Multipath Mitigation Performance Comparison of Strobe Correlators in GNSS Receivers

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BIOGRAPHY

Jinghui Wu is a PhD candidate in the School of Surveying and Spatial Information Systems at the University of New South Wales, Sydney, Australia. She received her MEngSc Degree in 2006 from the School of Electrical Engineering and Telecommunications at the University of New South Wales, specializing in signal processing. She obtained her B.Eng. degree in Electrical Engineering & Automation, Beijing University of Aeronautics & Astronautics, P.R. China, in 2004, specializing in Instrument and Automation engineering. Her current research activity focuses on BOC signal processing (Acquisition and Tracking algorithms) for GNSS receiver design.

Andrew G Dempster (M'93–SM'04) has a BE (1984) and MEngSc (1992) in Electrical Engineering from the University of New South Wales, Sydney, Australia and PhD (1995) in Signal Processing from Cambridge University, UK. He has worked for STC in Sydney as a Telecommunications Design Engineer, for Auspace Limited in Canberra as a Systems Engineer and Project Manager, and for University of Westminster in London as a Lecturer, Senior Lecturer and Senior Academic. He is currently Director of Research in the School of Surveying and Spatial Information Systems at the University of New South Wales. His current research interests cover satellite navigation receiver design, interference effects, weak-signal GNSS, new positioning technologies, integration of location technologies, and software defined radio.

ABSTRACT

This paper introduces effective methods of decreasing multipath errors by utilizing strobe correlators designed for GPS coarse-acquisition (C/A) code for future modernized signals including the BOC (n,n) modulation used for GPS L1C, Galileo E1 and the GLONASS new CDMA signal. The implementation and performance of different types of strobes are compared and discussed. The strobe concept is especially investigated for BOC (n,n), in order to identify a suitable locally generated tailored reference code to produce an unambiguous discriminator function for the receiver Delay Locked Loop. The new strobe correlators produce significant multipath resistance (especially to the medium-delayed multipath interference) and false tracking event elimination. The multipath rejection and tracking performance are quantitatively analyzed and discussed by utilizing a proposed methodology, so the best performing strobe for a particular application can be selected.

KEYWORDS: BOC (n, n); Discriminator; Delay Locked Loop; Multipath.

I. INTRODUCTION

Multipath signals are generally those additive reflected signals which travel along extra propagation paths before arriving at the Global Navigation Satellite Systems (GNSS) receiver antenna, as opposed to the desired line of sight (LOS) signal (i.e. the direct signal). The direct signal combined with the delayed multipath signal forms a composite signal and is tracked by the GNSS receiver. In the most commonly used GNSS receiver architecture, the tracking loops operate based on the interoperation of the inter-dependent carrier and code tracking loops. Since the multipath interference usually differ to the direct signal in terms of code and carrier phases, due to the varying geometric propagation and the properties of the reflectors, the actual received GNSS signal is usually corrupted by the multipath interference (Irsigler, Rodrıguez, & Hein, 2005). Hence, in the presence of multipath, the resulting estimated carrier / code phases are affected by the carrier phase multipath error and ranging error. The scale of multipath distortion is a function of several signal characteristics, including the spreading code chipping rate, signal to multipath relative strength and phase shift. Also, the multipath errors are determined by the estimation mechanisms applied in the code tracking loop and carrier tracking loop.

To improve the positioning accuracy with respect to multipath and narrowband interference resistance, the binary offset carrier (BOC) (n, n) has been selected by three GNSS providers, GPS, Galileo and GLONASS, as the future modernized GNSS Code Division Multiple

Access (CDMA) signal modulation scheme (Gibbons, 2008; EU/US agreement, 2004). However, multipath interference remains a major error source for current GPS positioning, even though the overall multipath error for new GNSS signal is reduced (Hein, Irsigler, Rodriguez, & Pany, 2004; Irsigler, Rodrıguez, & Hein, 2005).

The multipath errors include carrier phase multipath error generated in the carrier tracking loop and ranging error produced inside the code tracking loop. The existing multipath mitigation techniques can be grouped into 2 major categories, carrier phase multipath mitigation and reference waveform based code ranging multipath error mitigation.

The carrier phase mitigation techniques focus on the energy redistribution between the In-phase (I) and Quadra-phase (Q) components in the Phase Lock Loop (PLL) that happens at each code phase transition. Those techniques include the Vision Correlator (introduced by the NovAtel Inc.) (Fenton & Jones, 2005), the transition trajectory observation based phase multipath mitigation (introduced by the NavCom Technology, Inc.'s) (Hatch, Knight, & Dai, 2007), and the recently proposed "Early Late Phase" mitigation techniques (Mubarak, 2008)

Code ranging multipath error mitigation is currently the most commonly used methodology. It uses shaping techniques (i.e. the discriminator shaping and correlation shaping (Braasch, 2001)) in the Delay Lock Loop (DLL). The basic principle of DLL tracking relies on the correlation process (Dempster, 2006) between the receiving signal and the locally generated reference signal (denoted as LS). The discriminator shaping techniques include the Narrow Correlator and Pulse Aperture Correlator (PAC), where the desired discriminators are generated through linear combinations of several correlator outputs; while in the correlation shaping mechanism, the desired correlation output is produced by despreading the received signal with specially tailored LS. The later shaping technique includes the strobe correlator and High Resolution Correlator (HRC) (Veitsel, Zhdanov, & Zhodzicshky, 1998; McGraw & Braasch, 1999). In general, since correlation is a linear process, different shaping techniques can be summarized as the linear combination (i.e. addition or subtraction) of the results of the correlation processes between the received signal and several different specially tailored LSs. This methodology will be investigated in detail throughout this paper.

