Hindawi Publishing Corporation
Mathematical Problems in Engineering
Volume 2009, Article ID 106870, 20 pages
doi:10.1155/2009/106870

Research Article

GPS/Galileo Multipath Detection and Mitigation Using Closed-Form Solutions

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Received 11 March 2009; Accepted 3 September 2009

Recommended by Francesco Pellicano

We propose an efficient method for the detection of Line of Sight (LOS) and Multipath (MP) signals in global navigation satellite systems (GNSSs) which is based on the use of virtual MP mitigation (VMM) technique. By using the proposed method, the MP signals' delay and coefficient amplitudes can be efficiently estimated. According to the computer simulation results, it is obvious that our proposed method is a solution for obtaining high performance in the estimation and mitigation of MP signals and thus it results in a high accuracy in GNSS positioning.

1. Introduction

In GNSS systems such as Global Positioning System (GPS) and future Galileo the positioning accuracy is seriously degraded in the presence of MP propagation [1]. In effect, MP signals provoke tracking error in the Delay Locked Loop (DLL) [1, 2]. Therefore, it is necessary to eliminate MP errors in the DLL discriminator and track the LOS signals transmitted from satellites. Here, various techniques are proposed to mitigate the MP effect [3–10]. In [5], an analysis of feedback as well as feedforward code tracking algorithms has been done. Then, the peak tracking methods have been proposed as a combination of both feedback and feedforward structures that utilize the inherent advantages of both structures. Yet, at low signal-to-noise ratio (SNR), narrow correlator (NC) [6] is still the best choice among the considered algorithms. The MP Estimating Delay Locked Loop (MEDLL) [10] is one of the analyzed algorithms. It estimates the parameters of LOS and MP signals such as delays, amplitudes, and phases. The former MEDLL proves to have the best performance in MP environments [10, 11]. However, MEDLL requires a lot of hardware resources. Recently, VMM technique for determining the position of the LOS has been introduced [7]. This technique is shown to give superior performance on the detection of the peak location of the LOS signal in the ideal case. However, this technique proves limited due to the finite-bandwidth filter in the receiver which shows that there is an offset between the peak locations of both the virtual LOS and the actual LOS. This is due to the fact that the virtual LOS correlation function (VLOSCF) used to estimate the LOS delay is distorted. Therefore, it is necessary to estimate all the components of the received signal in order to mitigate the estimated MP signals, and locate the peak of LOS signal from the resultant signal, afterwards. Hence, in this paper, we aim at using the concept of VMM introduced in [7] differently in the sense that we use it to estimate the components of LOS and MP signals such as delays and coefficient amplitudes. In effect, we can separate all the components of the received signal. Moreover, we propose closed-form solutions to calculate the delays and the coefficient amplitudes of both LOS and MP signals. We have labeled our proposed method Reference Correlation MP Mitigation (RCMPM). The RCMPM is discussed for Both Coarse Acquisition GPS code (C/A-GPS) and Binary Offset Carrier Galileo code (BOC(1, 1)-Galileo). Since low-energy-path contribution estimators have high variance and should therefore be given weak weights or simply suppressed in combining strategies [12], it is of interest to estimate the parameters of the strongest paths only.

2. Correlation Function (CF)

In the absence of MP signals, the CF of C/A-GPS and BOC(1, 1)-Galileo codes can be approached by the following expressions, respectively:

$$R_{\mathrm{GPS}}(\tau) = \begin{cases} a_0\left(1 - \dfrac{|\tau|}{T_c}\right) & \text{for } -T_c \le \tau \le T_c, \\ 0 & \text{elsewhere,} \end{cases} \tag{2.1}$$

$$R_{\mathrm{Galileo}}(\tau) = \begin{cases} a_0\left(-1 + \dfrac{|\tau|}{T_c}\right) & \text{for } \dfrac{T_c}{2} \le |\tau| \le T_c, \\ a_0\left(1 - 3\dfrac{|\tau|}{T_c}\right) & \text{for } -\dfrac{T_c}{2} \le \tau \le \dfrac{T_c}{2}, \\ 0 & \text{elsewhere,} \end{cases} \tag{2.2}$$

with

a_0: LOS signal coefficient amplitude,
T_c: code chip spacing,
τ: phase shift of the pseudo noise (PN) code.

Figure 1 shows the form of these CF's in the absence of the MP signals.

3. MP Signals Model

In the presence of MP signals the baseband signal model is defined as follows [7]:

$$S_r(t) = A(t)p(t-\tau) + \sum_{k=1}^{N} \alpha_k \cdot p(t - \tau - \tau_{rk})e^{j\phi_k} + n(t), \tag{3.1}$$

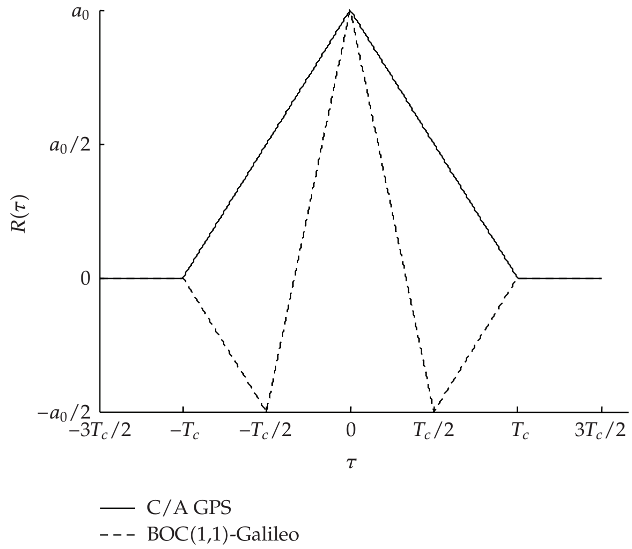

Figure 1: Correlation functions in the absence of MP signals for both C/A-GPS and BOC(1, 1)-Galileo.

with

$\tau = \tau_f + \tau_0$,

$\tau; \tau_{rk}$: delay of LOS or MP signal (τ_0: fraction of the time delay τ. τ_f: portion of time delay corresponding to the integer number of chips which is determined by signal acquisition processes in the receiver),

$A(t); a_k$: LOS or MP signal amplitudes,

ϕ_k: phase shift due to the MP signals,

N: number of MP signals,

$n(t)$: noise.

$p(t)$: PN code.

