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Unambiguous Techniques in Modernized GNSS Signals

Surveying the solutions

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Global navigation satellite systems (GNSSs) remain, by far, the most reliable and widely spread sources of accurate outdoor positioning. With the advent of the new and modernized signals, novel challenges related to GNSS receivers have also been recognized. One of the most important challenges in dealing with modernized GNSS signals is posed by the oscillatory behavior of the autocorrelation of some of those signals, which causes ambiguities in the measurement of the propagation delay. This article is an extensive survey of the solutions in this area proposed during past decades. Not only does it illustrate that a large pool of solutions is available, but it also shows that none of these solutions alone can currently overcome all of the challenges related to GNSS ambiguities. A thorough overview of the problems caused by the ambiguities in the delay estimation and the unambiguous techniques proposed to counteract them is presented. We hope to spark the interest of the signal processing community and to stimulate new advances in this field. Unambiguous methods are classified into three main classes, and we compare the main solutions in terms of complexity and performance to identify the most promising techniques and directions to be followed. We point out that there is an inherent tradeoff between the unambiguous acquisition and unambiguous tracking, and that the receiver stages of acquisition and tracking can be designed in a disjoint manner when dealing with the ambiguities.

Introduction

Positioning has become a key component in wireless devices today. Users exploit location information for all types of applications, ranging from car navigation, ships and aircraft guidance, and tourist guidance to social networking, photography geocoding, e-health, or infotainment applications. Outdoor positioning techniques rely heavily on GNSSs. Today, we have four GNSSs in the sky, two of which are fully functional—the U.S. global positioning system (GPS) and the Russian Glonass

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system—and two in a developmental phase, the Chinese BeiDou and the European Galileo [1], [2]. All of the GNSS signals employ the direct sequence spread spectrum (DS-SS) technique [3], where the data is spread via system-specific pseudorandom codes [1], [2]. In addition, most of the modernized GNSS signals make use of different variants of a split-spectrum modulation class, called *binary offset carrier* (*BOC*) modulation [2], [4], [5], which is the focus in this article.

One of the most important challenges in dealing with modernized GNSS signals is posed by the oscillatory behavior of the autocorrelation of some of those signals, which causes ambiguities in the measurement of the propagation delay.

The first task of a GNSS receiver is the acquisition, where the receiver calculates a coarse estimation of the code delay, code frequency, and phase shifts. The next task is the tracking, where the receiver more accurately estimates the code delay, phase, and frequency estimates and keeps track of them. The acquisition and code-tracking processes in any DS-SS receiver are typically based on the correlation between the incoming signal and a reference code at the receiver. The main acquisition challenge in a DS-SS receiver is to design an algorithm that is fast, has low complexity, and low power consumption [3], [6]. The main code-tracking challenges in DS-SS are to avoid losing track of the signal (loss-of-lock situation), to operate well under noisy conditions, and to achieve high accuracy of the code and carrier estimates in both single and multipath channel conditions, while preserving a reasonable complexity of the receiver [3].

When a DS-SS signal also uses BOC modulation [4], [5], there is a supplementary and major challenge that has to be considered. This is the challenge of ambiguities in the time delay estimates and it will form the core of this article. This challenge is caused both by the notches or low-level values and the multiple peaks appearing within ± one chip from the main correlation peak in the correlation envelope. The term *ambiguity* refers to the notches, as illustrated in Figure 1. To better illustrate this problem, the unambiguous shape of a binary phase-shift keying (BPSK)-modulated signal is also shown for reference. In the acquisition, the challenge stays in the tradeoff between a fast process (involving large steps in testing different possible correlation times) and a misdetection, which can be caused by a too-large step that would place consecutive correlations in the notches of Figure 1 instead of close to one of its peaks. In the tracking, the challenge comes from the presence of multiple peaks of the cross-correlation between the incoming signal and the issue of correctly discriminating between the "true" maximum peak and the rest of peaks ("false peaks"). The ambiguities discussed here are related only to the acquisition and code-tracking parts, and not to the carrier phase-tracking part. As a side note, the ambiguity terminology refers to a completely different thing in the context of precise point positioning (PPP) and carrier-phase trackers. The carrier-phase ambiguity or the integer ambiguity refers to the unknown number of integer carrier cycles that occur during the signal propagation from the satellite to the receiver. The code ambiguities addressed here refer to the notches in the envelope of the code correlation functions, as described previously. For readers interested in carrier-phase tracking, see the survey in [7]. For a PPP ambiguity treatment, more details can be found in [8].

Research on the GNSS signals' ambiguities and solutions has been active in the past decades, even from the first studies on the modernized GPS signals, but the ambiguities-related analyses and results have been typically presented in a nonunified manner and have not offered compact and unified views of the several existing approaches. This article aims to cover this gap by offering, from a signal processing perspective, a unified, comprehensive, and systematic coverage on the ambiguity challenges and proposed solutions in the context of acquiring and tracking modernized GNSS signals. The performance assessment under realistic standardized wireless channels of the solutions presented here is, however, outside the scope of this article. Interested readers can find a wide pool of standardized International Telecommunication Union-Radiocommunication (ITU-R) Sector channels for land mobile Earth-space telecommunication systems in [9].

Generic DS-SS receiver chain and code-tracker classification

Figure 2 shows a generic block diagram of the code acquisition-tracking chain of a GNSS receiver. The unambiguous

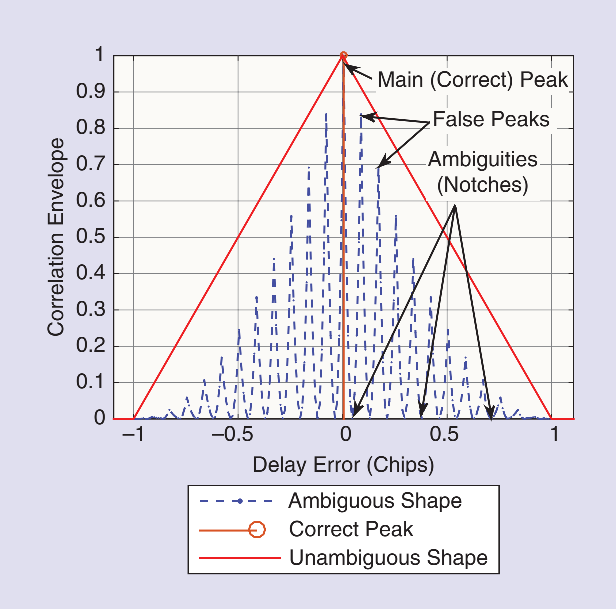

FIGURE 1. An illustration of the ambiguities and false peaks in the correlation envelope.

