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ASPeCT: Unambiguous Sine-BOC(n,n) acquisition tracking technique for navigation applications

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ASPeCT: Unambiguous Sine-BOC(*n,n*) Acquisition/Tracking Technique for Navigation Applications

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   This article presents a new tracking technique for sine-BOC(n,n) (or Manchester encoded) ranging signals, which will most likely be part of the new European Global Navigation Satellite System (GNSS), Galileo, signal plan. When traditional sine-BOC(n,n) tracking is considered, although offering excellent performance compared with current signals, it has the main drawback of potentially giving biased measurements. The new method presented herein allows the removal of this threat while maintaining the same level of performance. An adapted version of this technique can also be used for acquisition purposes.

I. INTRODUCTION

Global Navigation Satellite Systems (GNSS) are at an exciting stage of their existence as they are going through a process of diversification and enhancement. The U.S. Global Positioning System (GPS), the only existing and fully operational GNSS, is undergoing an extensive modernization process [1, 2], while the European Union, jointly with the European Space Agency, is in the midst of launching its own GNSS, known as Galileo [3]. In addition, Russia is restoring their GNSS called GLONASS [4].

Based on the extensive experience of the current GPS (deemed GPS I) operations, these new navigation systems will integrate several modifications in order to improve currently achievable positioning and timing accuracies. Among other changes, the use of up to three frequencies to provide signals which can be used to model the dispersive effect of the ionosphere and the transmission of dataless (or pilot) signals for more robust carrier-phase tracking can be cited. Galileo is a civil system based on a set of services (open, commercial, safety-of-life, publicly regulated and safety and rescue) and its full deployment is expected around 2010 [3]. GPS will remain a dual civil-military system and its first modernization phase (GPS II) is expected to be completed around 2012 [2]. A more detailed overview of the GNSS modernization process can be found in [5].

The new signals' modulations have been adapted to meet ever increasing user needs in terms of accuracy and reliability, but with the obligation to limit spectral overlapping that could lead to significant inter- and intra-system interference. Indeed, GNSSs have to coexist in a limited number of frequency bands [6]. The current GPS uses a spread spectrum technique with a bi-phase shift keying (BPSK) modulation. With the upcoming GNSS generation some civil signals will implement a binary offset carrier (BOC) modulation that allows improved code delay tracking while offering a spectral separation from BPSK signals due to its split spectrum [7, 8]. However, the main drawback of every BOC-modulated signal is its multi-peak autocorrelation function that implies possible false acquisition or biased tracking which can result in ambiguous (or biased) measurements if no special care is taken. When considering accurate positioning, this event is obviously unacceptable. Several techniques have been investigated to remove this bias threat [9–13]. They are always generic to all BOC signals, but are often not optimal in terms of tracking performance, as a tradeoff between reliability and accuracy has to be made. This paper presents a different approach by proposing a solution to this bias problem dedicated to a specific family of BOC signals, the sine-BOC(n,n), also known as

Manchester-encoded ranging signals. This family of modulation is of great interest for navigation since it is being considered for one of the Galileo civil signals that will supply mass market applications. It should be noted that an optimized version of this modulation is currently being studied by the Galileo Signal Task Force; however, this optimized signal will incorporate only limited changes and is expected to be compatible with a "sine-BOC(1,1) tracking architecture" and thus with the method proposed herein [14]).

As a signal supporting mass market applications, the Galileo L1 signal intends to provide accurate positioning to most users such as pedestrians, mobile phone users, drivers, etc.… Consequently, offering a close-to-optimal tracking solution (in terms of tracking degradation due to thermal noise, multipath and narrow-band interference) while reliably canceling the sine-BOC(n,n) inherent bias threat would provide an excellent and potentially widely used tool. It is interesting to know that the sine-BOC(n,n) modulation is also the leading candidate for GPS III [15, 16]. The new tracking method presented herein is referred to as the autocorrelation side-peak cancellation technique (ASPeCT). It is based on the combination of two correlation functions that removes the inherent sine-BOC(n,n) autocorrelation side peaks.

Section II gives a background on BOC signal properties and illustrates the ambiguity threat, focusing on sine-BOC(n,n) signals. Section III explains the essence of ASPeCT as well as its theoretical formulation while Section IV investigates the impact of the most significant disturbances (thermal noise and multipath) on code tracking using the new proposed method. The use of a modified version of ASPeCT for unambiguous acquisition is studied in Section V.

II. SINE-BOC(n,n) SIGNALS

A. General Background on BOC Signals

A BOC signal is obtained through the product of a bi-phase spreading pseudo random noise (PRN) code with a square-wave subcarrier. This square wave can either be sine or cosine phased, which leads to different signal characteristics. They are referred to as sine-BOC and cosine-BOC, respectively, [16]. In the navigation community, a BOC signal is characterized by its spreading code frequency $f_c = 1/T_c$ ($m \times 1.023$ MHz), its subcarrier frequency f_s ($n \times 1.023$ MHz), n and m being constrained to positive integers, $n \geq m$, and the ratio $k = 2n/m$ being a positive integer. Each family defined by these two parameters is referred to as a BOC(n,m) modulation and has its specific spectral characteristics [8, 17].

The resulting received BOC(n,m) signal can be modeled as

$$s(t) = AC\left(t - \frac{\tau}{T_c}\right)\left(t - \frac{\tau}{T_c}\right)S_C\left(t - \frac{\tau}{T_c}\right)\cos(2\pi f_0 t + \varphi)$$
$$+ N(t) \qquad (1)$$

with

$$S_C(t) = \text{sgn}(\sin(2\pi f_s t + \phi)) \qquad (2)$$

where
   A is the signal's amplitude,
   C is the PRN spreading code sequence (NRZ),
   D represents the navigation data (NRZ), if any,
   τ is the code delay (in chips, one chip being one spreading code bit),
   f_0 is the carrier frequency (in Hz),
   φ is the carrier phase (in rads),
   N represents any external disturbances,
   S_C represents the square-wave subcarrier (NRZ),
   sgn is the sign function,
   ϕ defines the subcarrier as square-wave sine ($\phi = 0$) or cosine ($\phi = \pi/2$).

The subcarrier modulates the spreading code, symmetrically splitting the main energy component of the signal spectrum, and placing it around multiples of the subcarrier frequency at baseband. Consequently, it allows for a spectral separation from BPSK spectrums, as shown later with the sine-BOC(n,n) signals as examples. In the context of a future GNSS, a relevant choice of BOC signal can drastically limit the potential interference with the civil GPS legacy signal (BPSK) [6, 7].

The theory of spread spectrum signal tracking is very well documented [18] and consequently is not further described herein. BOC(n,m) signal tracking has also well-known characteristics that are summarized in [8]. It is worth noting that due to their higher RMS bandwidth compared with traditional BPSK signals with the same spreading code frequency (BPSK(m)), BOC(n,m) signals allow for better inherent mitigation of white Gaussian noise and narrowband interference during tracking. They also have an increased resistance to multipath. These properties are shown with the particular example of the sine-BOC(n,n) signal, which is described hereafter.

