output and used with a classical Early-minus-Late discriminator.

$$d(\varepsilon) = \psi_E - \psi_L \tag{16}$$

where $\psi_E$ and $\psi_L$ are the result of applying the TK operator to the CCF between the received signal and the early and the late version of the locally generate signal with $T_s = 2\Delta$ . This method has the advantage of using the well known classic DLL, keeping complexity low and improving the performance under a multipath environment.

## SIMULATION SETUP

To evaluate the performance of different techniques, a GNSS receiver and realistic multipath model were developed in *Simulink* with *GRANADA FCM (Factored Correlator Model) Blockset,* allows to quickly assess the receiver performance under different scenarios [14]. It was necessary to rewrite the some FCM internal functions so they could support also MBOC, the strobe correlator, and correlators with correlated noise.

By making use of the FCM multipath capabilities, the multipath simulation can be easily done by assigning each ray to one independent channel and summing the vector outputs of the FCM to obtain the combined correlation output $R_{sx}$ given by:

$$R_{sx}(\tau_1) = \sum_{k=1} a_k R_x(\tau_k) e^{i2\pi\phi_k} , \tag{17}$$

where $R_x$ is the autocorrelation function of the undisturbed signal, $a_k$ , $\tau_k$ and $\phi_k$ are the amplitude, delay and carrier phase of the *k*th ray, respectively. The parameters $a_k, \tau_k, \phi_k$ are determined according to a multipath model [15].

## RESULTS DISCUSSION

### Comparison Between Different Techniques

Fig. 7 shows the multipath error envelopes of the considered techniques for the BOC(1,1) modulatio and bandwidths. Considering the multipath error envelopes, W2, W3 and W4 CCRWs are expected to have the best multipath mitigation capabilities of all the tested techniques. W1 CCRW and HRC are other techniques expected to have good performance in the presence of multipath. NELP and RECT CCRW should have the worse performance in the presence of multipath.

Fig. 8 shows the normalized steady-state code error variance, $\overline{(\varepsilon/T_c)^2}$ , for the selected techniques and the different signals. It can be seen that the NELP and the HRC discriminators have lower steady-state error variance relative to CCRW discriminators. So, these techniques should offer superior performance in the presence of noise comparative to

CCRWs.

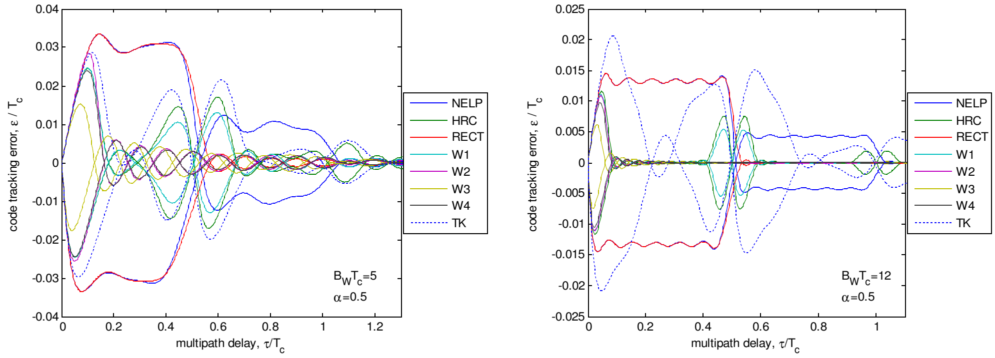


Fig. 7. Multipath error envelopes for BOC(1,1) signals, for the different techniques and bandwidths.

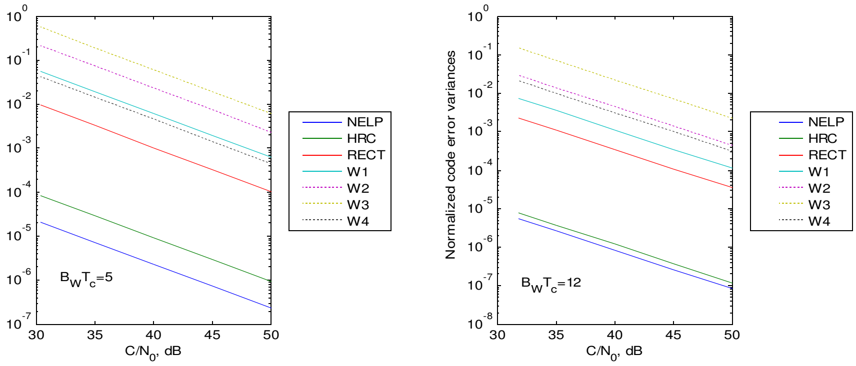


Fig. 8. Normalized code error variances for BOC(1,1) signals, for the different techniques and bandwidths.