Moreover, in the light of new GNSS signals, adopting the BOC(n,n) signal as the receiving spreading code also brings a potential challenge in the DLL design. Generating the ambiguous discriminator function (DF) during DLL tracking is problematic. The ambiguity of the DLL discriminator can cause problems in the presence of strong inference (Hollreiser, et al., 2007; Wu & Dempster, 2008a). Hence according to the realization of tailored reference code-based shaping techniques, the objective of this paper is to design an unambiguous DF generated with a novel method. The new unambiguous DF "looks like" the HRC for C/A code and the "shaping correlator" (Garin, 2005) for BOC (n,n) except that the DF is represented in a much simpler way. The corresponding code ranging multipath error mitigation performance is provided and discussed.

In this paper, section II gives the background information about the new signal modulation scheme principles and the theoretical underpinnings of tailored reference code based shaping techniques for conventional GPS C/A code. In section III, The shaping approach is employed for the BOC(n,n) waveform. The unambiguous discriminators are then introduced and discussed. The multipath resistance performance is illustrated and compared in section IV. Finally, conclusion remarks are given in section V.

II. THEORETICAL UNDERPINNINGS

BOC (n,n) VS. GPS C/A Code Modulation

The conventional GPS C/A code is also recognized as the pseudorandom noise (PRN) code, whose code chipping rate is denoted as fc(=1.023MHz). One PRN chip period is 9.7752e-7 s which is also denoted as Tc. Ideally, the autocorrelation function of the GPS C/A code is a triangle function (ACF) (illustrated in Fig 1.). The ideal ACF is a symmetrical function centered on zero chip delay and having zero energy beyond the operational range of ± 1chip. In practice, due to the pre-correlation filtering effect, the resulting correlation function is rounded and possibly asymmetrical and "echoed" beyond the operational range (Wu & Dempster, 2008b). For simplicity, the discussion and simulation results presented in this paper have assumed infinite pre-correlation filtering bandwidth. Moreover, in order to emphasize the multipath effect on the tracking loop, the PLL tracking loop is assumed to perfectly synchronize with the receiving composite carrier. The coherent code tracking loop is considered in this discussion although the multipath performances would also be valid for the non-coherent code tracking loop (Irsigler, Rodrıguez, & Hein, 2005). The considered two-path signal model is the dominant multipath scenario (no shadowing effect, using ideal spreading code and reflection coefficient α=0.5 are assumed). Only the near multipath interference is investigated (i.e. the multipath range delay falls within [0, 1.5] chip).

Contrastingly, the BOC signal is the modulo-2 added product of the PRN code and the sine-phased/cosine-phased square-wave (SW) subcarrier. For BOC(n, n), the conventional non-return to zero PRN code chipping rate (fc) equals the sine-phased SW subcarrier frequency (fs) (i.e. fs=fc=n x 1.023MHz). For instance, both the fc and the fs 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. It also has secondary peaks located at the ±0.5chip. As a standard example of BOC(n, n), BOC(1, 1) modulation is considered in this paper.

The generation of the BOC(1, 1) waveform and its associated PRN waveform is illustrated in Fig 2. It is noticeable that the transitions (i.e. where the values of the PRN waveform jump from 1 to -1 or vice versa) only happen at the edges of the PRN chip with a probability of 0.5, whereas the transition events on the BOC(1, 1) waveform have a probability of up to 0.75 thanks to the modulation of the SW, which leads to transitions always at the symmetric center of every PRN chip. Comparing the chip edge transitions on PRN code and the corresponding BOC (1, 1) waveform, it is also interesting to realize that the transition events and non-transition events are all inverted because of the SW.

Tailored Reference Code Based Shaping Techniques

The Narrow Correlator, PAC, strobe correlator, and HRC are some of the most frequently discussed correlation techniques applied in current GPS receivers for mitigation of code ranging multipath error. Recently, those techniques have been further summarized and adopted as baselines to assess the overall multipath performance of the new GNSS signals by Irsigler et.al. (2004). In their work, the techniques such as the PAC, strobe correlator and HRC responded to the "Double Delta Correlators (denoted as $\Delta\Delta$)", respecting to their structure similarity and identical performance. The bipolar symmetrical strobe pulse (denoted as W2-pulse) was proposed for GPS C/A signals in (Veitsel, Zhdanov, & Zhodzicshky, 1998) for the enhancement of the multipath resistance and further being employed by Nunes, M., & Leitão (2007) to BOC signals. Following the concept introduced in Veitsel, Zhdanov, & Zhodzicshky (1998), the aforementioned techniques can be summarized and represented as "strobe pulse correlations" or tailored reference code based shaping techniques.

According to the "DLL tracking model with strobe correlator" given in (Wu & Dempster, 2008b), which also originated from Weill (1998), the "strobe pulse correlations" can be realized as the correlation process where the ideal receiving GNSS signal (i.e. the GPS C/A code) correlates with the tailored locally generated reference signal passed through the shaping filter. Depending on the technique, the tailored reference signal is determined by three constraints: A. the location of the strobe pulses, B. the shape of the strobe pulses, and C. the width of the strobe pulses. Each of these 3 constraints includes several options and they are summarized in Table 1.