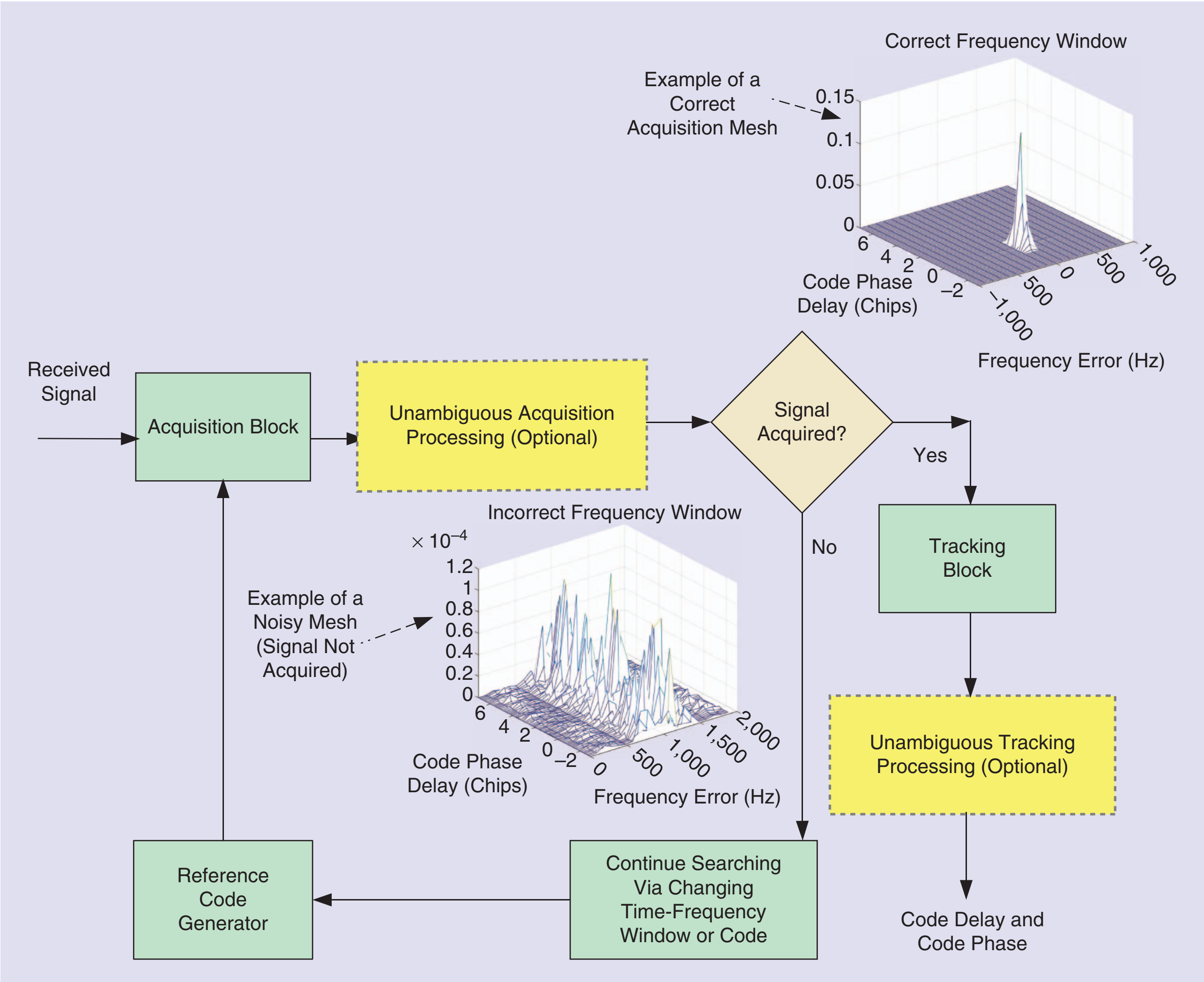

FIGURE 2. The acquisition-tracking chain of a GNSS signal, with the possible places of the unambiguous processing.

processing stages, as seen in Figure 2, can be added in the acquisition stage, the tracking stage, or both stages (see the section "Unambiguous Solutions"). We can classify the code trackers according to three classes, shown in Figure 3: 1) code trackers based only on correlation outputs and typically relying on at least three correlators, 2) code trackers based on some form of subspace processing, and 3) code trackers based on other forms of nonlinear processing. In addition to the code-tracking structures that output a code delay estimate, there are also alternative structures in GNSSs, which compute directly the position/velocity/time solution [10].

The class corresponding to multicorrelator structures [11], [12], which is also the class used in the simulations shown in this article, includes the majority of the code trackers. Typically, multicorrelator structures are quite robust to noise and those with more than three correlators are also usually able to cope with multipaths, to some extent. Multipaths refer to the nonline-of-sight (NLOS) components due to signal reflections, which affect the accuracy of the line-of-sight (LOS) delay estimate if unmitigated. The two most known and widely used code trackers in this category are the narrow correlator (NCORR) and the high-resolution correlator (HRC) [13], which are the ones used in our simulations. The second category of code trackers, based on subspace decomposition, includes algorithms well known in the signal processing community, such as multiple signal classification or space alternating generalized expectation maximization [12], [14]. Usually, such approaches have good accuracy and multipath mitigation capability in very good signal conditions, but they are sensitive to noise. A third category of code trackers, as shown in Figure 3, includes various nonlinear processing algorithms, such as peak tracking and the wavelet transform [2], [11]. Typically, such algorithms enhance the performance in multipath, at the expense of a higher complexity or less robustness to noise than other categories of code trackers. A direct estimation of the receiver position, without explicitly obtaining the delay estimates, is also possible and is done in the alternative structures shown on the right-hand side of Figure 3. Examples in this category includes the vector delay locked loop and the direct position estimator (DPE) [10].

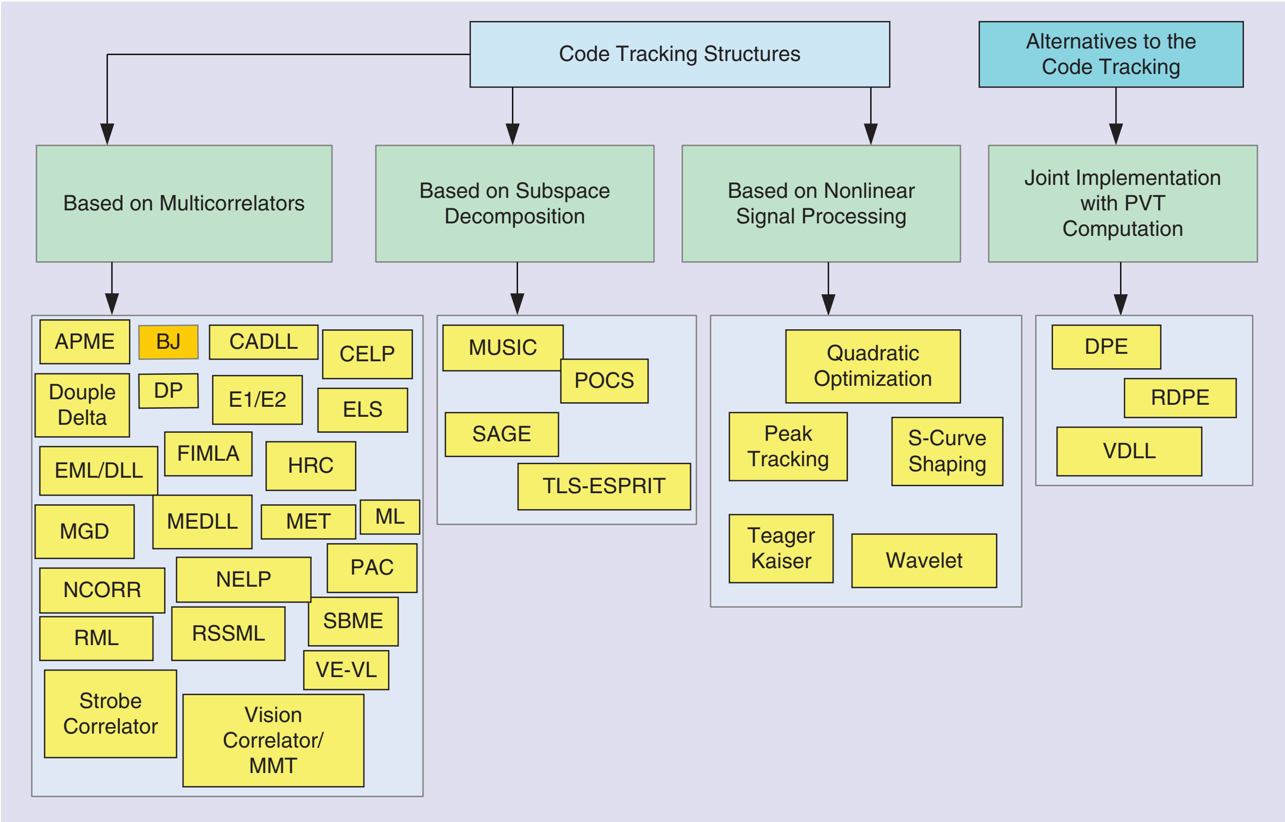

FIGURE 3. Our classification of the code trackers in generic DS-SS systems. PVT: position, velocity, time; MUSIC: multiple signal classification; SAGE: space alternating generalized expectation maximization; VDLL: vector delay locked loop; MGD: multiple gate delay; FIMLA: fast iterative maximum likelihood algorithm; RML: robust maximum likelihood; SBME: slope-based multipath envelope; VE-VL: very early-very late; MMT: multipath mitigation technique; RSSML: reduced search space maximum likelihood; CELP: coherent early late processing; ELS: early late slope; POCS: projection onto convex sets; TLS-ESPRIT: total least squares-estimation of signal parameters via rotational invariance techniques; NELP: noncoherent early late processing; MEDLL: multipath estimating delay lock loop; CADLL: coupled amplitude delay lock loop; APME: a posteriori multipath envelope; EML/DLL: early minus late/delay lock loop.

