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Effect of Pre-correlation Filter on BOC-Gated-PRN Discriminator

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Abstract

In this paper the authors analyze the effect of signal pre-correlation filtering in the "BOC-Gated-PRN" ("BOC-GPRN") discriminator technique, recently proposed for use within Global Navigation Satellite System receivers to handle the new signal modulation scheme). The proposed discriminator is introduced to eliminate the tracking ambiguity for Delay Locked Loops and strengthen multipath resistance for precise GNSS applications. In practice, a pre-correlation filter with insufficient bandwidth can, in general, increase the error due to multipath and noise. However, it is preferred that the bandwidth of the front end filter is kept as narrow as possible for other limitation. Hence focusing on the tracking performance, measured in terms of multipath error and discriminator gain optimization of the DLL tracking performance with the BOC-GPRN discriminator is investigated by adjusting the parameters of the proposed discriminator and the pre-correlation filter (e.g. the double-sided bandwidth and transition bandwidth). The relationship among those parameters is discussed.

Key words: GNSS receiver, BOC (n, n), strobe, Bandwidth, Delay Locked Loop, discriminator

1. Introduction

The binary offset carrier (BOC) (n, n) has been selected by three Global Navigation Satellite Systems (GNSS) (e.g. GPS, Galileo and GLONASS) as the future modernized GNSS Code Division Multiple Access (CDMA) signal modulation scheme for better positioning accuracy - with respect to improving multipath and narrowband interference resistance [1] [2]. The BOC signal is the mod-2 added product of the pseudorandom noise (PRN) and the sine-phased square-wave (SW) subcarrier. For BOC (n, n), the conventional non-return to zero PRN code chipping rate (f_c) equals the SW subcarrier frequency (f_s) (i.e. f_s=f_c=n x 1.023MHz). For instance, both the f_c and the f_s of the BOC (1, 1) signal equal 1.023MHz. The advantage of the BOC (n, n) signal is its wider signal spectrum and its novel auto-correlation function (ACF) shape, including a much sharper peak at the symmetric centre of the ACF.

However, adopting this new signal for conventional GNSS receiver design raises various challenges, one of which is the generation of the ambiguous discriminator function during Delay Locked Loop (DLL) tracking. The ambiguous discriminator function can lead to such effects as bias tracking, which results in biased positioning solutions. Hence the BOC-PRN [3] is introduced in order to eliminate the multiple zero-crossings on the discriminator function. However, the implementation costs include reduction of multipath resistance [4]. To compensate for this trade-off, the BOC-Gated-PRN (or denoted simply as BOC-GPRN) is a newly developed unambiguous discriminator for the DLL tracking of the BOC (n, n) signal [5]. The BOC-GPRN discriminator can be considered as a type of strobe correlator, where the locally generated reference signal is specially tailored before the correlation with the receiving signal. In a strobe correlator, the improvement of multipath rejection is achieved by preserving the energy of the high frequency components of the received satellite signal, but reducing the energy of those close to the baseband frequency. As a consequence, the pre-correlation filter has an important impact on the performance of the BOC-GPRN discriminator, especially when the bandwidths of the front end (or the pre-correlation) filter is relative narrow. However, in practice, the front end filter bandwidth cannot be infinitely wide. In fact, using a wide bandwidth front end could also increase the complexity of the receiver design, such as its ability to handle wideband interference. Hence it is necessary to quantify the effect of a narrowband front end on the BOC-GRPN discriminator in terms of multipath error and discriminator gain - which is a factor influencing the noise performance of the DLL tracking loop.

In this paper the theoretical basis is introduced in section 2, where the background and related criterion for DLL design are discussed. The DLL tracking model and multipath interference model are also presented in this section. Section 3 is an introduction to the BOC-GPRN discriminator. The effect of pre-correlation filtering is discussed in section 4; while the combination effect of the different parameters of the pre-correlation filter on BOC-GPRN discriminators with different gate width is analyzed in section 5. Finally, concluding remarks are given in section 6.