Table 1. Specification of the Strobe Pulses for C/A Waveform

Constraints	Option 1.	Option 2.	Option 3.
A. Location*[1]	Transition	Non-transition	Chip Edge
B. Shape *[2]	Simple	Square Wave	Complex
C. Width*[3]	Varying between [0, 1]chip		

*Note: 1. The transition and non-transition can only locate at the PRN chip edge.
2. The strobe shape discussed in this paper only considers symmetrical pulses
3. When the strobe width is Tc, the correlation corresponds to the Wide Correlator (Van Dierendonck, Fenton, & Ford, 1992)

The simulated (truncated) tailored reference waveforms are shown in Fig 3. a(1), b(1) and c(1). For the convenience of explanation, [A(1), B(1), C(0.2)]$_P$ denotes the normalized correlation function(denoted as CF) of the ideal PRN code and the tailored reference waveform defined by constraint A option 1, constraint B option 1 and constraint C with strobe width of 0.2chip. Similarly, the other resulting normalized CFs are denoted as [A(1), B(2), C(0.2)]$_P$ and etc. The corresponding normalized CFs are plotted in Fig 3. a(2), b(2) and c(2) respectively.

According to Figure 3, some of the existing shaping techniques mentioned above are summarized in Table 2.

Table 2. Existing Techniques Represented by Strobe Pulse Correlations(for C/A waveform)

Narrow Correlator	$\Delta\Delta$	W2-pulse
[A(1),B(1),C(0.2)**[1]]$_P$	[A(1),B(3),C(0.2)]$_P$**[2]	[A(3),B(3),C(0.2)]$_P$

**Note: 1. The constraint C determines the spacing between the Early and Late arms in the Narrow Correlator. So [A(1),B(1),C(1)] responds to the Wide correlator. The choice of constraint C for other techniques can be 0.2 chips. Actually, it can vary for the optimum results but it is not discussed in this paper.
2. The ideal ACF of the $\Delta\Delta$ can also be represented by [A(1),B(2),C(0.2)]$_P$

The same analysis approach can also be applied to the BOC(1,1) signal to summarize the current state of art.

III.APPLICATION ON BOC (1, 1) WAVEFORM

Specification of the Strobe Pulses for BOC (1, 1) Waveform

Since the BOC (1,1) signal is the modulation of the conventional PRN code and sine-phased SW, the transitions not only occur at the PRN chip edges but also at the symmetrical centers of the PRN chips. Hence, for BOC (1, 1), the constraint A. gains another option corresponding to those strobe pulses located at the chip centre. The modified specifications of the strobe pulses tailored for BOC (1, 1) waveform are summarized in Table 3.

Table 3. Specification of the Strobe Pulses for BOC(1,1) Waveform

Constraints	Option 1.	Option 2.	Option 3.	Option4.
A. Location***[1]	Transition	Non-transition	Chip Edge	Chip Center
B. Shape	Simple	Square Wave	Complex	Others
C. Width	Varying between [0, 1]chip			
***Note: 1. Again, the transition and non-transition only indicate those located at the PRN chip edge but their locations has exchanged respecting to those for C/A waveform (refer to Fig 2).				

Defining the strobe pulse constraints and options for BOC (1, 1) in Table 3, simplifies the realization of the exiting proposed multipath mitigation techniques for BOC (n, n).

Realization of the State of Art

It is necessary to keep in mind that the discriminator design not only needs to consider multipath resistance but also ambiguity. It is reported that, revisiting the multipath mitigation techniques initially developed for the GPS C/A signals results in ambiguous discriminators and poor medium-delay multipath interference resistance, even though the overall tracking performance can be better than those when receiving stand-alone GPS C/A signals (Irsigler, Hein, & Eissfeller, 2004; Garin, 2005; Nunes, M., & Leitão, 2007). Also, in practice, the thermal noise is a critical factor that limits tracking loop performance. It is therefore preferred to generate the DF according to a simple linear combination for the sake of better noise performance and simplicity of implementation. Based on this design preference, some discriminator designs for BOC (1, 1) signal are chosen to be investigated and realized by utilizing the same approach discussed in section II.

Generating the tailored reference according to the constraints and options defined in Table 3, the simulated (truncated) reference waveforms and the associated normalized CFs are plotted in Fig 4.

Employing the waveform generation method shown in Table 2 and considering the effect of extra strobe pulses introduced by the SW results in the ambiguous discriminators produced by the conventional techniques for the BOC(1, 1) signal (i.e. Narrow correlator, $\Delta\Delta$ DF and the Gating Function respecting to W2-pulse (Nunes, M., & Leitão, 2007)). The generation of the conventional ambiguous $\Delta\Delta$ DF is shown in Fig 5a. However, it is worth drawing attention to the new option contributed by the modulated SW. Actually, several proposed discriminator designs specially tailored for the BOC (n, n) signal can also be reproduced by using the stand-alone tailored reference waveforms specified in Table 3. For instance, $[A(4), B(1), C(0.2)]_B$ represents the BOC-Gated-PRN discriminator proposed by the authors in (Wu & Dempster, 2008); while $[A(4), B(2), C(0.2)]_B$ can represent the Bipolar Reference Waveform Cross Correlation Function(CCF) of the "Shaping Correlator" (Garin, 2005). Moreover, it is encouraging to notice that some techniques can even be reproduced when different shapes of tailored reference waveforms are linearly combined. For example, $\{[A(1), B(1), C(0.2)]_B + [A(2), B(2), C(0.2)]_B\}$ results in the Gated-BOC-PRN (shown in Fig 5b), mentioned in (Wu & Dempster, 2008a) and originally proposed in (Dovis, Mulassano, & Presti, 2005).

