

A Novel Evaluating method for New GNSS Signal Deformation

^{1, 2} Chengyan He, ^{1, 2} Ji Guo, ¹ Xiaochun Lu, ¹ Li Kang, ^{1, 2} Meng Wang

¹National Time Service Center, Chinese Academy of Sciences, Xi'an, Shaanxi, China

² State Key Laboratory of Geo-information Engineering, Xi'an, Shaanxi, China

¹hechengyan@ntsc.ac.cn

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Abstract: It is well known that the traditional evil waveform evaluating method for Binary Phase Shift Keying (BPSK) or Quadrature Phase Shift Keying (QPSK) is the 2nd Order Step (2OS) thread model adopted by the International Civilian Aviation Organization (ICAO). Although there are some new methods to evaluate new Global Navigation Satellite Systems (GNSS) signals, they are all for the analysis of the width and amplitude of signal waveforms. No research has been done on waveform symmetry yet. It has been observed through experiments that waveform asymmetry could also result in tracking errors, range biases, and position errors in GNSS receivers. In order to better evaluate the characteristics of most new navigation signals, the mathematical models for GNSS signals are presented and the extended general thread models are provided from the traditional 2OS thread model. A novel Waveform Rising and Falling Edge Symmetry (WRaFES) model determined for evaluating the asymmetry of GNSS signal waveform is proposed and introduced in details, as well as the evaluating method for Binary Offset Carrier (BOC) correlation curves. WRaFES model characteristics are analyzed in details from the aspects of time domain waveform, correlation domain and S curve bias. Finally, taking the first modernized BeiDou Navigation Satellite System (BDS) satellite M1-S B1Cd signal as an example, the thresholds for signal deformation detection and experimental results from these proposed methods are given. Simulation results and test results show that WRaFES model is very effective not only in detecting waveform asymmetry with high accuracy, but also in analyzing the relationship between waveform asymmetry and tracking error.

1. Introduction

Global Navigation Satellite System (GNSS) includes four main global systems as Global Positioning System (GPS), GLObalnaya NAvigatsionnaya Sputnikovaya Sistema (GLONASS), BDS and Global Positioning System (Galileo) and regional systems as Quasi-Zenith Satellite System (QZSS) and Indian Regional Navigation Satellite System (IRNSS), together with some other augmentation systems such as Wide Area Augmentation System (WAAS), System of Differential Correction and Monitoring (SDCM), European Geostationary Navigation Overlay Service (EGNOS), Multi-Functional Satellite Augmentation System (MSAS) and PS Aided Geo Augmented Navigation (GAGAN). GNSSs are ubiquitous and widely used in various applications including geodesy, aerospace, aviation, marine, search and rescue, transportation, agriculture and other fields (Afraimovich et al., 2010; He, 2013). GNSSs can provide global users with accurate position, velocity and timing (PVT) information in real time.

Today there is not any more a sole global positioning system and the coexistence between different GNSSs particularly challenges engineers to understand how the coexistence of current and future signals can be guaranteed. As the evolution of the different navigation systems has shown, all modernized GNSSs provide more complex signal waveforms compared to the past. Satellite navigation signal is of vital importance for a GNSS to achieve its high performance, as navigation signal is the sole interface between GNSS and receivers (Yao, 2016). Improvements in GNSS signal design alone are not sufficient to solve an array of issues related to signal generation. Therefore, in

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this paper we are focusing on issues related to signal generation. The potential performance of GNSS signal is the determinant of GNSS performance limitation. Despite of the optimized design of any other parts, GNSS could not achieve better performance in positioning, navigation, velocity, timing, anti-interference, compatibility and interoperability, etc. when there is a fatal defect in signal (Lu et al., 2016). As a result, signal design and evaluating has become a topic of great interest and subject to intensive research.

