Multipath Mitigation in GPS/Galileo Receivers with Different Signal Processing Techniques

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Abstract: It is well known that multipath error is one of the major error sources affecting the positional accuracy of Global Positioning System (GPS). Multipath effect can be reduced by several methods essentially by signal processing techniques which can be realized at the correlator level, by using new signals (BOC or MBOC) or with adaptive techniques. The main motivation of this paper is to provide these methods for assessing multipath performance, first we implement each approach separately than we propose to combine them, concern adaptive techniques we choose an NLMS algorithm. The obtained results are presented and analyzed through multipath errors envelope.

Key words: GPS, Galileo, multipath mitigation, NLMS, DLL.

1. State-of-the-art

As the dominant error source in high-accuracy GPS applications, multipath was the subject of several research work for this last years. A number of signal processing techniques have been proposed to detect and mitigate multipath errors on both range and phase measurements. Many of those are based on the tracking loop discriminator, in this context the narrow correlator was proposed by Van Dierendonck and al [2]. The narrow correlator employs a DLL with very small chip spacing between Early and Late code local replicas. Strobe and Edge Correlators [2], High Resolution Correlator (HRC) [8], double delta correlator [4] or the Gated Correlator [9], are proposed, they achieve similar performance with narrow correlator. Waveform optimization was another approach to improve tracking performance in multipath. A new signals based on new modulation scheme are proposed in modern navigation satellite system. Binary offset carrier (BOC) spreading modulations [5] are one way to accomplish this, and a BOC(1,1) spreading modulation was selected as the baseline for the future GALILEO L1 OS and GPS L1C signals. Betz and J.W [5] show that BOC signal provide better performance than C/A code. MBOC waveforms provide typically smaller average errors than BOC(1,1) waveform [7]. Another waveform options, TMBOC(6,14/33), shows an average error less than those of any other option for all delays [12].

Another category of techniques relies on an estimation of the parameters (amplitude, delay and phase) of the line-of-sight (LOS) signal along with those of all the multipath components. It includes a multipath estimation technique (MET) proposed by Townsend and Fenton [4], based on the slope of the autocorrelation function to estimate the code phase offset delay of the direct signal, this technique has been utilized to reduce only code-phase error in DLL and the effect of PLL carrier-phase error is not considered. From these reasons, van Nee and R.D [14] employed a multipath estimation delay lock loop (MEDLL) to estimate multipath signals and mitigate code and carrier-phase errors. Minami and Morikawa [10] propose an RLS adaptive filter based multipath mitigation technique. An adaptive filtering process is used for estimating a multipath delay profile witch is used for subtracting the estimated multipath effects from the measured autocorrelation value of GPS signal.

In this paper, we will at first analyze multipath performance based on waveform optimization; comparison based on multipath error envelope will be presented. Than, we propose to use narrow and double-delta correlator, the subject is to identify the best combination between signal and correlator that will be used next. Second, we propose an adaptive filtering approach to multipath mitigation based on NLMS algorithm. We will estimate the direct plus multipath signal parameters to separates them and
subtract this later signal from the measured autocorrelation value of received signal. Finally, we propose to associate all this methods, simulation results are presented to compare the performance of the proposed methods.

2. Introduction

Global Positioning System (GPS) is a satellite-based navigation system designed and developed by US Department of Defence (DoD) to provide instantaneous 3D position, velocity and time information almost anywhere on or above the surface of the earth at any time, and in any weather. The GPS receives right-hand, circularly polarized signals from a number of satellites. The circularly polarized signals facilitate the rejection of multipath signals. The current GPS receivers operate at L1 (1575.42 MHz) and L2 (1227.6 MHz). The positional accuracy provided by GPS is limited by various errors. Also, the GPS pseudorange obtained by either carrier-phase or code-phase measurements are affected by several types of random errors and biases (systematic errors). These errors can be classified as those originating at the satellites, those originating at the receiver and those that are due to signal propagation, we can note orbital errors, satellite clock errors, and multipath errors.

With the use of differential techniques it is possible to remove many of the common-mode error sources, but the error effects of multipath have proven much more difficult to mitigate. Multipath is when the line-of-sight first comes to the receiver and the same signal, a little bit weaker, comes again as a delay. This delayed signal is created when the line-of-sight signals has bounced on buildings, mountains, trees or the ground before reaching the receiver. Multipath signals are characterized by four parameters and all are relative to the direct line-of-sight signals. These are amplitude, time delay, phase and phase rate change.