Generation of the "New" Unambiguous $\Delta\Delta$ Discriminator

Applying the methodology investigated above, a "new" unambiguous $\Delta\Delta$ discriminator can be generated by performing a simple linear subtraction between the specified tailored reference waveform plotted in Fig 4. The normalized CCF produced by the combination of $\{[A(4), B(2), C(0.2)]_B - [A(1), B(2), C(0.2)]_B\}$ is identical to that of the HRC (refer to Fig 3.) for GPS C/A code and similar to the BOC(1,1) SC-V2 Cross Correlation of the "shaping correlator" (Garin, 2005). As expected the resulting discriminator produced by $\{[A(4), B(3), C(0.2)]_B - [A(1), B(3), C(0.2)]_B\}$ is unambiguous in the operational range delay (i.e. [-1, 1] chip). The novelty of this unambiguous discriminator lies in the fact that it is tailored for BOC(1,1) even though the discriminator envelope is identical to the $\Delta\Delta$ discriminator for GPS C/A signal. Moreover, the new unambiguous $\Delta\Delta$ discriminator is generated through relatively simple linear combination. However, the common limitations of this type of tailored reference code based shaping techniques are inherited, such as the reduction in C/No tracking level and the pre-correlation filtering effect. The generation of the CF and DF are portrayed in Fig 6(a) and Fig 6(b) respectively.

The ambiguous and unambiguous discriminators designed for the BOC (1, 1) signal mentioned in this section can be further summarized with the concept of the strobe pulse correlations as in Table 4.

Table 4. Existing Techniques Represented by Strobe Pulse Correlations(for BOC (1,1) waveform)

Ambiguous DF	
Narrow Correlator	ΔΔ
{[A(1),B(1),C(0.2)]$_B$ +[A(4),B(1),C(0.2)]$_B$ }	{[A(1),B(3),C(0.2)]$_B$ +[A(4),B(3),C(0.2)]$_B$}****[1]
Gating Function	Gated-BOC-PRN
[A(3),B(3),C(0.2)]$_B$	{[A(1), B(1), C(0.2)] $_B$ +[A(2), B(2), C(0.2)] $_B$ }
Unambiguous DF	
BOC-Gated-PRN	CCF of Shaping Correlator
[A(4),B(1),C(0.2) ****[2]]$_B$	[A(4), B(2), C(0.2)] $_B$
new unambiguous ΔΔ discriminator****[3]	
{[A(4), B(3), C(0.2)] $_B$ - [A(1), B(3), C(0.2)] $_B$ }	
****Note: 1. The ideal ACF of the ΔΔ can also be represented by {[A(1),B(2),C(0.2)]$_B$+[A(4),B(2),C(0.2)]$_B$} 2. When the strobe width equals to Tc (i.e. [A(4),B(1),C(1)]$_B$ (plotted in Fig 4a(2) blue line)), the correlation corresponds to the BOC-PRN discriminator discussed in (Wu & Dempster, 2007; Dovis, Mulassano, & Presti, 2005) 3. The ideal ACF of the new unambiguous ΔΔ can also be represented by {[A(4), B(2), C(0.2)] $_B$ - [A(1), B(2), C(0.2)] $_B$ }	

IV. PERFORMANCE COMPARISON

As the resulting new unambiguous ΔΔ DF has an identical correlation envelope to the conventional ΔΔ DF for GPS C/A code, the relative tracking performance (in terms of the code ranging multipath error mitigation performance and noise performance in DLL tracking) is also the same. As this new ΔΔ DF is unambiguous, as expected, it has better resistance compared to the conventional ambiguous ΔΔ DF for the BOC (1, 1) signal to medium-delay multipath interference. The multipath mitigation performance is simulated and plotted in Fig 7 where the conventional ambiguous ΔΔ DF and the new unambiguous ΔΔ DF are compared. The multipath performances are assessed, by using three criteria (includes code ranging error envelope running average of multipath error envelope and normalized multipath error area), which are introduced in (Irsigler, Rodrıguez, & Hein, 2005).

It may also be worth to mention that, even though the new GNSS signal (i.e. BOC (n,n)) may be unable to gain better tracking performance in the DLL in terms of code phase tracking error and possibly noise performance by employing this algorithm, the new signal characteristic can gain an advantage in PLL tracking. The maximum carrier multipath error can only be determined by the multipath amplitude and relative delay in time (Brodin & Daly, 1997). Due to the unique ACF of the new signal, the resulting carrier phase multipath error will vary accordingly, if the tracking loop architecture introduced in Wu & Dempster (2007) is applied.

V. CONCLUSION

Various multipath mitigation techniques for GPS C/A signal are investigated by taking the concept of "strobe pulse correlations". This methodology is further modified and employed with the new GNSS signal (i.e. BOC(n,n)). BOC (1,1) was used as a representative of BOC(n,n) to examine the existing multipath mitigation techniques. Considering the DLL tracking performance and simplicity of implementation, a new unambiguous ΔΔ discriminator function tailored for the BOC (n,n) signal is generated by following the proposed methodology. The advantage of this proposed design lies in its simplicity and lack of ambiguity. However, since the new unambiguous discriminator function has an identical envelope to the conventional ΔΔ discriminator for GPS C/A signal, it is expected to inherent the limitations of the conventional ΔΔ discriminator in the code tracking loop, even though the performance of the PLL would be better for the new GNSS signal.