Spread spectrum modulation technique is of key importance for any GNSS to achieve its performance limitation. Only when most of the signal power is allocated to the occupied band edges, could the signal achieve its designed performance limitation. With the modernization and the advent of new GNSSs, new signal waveforms such as Binary Offset Carrier(BOC) (Betz 1999; Liu 2011; Rebeyrol 205), Time- Multiplexed Binary Offset Carrier (TMBOC) (Hein 2006), Composite Binary Offset Carrier(CBOC) (Lohan 2010), Alternative Binary Offset Carrier (AltBOC) (Lestarquit 2008), Asymmetric Constant Envelop Binary Offset Carrier (ACE-BOC) (Yao 2016), etc., have been introduced in order to improve the performance with respect to the first generation GPS signals for its outstanding advantages such as better correlation performance, better anti-interference performance, better band sharing and spectral separability (Ries 2002; Ruan 2016; Yao 2010). This new modulated signals can ensure compatibility and interoperability within different signals and systems. In addition, most of the signal powers are shifted to band edges.

New signals could achieve higher positioning and anti-interference performance compared with traditional BPSK or QPSK modulated signals. However, there are usually multi-level voltages for new generation signals, which will increase the complexity of signal design and receiving.

Although GNSS reliability is highly respected and has attracted considerable attention in the design process, signal distortion is still difficult to be avoided, with severe cases leading to disastrous consequences. It is often presumed that all incoming ranging codes (e.g., C/A codes) are effectively ideal. However, nominal signal deformations—deviations of broadcast GNSS satellite signals from ideal –will result in tracking errors, range biases, and position errors in GNSS receivers. It is thus imperative that these errors are quantified, to enable the design of appropriate error budgets and mitigation strategies for various application fields.

The most typical signal waveform deformation occurred on GPS in 1993. Trimble Navigation, Ltd. noted that there were asymmetry and 10 dB carrier leakage in the PSD (Power Spectral Density) of L1 signal for GPS SV 19 (Edgar, 1999). Based on code pseudo-range measurements, they noted that differential position accuracies were less than 50 cm when SV19 not included. However, when using SV19, the vertical position accuracy of the differential code phase solution degraded to anywhere from 3 to 8 meters (He et al., 2015). Another example is about GPS SVN49 satellite which was launched in 2009 carrying the first L5 signal. It got famous sooner because there were L1 and L2 legacy in the broadcasted L5 signal waveform. As a result, this kind of distortion in signal generation led to a positioning bias of around 1 meter.

Then several candidate threat models were initially proposed to explain the SV19 event. Such threats manifest themselves in the form of an anomalous correlation peak. Dr. Robert Eric Phelts proposed the 2nd-Order Step (2OS) threat model which was adopted by the International Civilian Aviation Organization (ICAO) for GPS signals since May 2000 (Enge et al., 1999; Jakab et al., 1999; Rebert et al., 2000 and 2011). The model describes the anomalous waveform or evil waveform (EWF), as three kinds of deformation as digital distortion, analog distortion and combined distortion. The effect of such deformations is described in the time domain and consists of dead zones, distortions, and false peaks on the receiver correlation shape.

However, those thread model are more for BPSK like signals. The advent of new modulations and new receiver configurations introduces the necessity to extend already accepted failure models for existing signals to the new ones. In fact, up to now, signal deformation threat models specific to each of the new modernized signals have not yet been defined. In addition, there has been no research on the symmetry between the rising edge and falling edge of navigation signal waveform yet. Initial study showed that, this kind of waveform distortion could also result in tracking errors, range biases, and position errors in GNSS receivers.



In order to better evaluate the characteristics of most new navigation signals, the mathematical models for GNSS signals are given in the beginning. Then starting from the traditional 2OS thread model, the extended general thread models are proposed for the new GNSS signals. Then a novel WRaFES model determined for evaluating the asymmetry of GNSS signal waveform is proposed and introduced in detail. Finally, since the aim of these whole threat models is mainly the prevention of hazardously misleading information (HMI) to be provided to airborne users, the determination and validation of appropriate thresholds is fundamental. Take the first modernized BDS satellite M1-S B1Cd signal as an example, the thresholds for signal deformation detection and experimental results using these proposed methods are given. Results show the effectiveness and robustness of the novel methods.