Multipath can be mitigated at three different levels: antenna, signal processing and navigation. In our work we focus on the signal processing level which can be decomposed in two kinds: ones that attempt to mitigate it without estimating it, here we will study the influence of multipath on different signals and also different correlators and ones that estimate the multipath, here we will develop an adaptive method NLMS algorithm based.

3. Multipath effect

To demodulate the navigation data successfully an exact carrier wave and code replicas has to be generated. To do that a Costas Loop is often used associated to DLL loop, we focus first on DLL. The goal for a code tracking loop is to keep track of the code phase of a specific code in the signal, the output of such tracking loop is a perfectly aligned replica of the code. The code tracking loop in the GPS receiver is a delay lock loop (DLL) called an Early-Late tracking loop, the idea is to correlate the input signal with three local replicas of the code, Prompt, Early and Late separated with precise chip spacing and than tracks the zeros-crossing of the discriminator response. In presence of multipath (we suppose a single reflection) the received GPS signal can be expressed as:

\[
\begin{align*}
    s(t) &= A_0 \cdot d(t - \tau_0) \cdot c_f(t - \tau_0) \cos(2\pi f_t t - \theta_0) \\
    &+ A_1 \cdot d(t - \tau_1) \cdot c_f(t - \tau_1) \cos(2\pi f_t t - \theta_1) + b(t)
\end{align*}
\]

When we develop the discriminator response of this composite signal we can obtain Fig.1 witch shows the effect of the multipath in case of a coherent Early-Late DLL, it can be seen that the discriminator zeros-crossing is shifted, thus introducing an error in the estimated code delay.

![Figure 1. Code delay error in the presence of multipath](image-url)

In order to assess and study multipath effect and its related mitigation techniques, it is useful to simulate multipath error envelope which assume a single reflection of LOS signal, then the delay of this reflected signal is swept through a range of values to evaluate the code delay errors in the code tracking loop. The use of such error envelopes is a good and comprehensive way to compare the multipath performance of different signal with respect to each other. In the case of C/A code used in actual GPS signal, where the correlation function presented in Fig.3 and if we use a coherent Early-Late discriminator we can show that the theoretical error envelope is given mathematically as:

\[
\begin{align*}
    g_0 &= g_{\Delta t=0} \\
    \Delta \tau_{1,2} &= (1 + \alpha) \frac{C_s}{2} \\
    \Delta \tau_{2,3} &= T_c - (1 - \alpha) \frac{C_s}{2} \\
    \Delta \tau_{3,4} &= T_c + \frac{C_s}{2}
\end{align*}
\]
Next we determine \( t \) for BOC than C/A code. Correspond to the chip spacing. The multipath component is proportional to this coefficient. We observe that the error induced by multipath is out of phase and with \( \pi \) radians, the multipath component is in out of phase.

In the framework of the modernization plans of Global Navigation Satellite Systems (GNSS) a new modulation has been proposed as a possible Signal–In–Space (SIS) with improved performance with respect to the robustness against external sources of degradation, mainly multipath. We speak about Binary Offset Carrier (BOC: Binary Offset Carrier) modulation. A BOC(n,m) modulation has a CDMA spreading code clocked at frequency \( m \cdot f_{C/A} \) multiplied by a binary valued \((1 \text{ or } -1)\) square wave at frequency \( n \cdot f_{C/A} \) (the offset carrier), where \( f_{C/A} \) is a fundamental frequency unit used in satellite navigation, 1.023MHz. In this case the satellite transmitted signal is given as follows:

\[
S(t) = A d(t) C A(t) S_{boc}(t) \cos(2 \pi L t + \phi) \quad (4)
\]

with:

\[
S_{boc}(t) = \text{sign}(\sin(2 \pi f_{s_{boc}} t)) \quad (5)
\]

Fig.3 shows the autocorrelation function of Boc(1,1) signal. Comparing with C/A code autocorrelation function, we observe a narrower peak for Boc than C/A code.