Further analysis of the overall tracking performance including the PLL and DLL tracking is planned.

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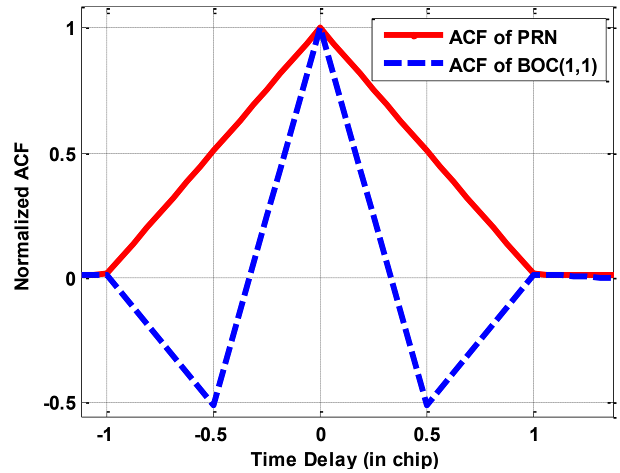


Fig. 1 Normalized ACF of PRN and BOC (1, 1)

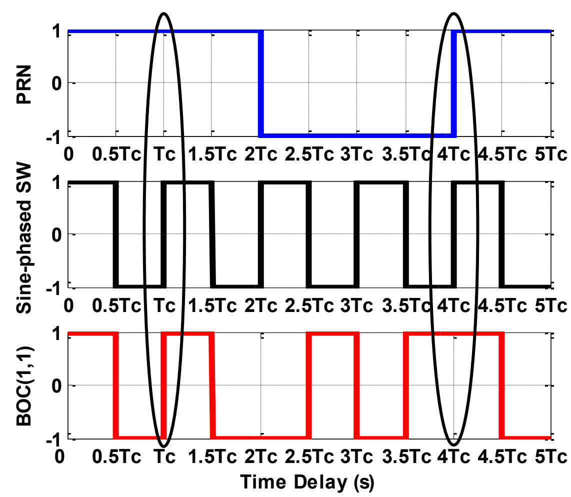


Fig. 2 Modulation scheme of BOC (1, 1) signal and the corresponding PRN waveform

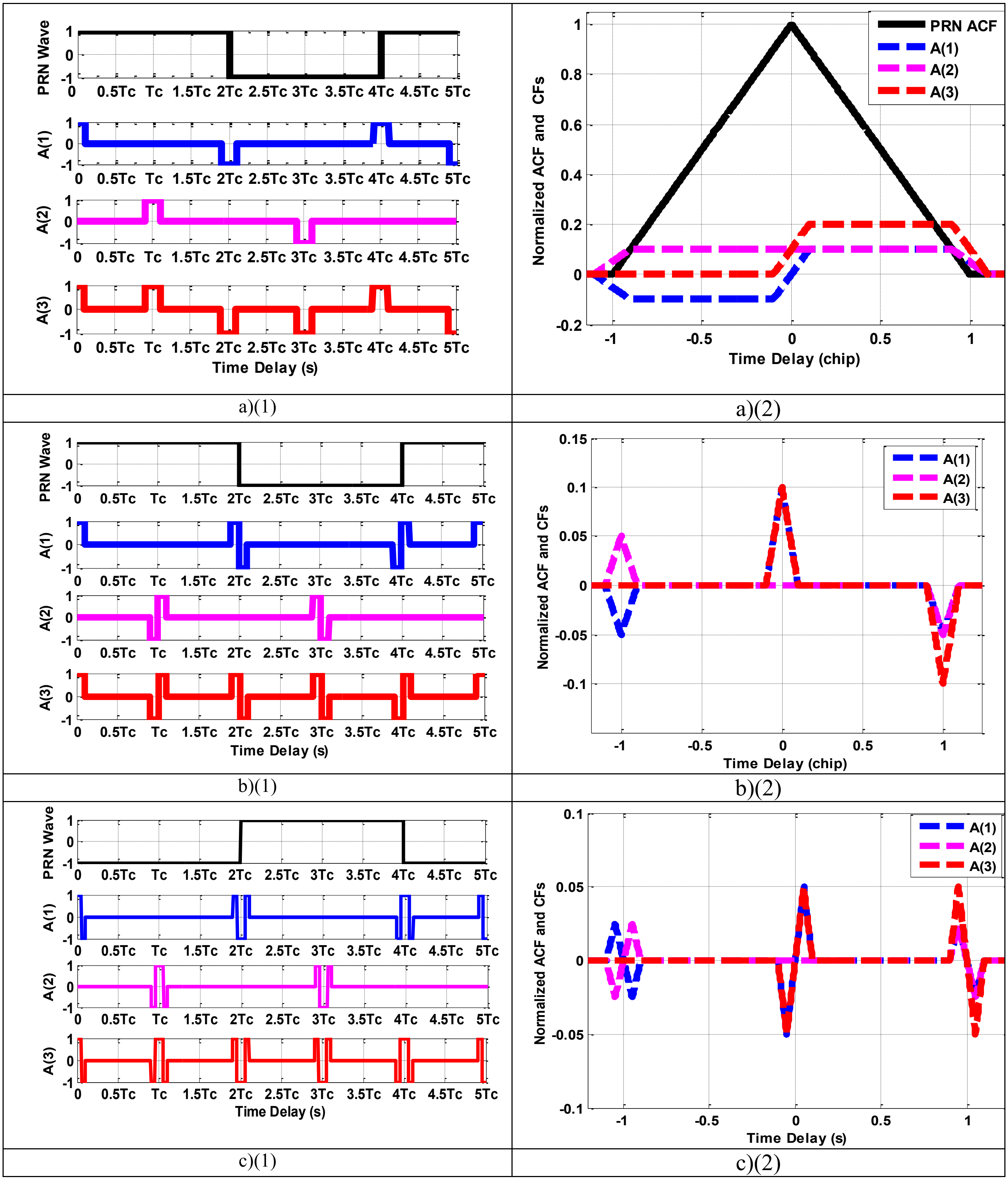