B. Sine-BOC(n,n) Signal Main Characteristics

Sine-BOC(n,n) signals correspond to $\phi = 0$ and $f_s = f_c$ in (2). They possess the characteristics of having exactly one subcarrier period in one code chip. The resulting normalized power spectrum density (PSD), at baseband, is given by [8, 17, 19]:

$$G_{\text{B}}(f) = \frac{1}{T_c}\left(\frac{\sin\left(\frac{\pi f T_c}{2}\right)\sin(\pi f T_c)}{\pi f \cos\left(\frac{\pi f T_c}{2}\right)}\right)^2. \qquad (3)$$
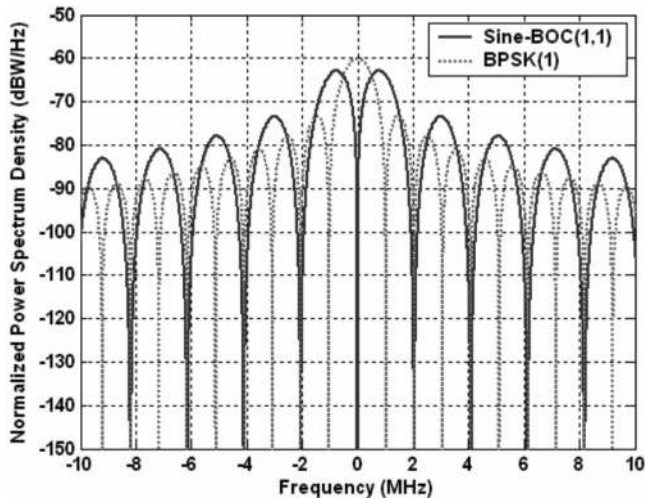
Fig. 1. Normalized sine-BOC(1,1) and BPSK(1) power spectrum densities.

Fig. 2. BPSK(n) and sine-BOC(n,n) normalized autocorrelation functions.

In terms of frequency occupation, BOC(n,n) signals are the most compact of all BOC signals for a given spreading code frequency. Sine-BOC(n,n) signals gather the main part of their power within a very limited frequency band (86% of total power in $4f_s$ Hz, 90% in $6f_s$ Hz, 94% in $10f_s$ Hz, 98% in $20f_s$ Hz (double-sided)). Fig. 1 shows the normalized sine-BOC(1,1) PSD along with the BPSK(1) PSD. This limited spectrum occupation allows for usage in a receiver utilizing a limited sampling frequency, which is of great interest for applications requiring low power, such as cellular telephones. It can also be noted that the sine-BOC(1,1) PSD sidelobes fall in the zeros of the BPSK(1) PSD, allowing for low inter-signal interference.

The associated normalized theoretical sine-BOC(n,n) autocorrelation function without front-end filtering equals [20]:

$$R_B(\tau) = \mathrm{tri}\left(\frac{\tau}{\frac{1}{2}}\right) - \frac{1}{2}\left(\mathrm{tri}\left(\frac{\tau - \frac{1}{2}}{\frac{1}{2}}\right) + \mathrm{tri}\left(\frac{\tau + \frac{1}{2}}{\frac{1}{2}}\right)\right)$$

(4)

where $\mathrm{tri}(x/y)$ is the triangular function of width $2y$, centered in $x = 0$ where it has a unity value.

This autocorrelation function is shown in Fig. 2 along with the normalized BPSK(n) autocorrelation function.

A traditional GNSS receiver uses a delay lock loop (DLL) with early, late, and prompt correlators to track the signal code delay. A traditional DLL architecture adapted to BOC signals is represented in Fig. 3. The general operation of a DLL is well documented in the literature [18, 21] and consequently will not be described further herein.

Assuming an incoming white Gaussian noise with a constant PSD of $N_0/2$ dBW/Hz and a slowly varying code delay and carrier phase, the in-phase (I_{X_B}) and quadra-phase (Q_{X_B}) correlators output can be modeled
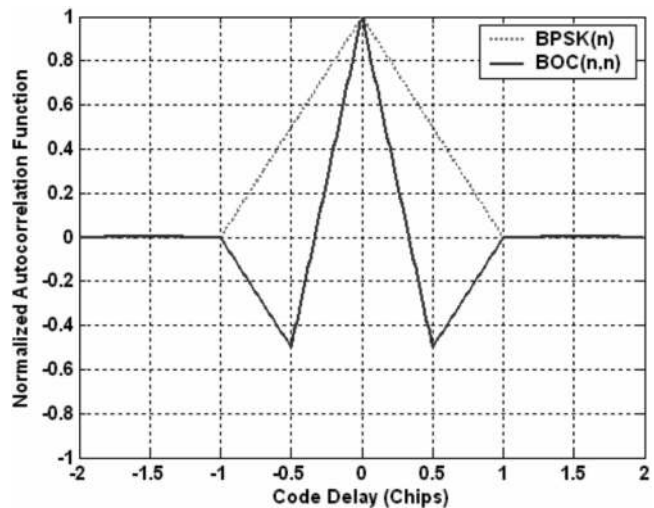

Fig. 3. Traditional DLL architecture.

as

$$I_{X_B} = \int_0^{T_I} s(t)c\left(t - \frac{\hat{\tau}}{T_c} - \frac{\tau_X}{T_c}\right)\cos(2\pi\hat{f}_0 t + \hat{\varphi})dt$$

$$\approx \frac{A}{2}R_B\left(\frac{\varepsilon_\tau - \tau_X}{T_c}\right)\mathrm{sgn}(D)\frac{\sin(\pi\Delta fT_I)}{\pi\Delta fT_I}\cos(\varepsilon_\varphi) + n_I(t)$$

(5)

$$Q_{X_B} = \int_0^{T_I} s(t)c\left(t - \frac{\hat{\tau}}{T_c} - \frac{\tau_X}{T_c}\right)\sin(2\pi\hat{f}_0 t + \hat{\varphi})dt$$

$$\approx \frac{A}{2}R_B\left(\frac{\varepsilon_\tau - \tau_X}{T_c}\right)\mathrm{sgn}(D)\frac{\sin(\pi\Delta fT_I)}{\pi\Delta fT_I}\sin(\varepsilon_\varphi) + n_Q(t)$$

(6)

where

X corresponds to the early (E), late (L), or prompt (P) correlator,

T_I is the coherent integration time used in the correlation process (defining the integrate and dump (I&D) filter in Fig. 3), and is assumed to be within one data bit (if present),

$\hat{\tau}$ is the estimate of the incoming signal's code delay made by the receiver (in chips),

$\hat{f}_0$ is the estimate of the incoming signal's frequency made by the receiver (in Hz),

$\hat{\varphi}$ is the estimate of the incoming signal's carrier phase made by the receiver (in rads),

τ_X is the code delay of the signal replica ($\tau_P = 0$, $\tau_E = -d/2$, $\tau_L = d/2$ s),

R_B is the autocorrelation of the sine-BOC(n,n) spreading waveform,

d is the early-late chip spacing (in chips),

Δf is the frequency wipe-off error (in Hz),

ε_τ and ε_φ are the code delay and carrier phase estimation errors (in chips and rads respectively), and

n_I and n_Q are independent Gaussian noise with a variance of $N_0/4T_I$ dBW.

Most GNSS receivers use a noncoherent DLL discriminator in order to remove the impact of potential carrier phase error on the code tracking estimation process [21]. They directly estimate the code delay error using the correlator's output. The most widely used noncoherent discriminators are the early-minus-late-power (EMLP) and the dot-product (DP) discriminators [21, 22]. Due to space limitations, only the DP discriminator is studied here (a study of the EMLP discriminator is given in [20]). Its classical expression for a general sine-BOC(n,m) signal, is

$$D_{DP}^B = \frac{(I_{E_B} - I_{L_B})I_{P_B} + (Q_{E_B} - Q_{L_B})Q_{P_B}}{2\left(4\frac{n}{m} - 1\right)}. \quad (7)$$

Since the output of (7) is dependent upon the useful signal power, it is common to normalize it by the instantaneous power estimate [23]. For a sine-BOC(n,m), it gives

$$D_{DPN}^B = \frac{(I_{E_B} - I_{L_B})I_{P_B} + (Q_{E_B} - Q_{L_B})Q_{P_B}}{2\left(4\frac{n}{m} - 1\right)(I_{P_B}^2 + Q_{P_B}^2)}. \quad (8)$$

The code tracking error variance due to thermal noise using the classical (not normalized) DP discriminator, and assuming no front-end filtering, is given by (obtained using calculations similar to [18, 24]):

$$\sigma_{BOC}^2 = \frac{B_L d}{2\left(4\frac{n}{m} - 1\right)\frac{C}{N_0}}\left(1 + \frac{1}{\frac{C}{N_0}T_I}\right) \text{(chips}^2) \quad (9)$$

where B_L is the one-sided DLL loop filter bandwidth (in Hz).