Some important characteristics of the MP signals are summarised as follows:

(i) The MP signals arrive after the LOS signal because it must travel a longer propagation path.

(ii) If the delay of the MP is less than one T_c code PN chip lengths, the internally generated receiver signal partially correlates with it.

(iii) The MP signals can be stronger or weaker than the LOS signal.

In all the figures of the paper, the delays are normalized with respect to the LOS. In effect, "0" represents τ_0.

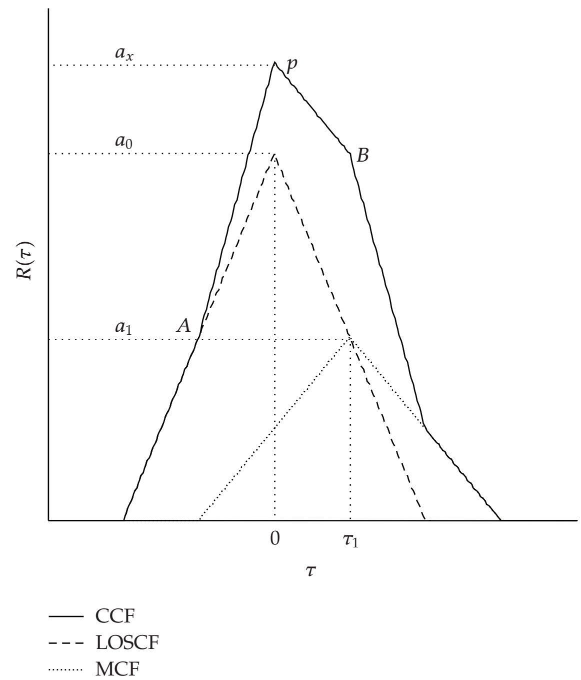

Figure 2: LOS, MP and CCF (weak MP "GPS-code").

4. Description of the Proposed Method

4.1. Detection of a Single MP Signal

In presence of a single MP component, the normalized input signal with respect to τ_f is defined as follows [7]:

$$S_{r1}(t) = a_0 p(t - \tau_0) + a_1 p(t - \tau_1) + n(t) \tag{4.1}$$

with:

a_1: MP signal coefficient amplitude,
a_0: LOS signal coefficient amplitude,
$\tau_1 = \tau_{1r} - \tau_f$: fraction of the delay of MP signal.

4.1.1. Case of C/A-GPS Signal

(1) Presence of a Weak MP Signal

The relationship between the amplitudes of LOS and MP signals is given as $a_0 > a_1$.

In presence of a LOS and single weak MP signals, the receiver tries to correlate with these two components. The resulting CF is distorted as shown in Figure 2. Analytically, the LOS and MP signals may be treated separately. Thus, one may consider the CF associated with LOS (LOSCF) and the CF associated with MP signal (MCF). At any point, these two functions can be vector summed to yield the CF associated with the composite signal

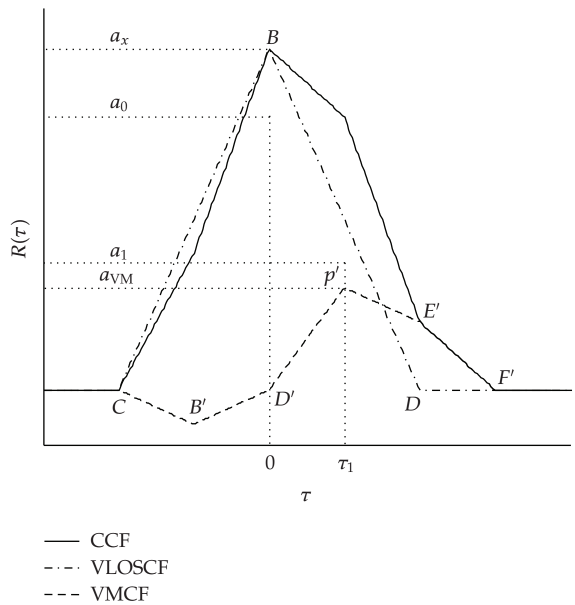

Figure 3: Concept of VMM (weak MP "GPS-code").

(CCF). To estimate each component of the received signal, we should estimate its amplitude coefficient and its delay.

The mathematical expression of the MCF can be obtained from (2.1) as follows:

$$R_{\mathrm{MCF}}(\tau) = \begin{cases} a_1\left(1 - \dfrac{|\tau - \tau_1|}{T_c}\right), & \text{for } -\mathrm{T_c} \le \tau - \tau_1 \le \mathrm{T_c}, \\ 0, & \text{elsewhere.} \end{cases} \tag{4.2}$$

The concept of the VMM, that is, the plot of CBD (VLOSCF), is illustrated in Figure 3.

The VLOSCF has peak amplitude equal to the maximum value of the CCF and has a width of two code chips on the horizontal axis.

The mathematical expression of VLOSCF can be derived from (2.1) as follows:

$$R_{\mathrm{VLOSCF}}(\tau) = \begin{cases} a_x\left(1 - \dfrac{|\tau|}{T_c}\right), & \text{for } -T_c < \tau < Tc, \\ 0, & \text{elsewhere.} \end{cases} \tag{4.3}$$

The mutual maximum of the VLOSCF and CCF is given as follows:

$$a_x = \max(\mathrm{CCF}) = \max(\mathrm{VLOSCF}) = -\frac{a_1}{T_c}\tau_1 + a_1 + a_0. \tag{4.4}$$

The mathematical expressions of the line segments PA and PB are given by the following expressions, respectively:

$$R_{PA} = \left[\frac{a_1 + a_0}{T_c}\right]\tau - a_1\frac{\tau_1}{T_c} + a_1 + a_0, \tag{4.5}$$

$$R_{PB} = \left[\frac{a_1 - a_0}{T_c}\right]\tau - a_1\frac{\tau_1}{T_c} + a_1 + a_0. \tag{4.6}$$

In these two equations, the slopes of R_{PA} and R_{PB} are defined as follows:

$$\begin{aligned} S_{PA} &= \frac{a_1 + a_0}{T_c}, \\ S_{PB} &= \frac{a_1 - a_0}{T_c}. \end{aligned} \tag{4.7}$$

Since $a_0 > a_1$, then

$$S_{PA} > 0, \quad S_{PB} < 0. \tag{4.8}$$

Inequality (4.8) guarantees that the resulting CF, obtained after subtracting VLOSCF from the CCF, is aligned with MCF as illustrated in Figure 3, that is, $CB^{'}D^{'}P^{'}E^{'}F^{'}$ (dashed line). The resulting CF is named "the virtual MP CF" (VMCF).