Fig. 3 **Tailored reference waveforms for GPS C/A code and the corresponding normalized CFs**

Note: * a) is for B(1), b) is for B(2) and c) is for B(2);

* The width of the symmetrical strobe pulse is 0.2chip

* (1) is for waveforms and (2) is for the plot of the corresponding normalized CFs

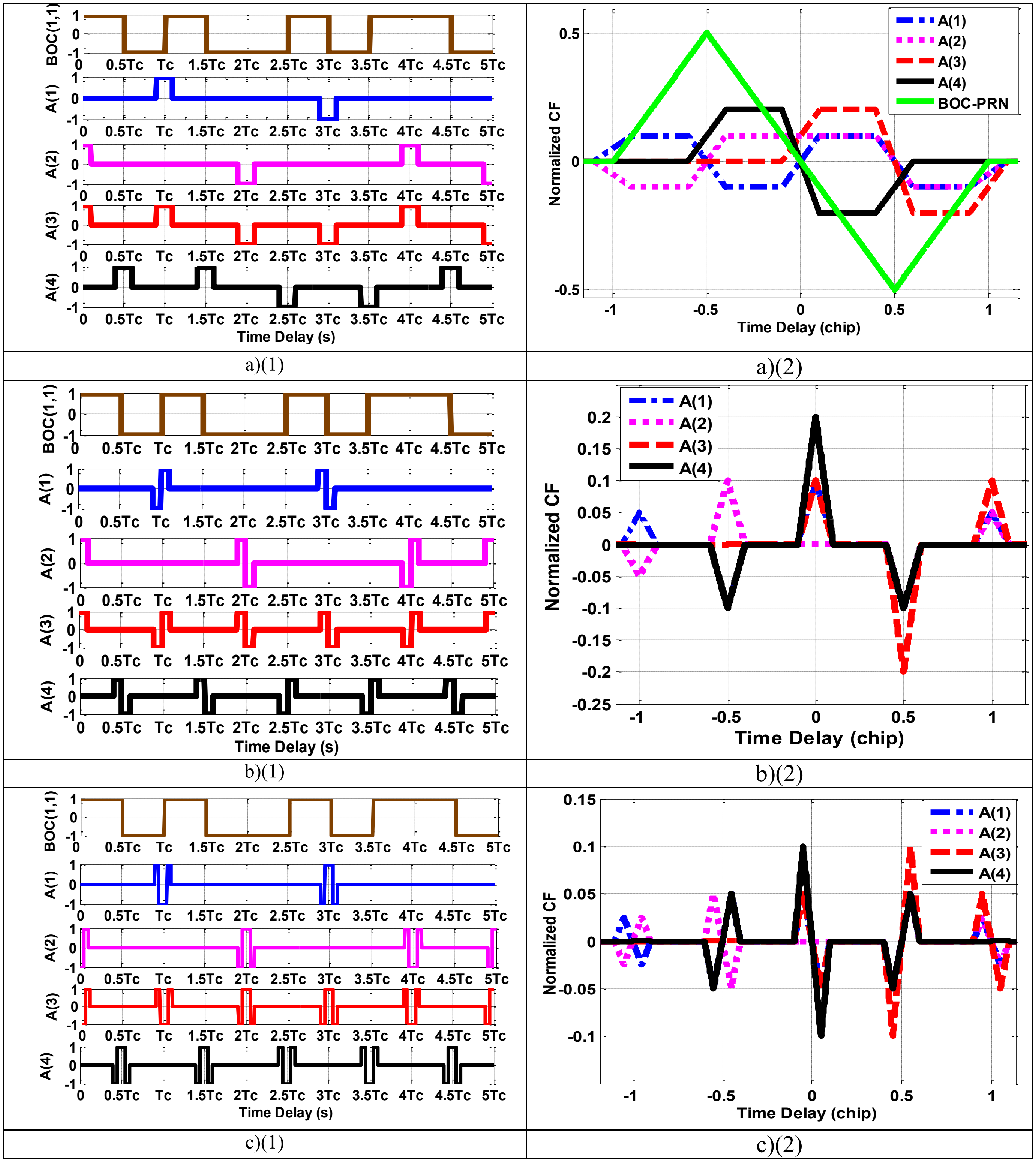
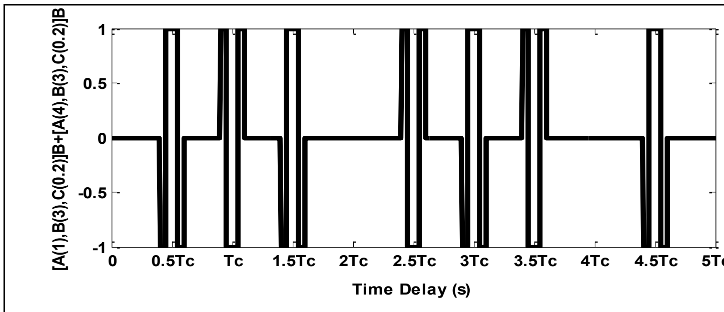