2. Mathematical Models for GNSS Signals

For new GNSS signals, each of the spreading code can be seen as a sequence of spreading symbols each of which has equal-length deterministic segments called multilevel coded symbol (D. Fontanella et al., 2010). Assuming there are N^{sub} number of equal-length segments or sub-chips within one chip, each segment with the amplitudes of A_n , $n = 1, 2, \dots N^{sub}$. The shape function of sub-chip $g^{chip}(t)$ can be expressed as follows:

$$g^{chip}(t) = \sum_{n=1}^{N^{sub}} A_n g^{sub}(t - n \frac{T_c}{N^{sub}})$$
(1)

Now it is possible to represent DSSS navigation signal as the following general sequence:

$$S(t) = \sum_{n=-\infty}^{+\infty} C_n g^{chip} (t - nT_c)$$
⁽²⁾

Where C_n is the amplitude of PRN code sequence. Assume that PRN code shows ideal statistical properties, so $g^{sub}(t)$ is a rectangle waveform. The PSD of S(t) can be written as:

$$G_{S}(f) = \frac{1}{T_{c}} \frac{\sin^{2}(\frac{\pi f T_{c}}{N^{sub}})}{\pi^{2} f^{2}} \left\| \sum_{n=1}^{N^{sub}} A_{n} e^{-\frac{j2\pi f T_{c}}{N^{sub}}} \right\|^{2}$$
(3)

The first term corresponding to the PSD of $BPSK(N^{sub})$ modulated signal denoted as $G_S^{bpsk(N^{sub})}(f)$, and the second term represents the modulation as $G_S^{boc_-mod}(f)$. So PSDs of all the new generation signals can be written as:

$$G_{S}(f) = G_{S}^{bpsk(N^{sub})}(f)G_{S}^{boc} - \operatorname{mod}(f)$$
(4)

In the next section, we would use these general formulas to express the extended thread models for new GNSS signals (E. Rebeyrol et al., 2005; J.A et al., 2008; Thoelert et al., 2011).

3. ICAO adopted and extended thread model

3.1 ICAO adopted thread model

The 2nd-order Step model proposed by Dr. Robert Eric Phelts of Stanford University is the most popular thread model for signal distortion evaluation. There are three kinds of thread model defined as follows:

- TMA: known as digital failure mode, where there is a lead/lag of the pseudorandom noise code chips.
- TMB: known as analog failure mode, where there is a second-order ringing in the amplitude of



code chips.

• TMC: known as the combination of TMA and TMB.

Figure 1 shows the time waveform and correlation peaks of evil waveform with TMA/TMB/TMC. And figure 2 gives parameter settings of thread models.



Fig. 1. Time waveform and correlation peaks of evil waveform



Fig. 2. Parameter setting ranges of thread models

Since the waveform, PSD and correlation curve of TMC contains characteristics of both TMA and TMC, they are not shown here for sake of brevity. Figure 3 shows the PSDs of TMA with $\Delta = 0.09$ Tc and TMB with $\sigma = 4.8$ Mnepers/s, $F_d = 10$ MHz.



Fig. 3. $\Delta = 0.09$ Tc (Left) , $\sigma = 4.8$ Mnepers/s & $F_d = 10$ MHz (Right)

Results show that:

- TMA evil waveforms add a periodic line spectrum which has a $\sin(\pi f \Delta) / \pi f \Delta$ envelope.
- TMA evil waveforms raise the DC component by $\Delta/2$ due to imbalance of 0 and 1s.
- TMA evil waveforms induce a plateau of width Δ and cross-correlation shifts: if $\Delta > 0$ it shifts left, vice versa, it shifts right when $\Delta > 0$.
- TMB evil waveforms raise those frequency components located around *F*_d, so the cross-correlation function is filtered by the 2nd order filter.
- TMC evil waveforms are a combination of TMA and TMB.