By comparison, for a BPSK(n) signal without front-end filtering, the code tracking error variance due to thermal noise for a normalized DP discriminator is [18, 21]:

$$\sigma_{BPSK}^2 = \frac{B_L d}{2\frac{C}{N_0}}\left(1 + \frac{1}{\frac{C}{N_0}T_I}\right) \text{(chips}^2). \quad (10)$$
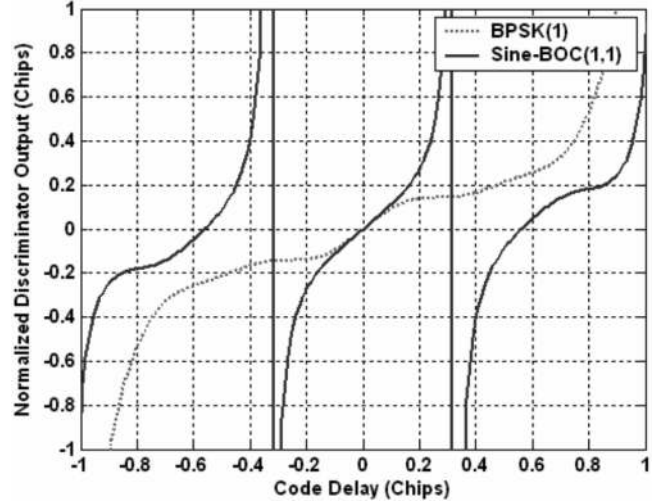

Fig. 4. Normalized discriminator output for sine-BOC(1,1) and BPSK(1) signals for an early-late spacing of 0.2 chips, and a 6 MHz front-end filter (double-sided).

From (9) and (10), it is obvious that the use of a sine-BOC(n,n) signal provides a reduction of the code tracking error variance by a factor of 3 (or 4.7 dB) over the use of a BPSK(n) signal. This is due to the sharpness of the main peak of the sine-BOC(n,n) autocorrelation function compared with the main peak of the BPSK(n) autocorrelation function, as shown in Fig. 2, that results in a better mitigation of thermal noise.

The relative compact spectral occupation of a sine-BOC(n,n) signal, its spectral separation over BPSK(n) signals, and its advantage in terms of tracking over BPSK(n) signals make it the main candidate for a future Galileo mass-market navigation signal (as the current GPS civil signal uses a BPSK(1) signal) [16]. However, the use of sine-BOC(n,n) signals also has drawbacks, which are explained in the next section.

C. Sine-BOC(n,n) Bias Threat

The main drawbacks associated with sine-BOC(n,n) signal (and any BOC(n,m) signals) tracking can be easily shown when plotting the normalized DP discriminator output. An example is given in Fig. 4 for a sine-BOC(1,1) signal and a BPSK(1) signal with $d = 0.2$ chips and a front-end filter of 6 MHz (double-sided). It appears that the stability domain of the sine-BOC(n,n) signal is smaller than the one of the BPSK(n). This is, however, somewhat compensated by the better sine-BOC(n,n) tracking accuracy already mentioned. It is also obvious, from Fig. 4, that the sine-BOC(n,n) DP discriminator output has two stable false lock points at ± 0.56 chips (or approximately 150 m for a sine-BOC(1,1) signal) which are due to the side peaks of the sine-BOC(n,n) autocorrelation function. It is then possible to have the DLL locking

on one of the sine-BOC(n,n) side peaks. This would result in intolerable biased measurements. It is also interesting to note that these false lock points are not located exactly at ±0.5 chips (the location of the autocorrelation side peaks) due to the difference in the autocorrelation function slopes on each side of the side peaks.

This bias threat due to the sine-BOC(n,n) autocorrelation side peaks signal does not only impact code tracking. It also affects signal acquisition. The acquisition process consists of detecting the incoming signal energy through a search for an approximate carrier frequency and code delay. The detection criterion usually used is [21]:

$$T_B = \sum_{k=1}^{M} (I_{P,k}^2 + Q_{P,k}^2) \qquad (11)$$

where M is the number of successive correlator outputs used, or noncoherent summations.

It can be understood from (5), (6), and (11) that accurate estimation of the signal Doppler and code delay will result in a maximization of the detection criterion. It is also interesting to note that assuming a small frequency wipe-off error (typically $\leq 1/4T_I$ Hz), the signal detection criterion then mainly depends upon the square of the autocorrelation function R_B. Fig. 2 and (4) show that the sine-BOC(n,n) squared autocorrelation function possesses two nonnegligible side peaks with a magnitude that is one-quarter of the main peak's magnitude. Consequently, the sine-BOC(n,n) autocorrelation side peaks should also be considered as nonnegligible threats in the acquisition process. There is no such problem for the acquisition of the BPSK(n) signals.

Many sources of error, such as high incoming noise, a short loss of lock, or a false acquisition can cause the DLL to lock on one of the side peaks. An example of such an event is given in Fig. 5 for a signal power-to-noise PSD (C/N_0) of 40 dB-Hz. The initial code error of -0.5 chips simulates false acquisition.

As a consequence, special care has to be taken to completely and reliably eliminate such a possibility. An inventory of methods trying to remove this bias threat is given in the following section.

D. Possible Solutions

Several solutions have been proposed to remove this bias threat for generic BOC(n,m) signals. They are, consequently, also suitable for sine-BOC(n,n) signals. Two of them are of particular interest and widely referenced.

The first one, described in [9] and referred to as "bump and jump" (BJ) technique, consists of traditional tracking of the BOC signal (using a DP discriminator for instance). This technique also uses,
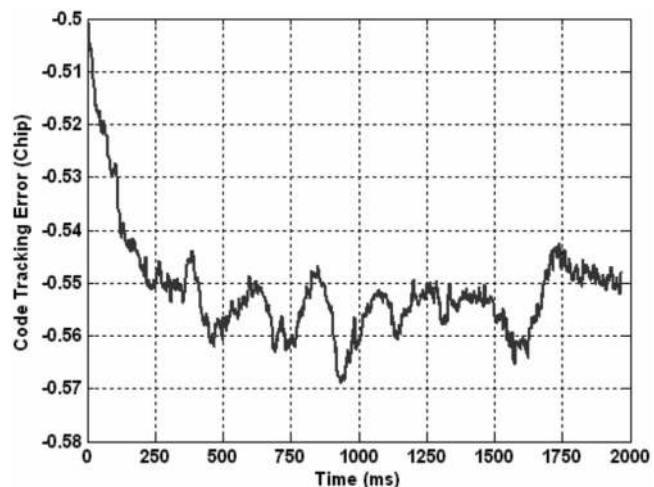

Fig. 5. Example of biased sine-BOC(1,1) tracking on false peak with an initial code delay error of -0.5 chips (2 Hz DLL) for a C/N_0 of 40 dB-Hz.

in parallel, extra correlators located at the side peaks (referred to as very early (VE) and very late (VL) correlators) to constantly check that the peak tracked is the "highest" one. This method has been shown to be efficient in detecting false locks under normal conditions. However, because it is based on a test comparing the main and side peaks magnitudes, it may fail and/or provoke false tracking for low signal power or if the signal characteristics change significantly during the test. It may as well take time to actually detect the bias which might be intolerable for some critical applications such as aircraft landing. On the positive side, when locked onto the main peak, this technique has the advantage of using a traditional BOC tracking scheme, and the improved tracking performance, described in Section IIB, associated with it.