As shown in Figure 3, the VMCF is negative in the point $B^{'}$; this implies that the maximum of the VMCF is aligned with the MCF.

The peak location of the VMCF corresponds to the MP delay τ_1. The amplitude a_{VM} characterized by the point $P^{'}$ can be derived from (4.3) and (4.6) as follows:

$$a_{VM} = \frac{a_1(2T_c - \tau_1)\tau_1}{T_c^2}. \tag{4.9}$$

The mathematical expressions of the line segments $P'D'$ and $P'E'$ are given in the following expressions, respectively:

$$\begin{aligned} R_{P'D'} &= \frac{2a_1\tau}{T_c} - \frac{a_1\tau_1\tau}{T_c^2}, \\ R_{P'E'} &= \frac{2a_1\tau_1}{T_c} - \frac{a_1\tau_1\tau}{T_c^2}. \end{aligned} \tag{4.10}$$

To estimate the delay τ_1 and the coefficient amplitude a_1 of the MP signal, we use the following proposed equations:

$$\hat{\tau}_1 = \arg(\max[R_{P'D'}(\tau) = R_{P'E'}(\tau)]) = \arg(\max[R_{\mathrm{VMCF}}(\tau)]),$$
$$\hat{a}_1 = \begin{cases} \dfrac{a_{1VM}T_c^2}{(2T_c - \hat{\tau}_1)\hat{\tau}_1}, & \text{for } \tau_1 \le T_C, \\ a_{1VM}, & \text{for } \tau_1 \ge T_C. \end{cases} \tag{4.11}$$

After estimating both delay $\hat{\tau}_1$ and amplitude coefficient $\hat{a}_1$ we can subtract MCF corresponding to the MP signal from CCF. The resulting CF corresponds to only LOSCF. By using the following proposed equations, we can estimate τ_0 and a_0

$$\hat{\tau}_0 = \arg\left(\max\left\lfloor R_{\mathrm{CCF}}(\tau) - \hat{R}_{\mathrm{MCF}}(\tau)\right\rfloor\right),$$
$$\hat{a}_0 = \max\left\lfloor R_{\mathrm{CCF}}(\tau) - \hat{R}_{\mathrm{MCF}}(\tau)\right\rfloor,$$
$$\hat{R}_{\mathrm{MCF}}(\tau) = \begin{cases} \hat{a}_1\left(1 - \dfrac{|\tau - \hat{\tau}_1|}{T_c}\right), & \text{for } \; -T_c \le \tau - \hat{\tau}_1 \le T_c, \\ 0, & \text{elsewhere.} \end{cases} \tag{4.12}$$

(2) Presence of a Strong MP

In this case, the relationship between the amplitudes of the LOS and MP signals is given as $a_1 > a_0$.

In presence of a strong MP signal, the CCF is not aligned with LOSCF but with the MCF as shown in Figure 4. This is true as long as inequality (4.8) is not satisfied. Since the maximum of CCF is aligned with MCF, we apply a virtual CF aligned with MCF "virtual MP CF (VMCF)."

As shown in Figure 5, the resulting CF "virtual LOS CF (VLOSCF)," that is, $A'AP'B'C'D$ (dashed line) is aligned with the LOSCF.

The mathematical expression of VMCF can be derived from (2.1) as follows:

$$R_{\mathrm{VMCF}}(\tau) = \begin{cases} a_x\left(1 - \dfrac{|\tau - \tau_1|}{T_c}\right), & \text{for } \; -T_c \le \tau - \tau_1 \le T_c, \\ 0, & \text{elsewhere.} \end{cases} \tag{4.13}$$

The amplitude a_{VLOS} characterized by the point P' can be derived from (4.5) and (4.13) and is given in the expression below

$$a_{\mathrm{VLOS}} = \frac{a_0(2T_c - \tau_0)\tau_0}{T_c^2}. \tag{4.14}$$

From Figure 5 we can verify the nonsatisfaction of inequality (4.8).

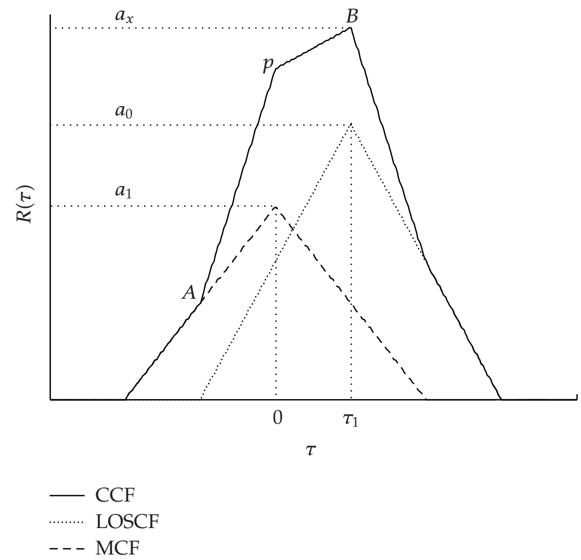

Figure 4: LOS, MP, and CCF (strong MP "GPS-code").

In this case, to estimate the delays τ_0 and τ_1 and the coefficient amplitudes a_0 and a_1, we use the following proposed equations:

$$\widehat{\tau}_0 = \arg(\max[R_{\mathrm{VLOSCF}}(\tau)]),$$

$$\widehat{a}_0 = \begin{cases} \dfrac{a_{\mathrm{VLOS}} T_c^2}{(2T_c - \widehat{\tau}_0)\widehat{\tau}_0}, & \text{for } \tau_1 \le T_C, \\ a_{\mathrm{VLOS},} & \text{for } \tau_1 \ge T_C, \end{cases}$$

$$\widehat{\tau}_1 = \arg\left(\max\left[R_{\mathrm{CCF}}(\tau) - \widehat{R}_{\mathrm{LOSCF}}(\tau)\right]\right), \tag{4.15}$$

$$\widehat{a}_1 = \max\left[R_{\mathrm{CCF}}(\tau) - \widehat{R}_{\mathrm{LOSCF}}(\tau)\right],$$

$$\widehat{R}_{\mathrm{LOSCF}}(\tau) = \begin{cases} \widehat{a}_0\left(1 - \dfrac{|\tau - \widehat{\tau}_0|}{T_c}\right), & \text{for } \; -T_c \le \tau - \widehat{\tau}_0 \le T_c, \\ 0, & \text{elsewhere.} \end{cases}$$