3.2 Novel thread models

As already said previously, although those models have been adopted by ICAO as the standard thread scenario, they are suitable for only BPSK like modulated signals. There is still no agreement for modernized new GNSS signals such as BOC. In addition, no research has been done on waveform symmetry yet. In this work, some assumptions are made to extend the ICAO model to new signals.

There are mainly two possibilities where waveform distortions occur for a new signal: on the squared wave generator before code spread and on the sub-code generation after code spread. Here we assume the former case, so we have to consider the sub-chip autocorrelation peak instead of the chip autocorrelation peak.

Taking BOC(m,n) signal as an example and as shown in figure 4, we assume that the normal



signal is denoted as $_{m,n}s_{nom}(t)$, signal with digital distortion is denoted as $_{m,n}s_{TMA}(t)$, signal with analog distortion as $_{m,n}s_{TMB}(t)$, and signal with combination distortion as $_{m,n}s_{TMC}(t)$. Then evil signals can be expressed as follows:

$$\begin{cases} m_{n,n} s_{\text{TMA}}(t) = m_{n,n} s_{\text{nom}}(t) + m_{n,n} s_{\Delta}(t) & \text{TMA} \\ m_{n,n} s_{\text{TMB}}(t) = m_{n,n} s_{\text{nom}}(t) \cdot e_{\sigma, f_{d}}(t) & \text{TMB} \end{cases}$$
(5)

$$\int_{m,n} s_{\text{TMC}}(t) = [m,n s_{\text{nom}}(t) + m,n s_{\Delta}(t)] \cdot e_{\sigma,f_{d}}(t) \text{ TMC}$$

Where $e_{\sigma,f_d}(t)$ is the 2 order step transmission function, digital distortion $_{m,n}s_{\Delta}(t)$ can be expressed as:

$${}_{m,n}s_{\Delta}(t) = \begin{cases} \max\left[{}_{m,n}s_{nom}(t+\tau_{d}) - {}_{m,n}s_{nom}(t), 0 \right] & \Delta < 0 \\ \min\left[{}_{m,n}s_{nom}(t+\tau_{d}) - {}_{m,n}s_{nom}(t), 0 \right] & \Delta > 0 \end{cases}$$
(6)

Where τ_{d} is as follows:

 $\tau_{d} = \begin{cases} 2T_{s} - \Delta & M \text{ is an odd number} \\ T_{s} - \Delta & M \text{ is an even number,Pseudo - code symbol is -1} \\ \Delta & M \text{ is an even number,Pseudo - code symbol is +1} \end{cases}$ (7)

In equation (7) *M* is the order of BOC(*m*,*n*) with M = 2m/n. T_s is the half period of subcarrier with $T_s = 1/(2m*1.023 \text{ MHz})$.



Fig. 4. Time domain block diagram for TMA/TMB/TMC threat model

3.2.1 Extended TMA

The variation in the timing of each PRN chip transition with respect to the ideal is considered as TMA. Assuming $S_{ideal}(t)$ is the ideal signal, while $D_{evil}(t)$ is the deformation part of received signal $\tilde{S}(t)$ compared with $S_{ideal}(t)$, then we can deduce the following expressions:

$$S(t) = S_{ideal}(t) + D_{evil}(t)$$

$$R_{S_{ideal}}(t) = R_{S_{ideal}}^{bpsk(N^{sub})}(t) * R_{S_{ideal}}^{boc} - \operatorname{mod}(t)$$

$$\begin{split} R^{TM_{-}A}_{\sim}(t) &= S(t) * S_{ideal}(t) = R_{D_{evil},S_{ideal}}(t) + R_{S_{ideal}}(t) \\ &= \left[R^{bpsk(N^{sub})}_{D_{evil},S_{ideal}}(t) + R^{bpsk(N^{sub})}_{S_{ideal}}(t) \right] * R^{boc_{-}mod}_{S_{ideal}}(t) \quad (8) \\ &= \left[R^{bpsk(N^{sub})}_{D_{evil},S_{ideal}}(t) * R^{boc_{-}mod}_{S_{ideal}}(t) \right] + R_{S_{ideal}}(t) \end{split}$$