The second method, described in [10] and [11], consists of noncoherently using each main sidelobe of the BOC split spectrum in order to "mimic" nonambiguous BPSK(m) tracking. It is referred to as the single sidelobe (SSL) technique. Although totally unambiguous, it completely removes all of the advantages of BOC signal tracking since it is somewhat equivalent to BPSK(m) tracking.

Other methods [12, 13] have been proposed recently. However, their exact performance with sine-BOC(n,n) signals has not been described in the literature.

A newly developed technique, ASPeCT, focuses specifically on sine-BOC(n,n) signals and its characteristics to cope with the ambiguous tracking problem. It is described in the following section.

III. ASPECT

ASPeCT's essence is to remove the side peaks of the sine-BOC(n,n) autocorrelation function in order to
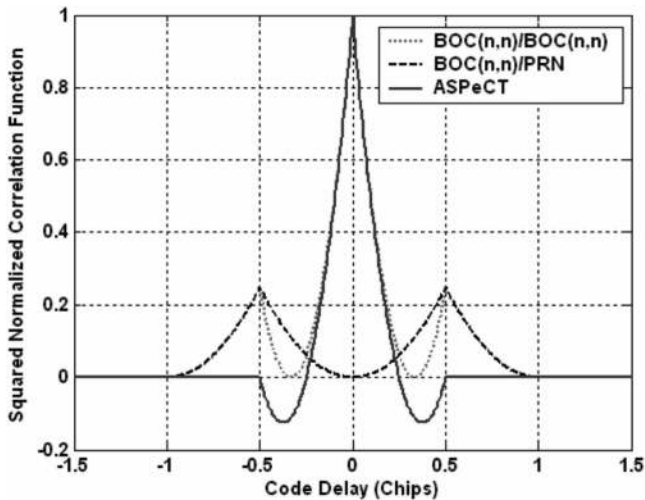
Fig. 6. Sine-BOC(n,n)/sine-BOC(n,n), sine-BOC(n,n)/PRN squared normalized correlation functions and ASPeCT modified correlation function without front-end filter.
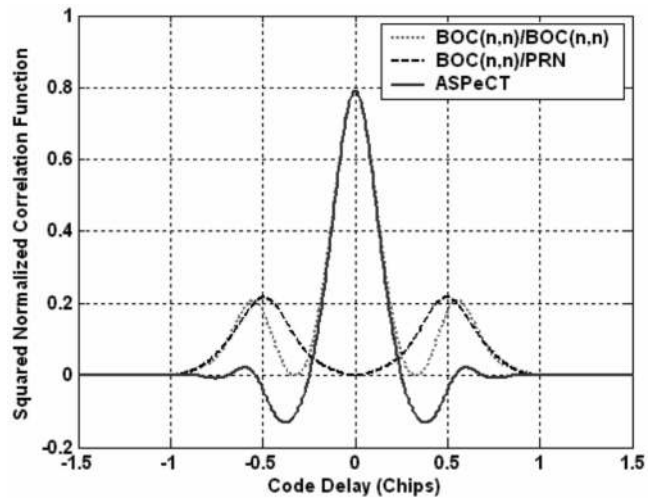

Fig. 7. Sine-BOC($1,1$)/sine-BOC($1,1$), sine-BOC($1,1$)/PRN squared normalized correlation functions and ASPeCT-modified correlation function with a 6 MHz front-end filter (double-sided).

be able to reliably obtain unambiguous measurements. To do so, it is interesting to calculate the correlation of the sine-BOC(n,n) modulated spreading code (PRN code × square-wave subcarrier) with the PRN code only. Without considering front-end filtering, it is equal to [20]

$$R_{B/P}(\tau) = \frac{1}{2}\left(\text{tri}\left(\frac{\tau - \frac{1}{2}}{\frac{1}{2}}\right) - \text{tri}\left(\frac{\tau + \frac{1}{2}}{\frac{1}{2}}\right)\right). \quad (12)$$

Equation (12) shows that $R_{B/P}$ consists of two triangles perfectly located on the side peaks of the sine-BOC(n,n) autocorrelation function, and with exactly the same magnitude. As a consequence, the idea on which ASPeCT is based is to form a synthesized correlation function by subtracting $R_{B/P}^2$ from R_B^2 to remove the undesired side peaks. This is successfully shown in Fig. 6.

However, in reality, one has to take into account the impact of the front-end filter on each correlation function, and as a consequence, on the alignment of the peaks and their respective magnitudes. Fig. 7 shows the impact of a 6 MHz front-end filter bandwidth (double-sided) on the sine-BOC($1,1$) signal. It underlines that a narrow front-end filter could misalign both correlation functions' peaks, inducing the appearance of very small peaks around ±0.6 chips. This can translate into false lock points for high C/N_0 (only peaks of the squared correlation function pointing upward can lead to stable false lock points). This problem has to be taken into account in the design of the code delay discriminator. A solution is to use a coefficient β in the combination of the two squared correlation functions in order to eliminate any small remaining peak. This can be modeled as

$$R_{ASPeCT}(\tau) = \bar{R}_B^2(\tau) - \beta \bar{R}_{B/P}^2(\tau) \quad (13)$$
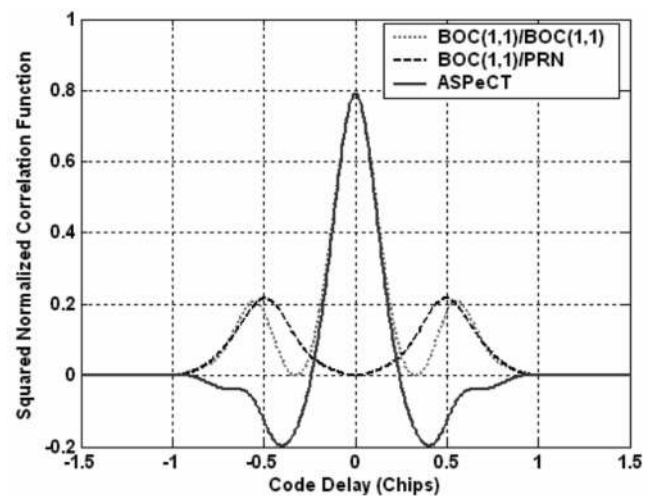
Fig. 8. Sine-BOC($1,1$)/sine-BOC($1,1$), sine-BOC($1,1$)/PRN squared normalized correlation functions and ASPeCT modified correlation function with a 6 MHz front-end filter (double-sided) and $\beta = 1.4$.

where the bar represents the effect of the front-end filter on the correlation functions.

Fig. 8 shows the ASPeCT-modified correlation function using an experimental β value of 1.4 for a sine-BOC($1,1$) signal using a 6 MHz front-end filter bandwidth (double-sided). There is no side peak remaining in the modified correlation function close to the sine-BOC($1,1$) autocorrelation side peaks.

Consequently, a new DLL architecture, based on the previous correlation functions can be proposed. This new architecture is depicted in Fig. 9.

In order to focus on the tracking performance, a modified version of the normalized DP discriminator presented in (8), and based on ASPeCT-modified

Fig. 9.   ASPeCT DLL architecture.