The motivation of having so many available code-tracking structures (Figure 3) comes from the fact that there is not a unique optimization criteria to be targeted, but instead, different trackers address different criteria, such as maximizing accuracy, minimizing mean time to lose lock, minimizing implementation complexity, etc. Furthermore, a systematic approach for deriving these trackers is sometimes missing, as they are often proposed in an ad-hoc manner based on empirical evidences. In addition, finding nonpatented solutions may also be a target, as many of the structures enumerated in Figure 3 are already covered by patents. To the best of our knowledge, there is no exhaustive comparison between all of the available code-tracking structures in terms of their performance and complexity, but partial results can be found, e.g., in [12] for comparing several open-loop code trackers, in [14] for a brief survey of tracking loop-based multipath mitigation techniques, in [11] for another survey of multipath mitigation techniques for GNSS, and, finally in [2] for a classification of code-tracking methods in GNSS. More advanced tracking structures, such as those based on antenna arrays, are discussed, for example, in [15] and are out the scope of this article.

The code trackers enumerated in Figure 3 are generic (for any DS-SS) and they do not treat explicitly the additional challenges created by BOC modulation, with the exception of the bump jumping (BJ) technique (shown with different color), which can be used with and without ambiguities. BJ will be discussed in more detail in the section "Comparative Summary." However, as described next, such generic structures can be combined with unambiguous stages.

BOC modulation and the challenges of the ambiguities

BOC modulation

A BOC-modulated signal is a signal with a split spectrum, when the baseband signal energy is moved away from the zero frequency and there is a notch in the signal spectrum at zero frequency. Such a frequency split is realized dividing the signal into subchips or BOC units with alternating sign. The number of BOC units per one chip is called the *BOC modulation factor,* and it is denoted here via N_B [16]. There are two basic types of BOC modulation: a sine BOC modulation, referred to as BOC from now on (created by taking the sign of a sine carrier), and cosine BOC modulation, which we will refer to as BOCc (created by taking the signum of a cosine carrier):

$$s_{\mathrm{BOC}}(t) = \mathrm{sign}(\sin(N_B \pi t f_c)), 0 \le t \le 1/f_c$$
$$s_{\mathrm{BOC}_c}(t) = \mathrm{sign}(\cos(N_B \pi t f_c)), 0 \le t \le 1/f_c, \quad (1)$$

where f_c is the code chip rate. If we consider the reference chip rate of a C/A GPS code f_{ref} = 1.023 MHz, the typical notations for BOC and BOC_c modulations are $\mathrm{BOC}(m, n)$ and $\mathrm{BOC}_c(m, n)$, respectively, with $m = N_B f_c / 2 f_{ref}$ and $n = f_c / f_{\mathrm{ref}}$. It is noted that there can be many BOC or BOC_c waveforms of the same order N_B. For example, BOC(1, 1) and BOC(2, 2) modulations have exactly the same modulation order N_B = 2, but different chip rates: 1.023 MHz and 2.046 MHz, respectively. The relationship between the BOC modulation order and the m, n parameters of a BOC modulation is $N_B = 2m/n$.

As an example, let us assume that a three-chip sequence [1, 1, –1] is transmitted via a BOC-modulated signal of order $N_B = 2$. The BOC-modulated signal will basically "split" each chip into two alternating subchips 1, –1, and the resulting sequence to be transmitted will be [1, –1, 1, –1, –1, 1]. In the BOCc case, the resulting signal looks like splitting each subchip further into two sub-subchips with alternating sign [16]. The BOCc-modulated signal of order NB = 2 of the aforementioned chip sequence will be [1, –1, –1, 1, 1, –1, –1, 1, –1, 1, 1, –1], where the corresponding duration of each digit will be half compared to the BOC case. It is as if the BOCc modulation acts as a double BOC modulation [16], and that is why we can model both sine and cosine BOC modulations with an additional parameter called $N_{\cos}$, which is equal to one for BOC and equal to two for BOCc signals. In addition to the basic sine and cosine BOC waveforms, there are several other BOC-based modulations typically obtained by combining sine and cosine BOC modulations of various orders. For example, the multiplexed BOC (MBOC) modulation used in Galileo and modernized GPS is obtained as a combination of two BOC signals of orders $N_B = 2$ and N_B = 12, respectively, and it has two main variants: a composite BOC (CBOC), relying on weighted multiplexing, and a time MBOC (TMBOC), relying on time multiplexing. The alternate BOC (AltBOC) modulation is obtained as a combination of a BOC with a BOC_c of the same orders. More details on various BOC modulation classes and their equivalent models can be found, e.g., in [1], [2], [5], and [16].

Ambiguity-related challenges

The notches or ambiguities are very challenging in the acquisition process because, for correctly acquiring a correlation peak, the time distance between two consecutive correlations, also called the *search step in time* $(\Delta\tau)_{\mathrm{bin}}$, has to be sufficiently small to not miss a correlation peak, but at the same time, it has to be sufficiently high to ensure a fast acquisition process. For example, in BPSK-modulated codes in GPS, where the main lobe width is two chips, a time-bin step of 0.5 chips is typically used [2], [3], [6]. However, in a BOC-modulated case, the main lobe of the correlation envelope (see an example in Figure 1) has a width close to $1/N_B$, which means that a time-bin step higher than this value can significantly increase the misdetection probability in the acquisition stage. This approximation of the main lobe width is more exact as the N_B increases; the exact main lobe width values are shown in Table 1. To minimize the misdetection probability in the acquisition, it is good to choose a small time-bin step: $(\Delta\tau)_{\mathrm{bin}} \le 1/(2N_B)$. On the other hand, the acquisition time and complexity are inversely proportional to the search step (a larger time step means a faster acquisition), meaning an acquisition complexity of the

Table 1. A list of signals proposed or already in use for GNSS that are vulnerable to ambiguities.

Modulation Type	Ambiguous (Yes/No)	Number of ambiguities within one chip	Main lobe width [chips]	Where used [1], [2]
CBOC(+)	Yes	2	0.70	Galileo (E1-B)
CBOC(–)	Yes	2	0.69	Galileo (E1-C)
TMBOC	Yes	2	0.70	GPS(L1C-p), BeiDou (B1-C)
TMBOC	Yes	2	0.70	GPS(L1C-p), BeiDou (B1-C)
AltBOC (15, 10)	Yes	4	0.33	Galileo(E5)
BOC (1, 1)	Yes	2	0.67	GPS(L1C-d), Glonass (L1OC-p, L1OCM), BeiDou (B1-C)
BOC(5, 2.5)	Yes	6	0.28	Glonass (L1SC)
BOC (10, 5)	Yes	6	0.28	GPS(M-code)
BOC (14, 2)	Yes	12	0.07	BeiDou (B1-D, B1-P)
$\mathrm{BOC}_c(10, 5)$	Yes	8	0.22	Galileo (E6-A)
$\mathrm{BOC}_c(15, 2.5)$	Yes	24	0.08	Galileo (E1-A), BeiDou (B3-A)

order $O(1/(\Delta\tau)_{\text{bin}})$. If we assume that the code length in chips is L_{code} and the number of frequency bins to be searched in the acquisition stage is N_{freq}, Table 2 shows the required number of correlators to search the whole time-frequency space and the minimum possible sampling frequency to acquire the desired time resolution. The number of multiply and accumulate (MAC) operations per one frequency bin are also showing, assuming a fast Fourier transform (FFT) implementation of the acquisition stage with N_{fft} FFT points. N_{fft} is typically taken as the next power of two higher or equal with the number of required correlators. Clearly, $(\Delta\tau)_{\text{bin}}$ plays an important role and defines the tradeoff between a low-complexity acquisition and a high-resolution or accurate acquisition.

Table 2. Acquisition complexity as a function of $(\Delta\tau)_{\text{bin}}$.

Number of correlators N_{corrs}	$L_{\text{code}} * N_{\text{freq}} / (\Delta\tau)_{\text{bin}}$	$O\left(\frac{1}{(\Delta\tau)_{\text{bin}}}\right)$
Minimum sampling frequency f_s	$\left\lceil \frac{1}{(\Delta\tau)_{\text{bin}}} \right\rceil$	$O\left(\frac{1}{(\Delta\tau)_{\text{bin}}}\right)$
MAC operations [17] in an FFT-based acquisition	$9N_{\text{fft}} + 4N_{\text{fft}}\log_2(N_{\text{fft}})$ $N_{\text{fft}} = next2pow(N_{\text{corrs}})$	$O\left(\frac{1}{(\Delta\tau)_{\text{bin}}\log_2((\Delta\tau)_{\text{bin}})}\right)$

To increase the speed and decrease the complexity of the acquisition, methods that deal with the notches in the ambiguous function have been found to be able to use a larger value of $(\Delta\tau)_{\text{bin}}$ (for example the same 0.5 chips as used in the legacy GPS signals). Such methods will be discussed in the section "Unambiguous Solutions."