2. Theoretical underpinnings

In contrast to traditional PRN codes whose spreading symbols are simple rectangles, the BOC spreading symbols are segments of a square waveform [6]. The new signal modulation scheme results in a narrower and sharper ACF. To be precise, this ACF is a cross-correlation function (CCF), which is the output of the receiver correlator, and is an imperfect match between the received signal and the locally generated ideal reference signal due to the existence of the pre-correlation filter. As the shape of the CCF is the foundation of most of the DLL discriminator techniques, this CCF results in different shapes of the associated discriminator function as generated by implementing the traditional techniques. One of the traditional discriminator techniques is so-called "narrow correlator", originally designed for the traditional PRN Binary Phase Offset keying (BPSK) modulation. Although the noise performance would be improved due to the increase in discriminator gain as a result of the sharper CCF, the discriminator function, which is obtained by subtraction between the early and late version of the CCF, has multiple zero-crossings, among which only the centre one corresponds to the correct alignment between the received signal and the locally generated reference signal. Hence this resulting discriminator is "ambiguous" for DLL tracking. Fig.1 shows the ACFs of PRN and BOC (1,1) and their corresponding ambiguous Narrow correlaters (where the Early to Late spacing is 0.25chip). The shape of the CCF also affects the multipath rejection performance. Since the multipath error is caused by the distortion of the shape of CCF when the delayed reflected signals overlap onto the direct signal, the narrower the CCF the less the range of delayed reflected signals which can overlap with the direct one.

The strobe correlator is another traditional discriminator technique. In contrast to the "narrow correlator", its locally generated signal is tailored to remove some less relevant information before it passes through the correlator. Hence the resulting shape of the CCF is relative small in terms of delay range ("width") and tracking error magnitude ("height"). If the tailored CCF is an odd function, it can be treated as a discriminator function, in order to simplify the receiver architecture. This tracking model was introduced in [7] and is illustrated in Fig. 2, where the pre-correlation filter is denoted as H (ω); while the tailored filter is denoted as G(ω) in their Fourier transform. The resulting CCF can be expressed as in (1) in the time domain, and (2) in the frequency domain, as in [7].

$$R(\tau)=\int_{T_1}^{T_2} s(t)ref(t-\tau)dt \qquad (1)$$

$$R(\tau)=\frac{1}{2\pi}\int S(\omega)REF^{*}(\omega)\exp(j\omega\tau)d\omega \qquad (2)$$

However, the traditional type of strobe correlator also needs to be modified to eliminate any bias tracking states. To solve this problem the BOC-GPRN discriminator was introduced [5]. The principle of this novel discriminator is presented in section III.

For simplicity, the discussion and simulation results presented in this paper are based on the following assumptions:

1. The PRN code values are equally likely, independent, and identically distributed, and the codes are sufficient long.

2. The baseband signal usually involves complex forms (In-phase and Quadrature). For simple exposition, the signal is modeled as real baseband signal, although the analysis is also valid for the complex signal model.

3. Without loss of generality, the BOC (1, 1) is considered in this paper as a standard surrogate for BOC (n, n).

4. The two-path signal model is the dominant multipath scenario, and considered in this paper. The complex form of the two-path signal can also be expressed ([7]) by (3) and (4):

$$s(t)=ae^{j\phi_1}c(t-\tau_1)+be^{j\phi_2}c(t-\tau_2)+n(t) \qquad (3)$$

$$\alpha=\frac{b}{a} \qquad (4)$$

In (3) and (4), a and b are the signal amplitudes, and α is the ratio between them. In this paper the reflected signal is assumed to have half the signal amplitude of the direct one (i.e. α =0.5). Φ1 and Φ2 are the carrier phases. The difference between these two phases is assumed to be zero° (i.e. the second-path signal is causing constructive interference) or 180° (i.e. the second-path signal is causing destructive interference), so that the maximum code phases error (i.e. maximum multipath error envelope) is obtained in the DLL output.

5. The multipath error envelopes and discriminator gain are established based on CCF normalized by the maximum magnitude value of the ideal ACF. Moreover, the same loop filter is applied to the DLL for all the discriminators discussed in this paper. Hence according to Holmes [8], the closed loop code tracking error variance σ^2_ε has a relationship with the discriminator gain K_D according to:

$$\sigma^2{}_{\varepsilon}=\frac{F(B_L,T_I,S_N(0),a)}{K_D^2} \qquad (5)$$

where $F(B_L,\ T_I,\ S_N(0),\ a)$ is a function of B_L the equivalent DLL loop bandwidth, T_I the integration time,

$S_N(0)$ the discriminator noise power spectral density (PSD),- which is a function of baseband equivalent noise PSD and CCF function $R(0)$, and a the signal amplitude . Therefore, the discriminator gain around the zero code phase delay (i.e. the zero-crossing point indicating perfect alignment) is an important influence that determines the noise performance of the DLL.