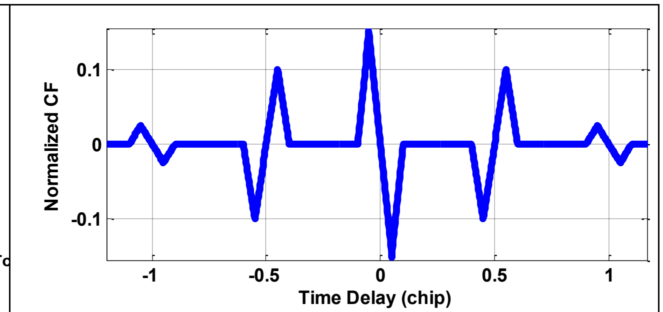
Fig. 4 **Tailored reference waveforms for BOC(1,1) code and the corresponding normalized CFs**

Note: * a) is for B(1), b) is for B(2) and c) is for B(2);

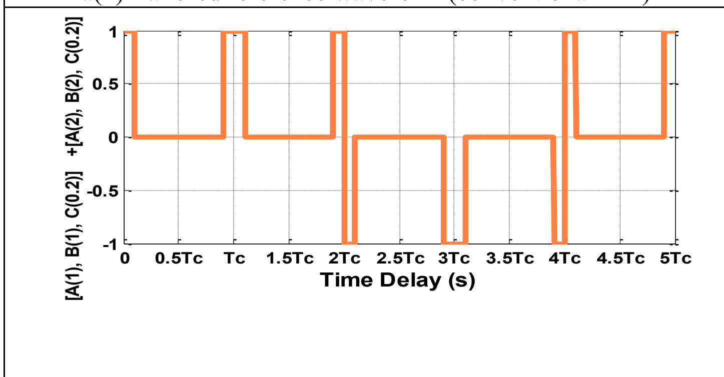
* The width of the symmetrical strobe pulse is 0.2chip
* (1) is for waveforms and (2) is for the plots of the corresponding normalized CFs (The phase is inverted with respect to the waveforms shown in Fig 3).



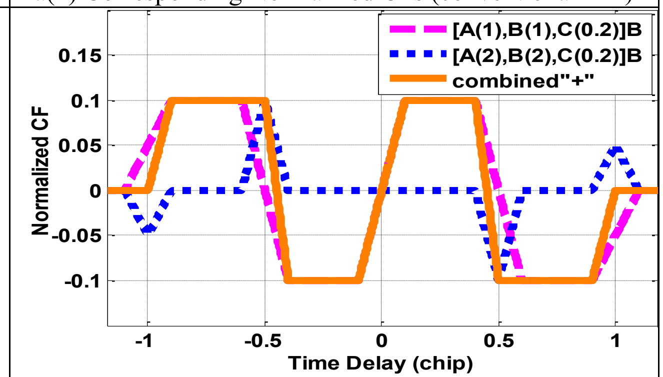
a(1) Tailored reference waveform (conventional ΔΔ)



a(2) Corresponding Normalized CFs (conventional ΔΔ)

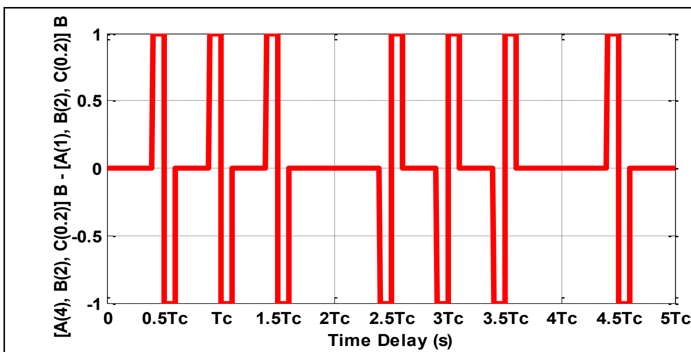


b(1) Tailored reference waveform(Gated-BOC-PRN)

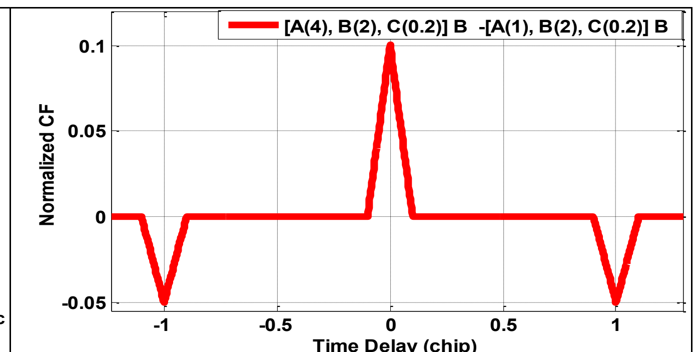


b(2) Corresponding Normalized CFs(Gated-BOC-PRN)