4.1.2. Case of BOC*(1, 1)-Galileo Signal*

(1) Presence of a Weak MP

The relationship between the amplitudes of the LOS and MP signals is given as $a_0 > a_1$. Similarly, the mathematical expression of MCF and VLOSCF can be obtained from (2.2),

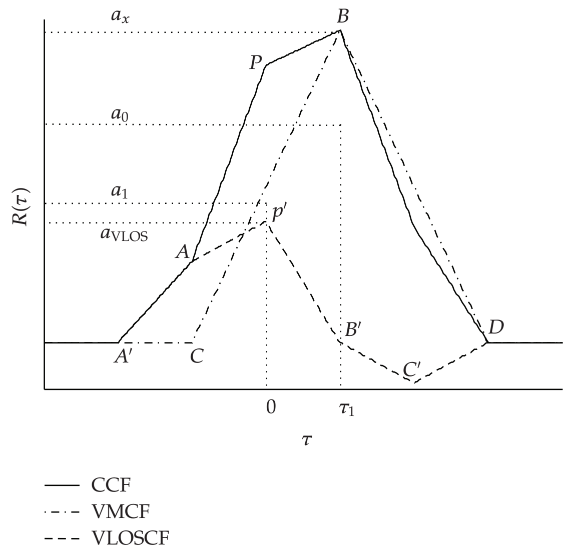

Figure 5: Concept of VMM (strong MP "GPS-code").

respectively, as follows:

$$R_{\mathrm{MCF}}(\tau) = \begin{cases} a_1\left(-1 + \dfrac{|\tau - \tau_1|}{T_c}\right), & \text{for } \dfrac{T_c}{2} \leq |\tau - \tau_1| \leq T_c, \\ a_1\left(1 - 3\dfrac{|\tau - \tau_1|}{T_c}\right), & \text{for } -\dfrac{T_c}{2} \leq \tau - \tau_1 \leq \dfrac{T_c}{2}, \\ 0 & \text{elsewhere,} \end{cases}$$

$$R_{\mathrm{VLOSCF}}(\tau) = \begin{cases} a_y\left(-1 + \dfrac{|\tau|}{T_c}\right), & \text{for } \dfrac{T_c}{2} \leq |\tau| \leq T_c, \\ a_y\left(1 - 3\dfrac{|\tau|}{T_c}\right), & \text{for } -\dfrac{T_c}{2} \leq \tau \leq \dfrac{T_c}{2}, \\ 0, & \text{elsewhere.} \end{cases} \tag{4.16}$$

The CFs of the received signal and the concept of the VMM are illustrated in Figures 6 and 7, respectively.

The maximum of the VLOSCF and CCF is given as

$$a_y = \max(R_{\mathrm{CCF}}(\tau)) = -\frac{3a_1}{T_c}\tau_1 + a_1 + a_0. \tag{4.17}$$

The obtained VMCF (A1A2A3A4A5A6 in Figure 7) after subtraction of the VLOSCF is characterized by the coefficient amplitude a_{VM} and the delay τ_1.

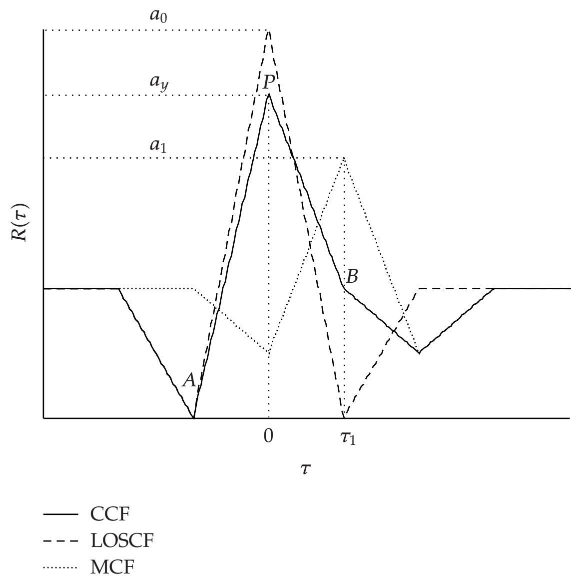

Figure 6: LOS, MCF, and CCF (weak MP "BOC(1, 1)-Galileo-code").

To estimate the delays τ_0 and τ_1 and the coefficient amplitudes a_0 and a_1, we use the following proposed equations:

$$\begin{aligned}
&\widehat{\tau}_1 = \arg(\max[R_{\mathrm{VMCF}}(\tau)]),\\
&\widehat{a}_1 = \begin{cases} \dfrac{a_{VM}T_c^2}{3\tau_1(2T_c - 3\widehat{\tau}_1)}, & \text{for } \tau_1 \le \dfrac{T_C}{2},\\[2ex] \dfrac{a_{VM}T_c^2}{(2T_c - \widehat{\tau}_1)\widehat{\tau}_1}, & \text{for } \dfrac{T_C}{2} \le \tau_1 \le T_C,\\[2ex] a_{1\mathrm{VM},} & \text{for } \tau_1 \ge T_C, \end{cases}\\
&\widehat{\tau}_0 = \arg\Big(\max\Big|R_{\mathrm{CCF}}(\tau) - \widehat{R}_{\mathrm{MCF}}(\tau)\Big|\Big),\\
&\widehat{a}_0 = \max\Big|R_{\mathrm{CCF}}(\tau) - \widehat{R}_{\mathrm{MCF}}(\tau)\Big|,\\
&R_{\mathrm{MCF}}(\tau) = \begin{cases} \widehat{a}_1\left(-1 + \dfrac{|\tau - \widehat{\tau}_1|}{T_c}\right), & \text{for } \dfrac{T_c}{2} \le |\tau - \widehat{\tau}_1| \le T_c\,,\\[3ex] \widehat{a}_1\left(1 - 3\dfrac{|\tau - \widehat{\tau}_1|}{T_c}\right), & \text{for } -\dfrac{T_c}{2} \le \tau - \widehat{\tau}_1 \le \dfrac{T_c}{2},\\[2ex] 0, & \text{elsewhere.} \end{cases}
\end{aligned} \tag{4.18}$$