Fig. 10.   ASPeCT DP proposed discriminator output with $\beta = 1$ and $\beta = 1.4$ for an early-late spacing of 0.2 chips and a 6 MHz front end bandwidth (double-sided).

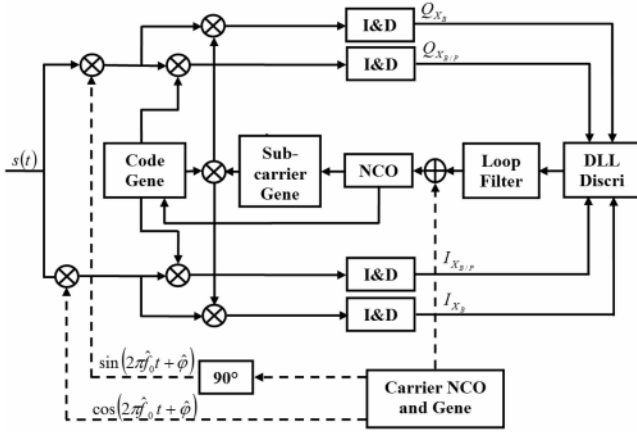correlation function, is proposed hereafter:

$$D_{\mathrm{DP}}^{\mathrm{ASPeCT}}(\varepsilon_\tau)$$

$$= \frac{\left(\begin{array}{c} [(I_{E_\mathrm{B}} - I_{L_\mathrm{B}})I_{P_\mathrm{B}} + (Q_{E_\mathrm{B}} - Q_{L_\mathrm{B}})Q_{P_\mathrm{B}}] \\ -\beta[(I_{E_{\mathrm{B/P}}} - I_{L_{\mathrm{B/P}}})I_{P_{\mathrm{B/P}}} + (Q_{E_{\mathrm{B/P}}} - Q_{L_{\mathrm{B/P}}})Q_{P_{\mathrm{B/P}}}] \end{array} \right)}{(6 + \beta d)(I_{P_\mathrm{B}}^2 + Q_{P_\mathrm{B}}^2)}.$$

(14)

Fig. 10 shows ASPeCT DP discriminator output for a sine-BOC$(1,1)$ signal using a 6 MHz (double-sided) front-end filter for $\beta = 1$ and $\beta = 1.4$ and $d = 0.2$ chips. It also shows the traditional BOC DP discriminator output using the same front-end filter. The choice of $\beta = 1.4$ clearly removes any potential false lock point around ± 0.56 chips. Moreover, it is interesting to note that the discriminator stability domain slightly increases with β: from $[-0.33; 0.33]$ chips for the traditional tracking technique to $[-0.36; 0.36]$ chips for ASPeCT with $\beta = 1$, to $[-0.39; 0.39]$ chips for ASPeCT with $\beta = 1.4$. This is very important when considering the DLL stability for low C/N_0. However, ASPeCT stability domain remains significantly lower than for the BPSK(n) signal tracking, which constitutes the main advantage of the SSL technique (see Fig. 4).

Finally, $\beta = 1.4$ appears to create a false lock point around ± 0.95 chips. This is, however, not a real threat as there is no energy at that location on the ASPeCT-modified correlation function ($R_{\mathrm{ASPeCT}}(0.95) \approx 0$) as already seen in Fig. 8. As a consequence, no false lock will occur even for high C/N_0, as shown in Fig. 11, for a coherent integration time of 1 ms. No false lock was detected at this C/N_0 for a coherent integration time of 20 ms as well.

It is also important to note that the optimal choice of β depends upon the front-end filter and the early-late correlator chip spacing.

Now that ASPeCT's principles have been explained in detail and its unambiguous property has been shown, it is important to study the impact
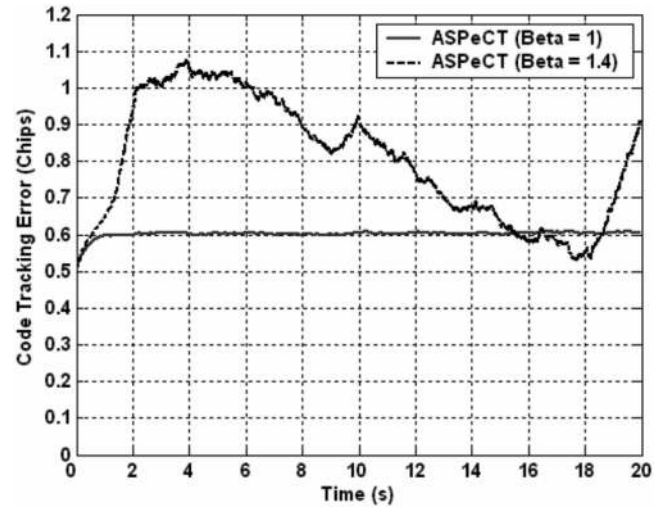
Fig. 11.   Code delay error for a sine-BOC$(1,1)$ signal tracking starting with an initial code delay error of -0.5 chips (2 Hz DLL), an integration time of 1 ms, and for a C/N_0 of 50 dB-Hz for ASPeCT ($\beta = 1$ and $\beta = 1.4$).

of the main sources of error on the code tracking performance to ensure that it does not imply significant drawbacks. As a consequence, the effect of thermal noise and multipath are investigated in the following section.

IV.   IMPACT OF THERMAL NOISE AND MULTIPATH ON ASPECT

A.   Thermal Noise

ASPeCT's code tracking error variance using the nonnormalized DP discriminator and assuming an infinite front-end filter is given by (this is an extension of the formula given in [25], where no
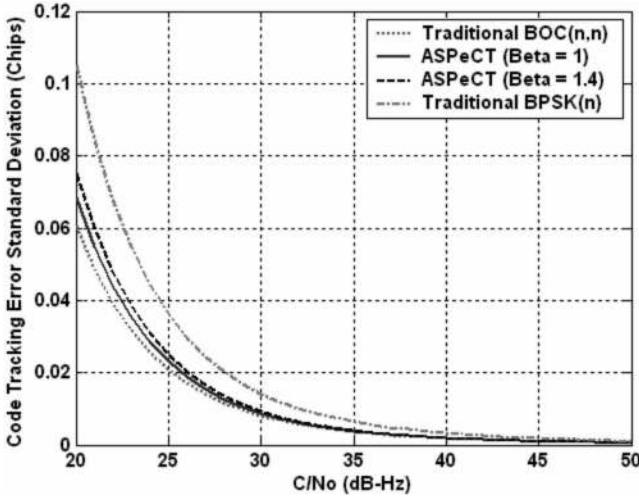
Fig. 12. Code tracking error standard deviation versus the C/N_0 for the traditional sine-BOC(n,n) tracking and ASPeCT ($\beta = 1$ and $\beta = 1.4$) with an early-late spacing of 0.2 chips and a coherent integration time of 1 ms.
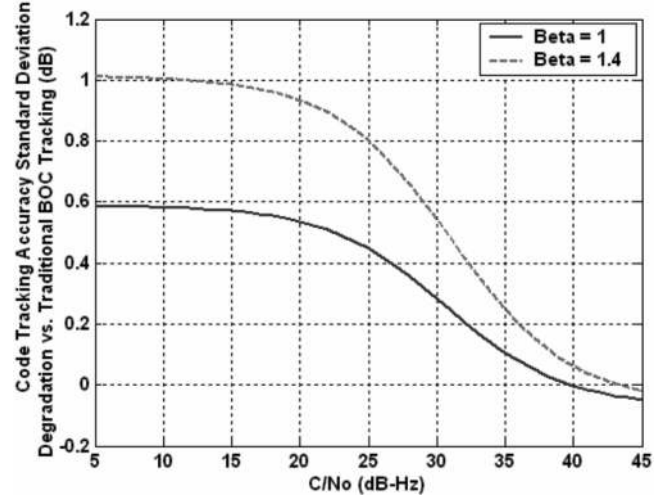
Fig. 13. Code tracking error standard deviation degradation for ASPeCT and traditional sine-BOC(n,n) versus C/N_0 for $\beta = 1$ and $\beta = 1.4$ for an early-late spacing of 0.2 chips and a coherent integration time of 1 ms.