3.2.2 Extended TMB

The amplitude ringing at the individual PRN chip transition is described as TMB which is independently of TMA. The impulse response of this system is described as:

$$h(t) = \begin{cases} 0 & t \prec 0\\ \frac{\omega_n}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t} \sin(\omega_d t) & t \ge 0 \end{cases}$$
(9)

where $\omega_d = \omega_n \sqrt{1 - \zeta^2}$ is the damping frequency and the damping factor is $\sigma_d = \zeta w_n$. Then the correlation of $\tilde{S}(t)$ with ideal $S_{ideal}(t)$ can be expressed as:

$$R_{\tilde{S},S}^{TM-B}(t) = \left[h(t) * R_{S_{ideal}}^{bpsk(N^{sub})}(t)\right] * R_{S_{ideal}}^{boc-mod}(t) = h(t) * R_{S_{ideal}}(t)$$
(10)

3.2.3 Extended TMC

Since it is the combination of TMA and TMB, here we just show the correlation function:

$$R_{\widetilde{S},S}^{TM_{-}C}(t) = h(t) * \left[R_{D_{evil},S_{ideal}}^{bpsk(N^{sub})}(t) + R_{S_{ideal}}^{bpsk(N^{sub})}(t) \right] * R_{S_{ideal}}^{boc_mod}(t) (11)$$

4. WRaFES model

Whether it is ICAO adopted thread model or extended model for new GNSS signals, it only deals with the width and amplitude of an evil waveform. In fact, up to now, there has been no research on the symmetry between the rising edge and falling edge of navigation signal waveform yet. However, this kind of waveform distortion could also result in tracking errors, range biases, and position errors in GNSS receivers.

As those thread models introduced above cannot be able to describe waveform asymmetry, here we proposed a novel thread model called Waveform Rising & Falling Edges Symmetry model, or WRaFES model.



Fig. 5. WRaFES model

Here we take the BPSK modulation signal as an example to introduce this method for the sake of brevity, and it is also suitable for new GNSS signals. Figure 5 gives a show of WRaFES model. Simulation results show that asymmetries in $W_{\pm 0.5}$ and the two ends of each falling and rising edge are more harmful to users. So we decide to select two points near the ends and three points near 0.5 chips for simulation. Notice that the number and values of n could be changed according to different kinds of waveforms. Here $W_{\pm n}$ denotes different points in the evil waveform, n is the distance from the center of the waveform, usually denoted in chips.

Table 1 shows WRaFES model metrics for SQM (Signal Quality Monitoring). They include $\Delta\Delta$ -Tests, Symmetric Ratio Tests, Asymmetric Ratio Tests and Symmetric Area Ratio Test metrics.

• $\Delta\Delta$ -Tests describe the waveform symmetry of segments that are between the rising edge and falling edge around zero, $\Delta\Delta$ -Tests are considered as Gaussian variables with zero means;



- Symmetric Ratio Tests describe the waveform symmetry between the whole rising edge and the whole falling edge, they are considered as Gaussian variables with zero means;
- Asymmetric Ratio Tests can be used to evaluate whether there is distortion or not for each selected point. The difference between the point in the rising edge and the corresponding point in the falling edge is considered as a Gaussian variable with zero mean.