Another interesting signal in BOC family is the so called MBOC. The European approach to the MBOC implementation consists in adding in time a BOC(1,1) and a BOC(6,1) code, defined as composite BOC modulation, such a signal structure allows the receivers to obtain high performance in terms of multipath rejection and tracking. This is mainly due to a higher transition rate brought by the BOC(6,1) on top of the BOC(1,1). The notation introduced in [9] is MBOC(6,1,1/11), where the term (6,1) refers to the BOC(6,1), and the ratio 1/11 represents the power split between the BOC(1,1) and BOC(6,1) spectrum components as given by:

\[
G_{MBoc}(f) = \frac{10}{11} G_{Boc(1,1)}(f) + \frac{1}{11} G_{Boc(6,1)}(f) \quad (6)
\]

where GBOC(m,n)(f) is the unit-power spectrum density of a sine-phased BOC modulation as defined in [10].

The normalized autocorrelation function of the MBOC(6,1,1/11) spread spectrum time series, computed over infinite bandwidth and with ideal spreading codes, is illustrated in Fig.3, along with the autocorrelation function for C/A and BOC(1,1) codes. Observe that MBOC(6,1,1/11)’s correlation function peak is narrower than that of BOC(1,1), but the widths at values of 0.5 and at the zero crossing are virtually the same. Also we observe the apparition of undulations that certainly influences on the multipath error envelop shape.
The result is plotted in Fig.5. Comparing Fig.4 and 5 for standard correlator spacing (d=0.5) we see that the C/A code multipath error envelop is sensitive for multipath signals with a relative path delay up to 300 m. as an example, The resulting range errors in case of BOC(1,1) at 250m multipath delay with $\alpha = 0.5$ is about 4 m, but in case of C/A code is about 60m. This demonstrates that BOC(1,1) signals are better to handle multipath signals than C/A code signals.

In Fig.6 MBOC(6,1,1/11) error envelope is presented, we remark that this signal provide an error envelopes that are smaller than both C/A and BOC(1,1) signal for the small values of path length delays.

4. Minimisation by using different correlators

The presented results are obtained in the case of a wide correlator/standard correlator, that use one correlator at 0.5 chips before the assumed punctual top of the peak and another delayed with 0.5 chips, this is for different types of signal. In multipath mitigation context at signal processing level we can use another types of correlators, in this paper we have study a narrow correlator and double difference correlator.

4.1. Narrow correlator

To avoid big parts of the influence of multipath, the narrow correlator concept was developed. The narrow correlation technique has been first proposed in 1992 [3] and introduced to GPS receiver by NovAtel. Instead of using a standard correlator with chip spacing of 1 chip between the Early and Late replicas, the chip spacing of a narrow correlator is less than 1 chip, usually 0.1 chip is used to build up the discriminator function. This principle is presented in Fig.7 bellow.

4.2. High resolution correlator

This type of correlator is in the family of double difference correlators which use two correlator pairs instead of only one in their code discriminator functions. To provide multipath mitigation this type of correlator employ two correlators in parallel as illustrated in Fig.8, the wide pair has exactly double the chip spacing of the narrow pair. The narrow pair generally has a chip spacing of ±0.1 chips; the wide correlator has a chip spacing of ±0.2. Code discriminators is based on linear combination of
two early minus late discriminators, the first one is made up of an early E₁, prompt P₁, and late L₁, the second is made up of an early E₂, prompt P₂, and late L₂. In this work we choose as a linear combination:

\[ D_{HBC} = (E_1 - L_2) - \frac{1}{2}(E_2 - L_2) \]  

(7)

Like early-late processing, double-delta multipath mitigation processing is a known processing technique that was designed for BPSK-R spreading modulations, but may be applied to more advanced modulations as well.

Smaller multipath error envelopes may be obtained when we applied narrow or double delta correlator. Fig.9 shows the multipath errors resulting from a narrow correlator processing with the same multipath propagation model used previously for different value of reflection coefficient \( \alpha \). In this figure, we can easily remark the significant improvement given by this correlator. The multipath error envelopes has a maximum value of 10 m for \( \alpha = 0.8 \) and 8 m for \( \alpha = 0.5 \) comparing with Fig.4 which we have a maximum of 120 m for \( \alpha = 0.8 \) and 70 m for \( \alpha = 0.5 \).