## Simulation Results

Fig. 9 plots the mean (colour bars) and standard deviation (error bars) of the code tracking error for all multipath scenarios, normalized pre-correlation bandwidth $B_W T_c = 12$ and different techniques and signals. Lower expected values and variances means that a technique has a better performance. It is possible to see that the HRC offers the best performance. The W3 CCRW also provide good performance. The performance of W1, W2 and W4 is slightly worse than for the W3 CCRW. As expected, considering the multipath error envelopes, the TK algorithm was the worst technique. In a general way, there is an improvement in the results when using the BOC(1,1) modulation and special the CBOC(6,1,1/11) modulation.

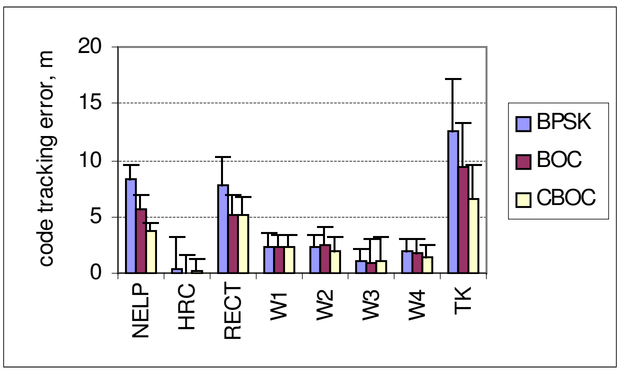


Fig. 9. Code tracking error mean and variance (average of the eight scenarios) for normalized bandwidth $B_W T_c = 12$, different techniques and modulations.

Some words must be addressed regarding the complexity of the different techniques. The CCRW techniques require four correlators and the discriminator has two multiplications and one addition. The NELP requires six correlators, four additions and four multiplications. The HRC requires ten correlators and the discriminator two multiplications and six additions. The TK is by far the most complex.

## CONCLUSION AND FINAL REMARKS

### Summary

This dissertation focused in multipath mitigation techniques suitable for civilian low cost GNSS receivers.

The basic concepts of GNSS were introduced. GNSS navigation signals were described, namely GPS L1 and L1C, and Galileo E1 signals. The operation of GNSS receiver tracking loops was described. It was explained what is multipath, when it happens and what is its effect on the tracking loops.

It was given an overview of current multipath mitigation techniques, with focus on the correlation based techniques. Several techniques were analysed: NELP, HRC, CCRW with several waveforms and a TK based technique.

A GNSS receiver simulator was implemented in *Simulink* using the *GRANADA FCM blockset*. The developed receiver simulator required also the implementation of a correlator noise generator, a stochastic multipath model and some workarounds, so *GRANADA FCM blockset* could support MBOC signals and CCRW. Some multipath environments were described and some techniques were picked up for simulation.

The simulation results were presented and discussed, and the techniques suitable for implementation on mass market civilian receivers were identified.

### Conclusion

The purpose of this thesis was to study and identify multipath mitigation techniques for urban scenarios, which are suitable for low cost GNSS receivers. The main research objectives were accomplished: the GNSS principles, different multipath mitigation techniques giving special attention to the correlation based techniques were studied and multipath mitigation techniques suitable for low cost GNSS receiver were identified.

All the techniques analysed operate at the tracking loops level and can be implemented in mass market receiver. However they behave differently in the presence of multipath and noise:

- NELP is not a bad option: it works well in the presence of weak multipath and its performance is good in the presence of noise. The negative point is that, in the presence of stronger multipath, the tracking error is large when compared with other techniques. The use of new signals, as BOC(1,1) and CBOC(6,1,1/11) signals, helps the NELP discriminator to achieve lower code tracking errors.
- HRC offers good performance. However, it has the disadvantage that, using CCRWs, it is possible to have similar performance and lower computational complexity.
- The performance of CCRWs are affected by the selected waveform. With exception to the RECT and New RECT CCRW, the tested CCRW presented good performance, however W3 CCRW offered the best performance among CCRWs.
- TK was the most complex (from the computational point of view), but the worse technique. Another disadvantage was the fact that from all the tested algorithms, this was the one that required a higher number of correlators and, hence, the most computationally heavier.

From all techniques, W3 CCRW is the one that offers the lowest computational complexity (as the others CCRWs) and the tracking performance nearest to the HRC. Thereby, from the tested techniques, this one was considered the most suitable for low cost receivers.

Other important conclusion, is that using larger pre-correlation bandwidths, it is possible to have a lower tracking error. Nevertheless, wider bandwidth required higher sampling frequencies and so, expensive hardware. Thus, if the cost does not exceed the receiver budget it is preferable to use larger bandwidth.

**Future Work**

The work developed in this dissertation was only “the tip of the iceberg”: many other techniques can be analysed, special CCRWs. As it was possible to see, the CCRW based techniques can be very flexible, and their performance can be tuned with different reference waveforms. There are unlimited possible waveforms to be tested. Also different CCRW can be combined in the same discriminator to achieve better performance.

The techniques were tested in a virtual environment: the *Matlab Simulink*. The next step is to test the techniques in a real GNSS receiver with real signals. The virtual environment can give a very good idea how the different algorithms and signals behaves, but it can not replace the tests in real environments.

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