In tracking, the challenges come from the presence of false peaks, because the code estimate can easily jump from the correct peak to a false peak (see Figure 1), especially when there are many false peaks within ±1 chip from the main peak. It is easy to see that both the number of ambiguities and the number of false peaks for a BOC-modulated signal is equal to $2(N_B + N_{\cos}) - 4$. The more ambiguities we have, the more challenging it is to mitigate them in acquisition and tracking. Higher-order BOC-modulated signals are more challenging than lower-order BOC modulation signals and cosine-BOC modulated signals are more challenging than sine-BOC modulated signals of the same N_B order. Also, the nearest incorrect peak to the main one is placed at $\pm 1/N_B$ from the main peak, so an increased BOC modulation order implies a closely spaced strong fake peak.

In addition to the basic sine and cosine BOC waveforms, there are several other BOC-based modulations typically obtained by combining sine and cosine BOC modulations of various orders.

Modulation types used in modernized GNSSs

It was previously mentioned that the ambiguities pose a threat in the modernized GNSS signals. To understand better which GNSS signals suffer of ambiguities, Table 1 shows the signals proposed or already in use in GNSS that will rely on BOC. The number of ambiguities (also equal to the number of false peaks) and the type of GNSS signals using such modulations are also shown. Details on various GNSS signals and bands can be found, e.g., in [1]. All future GNSS modulations will have to deal with the ambiguities. Also, as higher BOC modulation orders implies more challenging acquisition and tracking structures, the most challenging modulations in GNSS are the BeiDou B1-D, B3-A, and B1-P signals and the Galileo E1-A and E6-A signals.

Unambiguous solutions

Generic block diagram for unambiguous processing

To have a unified view of unambiguous techniques, we present them all via a generic block diagram, as shown in Figure 4. The general procedure is the following: first, the received signal and the reference codes are filtered with various linear or nonlinear filters (most cases use linear time-invariant or time-variant filters), denoted here via RxFilt$i$ (filters for the received signal) and CFilt$i$ (filters for the reference codes) with $i = 1:N$ and N being the number of (dual) branches, then correlated, possibly averaged coherently and then noncoherently combined or postprocessed. The filter purposes, filter types, number N of branches, and noncoherent processing in the combiner block differ for one algorithm to another. The main algorithms and how they fit into the block diagram of Figure 4 are presented next. As shown in Figure 4 and described in detail in the section "Principal Dichotomy of Unambiguous Solutions: Wide Main Lobe Versus Narrow Main Lobe," the unambiguous processing can be based either on widening the main correlation lobe, or on preserving the narrow main correlation lobe, while removing some or all of the sidelobes of the correlation envelope.

In Figure 4, we denote via $R_i, i = 1, 2, \ldots, N$ the outputs of the coherent integration. R_i in each branch clearly depend on the receiver and code filters (RxFilt and Cfilt) in that particular branch. Most unambiguous algorithms rely on $N = 1$ or $N = 2$ branches, but there are also some unambiguous algorithms employing a number of branches proportional to the BOC modulation order. For the solutions with $N = 1$ or $N = 2$, the combiner is typically a weighted combination of the envelopes or squared envelopes of the R_1 and R_2 correlations shown in Figure 4 followed by noncoherent averaging. In some unambiguous algorithms, not only are the envelopes $|R_1|$ and $|R_2|$ used in the weighted combinations, but also the envelope of their difference $|R_1 - R_2|$. To be able to use this generic model of Figure 4 for the vast majority of unambiguous approaches, in some algorithms, the RxFilt and CFilt filters are absent or the branch corresponding to them is absent. The ambiguous or full-BOC processing can also be modeled via the block diagram in Figure 4; for full-BOC, we have two dual branches ($N = 2$), the received signal filters RxFilt$_1$, RxFilt$_2$ are not used, and the reference code filters CFilt$_1$, CFilt$_2$ are the BOC modulation filters whose transfer functions are, e.g.,

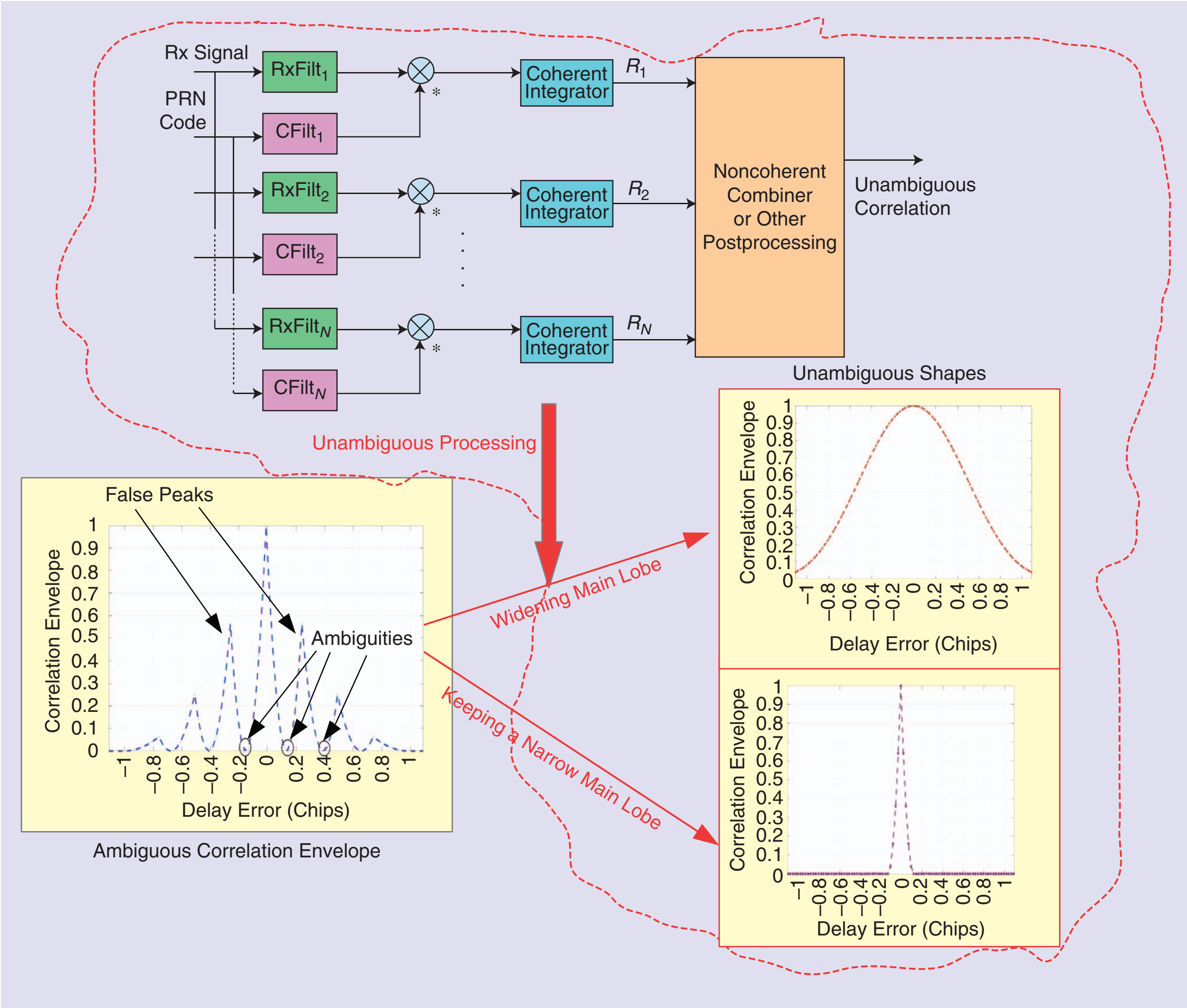

FIGURE 4. A generic block diagram of unambiguous processing, including examples of the two types of unambiguous shapes: with wide main lobe and with narrow main lobe.

found in [16]. Table 3 provides a snapshot of the exact mathematical expressions of the combiner/noncoherent processor and filters for eight unambiguous algorithms to provide an idea of how the different unambiguous algorithms can be easily modeled with the unique block diagram in Figure 4. The N_{nc} factor in Table 3 stands for the number of noncoherent blocks used in the postintegration, and $\alpha \in (0,1)$ is a variable parameter of the model, to be empirically chosen. The detailed mathematical derivations for all of the algorithms are, however, not within the scope of this article; interested readers are directed to the references shown in Table 4 for the mathematical details of other unambiguous algorithms. Additionally, the following sections provide a more detailed description of some of the most known unambiguous algorithms and their main characteristics.