Fig.10 shows the multipath errors resulting from narrow correlator and double delta processing. In this figure, for narrow correlator the chip spacing is \( C_s = 0.1 \) chips, in case of double delta correlator the outer early-late spacing is 0.1 chips and inner early-late spacing is 0.05 chips. We observe that the multipath error envelopes for the narrow correlator options are nearly the same as those for double delta correlator.

Fig.11 shows the multipath errors envelopes with a narrow correlator for both C/A, BOC(1,1) and MBOC(6,1,1/11) codes. We observe that MBOC(6,1,1/11) waveforms provide typically smaller average errors than either BOC(1,1) or C/A waveforms. An important feature of MBOC waveforms is that the error envelope diminishes at smaller path length delay values than for BOC(1,1) or C/A codes. At longer path length delay values, the MBOC waveforms provide lower average delays.
5. Adaptive Multipath Mitigation

The block diagram of the multipath mitigation system is shown in Fig.12. Received signal is processed in RF filter then down converted and sampled to a digital IF signal by an A/D converter. The tracking module composed of DLL and PLL receive a GPS IF signal and generate a local code and carrier replicas.

Multipath estimator is an adaptive filter NLMS based with IF signal as reference, he estimate a delay profile of multipath. The estimated signal parameters are used in the correlation extractor to determine a correlation value of delayed signal. The detailed process of the multipath estimator, the correlation value extractor, and the multipath cancellation will be presented as follows.

5.1. Multipath Estimator

The task of multipath estimator is to estimate the multipath delay profile by the use of adaptive filter. There are many algorithms that could be used in this context; most are variations of the least mean squared (LMS) algorithm. Some variations include normalized LMS (NLMS) and the recursive least squares algorithm (RLS). The NLMS algorithm was chosen because it is the most commonly used algorithm in adaptive filtering applications, he is powerful enough to accomplish the system’s requirements and is also relatively simple compared to the other algorithms. The NLMS algorithm uses relatively few calculations, which makes it suitable for the speeds of the DSP’s available today.

The NLMS algorithm in our case study seeks to minimize the excess MSE between the composite (LOS plus multipath) IF signal and a signal local replica at the output of tracking module as a reference signal. The communication network in Fig.13 has the necessary signals that are required by the LMS algorithm.

\[
\hat{y}(n) = \sum_{i=0}^{M} \hat{A}_i g(n - \hat{\tau}_i) \cos(wn + \hat{\phi}_i) + \eta(n) \tag{8}
\]

Where \(A, \tau\) and \(\phi\) are the amplitude, the code delay, and the carrier phase of \(m\) delayed signal. \(M\) is the number of multipath component, \(g\) is spread-spectrum code, and \(\omega\) is IF frequency and \(n\) is discrete time. The \(0\)th delayed signal corresponds to the direct signal. The parameter with the symbol “\(\wedge\)” denoted the estimated parameter. Because the parameters are impossible to be determined directly without any assumption about multipath signals, we utilize reference signals in estimation process. A reference signal is a replica of code and carrier obtained from output of DLL and PLL, and is written as:

\[
y(n) = \sum_{i=0}^{K} w_i x_i(n) + \eta(n) \tag{9}
\]

Where \(w = \hat{A}_0 e^{j(\theta_0)}\), the adjustable weight which is used to minimize the least squares criteria defined by using (8) and (9) as:

\[
L = \mathbb{E}[(y(n) - \hat{y}(n))(y(n) - \hat{y}(n))^*] \tag{10}
\]

where \(\mathbb{E}[.\] is a expectation operator, and the mark “\(*\)" represents complex conjugate.

The error signal \(e(n)\) is created from the subtraction of the desired signal from the output of the adaptive filter:

\[
e(n) = y(n) - \hat{y}(n) \tag{11}
\]
The adaptive LMS equation is given by:

\[ w(n+1) = w(n) + \mu e(n)x(n) \quad (15) \]

The reference signal \( x(n) \) generated at the output of the tracking module is used as an input to the adaptive filter so that the adaptive NLMS filter's response approximates the multipath system's frequency response. The error signal is feedback to the adaptive filter and is used as an input with the original input signal to update the NLMS adaptive filter. After several iterations, we can obtain estimated delay profile from filter taps and delay element, consequently multipath signal can be estimated.