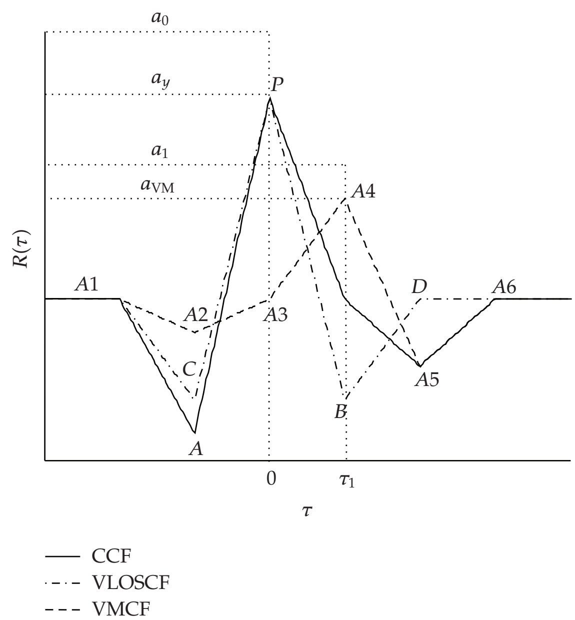

Figure 7: Concept of VMM (weak MP "BOC(1, 1)-Galileo-code").

(2) Presence of a Strong MP

With the same discussion and as the case of C/A-GPS signals, the resulting CCF and the concept of the VMM are illustrated in Figures 8 and 9, respectively.

The delays τ_0 and τ_1 and the coefficient amplitudes a_0 and a_1 can be estimated by the following proposed equations, respectively:

$$\begin{gathered}
\widehat{\tau}_0 = \arg(\max[R_{\mathrm{VLOSCF}}(\tau)]), \\
\widehat{a}_0 = \begin{cases} \dfrac{a_{\mathrm{VLOS}} T_c^2}{3\widehat{\tau}_0(2T_c - 3\widehat{\tau}_0)}, & \text{for } \tau_1 \leq \dfrac{T_C}{2}, \\ \dfrac{a_{\mathrm{VLOS}} T_c^2}{(2T_c - \widehat{\tau}_0)\widehat{\tau}_0}, & \text{for } \dfrac{T_C}{2} \leq \tau_1 \leq T_C, \\ a_{\mathrm{VLOS}}, & \text{for } \tau_1 \geq T_C, \end{cases} \\
\widehat{\tau}_1 = \arg\left(\max\left[R_{\mathrm{CCF}}(\tau) - \widehat{R}_{\mathrm{LOSCF}}(\tau)\right]\right), \\
\widehat{a}_1 = \max\left[R_{\mathrm{CCF}}(\tau) - \widehat{R}_{\mathrm{LOSCF}}(\tau)\right].
\end{gathered} \tag{4.19}$$

4.2. Detection of Two MP Signals

In presence of two MP and a LOS signals, the received signal can be expressed by the following equation [7]:

$$S_r(t) = a_0 \cdot p(t - \tau_0) + a_1 p(t - \tau_1) + a_2 p(t - \tau_2) + n(t), \tag{4.20}$$

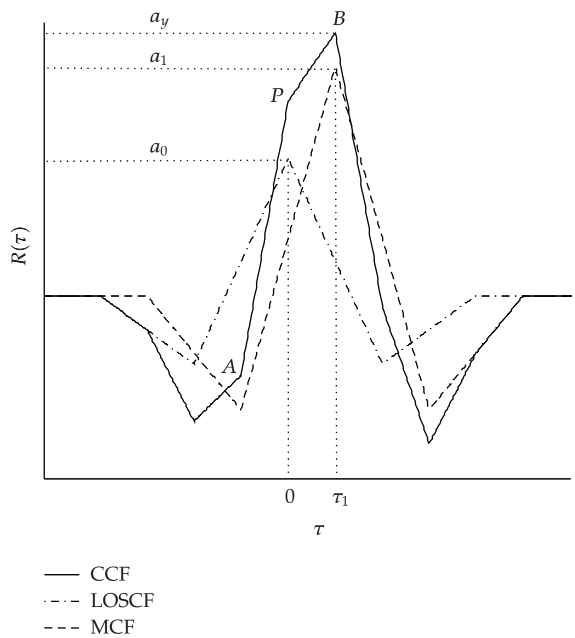

Figure 8: LOS, MCF and CCF (strong MP "BOC(1, 1)-Galileo-code").

with:

a_2: coefficient amplitude of second MP signal (MP2),
τ_2: delay of MP2,
ϕ_2 : phase shift due to the MP2.
The relationships of the amplitudes and the delays is:

$$a_2 < a_1 < a_0, \qquad \tau_1 < \tau_2. \tag{4.21}$$

4.2.1. Case of C/A-GPS Signal

Here, the mathematical expression MCF2 can be obtained from (2.1) as follows:

$$R_{\mathrm{MPCF2}}(\tau) = \begin{cases} a_2\left(1 - \dfrac{|\tau - \tau_2|}{T_c}\right), & \text{for} \quad -T_c \le \tau - \tau_2 \le T_c, \\ 0, & \text{elsewhere}. \end{cases} \tag{4.22}$$

Figures 10 and 11 illustrate the CF's (LOSCF, MCF1, MCF2, and CCF) and the concept of VMM, that is, the plot of CBD, respectively.

In the presence of two MP and LOS signals, the peak position of the CCF can be located on the peak of LOSCF or MCF1 or MCF2. In this paper, we discuss only the second case. Another discussion can be done for the first and the third cases.