Principal dichotomy of unambiguous solutions: Wide main lobe versus narrow main lobe

There are basically two approaches in trying to get rid of the ambiguities (illustrated in Figure 4): 1) we either try to recover a BPSK-like correlation envelope, or, equivalently to widen the main lobe width of any BOC modulated signal from subchip level (see Table 1) to two-chip width, which is the width of the BPSK modulation, or 2) we try to cancel most or all of the sidelobes and keep mainly or only the main correlation lobe. These two categories are referred to as *wide main lobe unambiguous methods* and *narrow main lobe unambiguous methods*. A combined or hybrid approach that mixes wide and narrow main lobe solutions is also possible and discussed next. These three classes (wide, narrow, and hybrid) are shown with three different colors in Figure 5.

Wide main lobe unambiguous processing

From the category of wide main lobe unambiguous methods, we have, for example: the Betz and Fishman (BF) methods, also known as *sideband processing methods* [4], [18], the Martin and Heiries (MH) methods, the unambiguous adjacent sidelobe (UAL) methods, the Benedetto methods [19], the zero-forcing shaping (ZFS) [20], and the minimum mean square error shaping (MMSES) [20]. BF, MH, and UAL all have either single sideband or dual sideband implementation, according to whether only one side frequency lobe (upper or lower) or both are used in the noncoherent combiner, i.e., $N = 1$ for single sideband and $N = 2$ for dual sideband processing. The differences between the BF, MH, and UAL algorithms lie mainly in the way the signal and the reference codes are filtered. For example, in BF approaches, only the main frequency lobes of both the received signal and reference codes are used; in MH approaches, both main frequency lobes and everything in between are used, while in UAL approaches, there is no lobe selector applied on the received signal; in this latter approach, only a frequency shift filter is used to align the main frequency lobes (occurring at $\pm N_B f_c/2$) to zero frequency and to be able to correlate them with a BPSK reference code, whose main spectral energy is also around zero frequency. Also, modified approaches mBF and mMH have been proposed [18] for a lower-complexity implementation of BF and MH, respectively, but the performance remains the same as with BF and MH. The Benedetto methods rely on filtering the ambiguous correlation function with two types of filters: either with a low-complexity three-tap filter (Benedetto method 1) or with a seven-tap filter (Benedetto method 2), which also eliminates the unwanted BOC spectrum replicas [19]. The ZFS and MMSES rely on equalization in the frequency domain and aim at recreating a BPSK-like correlation shape through zero-forcing or MMSE equalization [20]. It was shown in [20] that such methods are very sensitive to noise; their complexity is also quite high.

The more ambiguities we have, the more challenging it is to mitigate them in acquisition and tracking.

Narrow main lobe unambiguous processing

In this category, we have, for example,

- the pseudocorrelation function (PCF) or PCF-based unambiguous delay lock loop (PUDLL) algorithms [11], [21]
- the general removing ambiguity via sidepeak suppression (GRASS) [21]
- the improved GRASS (IGRASS) [22]
- the simultaneous perturbation stochastic approximation (SPSA) [23]
- the sidelobe cancelation method (SCM) [24]
- the sidelobe cancelation (SLC) algorithm [25]
- QBOC [26]
- Ren et al. [27]
- Huihua et. al [28].

PCF/PUDLL, GRASS, IGRASS, and SPSA are based on the generic block diagram of Figure 4 with $N = 2$. For example, PCF and PUDLL use the unfiltered received signal (i.e., RxFilt_1 and RxFilt_2 are absent), and they filter the reference codes with several subcorrelation shapes filters, ($\mathrm{CFilt}_1 \neq \mathrm{CFilt}_2$), to get rid of the ambiguities. A similar approach as for PCF/PUDLL is used in the GRASS and SPSA, with the main differences in the subcorrelation shapes filters and in the combining rule. The difference between IGRASS and GRASS lie in the fact that IGRASS works for all types of BOC modulations, while GRASS is limited to even BOC modulation orders. Nevertheless, since currently in GNSS we only have even BOC modulation orders and since IGRASS complexity is higher than GRASS complexity, the IGRASS algorithm is (despite its name) is outperformed by GRASS.

The SCM starts from the ambiguous correlation and applies a nonlinear pulse subtraction filter to the noncoherent ambiguous BOC correlation to diminish or remove the sidelobes. The pulse subtraction filter is designed according to the BOC modulation order [24]. The SLC, despite its close name to the SCM, uses a completely different approach: it filters the reference code with $N \geq 2$ subcorrelation shape filters, with N depending on BOC modulation order and the sine/cosine type (N can be up to 24), and it correlates the filtered reference code with

Table 3. A snapshot of linear time-variant filters and combiner rules in the generic block diagram of Figure 4 for eight unambiguous algorithms: dual BF, single BF, dual UAL, GRASS, PUDLL/PCF, ZFS, MMSES, and quadratic BOC (QBOC); see the section "Principal Dichotomy of Unambiguous Solutions: Wide Main Lobe Versus Narrow Main Lobe" for explanations on the abbreviations.

Technique	$\mathrm{RxFilt}_1\,(f,t)$	$\mathrm{CFilt}_1\,(f,t)$	$\mathrm{RxFilt}_2\,(f,t)$	$\mathrm{CFilt}_2\,(f,t)$	Combiner
BF dual	Upper main lobe selector	Same as RxFilt_1	Lower main lobe selector	same as RxFilt_2	$\frac{1}{2N_{nc}}\sum^{N_{nc}}(\lvert R_1\rvert^2+\lvert R_2\rvert^2)$
BF single	Upper main lobe selector	Same as RxFilt_1	0 (i.e., absent)	0	$\frac{1}{N_{nc}}\sum^{N_{nc}}(\lvert R_1\rvert^2)$
UAL dual	Frequency shift with $+N_B f_c/2$	Hold filter	Frequency shift with $-N_B f_c/2$	Hold filter	$\frac{1}{2N_{nc}}\sum^{N_{nc}}(\lvert R_1\rvert^2+\lvert R_2\rvert^2)$
GRASS	1	BOC filter	1	Subcorrelation shape filter	$\frac{1}{N_{nc}}\sum^{N_{nc}}(\lvert R_1\rvert-\alpha\lvert R_2\rvert)$
PUDLL/PCF	1	Subcorrelation shape filter 1	1	Subcorrelation shape filter 2	$\frac{1}{N_{nc}}\sum^{N_{nc}}(\lvert R_1\rvert+\lvert R_2\rvert-\lvert R_1-R_2\rvert)$
ZFS and MMSES	1	BOC filter and ZF or MMSE filter	0	0	$\frac{1}{N_{nc}}\sum^{N_{nc}}(\lvert R_1\rvert)$
QBOC	1	BOC filter	1	QBOC filter	$\frac{1}{N_{nc}}\sum^{N_{nc}}(\lvert R_1\rvert-\alpha\lvert R_2\rvert)^2$

Table 4. The summary of unambiguous methods. Ambiguous or full BOC is shown first, as a benchmark. N/A= not applicable.