3. Principle of the BOC-GPRN discriminator

To solve the ambiguity, the BOC-PRN was first introduced in [3] for the BOC (1, 1), and further improved in [4]. Its corresponding cross-correlation normalized PSD expression in the frequency domain is derived in [9]:

$$G_{BP}(f)=\frac{1}{nT_s}\cdot[\frac{-i}{(\pi f)^2}\cdot\frac{\sin^2(2\pi fT_s)\cdot\sin(\pi fT_s)}{\cos(\pi fT_s)}] \quad (6)$$

However, the shape of this normalized discriminator is not adjustable. Hence the locally generated reference code requires a tailored gating function in order to shape the CCF. The BOC-GPRN, introduced in [5], is a compromise between low complexity on the one hand, and the requirement for unambiguous multipath mitigation techniques on the other. The generation of the reference waveform associated with the BOC (1, 1) signal is shown in Fig. 3, where T_c is the PRN spreading code chipping period (i.e. 9.77517e-7 s) and W2 is the "gate width". In contrast to other strobe reference waveforms, each of the spreading symbols of the BOC-GPRN reference wave (i.e. BOC-GPRN ref (t)) can be treated as a symmetric rectangular function which has the same symmetric centre as the subcarrier spreading symbols. It has been shown that the BOC-GPRN discriminator has superior multipath rejection ability compared to the traditional "narrow correlator" and also to standalone BOC-PRN techniques, when infinite pre-correlation bandwidth is assumed. Since the shape of the normalized BOC-GPRN discriminator function is adjustable and has a smaller scale in terms of "width" and "height" along with reduction of the W2. Moreover, the discriminator gain K_D (or the slope of the function) around the zero code phase delay is linear and has a value of "2", when W2<0.5chip. This means that the discriminator gain K_D for different BOC-GPRN discriminators with different gate widths (W2) make an equal contribution to the σ^2_ε in the code tracking loop in the case of an ideal infinite pre-correlation bandwidth.

4. Effects of the pre-correlation filter

In practice, the pre-correlation filter is band limited. If the filter BW is insufficiently wide to accommodate most of the relevant frequency components of the CCF, distortion of the magnitude and phase responses of the CCF (or the resulting discriminator function) would occur. Moreover, the filter transition bandwidth (i.e. the region between pass band edge frequency (denoted as f_c) and stop band edge frequency ((denoted as f_s)) not only determines the "sharpness" of the filter magnitude response, but also quantifies the high frequency noise level introduced by the filter itself. As mentioned in previous sections, the shape of the CCF is the critical factor that dominates the tracking performance of the DLL discriminator design in terms of accuracy and stability. Hence a change in the parameters of the pre-correlation filter will influence the BOC-GPRN discriminator performance. For simulation purpose, two kinds of filters has applied: the Kaiser Filter (FIR window), and the Butterworth Filter (IIR).Two parameters have been examined: the filter transition bandwidth, and the double-sided bandwidth.

In order to eliminate the high frequency noise interference introduced by the pre-correlation itself, it is preferred that the transition bandwidth of the filter is as wide as possible, which is also beneficial for the BOC-GPRN discriminator performance. It is noted that the discriminators tend to generate ambiguous ripples at the sides of the discriminator function when the transition bandwidth of the filter decreases. In Fig. 5 a Kaiser Window Filter with 3MHz double-sided pass band BW and 2MHz transition BW was applied. This effect is even more obvious when the double-sided BW of the filter is narrowed to less than 20MHz and the W2 is less than 0.1chip. It has also been shown that due to *Gibbs Phenomenon*, the gain of the discriminator starts fluctuating according to the spectrum energy of the cross-correlation normalized PSD. This fluctuation can cause a variation in the gain along with a change of BW. The fluctuation of the gain value is plotted in Fig. 6, where the Butterworth filters with 2MHz of double-sided BW and varying transition BW are applied to different BOC-GRPN discriminators. The corresponding discriminator gains are compared to those with infinite BW. It shows that the discriminators with smaller GW have larger distortion with narrow BW. Those ripples create a risk of ambiguity in dynamic and/or strong interference environments. The ripple effects are also evident in Fig. 7, where the same discriminator (GW=0.1chip) was operated with a Butterworth filter with f_c=2MHz f_s=3MHz. Fig. 8 is a magnified portion of Fig. 7 around the ripples regions caused by the filter. It shows that the discriminator gain is not only a function of the BW but also varies depending on the filter shape. In Fig. 9 and Fig. 10, the closed multipath error envelope corresponds to the maximum multipath error for the filters, with different parameters for the same BOC-GPRN discriminator (W2=0.1chip). Fig. 9 and Fig. 10 together show that not only the BW of the pre-correlation filter is a factor that can lead to multipath resistance reduction, but also the filter transition bandwidth is a critical factor, especially when the cutoff frequency is less than 10MHz.