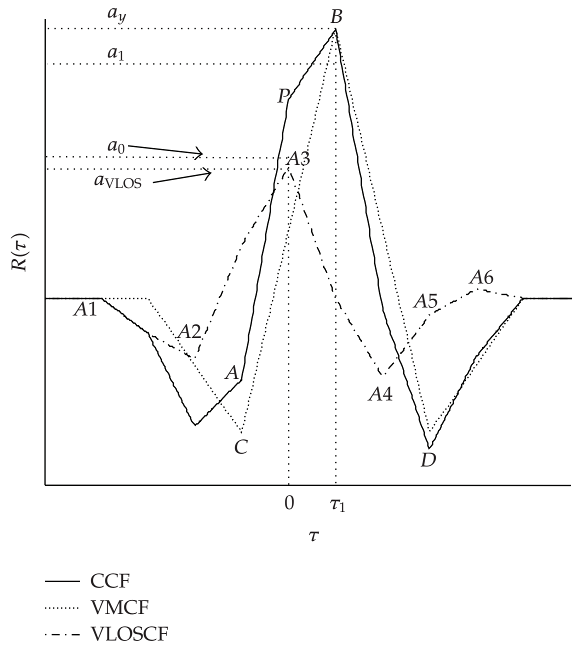

Figure 9: Concept of VMM (strong MP "BOC(1, 1)-Galileo-code").

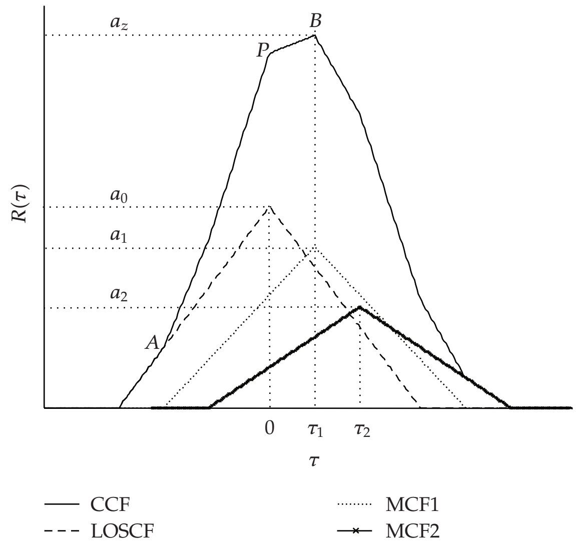

Figure 10: LOSCF, MCF1, MCF2, and CCF (two MP signals "GPS-code").

a_z represents the maximum value of the CCF and the VMCF and is given as

$$a_z = \max(R_{\mathrm{CCF}}(\tau)) = \left[\frac{a_0 - a_2}{T_c}\right]\tau_1 + a_0 + a_1 + a_2 - \frac{a_2\tau_2}{T_c}. \tag{4.23}$$

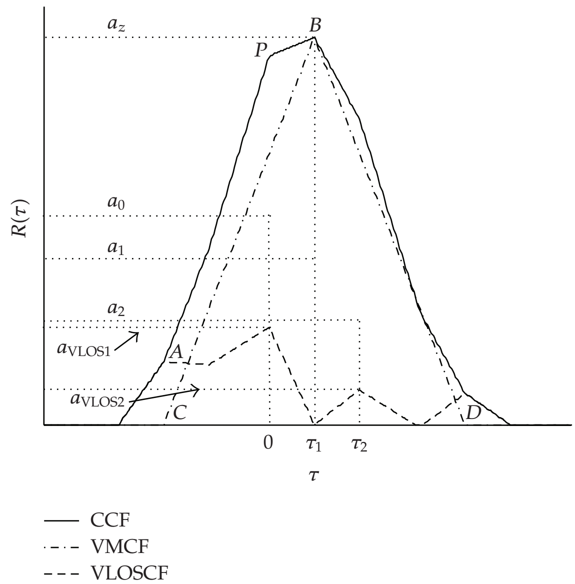

Figure 11: Concept of VMM (two MP signals "GPS-code").

By subtracting the VMCF from the CCF, we get the *VLOSCF* which is aligned on the maximum of the LOSCF, as illustrated in Figure 11. The values of the delays τ_0, τ_1, and τ_2 can be estimated using the following proposed equations, respectively:

$$\begin{aligned}
\widehat{\tau}_0 &= \arg(\max[R_{\mathrm{VLOSCF}}(\tau)] = a_{\mathrm{VLOS1}}), \\
\widehat{\tau}_1 &= \arg(\max[R_{\mathrm{CCF}}(\tau)]) = \arg([R_{\mathrm{VLOSCF}}(\tau) = 0]), \\
\widehat{\tau}_2 &= \arg([R_{\mathrm{VLOSCF}}(\tau)] = a_{\mathrm{VLOS2}}).
\end{aligned} \tag{4.24}$$

By solving the proposed equations' system (4.25) and (4.26), we can estimate the amplitude of LOS a_0 and the amplitude of the MP2 a_2

$$a_{\mathrm{VLOS1}} = \widehat{a}_0\left[\frac{2\widehat{\tau}_1}{T_c} - \frac{2\widehat{\tau}_1^2}{T_c^2}\right] + \widehat{a}_2\left[\frac{\tau_1^2 - \widehat{\tau}_1\widehat{\tau}_2}{T_c^2}\right], \tag{4.25}$$

$$a_{\mathrm{VLOS2}} = \widehat{a}_2\left[2 - \frac{\widehat{\tau}_2 - \widehat{\tau}_1}{T_c}\right](\widehat{\tau}_2 - \widehat{\tau}_1) + \widehat{a}_0\widehat{\tau}_1\left[\frac{\widehat{\tau}_2 - \widehat{\tau}_1}{T_c^2}\right]. \tag{4.26}$$

Finally, by the subtraction of the two estimated CFs LOSCF and MCF2, we can get the amplitude a_1 of MP1 signal as follows:

$$\widehat{a}_1 = \max\left|R_{\mathrm{CCF}}(\tau) - \widehat{R}_{\mathrm{LOSCF}}(\tau) - \widehat{R}_{\mathrm{MCF2}}(\tau)\right|. \tag{4.27}$$

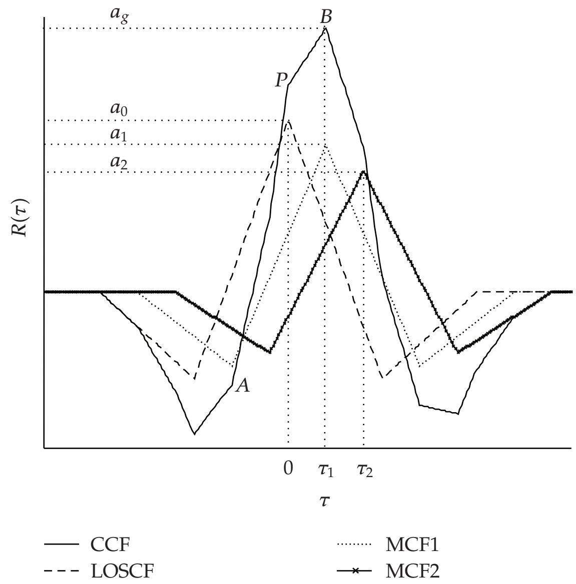

Figure 12: LOSCF, MCF1, MCF2, and the resultant CCF "BOC(1, 1)-Galileo-code."