Technique and year when first published	Examples of References	Wide main lobe (Yes/No)	Valid for all BOC (Yes/No/Both)	Complexity of unambiguous part	Noise robustness	Acquisition performance	Accurate tracking in noise	False lock threat mitigation	Performance in multipath
Full BOC or aBOC (2001)	[2], [4], [18]	No	Yes	None	High	Low	High	None	Moderate
Bump-Jumping (BJ) (1999)	[37]	No	Yes	Very little	High	Low	High	Moderate	Moderate
BF (single/dual) or Sideband Processing (2001)	[4], [18]	Yes	Yes	High	High	Very High	Low	High	Low
MH (single/dual) "BPSK-like," and modified MH (2004)	[18], [38]	Yes	Yes	High	Moderate	High	Low	High	Low
SCM (2007)	[24]	No	Yes	Low	High	Low	High	Low	High
AsPeCT (2007)	[39]	No	No, only BOC (n, n)	Low	High	Low	High	Moderate	High
UAL (single/dual) (2008)	[18]	Yes	Yes	Moderate	Moderate	High	Moderate	Moderate	Moderate
PUDLL and PCF (2010)	[11], [21] (ch. 3)	No	Yes	Low	Moderate	Low	Moderate	Moderate	Moderate
GRASS (2010)	[21]	No	No, only BOC/ BOCc with even N_B	Low	Low	Low	Low	Moderate	Moderate
DET and DE (2011)	[27], [31], [32], [33]	Both	Yes	Very High	Moderate	N/A	High	High	Moderate
ZFS and MMSES (2011)	[20]	Yes	Yes	High	Very Low	Moderate	Moderate	High	Moderate
Huihua (2011)	[28]	No	No, only BOC $(2n, n)$	High	Low	Low	Moderate	High	Moderate
Qi (2012)	[40]	No	No, only BOC(n, n)	Moderate	Low	Low	Moderate	Moderate	Moderate
SLC (2012)	[25]	No	Yes	Very High	Very low	Very low	Low	High	High
Lee (2012)	[41]	No	No, only Sin/BOC$_c$ with even N_B	High	Moderate	Low	Moderate	Moderate	High
Ren et al. (2013)	[27]	No	Yes	High	Moderate	Low	Low	Moderate High	Moderate
Code smoothing (2013)	[29]	Both	Yes	Moderate	High	N/A	High	Very High	Moderate
Benedetto (2013)	[19]	Yes	Yes	Low	Moderate	Low	Low	Moderate	Moderate
SLL (2013)	[42]	Yes	Yes	High	Moderate	Moderate	Moderate	Moderate	Moderate
SPSA (2013)	[23]	No	No, only BOC$_c$	Moderate	Low	Low	Moderate	Moderate	Moderate
Astrium correlator (2014)	[34]	Both	Yes	High	Moderate	N/A	High	High	Moderate
DPE1 (2014)	[30]	Both	Yes	Very High	Moderate	N/A	High	High	Moderate
IGRASS (2014)	[22]	No	Yes	High	Low	Low	Low	Moderate	Moderate
ISPA (2015)	[43]	No	Yes	Moderate	Low	Low	Low	Moderate	Moderate
CCART (2015)	[44]	No	No, only BOC with even N_B	Very High	Low	Moderate	Moderate	High	High
QBOC (2015)	[26]	No	Yes	High	Moderate	Low	Moderate	Low	Moderate
DDPE (2016)	[45]	Yes	Yes	High	Low	Moderate	Moderate	High	Low

the received BOC-modulated signal. The SLC is able to completely cancel all of the sidelobes, but it pays the price of a very low robustness to noise.

Hybrid unambiguous processing

The hybrid or combined wide/narrow main lobe algorithms either combine the full BOC with a wide main lobe algorithm (e.g., code smoothing [29]) or use the joint code and subcarrier ambiguity removal. In this way, these algorithms offer both a code-level wide main lobe correlation and a subcarrier narrow main lobe correlation (e.g., double phase estimator [30], double estimator technique [27], [31]–[33], and Astrium correlator [34]). Code smoothing [29] relies on combining and filtering the tracking outputs of a full BOC with an unambiguous BOC (e.g., BF). The Astrium correlator [34] uses two cooperative code-tracking loops: one for the subcarrier code phase and one for the carrier code phase, which are also aided by a carrier phase-tracking loop. It was shown in [34] that the tracking performance of the Astrium correlator is very similar to the double estimator technique (denoted as *DE* or *DET*) [27], [31], which also relies on adding a subcarrier code-tracking loop to the carrier code tracking as well as estimating simultaneously the carrier phase and the code phase. In the double phase estimator (denoted here as *DPE1* to make the distinction with the DPE in Figure 3), which is an improvement of DET, the subcarrier lock loop (SLL) is replaced by a subcarrier phase lock loop (SPLL), and a marginal tracking gain of about 0.3 dB can be achieved [30]. The differences between the Astrium correlator, DPE1, and DET/DE structures are rather subtle, and they are mainly related to the way of combining the two code-tracking loops (carrier and subcarrier): while in the Astrium correlator, the combining is done before the loop filtering, and in DET and DPE, the combining is done after the loop filtering (at pseudorange level), ensuring a slightly better performance.

As a general rule, the narrow and hybrid main lobe techniques offer a better performance than the wide main lobe techniques in terms of tracking error variance, multipath mitigation, and false lock threat mitigation.

Alternative classification based on the placement of filtering stages

We can also classify the unambiguous approaches according to the processing type/filtering stages in the three categories shown in Figure 5:

1) precorrelation processing algorithms, where the unambiguous processing is done before the correlation between the incoming signal and the reference codes

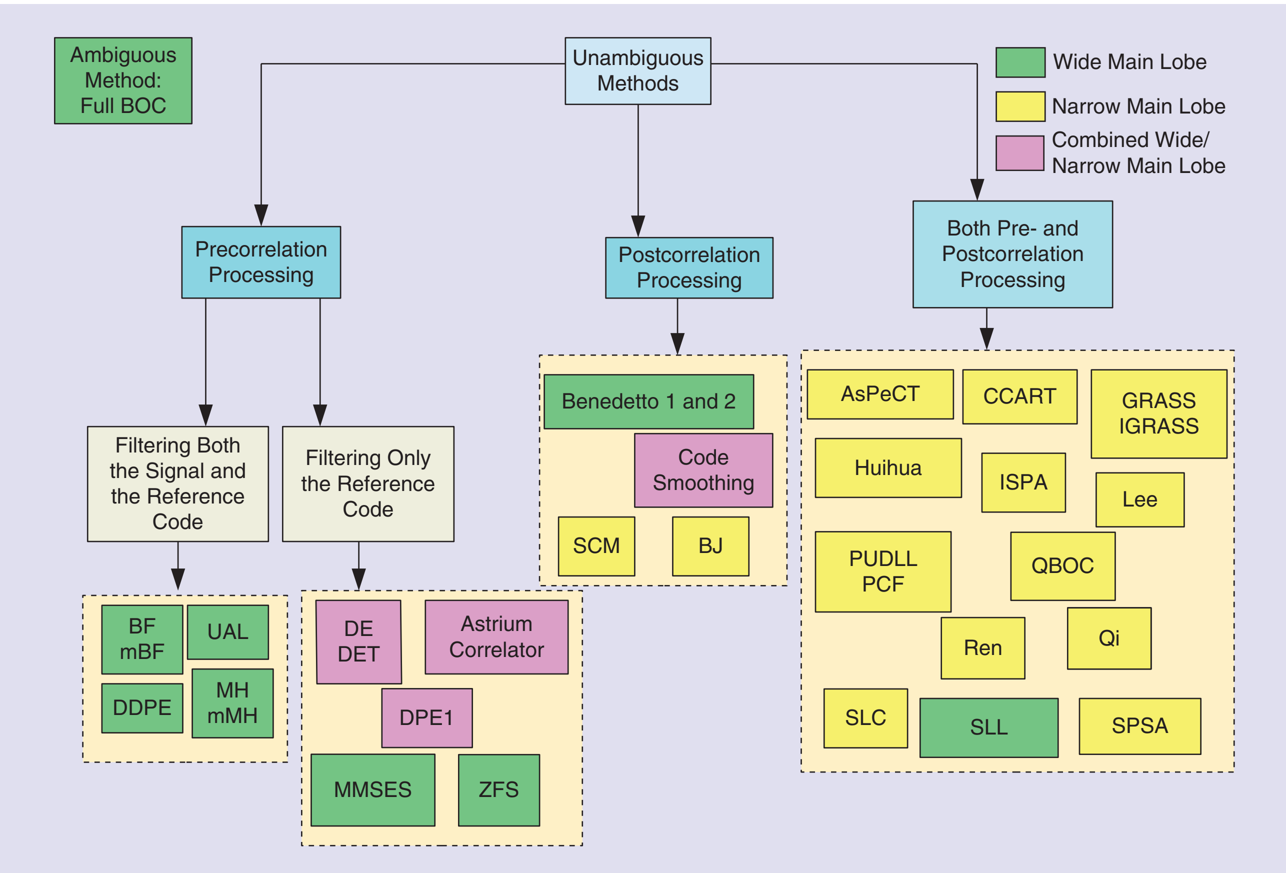

FIGURE 5. Different classifications of the unambiguous methods in GNSS. CCART: correlation combination ambiguity removing technology; AsPeCT: autocorrelation side-peak cancelation technique.

2) postcorrelation processing algorithms, where the unambiguous processing is done after the correlation
3) both pre- and postcorrelation processing, where their ambiguity removal stages are split before and after the correlation.