The parameter \( \mu \) determines the convergence or divergence speed and precision of the adaptive filter coefficients. If \( \mu \) is large, the filter will converge fast, but could diverge if \( \mu \) is too large. When \( \mu \) is large, the adaptation is quick, but there will be an increase in the average excess MSE. This excess MSE may be undesirable result. If \( \mu \) is small, the filter will converge slowly, which is equivalent to the algorithm having “long” memory, an undesirable quality.

5.2. Correlation Extractor

After obtaining the estimated delay profile, we separate multipath signals from direct signal, this is done through the subtraction of delayed signals correlation from that of received signal. We assume that the first peak of amplitude of the estimated delay profile is the direct signal, and the remainders are delayed signals. The component of the delayed signals is, then, used to compute the correlation value of delayed signals. The following equation represents the correlation value of one estimated delayed signal with amplitude \( A_m \), delay \( \tau_m \) and carrier phase \( \hat{\Theta}_m \):

\[ R_M(\tau) = A_m R(\tau - \tau_m) \exp j(\hat{\Theta}_p - \hat{\Theta}_m) \quad (16) \]

Where \( R_M(\tau) \) is the auto-correlation function of GPS signal:

\[ R(\tau) = E[p(n)p(n-\tau)] \quad (17) \]

Therefore, the correlation value of all estimated delayed signal \( R_d(\tau) \) is obtained as follows:

\[ R_d(\tau) = \sum_{m=p}^{\hat{\mu}} R_m(\tau) \quad (18) \]

5.3. Multipath Elimination

The correlation value of delayed signal \( y(t) \) is subtracted from the correlation value of received signal \( R_M(\tau) \), and the improved correlation value \( R_\epsilon(\tau) \) is obtained:

\[ R_\epsilon(\tau) = R_M(\tau) - R_L(\tau) \quad (19) \]

Since tracking errors caused by multipath in DLL and PLL mainly come from distortion of the correlation function of received signal, the subtraction of \( R_L(\tau) \) provides multipath mitigation in the tracking loop. Therefore, the use of \( R_\epsilon(\tau) \) enables the tracking loops to track direct signal more accurately. Although above processes (i.e., estimation, extraction, and elimination process) can reduce the effects of multipath on the auto-correlation of received signal, tracking errors in DLL and PLL are not eliminated completely. Because the reference signal used in multipath estimator contains multipath error, and estimated delay profile does not reflect correctly that of real multipath. To approach obtaining ideal delay profile of multipath, we apply the above processes recursively.

5.4. Simulations and results

As previously, we will build up the multipath error envelop associated to our proposed NLMS method, we note that a damping factor \( \zeta = 0.7 \) and bandwidth \( w = 170 \text{ Hz} \) has been used at PLL level. We consider a multipath with amplitude \( A=0.5 \) and a phase equal to zero degree than to \( \pi \) for several delays. Fig 14 shows simulation results in code and carrier phase error mitigation with NLMS method comparing with narrow correlator obtained result in case of C/A code. Simulation results show that by using adaptive multipath mitigation technique, multipath is considerably reduced. We observe that DLL with a narrow correlator has an error code phase of \( \pm 8 \) meters in presence of multipath signal, on the other hand, using multipath mitigation with NLMS adaptive method this error is reduced at 1 meter.

![FIGURE 14. Simulation results with NLMS based mitigation technique for C/A code](image)
In the case of BOC(1,1) code, multipath mitigation performances summarized by the multipath error envelop are presented in Fig. 15. We observe that the error don’t exceed 0.25 meters in the range 150-300 meters, this error is smaller than the case given by figures 11&14.

6. Conclusions

In this paper, a several multipath mitigation signal processing methods have been proposed for Galileo and GPS signals. We have evaluate the multipath error envelop for each presented case to illustrate and analyze the multipath influence on a tracking loop. As a first conclusion, we can say that BOC code is better than C/A code. Narrow correlator is a best choice for both C/A and BOC codes, however simulations revealed this correlator combined with BOC or MBOC codes are more attractive. By performing a normalized least squares algorithm, we observe that the multipath is successfully cancelled and we can make a reconstruction of the original signal. The obtained results confirm that the NLMS algorithm is a very powerful and simple tool for multipath mitigation for both GPS and Galileo receiver. The paper concluded that the adaptive methods are very promising as a solution to multipath mitigation issues in future GNSS receivers.

7. References