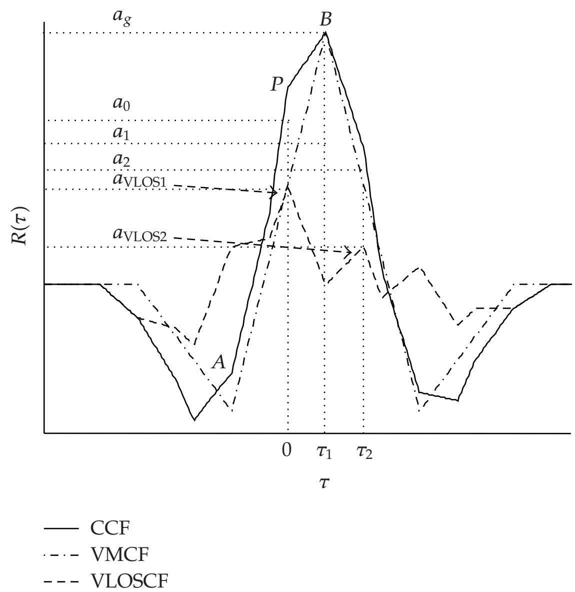

Figure 13: Concept of VMM (case of two MP signals "BOC(1, 1)-Galileo-code").

4.2.2. Case of BOC*(1, 1)-Galileo Signal*

With a similar discussion, Figures 12 and 13 illustrate the CFs (LOSCF, MPCF1, MPCF2, and CCF) and the concept of VMM, that is, the plot of CBD, respectively.

The values of the delays τ_0, τ_1, and τ_2 can be estimated using the following proposed equations, respectively:

$$\begin{aligned}
\hat{\tau}_0 &= \arg(\max[R_{\text{VLOSCF}}(\tau)]) = \arg(R_{\text{VLOSCF}}(\tau) = a_{\text{VLOS1}}), \\
\hat{\tau}_1 &= \arg(\max[R_{\text{CCF}}(\tau)]) = \arg([R_{VLOSCF}(\tau) = 0]), \\
\hat{\tau}_2 &= \arg(R_{\text{VLOSCF}}(\tau) = a_{\text{VLOS2}}).
\end{aligned} \tag{4.28}$$

We can estimate the amplitudes of LOS a_0 and of MP2 signal a_2 by solving the proposed equations' system (4.29) and (4.30).

$$a_{\text{VOLSCF1}} = \hat{a}_0 \frac{\hat{\tau}_1}{T_c}\left[6 - \frac{9\hat{\tau}_1}{T_c}\right] - 9a_2\hat{\tau}_1\left[\frac{\hat{\tau}_2 - \hat{\tau}_1}{T_c^2}\right], \tag{4.29}$$

$$a_{\text{VOLSCF2}} = a_2\left[6\left(\frac{\hat{\tau}_2 - \hat{\tau}_1}{T_c}\right) - 9\left(\frac{\hat{\tau}_2 - \hat{\tau}_1}{T_c}\right)^2\right] - 9a_0\tau_1\left[\frac{\hat{\tau}_2 - \hat{\tau}_1}{T_c^2}\right]. \tag{4.30}$$

Finally, by subtracting the two CFs (VLOSCF and MCF2), we can get the amplitude a_1 of MP1 signal as follows:

$$\hat{a}_1 = \max\left\lfloor R_{\text{CCF}}(\tau) - \hat{R}_{\text{LOSCF}}(\tau) - \hat{R}_{\text{MCF}_2}(\tau)\right\rfloor. \tag{4.31}$$

Note that the practical receiver implementation of all these closed form solutions requires that the complete correlation function of the received signal (CCF) to be measured in order to detect the shape and the distortions caused by MP. The CCF can be sampled via using a bank of correlators [10] (see the appendix).

5. Simulation Results

The impact of MP on code tracking accuracy is often represented as an error envelope which represents the maximum error resulting from one single MP with a certain phase delay and amplitude. The same method of analysis applied to the MP-induced error will be used for the discriminators considered herein. It is worth noting that computing the MP-induced code tracking error envelope (CTEE) is equivalent to finding the point, where the discriminator output crosses the origin because it represents the point where the DLL will lock. It is obvious that both the finite-bandwidth filter and the correlator spacing have an influence on the envelope. So, a large correlator spacing will result in a greater susceptibility of the tracking loop with respect to MP. Usually, a narrow finite-bandwidth filter will tend to increase the MP-induced error envelope. Thus, the GNSS positioning accuracy requires a rigorous choice of these two parameters.

In order to demonstrate that our RCMPM method performs better than a single NC, two schemes have been simulated: an NC with 0.1 chip spacing and our RCMPM method. For these simulated schemes, we consider a LOS and single MP signals and a band-limited CF of 20 MHz. The errors are computed versus MP signal that has amplitude of 0.5 and a delay that varies from 0 to 1.5 chips with respect to the LOS. The MP error envelopes are

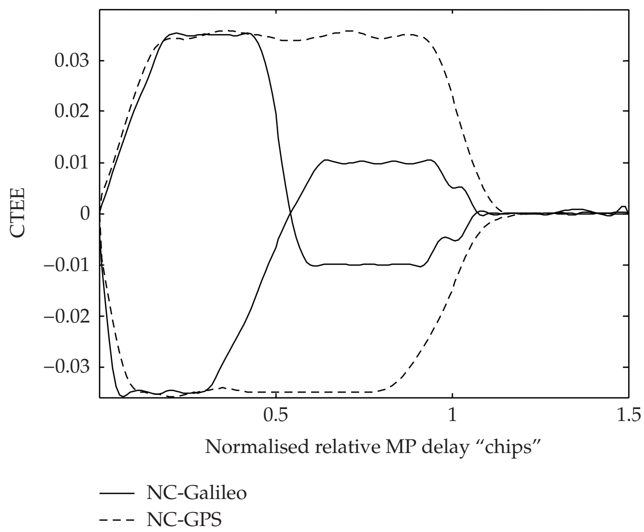

Figure 14: Code error envelope of NC.