5. Simulation results

To investigate the optimization of the BOC-GPRN discriminators, the Butterworth filters as a model of the last stage of digitized front end filter have operated on different BOC-GPRN discriminators whose gate width (W2) was changed from 0.1chip to 0.5chip. The filter transition bandwidth varied between 1MHz to 10MHz. The cutoff frequency of the double-sided pre-correlation filter increased from 2MHz to 40MHz. The amount of ripple allowed in the pass band is 0.01dB. The attenuation in the stop band is 80dB. The areas of the maximum multipath error envelopes are then obtained and compared with the ideal cases (the multipath error area of the discriminators operating with a filter having infinite BW). The ratios of differences over the ideal cases for different discriminators are plotted in Fig. 11. This figure shows that after the transition bandwidth of the Butterworth filter increases up to 5MHz, there is no significant multipath resistance reduction especially for discriminators with wider Gate width (e.g. W2>0.2chip). However, the discriminators with narrow Gate width of the reference code tends to suffer more from the ripple effects caused by the pre-correlation filters with narrow pass band bandwidth. Fig. 12 shows the same set of results, where the Butterworth filters with the same transition bandwidth (6MHz) are applied on different BOC-GPRN discriminators and varying the filter cutoff frequency. The multipath error areas are normalized by the maximum value of the ideal case (W2=0.5chip, BW=Infinite). It is interesting to note that the discriminators with large Gate Width (W2) tend to have minimum errors (compared to the ideal case), when the filters have double-sided BW of 4MHz~14MHz.

6. Concluding remarks

The BOC-GPRN discriminator is a kind of simple strobe discriminator designed for a BOC (n,n) signal GNSS receiver. Its tracking performance is dependent on the choice of the pre-correlation filter since the parameters of the filter determine the shape distortion of the discriminator function. Besides the filter bandwidth, the filter transition bandwidth is also a important factors that can affect the tracking performance in terms of multipath resistance and discriminator gain, , especially when the front end has narrow bandwidth. Moreover, it was also shown that the discriminator gain and multipath resistance are functions of the Gate width of the locally generated reference wave and the pre-correlation filter bandwidth and filter transition bandwidth. The selection of the BOC-GPRN discriminator can be optimized according to the parameters of the pre-correlation filters.

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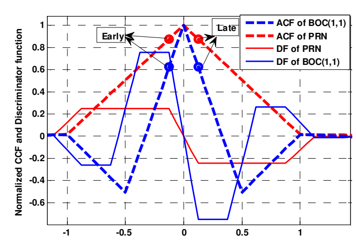


Fig. 1 ACF of PRN and BOC (1, 1) with their "Early-Late discriminators", Early to Late spacing=0.25chip