The noncoherent integration is not included in the postcorrelation processing because such a processing does not remove the ambiguities, per se. The classification in Figure 5 strictly refers to the processing stages involved in removing the ambiguities. While the first classification (see the section "Principal Dichotomy of Unambiguous Solutions: Wide Main Lobe Versus Narrow Main Lobe") helps a designer to better understand the possible behavior of an unambiguous algorithm in the presence of multipath (e.g., narrow main lobe algorithms are likely to better deal with multipath than wide main lobe algorithms), this second classification helps the designer to have an at-a-glance estimate of the complexity of each algorithm (e.g., the last category is likely to be more complex than the first two categories, and the first category is likely to be less robust to noise than the second category).

Performance and implementation complexity

Once the different techniques have been introduced, it is interesting to elaborate on the performance they provide, since this is one of the key aspects to be considered when choosing one technique in front of some other. Another key aspect is the implementation complexity, discussed in the section "Complexity Considerations."

Acquisition and tracking performance comparisons

Figure 6 illustrates the acquisition performance of full BOC (ambiguous) and 12 representative unambiguous algorithms, eight of them corresponding to the wide main lobe type and four of them for the narrow main lobe type. The example shown here is for a $\mathrm{BOC}_c(15,2.5)$ modulation, as one of the modulations with many ambiguities. In this example, the statistics are computed over 10,000 random points for single-path Nakagami-m fading channels, corresponding to a rural scenario. Here we used 4 ms coherent integration and two blocks of noncoherent integration ($N_c = 4$ ms, $N_{\mathrm{nc}} = 2$). In Figure 6(a), we used a 0.5 chip delay step for the acquisition stage, similarly with what is used traditionally in GPS receivers and ensuring a fast acquisition time. In Figure 6(b), we used a very small time-bin step of 0.01 chips to cover also the acquisition in narrowband mode, which is much slower, but slightly more accurate. The results are shown only for the single-path case, to focus solely on the ambiguities effects. However, similar observations can be drawn from results with multipath channels. The acquisition performance metric considered here is the detection probability of the LOS path at 10^{-3} false alarm probability. As a general rule, the best performance in fast acquisition (i.e., high time-bin case) is achieved with wide main lobe unambiguous approaches. The full BOC case is overlapping with the SCM case, and it is also rather close to the Benedetto algorithms. In particular, for the 0.5 time-bin step, the dual-sideband BF algorithm gives the best acquisition results. In slow acquisition or narrowband mode (i.e., small time-bin step), wide main lobe approaches are still among the best, but their performance is now very close to full BOC and SCM approaches, also overlapping in Figure 6. Also, as a general rule, the majority of unambiguous approaches with narrow main lobe exhibit a rather poor performance in the acquisition stage. Next, we show that their benefit stays in providing a lower tracking error variance than the wide main lobe unambiguous algorithms.

Regarding the tracking performance, there are myriad possible implementations of an unambiguous tracker. Readers are reminded of the discussion in the section "Generic

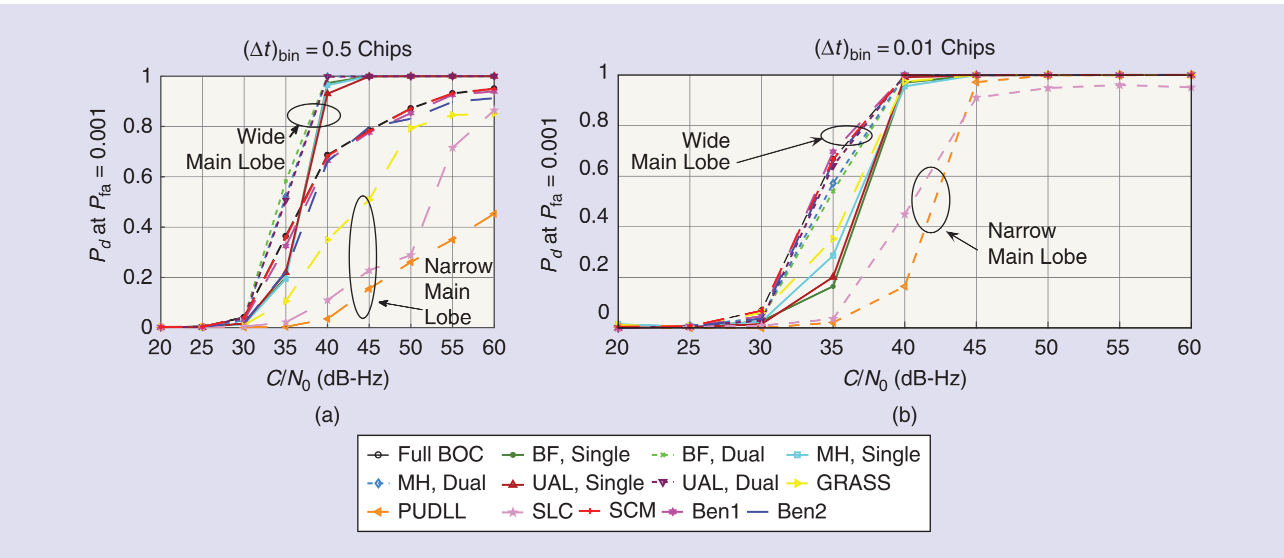

FIGURE 6. The acquisition performance of one ambiguous and 12 unambiguous algorithms. $\mathrm{BOC}_c(15,2.5)$ modulation. (a) 0.5 chips time-bin step. (b) 0.01 chips time-bin step.

DS-SS Receiver Chain and Code-Tracker Classification" and Figure 3, where we showed that there are many code trackers that can be used with any DS-SS system. When the ambiguities are also taken into account, any of the code trackers can be in fact combined with one of the unambiguous methods discussed in the section "Unambiguous Solutions"—this is how we obtained the overall unambiguous code-tracker structure, as shown in Figure 2. The tracking loop goal is to converge to the correct peak even if the acquisition stage converged to a wrong peak from the BOC-modulated envelope. Thus, there is a significant number of possible code-tracking combinations, and very few of them have been actually studied in the current literature.

Figure 7(a) illustrates an example of code-tracking performance when full BOC and four unambiguous algorithms (two with wide main lobe and two with narrow main lobe) are combined with NCORR and HRC, respectively, as two of the most used code trackers. This example is based on a BOC(1, 1)-modulated signal, an early–late spacing of 0.3 chips, a code loop bandwidth of 1 Hz, 20 ms of total integration time (10 ms coherent integration and two blocks of noncoherent integration), and a double-sided bandwidth of 40.92 MHz. The statistics were computed over 12,000 random points for Nakagami-m fading channels. The tracking performance metric shown in Figure 7(a) is the standard deviation of the delay error in the absence of multipaths; the standard deviation is also compared with the Cramer–Rao lower bound and with the theoretical NCORR performance as derived in the literature [35], [36]. Figure 7(b) shows a different metric: the multipath error envelope metric in the presence of multipaths. The multipath power was 3 dB lower than the LOS power in the multipath error envelope curve. For clarity of the curves, we have selected the BOC(1, 1) case in Figure 7(a) and (b), but similar observations hold for other BOC-based modulations encountered in GNSS. As seen in Figure 7 (and it has also been observed from an extensive search in the literature and additional simulations that we have run), the lowest tracking error variance is achieved with the basic NCORR structure and narrow main lobe unambiguous acquisition algorithms. The tracking error variance among the different narrow main lobe unambiguous trackers is rather similar and also close to the ambiguous error tracking variance. Thus, looking only at the code error variance, one could misleadingly draw the conclusion that a full BOC ambiguous approach with basic NCORR is the best in tracking. However, the tracking performance metrics are not only the variance of the code-tracking error, but also the probability to slide away from the main peak into a false peak, the probability to jump back to the correct peak (LOS peak) when starting the tracking from an incorrect delay, the mean time to lose lock while in tracking, the multipath robustness, and the complexity of the tracking stage, including the unambiguous processing part.