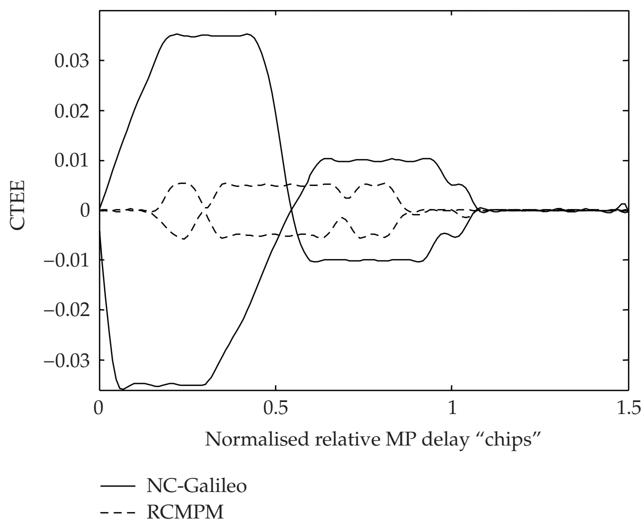

Figure 15: Code error envelope (RCMPM-Galileo and NC-Galileo).

calculated at the maximum points when the MP signal is at 0° in phase or 180° out of phase with respect to the LOS. The result is given in Figures 14 and 15, respectively.

As illustrated in Figure 14 that represents the error envelope for NC, the BOC(1, 1)-Galileo offers better resistance to the long delay MP than the C/A-GPS; however, they have exactly the same envelope for short delay MP. Since the error envelope of the NC for the Galileo receivers is inferior to that of the GPS, it suffices to compare the error envelope of our RCMPM method with that of Galileo receiver. As illustrated in Figure 15, it is clear that RCMPM method performs better than the NC in terms of the error envelope. Whatever the relative delay of the MP is, the offset error of our proposed method is always less than the NC error. In effect, our method shows the best overall MP performance, which is only sensitive for

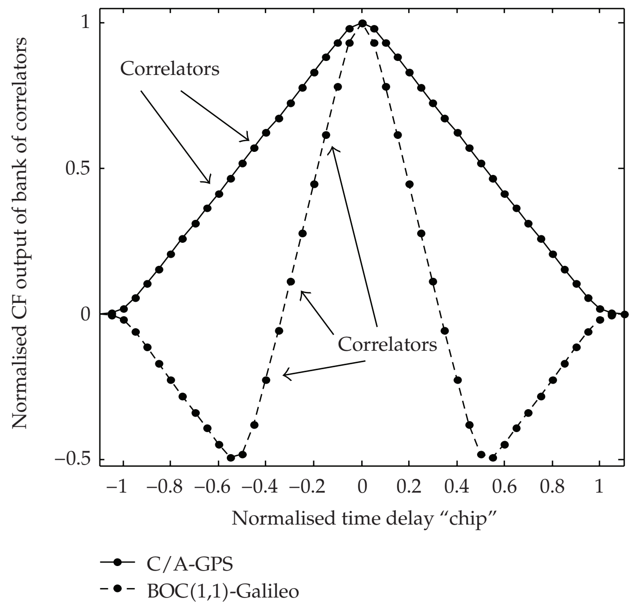

Figure 16: Multiple correlator sampling of the CF.

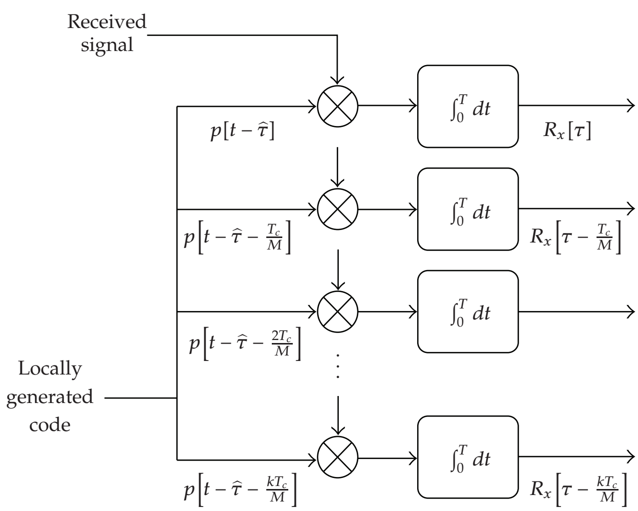

Figure 17: Block diagram of the bank of correlators.

medium MP delays. The code error envelopes decrease to zero for long and short MP delays. Before ending up, we can say that there are great differences between the MP performance obtained by the NC and MP performance obtained by our RCMPM method, because the error envelope of RCMPM is greatly smaller than the NC. In other words, the bias due to the MP is reduced by 40 to 95 percent than that of the NC. Also, the band of variation of the error is completely reduced. This shows that our method has better MP rejection.

6. Conclusion

An efficient method for the detection and mitigation of MP signals is proposed in this paper. This method is derived from the VMM technique [7]. The latter proves limited due to the finite-bandwidth filter in the receiver that creates an offset between the peak location of the virtual LOS and the actual LOS, leading to a code error tracking in positioning the receiver. In our proposed method we have used the concept of the VMM mitigation technique not only for the LOS delay estimation but for estimating amplitudes and delays of both LOS and MP signals as well. The estimated MP has then been subtracted from the composite signal in order to mitigate the MP effect and efficiently estimate the LOS delay. The simulation results have shown that our proposed method performs better than a single NC. Hence, the error and its band of variation are completely reduced vis-à-vis to what we observed for NC scheme.

Appendix

The samples of the CCF of both C/A-GPS and BOC(1, 1)-Galileo which are obtained by the use of the bank of correlators are shown in Figure 16.

In fact, we use the bank of correlators to calculate the CCF. The block diagram of the bank of correlators is shown in Figure 17. As illustrated in this figure, we use a number of correlators distributed across the received correlation function. Each correlator is positioned at unique values of t and it measures a single value of $R(\tau)(R_x(\tau))$ as shown in Figure 16.

The received signal is correlated with a number of correlators to get samples of the input correlation function $R(\tau)$.

$R_x(\cdot)$: the samples of CCF,

M: the number of correlators,

T_c: code chip spacing,

$\hat{\tau}$: the estimated delay.

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