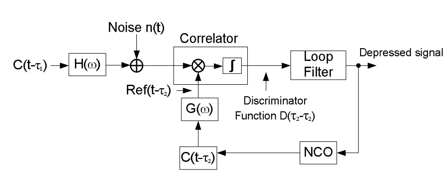


Fig. 2 DLL tracking model with strobe correlator

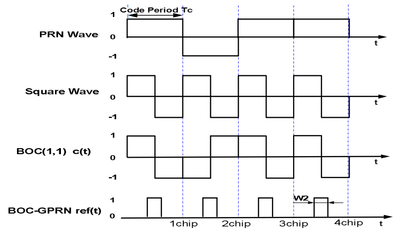


Fig. 3 BOC(1,1) & reference wave of BOC-GPRN

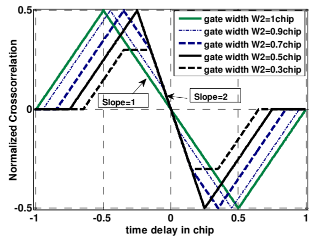


Fig. 4 BOC-GPRN discriminators with infinite BW

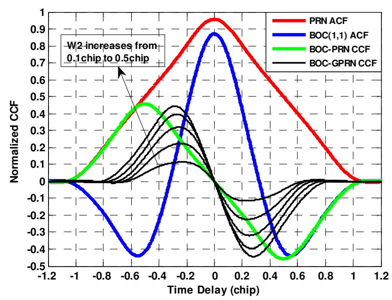


Fig. 5 Pre-correlation filtering effects with 3MHz Pass band BW 2MHz transition BW(Kaiser window)

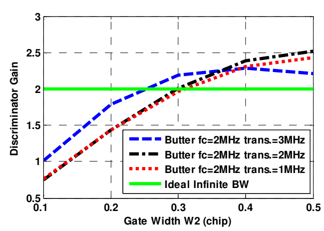
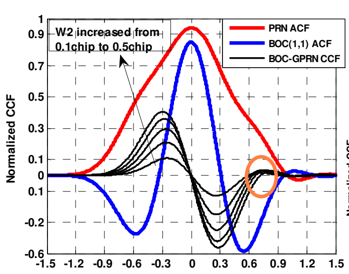


Fig. 6 The fluctuation of the discriminator gain



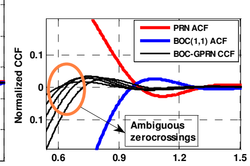


Fig. 7 (In left) Ripple effects the pre-correlation filter. (Butterworth, GW=0.1chip, f_c=2MHz f_s=3MHz)

Fig. 8 (In right) The Magnified portion of Fig.8 around the ambiguous ripples

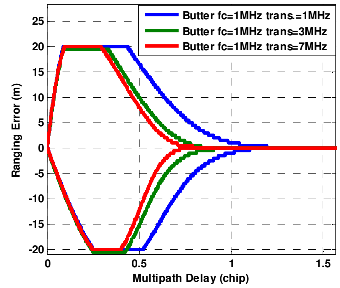


Fig. 9 Multipath error increased as the filter transition BW decreased(Butterworth; W2=0.1chip)

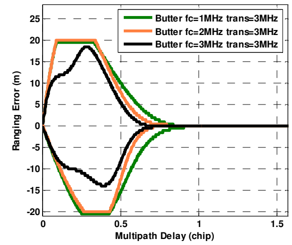


Fig. 10 Multipath error increased as the filter passband BW decreased(Butterworldth; W2=0.1chip)

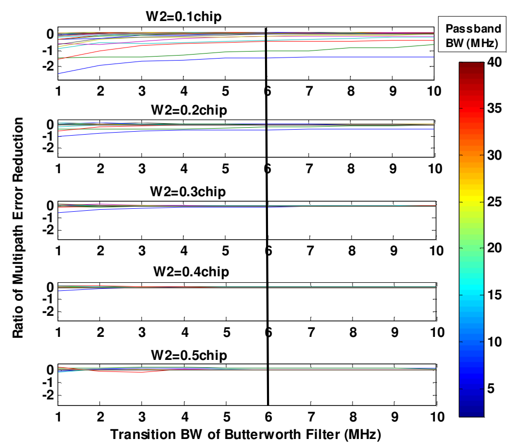


Fig. 11 The ratio of differences between multipath error areas (Limited BW VS. Infinite BW)

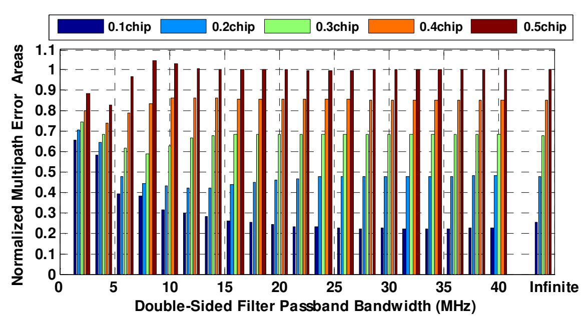


Fig. 12 The normalized multipath error areas for BOC-GPRN discriminators (varying W2 and Butterworth Filter BW, 6MHz Filter transition bandwidth,)