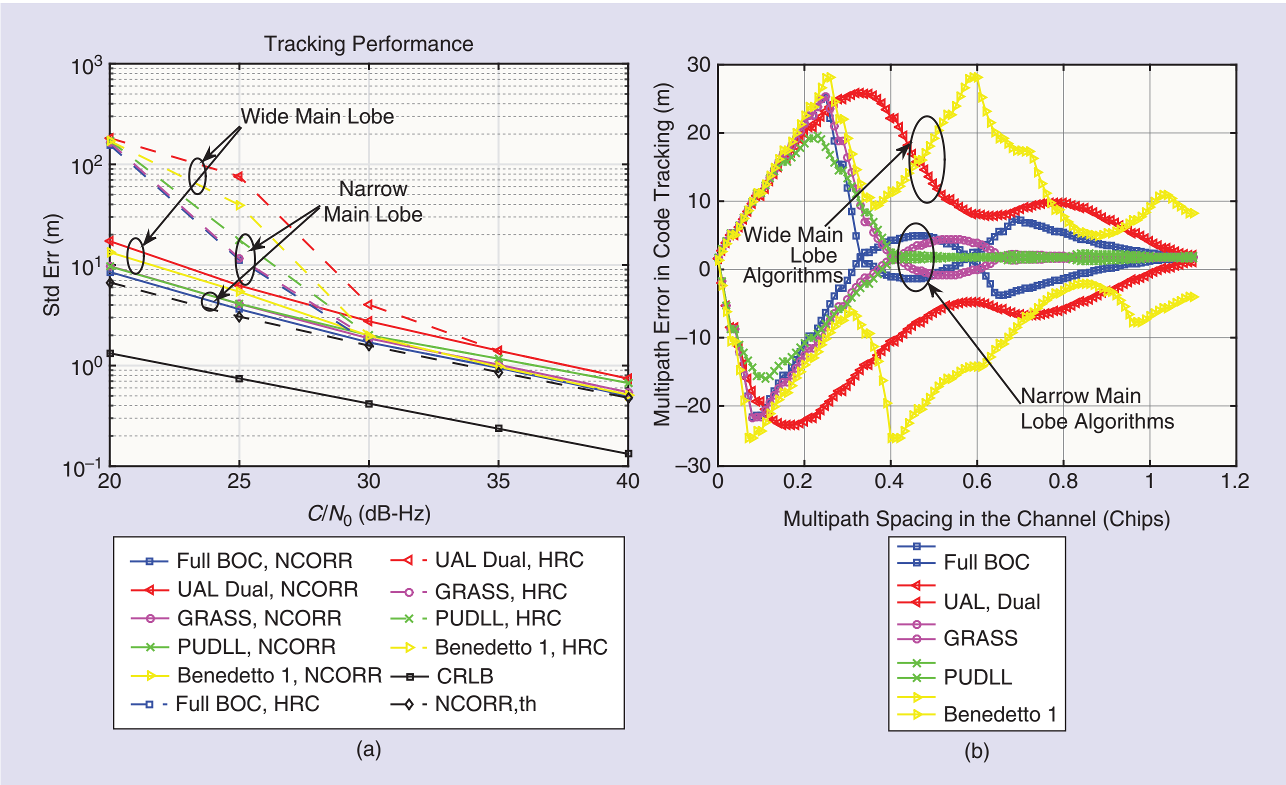

FIGURE 7. (a) The tracking error standard deviation of four unambiguous algorithms combined with two types of code trackers. (b) Errors due to multipaths in the absence of noise. One LOS and one NLOS spaced as shown on the x-axis. BOC(1, 1) modulation.

To the best of our knowledge, we are not aware of any research paper that addresses jointly or systematically all of these tracking performance metrics. Usually, when an unambiguous algorithm is presented in the literature, only one (or at best, two) of these metrics are looked at, such as code-tracking error variance and multipath performance. It is usually understood that, by removing or diminishing the sidelobes and keeping only a narrow main lobe, the false lock probability decreases, but analyses of the exact false lock probabilities and mean time to lose lock under various unambiguous algorithms are still missing in the literature. Due to these many metrics that have to be considered in tracking, the conclusions regarding the best algorithms in the code-tracking part are harder to reach than the conclusions regarding the acquisition. The section "Comparative Summary" recaps the advantages and disadvantages of the main unambiguous algorithms reported so far in the literature by looking at the different performance metrics in acquisition and tracking. As a general rule, the narrow and hybrid main lobe techniques offer a better performance than the wide main lobe techniques in terms of tracking error variance, multipath mitigation, and false lock threat mitigation.

A major challenge when designing a GNSS receiver for BOC-modulated signals is how to mitigate the ambiguities created by the oscillatory nature of the correlation curve.

Complexity considerations

A good measure of the complexity of the unambiguous approach is the number and complexity of the filters (see Figure 4) involved in the unambiguous processing. If we follow the division shown in Figure 5, typically the approaches involving both pre- and postcorrelation processing are more complex than the rest. Complexity analysis is also hard to find in existing literature of unambiguous approaches. Another complexity metric can be the simulation time to run the acquisition or tracking structures under identical parameters, but with different algorithms. One partial analysis we have done for the acquisition part with two GNSS modulations—$BOC_c(10,5)$ and $BOC_c(15,2.5)$—showed that, on average, compared with full BOC, SLC takes 15 times longer, BF and MH take 3.2 times longer, UAL takes 2.8 times longer, PUDLL takes 2.7 times longer, GRASS takes 1.85 times longer, and Benedetto and SCM algorithms take only 1.1 times longer. While these values depend on the signal and receiver parameters, such as integration times, modulation types, channel type, and so on, they give a very good estimate of the relative order of one algorithm with respect to another in terms of complexity.

Comparative summary

The three main classes introduced in the section "Principal Dichotomy of Unambiguous Solutions: Wide Main Lobe Versus Narrow Main Lobe" cover the full spectrum of techniques currently existing for the unambiguous acquisition and tracking of GNSS signals. The main approaches in each class are compared in Table 4. Some algorithms such as code smoothing, Astrium, DET, and DPE are not applicable in acquisition, as they rely on the outputs of three tracking loops (code, carrier, and subcarrier), and acquisition should be completed before the tracking starts.

Concluding remarks and further directions

Huge efforts are being carried out worldwide toward the modernization of GNSS. One underlying characteristic of most of the modernized GNSS signals is the use of split-spectrum BOC modulations to achieve higher positioning accuracy and less intersystem interference. A major challenge when designing a GNSS receiver for BOC-modulated signals is how to mitigate the ambiguities created by the oscillatory nature of the correlation curve. These ambiguities affect both the acquisition and the tracking stages of a GNSS receiver and there has been significant effort in the research community to overcome the ambiguities-related challenges. The ambiguity removal part can be built upon any GNSS basic acquisition or tracking structure, as shown in Figure 2. The basic tracking structures reported so far in the literature were summarized, and we discussed the tradeoff between achieving good multipath mitigation versus having a good noise robustness. Focus was given on the BOC-specific challenges and solutions. Those solutions were divided into three main classes: wide, narrow, and hybrid main lobe processing. We also divided the ambiguity mitigating solutions into three additional classes according to the processing steps involved in removing the ambiguities, and we discussed how the complexity of the unambiguous part is affected by the processing class. We have shown that a wide main lobe correlation is good in the acquisition, as it allows the use of a higher time-bin step and thus a faster acquisition. On the other hand, a narrow main lobe correlation better preserves the ability to cope with multipath and can remove the threat of the false locks if there is no additional sidelobe on which to lock. Thus, there is an inherent tradeoff between the unambiguous acquisition and unambiguous tracking. This means that, from a GNSS receiver design perspective, the two receiver stages of acquisition and tracking are better to be designed in a disjoint manner when dealing with the ambiguities.

For example, if the detection performance is the desired metric in the acquisition stage, then dual-sideband BF unambiguous approaches give the best performance. If the low complexity of the acquisition approach is the desired metric, then then single and dual sideband UAL unambiguous approaches are the best. In the tracking approach, there are even more metrics to consider, such as speed, complexity, accuracy, multipath and noise robustness, mean time to lose lock, etc. According to our studies and the results reported in the literature, some of the best tradeoffs between these various metrics are provided by the BJ, DET, and code-smoothing approaches. A joint optimum tracking metric is, however, yet to be found. An extensive comparison of 27 ambiguous and unambiguous approaches has been conducted, with few selected performance examples in terms of detection probabilities in acquisition, standard error deviation in code tracking, false lock threat mitigation, and multipath error envelopes.

This article presented an overview of one of today's important GNSS signal processing challenges and aimed at offering and attractive and stimulating starting point for further studies regarding the design of techniques for processing BOC signals, and especially high-order BOC signals, which are the most challenging. For future research directions, performance with more realistic channel models, such as the ITU-R channel models [9] or ray-tracing channel models, can be investigated to better understand the limitations of each unambiguous algorithm under a certain target scenario.

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