coefficient β was considered):

$$\sigma_{\text{ASPeCT}}^2 = \frac{B_{\text{L}} d(6 + \beta^2 d)}{\frac{C}{N_0}(6 + \beta d)^2} \left(1 + \frac{2(\beta d + 3 + \beta^2)}{\frac{C}{N_0} T_I (6 + \beta^2 d)}\right) (\text{chips}^2).$$

(15)

Fig. 12 shows ASPeCT code tracking error standard deviation for $\beta = 1$ and $\beta = 1.4$ compared with traditional sine-BOC(n,n) and BPSK(n) tracking for a coherent integration time of 1 ms and $d = 0.2$ chips. The degradation using ASPeCT appears to be small and dependent upon the value of β. The lower the value of β, the better the accuracy of ASPeCT's tracking performance. The code tracking error standard deviation degradation in terms of equivalent C/N_0 seems to stabilize for very low C/N_0 at 0.6 dB for $\beta = 1$ and 1 dB for $\beta = 1.4$. The degradation in terms of code tracking accuracy standard deviation for a given C/N_0 is shown in Fig. 13. It is fairly small and stabilizes as well for small C/N_0 at 0.6 dB for $\beta = 1$ and 1 dB for $\beta = 1.4$. It is interesting to see that for very high C/N_0, ASPeCT slightly outperforms the traditional sine-BOC(n,n) tracking.

Although slightly more susceptible to noise than the traditional sine-BOC(n,n) tracking technique for low C/N_0, ASPeCT still significantly outperforms the traditional BPSK(n) tracking performance. As a consequence, it would be preferable to an SSL technique that would only have the BPSK(n) tracking performance. The BJ method would exhibit a slightly better tracking performance than ASPeCT, but with the drawback of potential tracking jumps or false locks at low C/N_0 values.
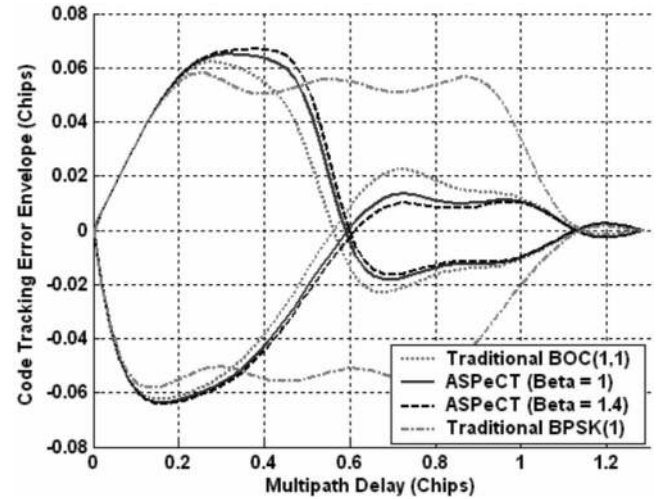
Fig. 14. Code tracking multipath envelope for traditional sine-BOC(1,1), traditional BPSK(1), and ASPeCT ($\beta = 1$ and $\beta = 1.4$) for an early-late spacing of 0.2 chips, and a 6 MHz front-end filter (double-sided).

B. Multipath

Multipath error is due to the mixing, at the antenna level, of the direct signal with delayed replicas of that same signal [26]. Its impact on code tracking depends upon the relative delay and phase difference of the multipath with respect to the direct signal, as well as its relative magnitude. When only one multipath is considered, its resulting error on code tracking is contained within the error created by in-phase and out-of-phase multipath.

Fig. 14 shows the multipath-induced error envelope for traditional sine-BOC(1,1) tracking, as well as for ASPeCT (for $\beta = 1$ and $\beta = 1.4$) for a signal-to-multipath-amplitude ratio of 0.5 and a 6 MHz (double-sided) front-end filter and $d = 0.2$ chips. The difference between the two tracking methods is minimal. For multipath delays within

[0.25;0.5] chips, the traditional method seems to mitigate multipath slightly better than ASPeCT, while for multipath delays within [0.6;1] chips, it is the opposite. The choice of β seems to have only a limited effect on the multipath envelope shape.

ASPeCT offers inherent multipath mitigation very similar to traditional sine-BOC(n,n) tracking. This is extremely important, as the SSL technique has a multipath envelope very similar to that of BPSK(n) signals, which is significantly larger (see Fig. 14). Moreover, ASPeCT is independent of the test required in the BJ technique that could strongly be affected during the checking process when strong multipath is present (and this can also happen when tracking onto a side peak).

C. Conclusions on ASPeCT's Tracking Capabilities and Implementation Issues

The study of the impact of thermal noise and multipath on ASPeCT's tracking performance has shown that it is close to traditional sine-BOC(n,n) tracking performances. The role of the parameter β in the magnitude of the resulting error in the presence of thermal noise and multipath seems very limited. This is of critical importance as it means that ASPeCT can be adapted to any front-end filter by a calibration of the value given to β without affecting its bias-free property, and without degrading significantly its tracking accuracy. A careful calibration should however be done during the receiver realization in order to insure total unambiguous tracking. For this reason, it might be preferable to slightly overestimate β, the counterpart being a slightly degraded tracking performance. In terms of resistance to thermal noise and multipath, ASPeCT would outperform the SSL technique, while performing comparably to the BJ method, however offering only reliable measurements: either the code delay estimation is correct, or the DLL would lose lock.

It is also interesting to note that the DP version of ASPeCT requires the same number of correlators as the BJ technique, which is often considered as the baseline. Still, the use of ASPeCT, or any tracking technique trying to mitigate the bias problem related to BOC modulations, requires the use of a larger number of correlators than classical BPSK tracking. This implies that Galileo L1 civil receivers will probably have a higher power consumption compared to GPS L1 receivers, which might be detrimental for untethered applications (this is emphasized by its wider spectral repartition compared to BPSK(n), that also requires a higher sampling frequency).

One of the potential drawbacks of ASPeCT is that it does not allow recovery from an initial error greater than approximately 0.38 chips, unlike the BJ technique, which can jump back to the main peak. This means that acquisition on a side peak, even

though it is only an error of 0.5 chips, will result in a loss of lock. To solve this problem, one solution is to use the SSL technique to first converge toward the correct code delay before transferring to code tracking using ASPeCT. This would be an approach similar to the one presented in [10]. Another solution is to use the ASPeCT-modified correlation function in an acquisition scheme to remove any potential biased acquisition, as it does not contain any side peaks. This is investigated in the next section.

V. ACQUISITION USING ASPECT-MODIFIED CORRELATION FUNCTION

A detailed description of the spread spectrum signal acquisition theory can be found in [27]. Based on that theory and on (11), the statistical test proposed for the acquisition scheme based on ASPeCT is

$$T_{\text{ASPeCT}} = \sum_{k=1}^{M} ((I_{P_{\text{B}},k}^2 + Q_{P_{\text{B}},k}^2) - \beta(I_{P_{\text{B/P}},k}^2 + Q_{P_{\text{B/P}},k}^2)).$$
(16)

This detection criterion appears as a linear combination of the traditional BOC and BOC/PRN correlation values. According to the ASPeCT-modified correlation function shape given in Fig. 7 and Fig. 8, the coefficient β is assumed equal to 1 from now on, as no major positive peak appears with this value. One drawback with (16) is that it requires two complex correlators (for BOC/BOC and BOC/PRN correlations) for each try, while a traditional acquisition scheme would only need one (BOC/BOC). This can be solved by increasing the number of correlators in the receiver.