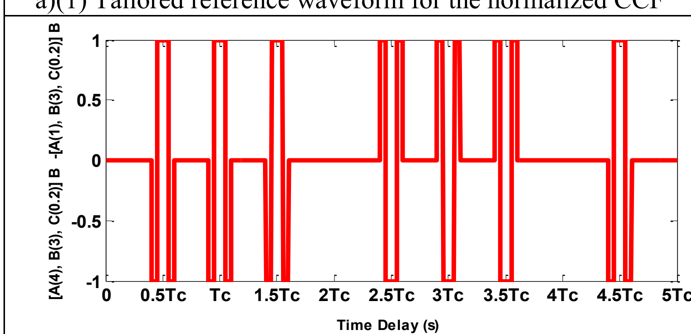
Fig. 5 Generation of conventional ΔΔ DF and "Gated-BOC-PRN" DF for BOC(1,1) signal, reproduced with "strobe pulse correlations"



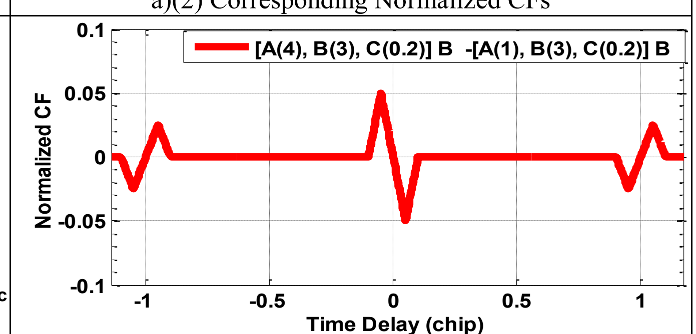
a)(1) Tailored reference waveform for the normalized CCF



a)(2) Corresponding Normalized CFs



b)(1) Tailored reference waveform for the normalized DF



b)(2) Corresponding Normalized CFs

Fig. 6 Generation of "new" unambiguous ΔΔ discriminator producing by "strobe pulse correlations"

Note * a) is for the Normalized CCF {[A(4), B(2), C(0.2)] $_B$ -[A(1), B(2), C(0.2)] $_B$ }

* b) is for the Normalized DF {[A(4), B(3), C(0.2)] $_B$ -[A(1), B(3), C(0.2)] $_B$ };

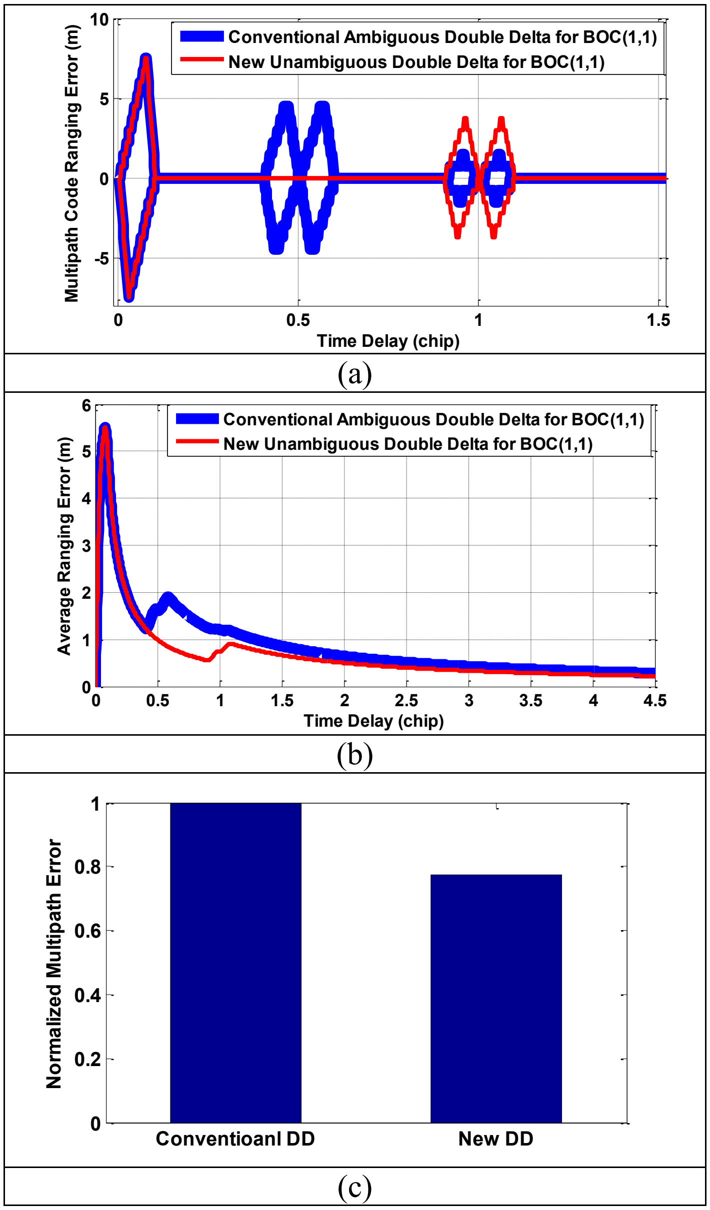


Fig. 7 Multipath resistance performance comparion between the conventional ambiguous $\Delta\Delta$ discriminator and the new unambiguous $\Delta\Delta$ discriminator for BOC(1,1) signal

Note: (a) Code ranging multipath error envelope
(b) Running average of multipath error envelope
(c) Multipath error area comparison

* the relative amplitude of signal to multipath interference is assumed to α=0.5.