It has been proven in [18] that the noise coming from BOC/BOC and BOC/PRN prompt correlation values were independent. Moreover, the difference between two independent random variables has a distribution that is the convolution between the distribution of the first random variable and the distribution of the opposite of the second random variable [28], i.e.:

$$p_{T_{\text{ASPeCT}}}(x) = p_{T_{\text{B}}}(x) \otimes p_{T_{\text{B/P}}}(-x) \qquad (17)$$

where p_α is the distribution of the random variable α.

Assuming Gaussian noise only, it is then possible to model the distribution of T_{ASPeCT} as the convolution of two chi-square distributions, and so to determine the probability of detection of the main peak given a certain probability of false alarm, and a certain C/N_0.

In order to have realistic values, an interfering signal is assumed to cause a cross-correlation peak that has to be taken into account in the acquisition process [27]. This is used to consider a worst case scenario. It allows for calculating the detection threshold from a false detection rate specification. For a given false alarm probability P_{fa}, the detection

Fig. 15. Probability of detection for proposed civil Galileo L1 signal assuming coherent integration time of 4 ms, noncoherent summations of 15 and 50, no code delay error, and probability of false alarm of 10^{-3}.
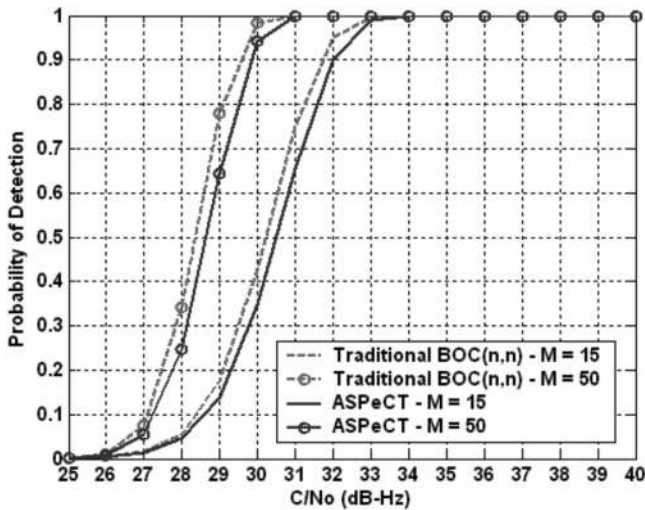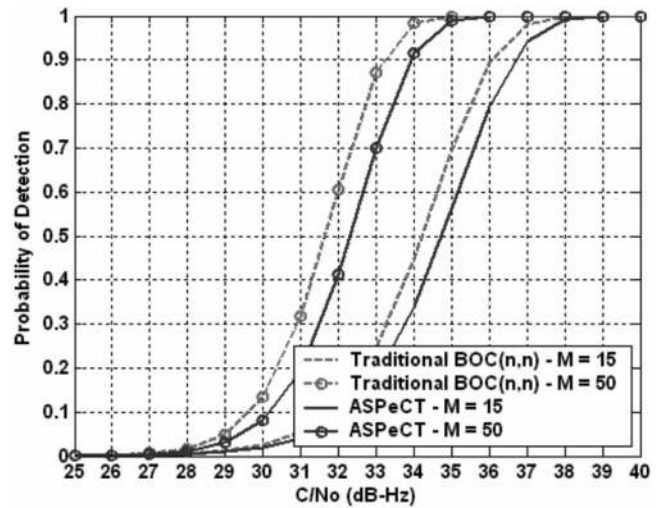

Fig. 16. Probability of detection for proposed civil Galileo L1 signal assuming coherent integration time of 1 ms, noncoherent summations of 15 and 50, no code delay error, and probability of false alarm of 10^{-3}.

threshold Th is given by

$$P(T|_{\text{NoSignal}+1\text{Interf}} > \text{Th}) = P_{\text{fa}}. \qquad (18)$$

Once this threshold has been determined, the probability of detection of the useful signal P_d is given by

$$P_d = P(T|_{\text{Signal}}) > \text{Th}. \qquad (19)$$

As an example, the proposed Galileo L1 signal has been taken into account [16]. It is a sine-BOC$(1,1)$ signal with a code length of 4092 chips. The maximum of the cross-correlation peak is assumed to be 25 dB lower than the main peak. Moreover, the interfering signal is assumed to have a maximum C/N_0 of 50 dB-Hz. The coherent integration time is assumed to be 4 ms. No code delay or Doppler error is assumed in this case, and the P_{fa} was set to 0.001. The resulting P_d is shown in Fig. 15 for a C/N_0 ranging from 25 to 40 dB-Hz, noncoherent summations of 15 and 50, and using both ASPeCT and traditional acquisition schemes. The sensitivity of the acquisition process using ASPeCT is only very slightly degraded (by less than 0.5 dB in terms of equivalent C/N_0) compared with the traditional acquisition scheme. Moreover, one has to keep in mind that the correlation on which ASPeCT's acquisition process is based does not contain sidelobes, making it more reliable than the traditional sine-BOC(n,n) acquisition scheme, which might detect one of the side peaks only 6 dB under the main peak.

It is well known that the probability of detection influences the acquisition time [18]. However, the 0.5 dB equivalent C/N_0 degradation is not expected to significantly degrade this time. Another factor influencing the acquisition time is the size of the acquisition uncertainty region defined as the product of the searched code cells and the number of Doppler bins. In the case of the proposed detection criterion, as the correlation peak is narrower than in the case of BPSK(n), the code cells should be approximately three times smaller, and it will result in a longer acquisition time. This is equivalent to what happens when a high code rate is used in the ranging signal. Yet, the increased acquisition time is balanced by a more accurate code delay estimate. This necessity of numerous correlators is however a drawback compared to a BPSK(n) signal acquisition, which is the approach used by the SSL technique.

It has been shown [20] that for longer coherent integration times (> 20 ms), the proposed acquisition scheme would outperform the traditional acquisition scheme. This phenomenon comes mainly from the fact that the noise component in the test criterion (16) is not purely positive, as it is the case in the classical acquisition criterion (see (11)). This can be very interesting for acquisition on dataless channels where the coherent integration time is unlimited a priori, which will not be the case for Galileo L1 civil signal [3]. Conversely, for shorter coherent integration times, the ASPeCT acquisition technique would have further degraded results, but this degradation compared with the traditional scheme would be around 0.5–1.0 dB only, as seen in Fig. 16 for a coherent integration time of 1 ms.

VI. CONCLUSIONS AND FUTURE WORK

This paper presents a new tracking technique, ASPeCT, dedicated to sine-BOC(n,n) signals, or Manchester encoded ranging signals, that has been shown to be reliably unambiguous. It can be adapted to different types of front-end filters (wide or narrow) in order to have the best tracking performance.

For tracking purposes, its stability domain is slightly greater than that of traditional ambiguous sine-BOC(n,n) tracking. It has also been shown to have very limited degradation compared with traditional tracking in the presence of white Gaussian noise (between 0.6 and 1 dB for the standard deviation for a C/N_0 of 20 dB-Hz). It also possesses an equivalent level of multipath rejection as traditional sine-BOC(n,n) tracking, thus outperforming the SSL tracking technique. Finally, it uses the same number of correlators as the BJ method, not adding any extra power requirements.

ASPeCT can also be used for the signal acquisition process, allowing for a comparable sensitivity to the traditional acquisition scheme, but eliminating any chance of a false peak acquisition. However, in this case, twice as many correlators would be needed to achieve the same mean-time-to-first-fix compared to a traditional acquisition scheme.

Finally, ASPeCT has the advantage of requiring very few changes in a typical GNSS receiver which makes it a promising technique when using sine-BOC(n,n) signals.

The current version of ASPeCT is dedicated to sine-BOC(n,n) signal tracking. Future possibilities to strengthen this technique include (1) trying to adapt the method to other BOC modulations (such as cosine-BOC(n,n), or BOC(n,m) in general) and (2) adapting the technique to evolving signal structure modifications.

REFERENCES

[1]   Spilker, J. J., and Van Dierendonck, A. J.
        Proposed new civil GPS signal at 1176.45 MHz.
        In *Proceedings of U.S. Institute of Navigation GPS Conference*, Nashville, TN, 1999, 1717–1725.

[2]   Fontana, R. D., Cheung, W., Novak, P., and Stansell, T. A.
        The new L2 civil signal.
        In *Proceedings of U.S. Institute of Navigation GPS Conference*, Salt Lake City, UT, 2001, 617–631.

[3]   Hein, G., Godet, J., Issler, J.-L., Martin, J.-C., Erhard, P., R. Lucas-Rodriguez, and Pratt, T.
        Status of Galileo frequency and signal design.
        In *Proceedings of U.S. Institute of Navigation GPS Conference*, Portland, OR, 2002, 266–277.

[4]   Slater, J. A., Weber, R., and Fragner, E.
        The IGS GLONASS pilot project—Transitioning an experiment into an operational GNSS service.
        In *Proceedings of U.S. Institute of Navigation GPS Conference*, Long Beach, CA, 2004, 1749–1757.

[5]   Prasad, R., and Ruggieri, M.
        Applied Satellite Navigation using GPS, GALILEO, and Augmentation Systems.
        Boston: Artech House, 2005.

[6]   Godet, J., de Mateo, J. C., Erhard, P., and Nouvel, O.
        Assessing the radio frequency compatibility between GPS and Galileo.
        In *Proceedings of U.S. Institute of Navigation GPS Conference*, Portland, OR, 2002, 1260–1269.

[7]   Betz, J., and Goldstein, D. B.
        Candidate Design for an Additional Civil Signal in GPS Spectral Bands.
        In *Proceedings of U.S. Institute of Navigation NTM Conference*, San Diego, CA, 2002, 622–631.

[8]   Betz, J. W.
        Binary offset carrier modulations for radionavigation.
        Navigation, Journal of the Institute of Navigation, **48**, 4 (2002), 227–246.

[9]   Fine, P., and Wilson, W.
        Tracking algorithm for GPS offset carrier signals.
        In *Proceedings of U.S. Institute of Navigation NTM Conference*, San Diego, CA, 1999, 671–676.

[10]   Martin, N., Leblond, V., Guillotel, G., and Heiries, V.
        BOC(x,y) signal acquisition techniques and performances.
        In *Proceedings of U.S. Institute of Navigation GPS/GNSS Conference*, Portland, OR, 2003, 188–198.

[11]   Heiries, V., Roviras, D., Ries, L., and Calmettes, V.
        Analysis of non ambiguous BOC signal acquisition performance.
        In *Proceedings of of U.S. Institute of Navigation GNSS Conference*, Long Beach, CA, 2004.

[12]   Lin, V. S., Dafesh, P. A., Wu, A., and Cahn, C. R.
        Study of the impact of false lock points on subcarrier modulated ranging signals and recommended mitigation approaches.
        In *Proceedings of of U.S. Institute of Navigation AM Conference*, Albuquerque, NM, 2003, 156–165.

[13]   Ward, P.
        A design technique to remove the correlation ambiguity in binary offset carrier (BOC) spread spectrum signals (revised version).
        In *Proceedings of U.S. Institute of Navigation NTM Conference*, San Diego, CA, 2004, 886–896.

[14]   Hein, G., Avila-Rodriguez, J. A., Ries, L., and Lestarquit, L., Issler, J.-L., Godet, J., and Pratt, T.
        A candidate for the Galileo L1 OS optimized signal.
        In *Proceedings of U.S. Institute of Navigation GNSS Conference*, Long Beach, CA, 2005, 833–845.

[15]   Gibbon, G.
        Welcome progress in GNSS talks.
        GPS World, Feb. 2004.

[16]   Hein, G., Irsigler, M., Avila Rodriguez, J. A., and Pany, T.
        Performance of Galileo L1 candidates.
        In *Proceedings of the European Navigation Conference GNSS 2004 Conference*, Rotterdam, The Netherlands, session "Galileo System Design," 18 pages, CD-ROM.

[17]   Rebeyrol, E., Macabiau, C., Lestarquit, L., Ries, L., Issler, J.-L., Boucheret, M.-L., and Bousquet, M.
        BOC power spectrum densities.
        In *Proceedings of U.S. Institute of Navigation NTM Conference*, San Diego, CA, 2005, 769–778.

[18]   Holmes, J. K.
        Coherent Spread Spectrum Communications.
        Melbourne, FL: Krieger Publishing Co., 1990.

[19]   Winkel, J. O.
        Modeling and simulating GNSS signal structures and receivers.
        Ph.D. dissertation, Federal Armed Forces University, Munich, Germany, 2000.

[20]   Julien, O., Macabiau, C., Lachapelle, G., Cannon, M. E., and Mongrédien, C.
        A new unambiguous BOC(n,n) signal tracking technique.
        In *Proceedings of the European Navigation Conference GNSS 2004 Conference*, Rotterdam, The Netherlands, session "Signal," 2004, 12 pages, CD-ROM.

[21] Van Dierendonck, A. J.
GPS receivers.
In *Global Positioning System: Theory and Applications*,
New York: AIAA, 329–408.

[22] Ward, P.
Satellite signal acquisition and tracking.
In *Understanding GPS—Principles and Applications*,
Norwood, MA: Artech House, 1997, 119–218.

[23] Van Dierendonck, A. J., Fenton, P., and Ford, T.
Theory and performance of narrow correlator spacing in a
GPS receiver.
Navigation: Journal of The Institute of Navigation, **39**, 3
(Fall 1992), 265–283.

[24] Holmes, J. K., Raghavan, S. H., and Lazar, S.
Acquisition and tracking performance of NRZ and
square-wave modulated symbols for use in GPS.
In *Proceedings of U.S. Institute of Navigation AM
Conference*, Denver, CO, 1998, 611–626.

[25] Julien, O., Macabiau, C., Cannon, M. E., and Lachapelle, G.
New unambiguous BOC(n,n) tracking technique.
In *Proceedings of NaviTec Conference*, Noordwidjk, The
Netherlands, 2004, 8 pages.

[26] Braasch, M. S.
Multipath effects.
In *Global Positioning System: Theory and Applications*,
New York: AIAA, 1996, 547–568.

[27] Bastide, F., Julien, O., Macabiau, C., and Roturier, B.
Analysis of L5/E5 Acquisition, Tracking and Data
Demodulation Thresholds, In *Proceedings of the U.S.
Institute of Navigation GPS Conference*, Portland, OR,
2002, 2196–2207.

[28] Papoulis, A.
Probability, Random Variables and Stochastic Processes
(3rd ed.), New York: McGraw-Hill, 1991.

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