$\Delta\Delta$ -Tests				
$M1 = \frac{(W_{-0.5} - W_{0.5}) - (W_{-0.47} - W_{0.47})}{W_0}$				
$M2 = \frac{(W_{-0.53} - W_{0.53}) - (W_{-0.5} - W_{0.5})}{W_0}$				
Symmetric Ratio Tests				
$M3 = \frac{(W_{-0.40} - W_{0.40})}{W_0} M4 = \frac{(W_{-0.43} - W_{0.43})}{W_0} M5 = \frac{(W_{-0.47} - W_{0.47})}{W_0}$				
$M6 = \frac{(W_{-0.50} - W_{0.50})}{W_0} M7 = \frac{(W_{-0.53} - W_{0.53})}{W_0} M8 = \frac{(W_{-0.57} - W_{0.57})}{W_0}$				
$M9 = \frac{(W_{-0.60} - W_{0.60})}{W_0}$				
Asymmetric Ratio Tests				
$M10 = \frac{W_{-0.40}}{W_0} M11 = \frac{W_{0.40}}{W_0} M12 = \frac{W_{-0.43}}{W_0} M13 = \frac{W_{0.43}}{W_0}$				
$M14 = \frac{W_{-0.47}}{W_0} M15 = \frac{W_{0.47}}{W_0} M16 = \frac{W_{-0.50}}{W_0} M17 = \frac{W_{0.50}}{W_0}$				
$M18 = \frac{W_{-0.53}}{W_0}M19 = \frac{W_{-0.53}}{W_0} \qquad M20 = \frac{W_{-0.57}}{W_0} \qquad M21 = \frac{W_{0.57}}{W_0}$				
$M22 = \frac{W_{-0.60}}{W_0} M23 = \frac{W_{0.60}}{W_0}$				
Symmetric Area Ratio Test				
$M_{24} = 20 * \log_{10} \left[rac{\int_{t=-0.6Tc}^{-0.4Tc} S(t)dt}{\int_{t=0.4Tc}^{0.6Tc} S(t)dt} ight]$				

Table 1.	List of	WRaFES	metrics
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5. Simulation results

5.1 Extended TMA/TMB/TMC

Research results show that the extended TMA /TMB /TMC models have similar characteristics as TMA /TMB /TMC models adopted by ICAO. The effects of new GNSS signal deformations are described in the time domain and consist of dead zones, distortions and false peak in terms of correlation peak (Misra et al., 2012). They are not shown here for the sake of brevity. Here we just show in figure 6 the correlation peak and PSD of BOC(1,1) with digital lag Δ =0.06*T*c.



Fig. 6. Digital distortion of BOC(1,1) with Δ =0.06Tc



5.2 WRaFES Model

An arbitrary waveform generator is designed here for analyzing the effect of waveform asymmetry. Different kinds of rectangle evil waveforms with different rising edge and falling edge can be generated.

In order to better analyze the effect of different asymmetries, here we mainly simulate four kinds of asymmetries in this paper:

- 1) Ideal symmetrical rectangle waveform;
- 2) Imperfect symmetrical waveform with slow rising and falling edge;
- 3) The same as the second one with just one point different in the rising or falling edge;
- 4) Imperfect asymmetrical waveform with totally different rising edge and different falling edge.



Fig. 7. Waveform analysis of WRaFES

In figure 7 the lines for "Fall Posi" and "Rise Posi" belong to waveform 3) described above. And the lines for "AsymLeft" and "AsymRight" belong to waveform 4), where "Left" or "Right" here means the integration area of the left part (rising edge) or the right part (falling edge) is higher than that of the other part. The "ideal" line represents waveform 1). We do not show waveform 2) here because there is only one point different compared with waveform 3).

In this section, the effects of waveform asymmetry are analyzed in detail in terms of WRaFES model metrics, correlation peak metrics and S curve bias.

5.2.1 WRaFES Model Metrics

The list of WRaFES metrics is shown in table 1. And since there are lots of WRaFES model metrics describing waveform asymmetry, here we only give our study results for the sake of brevity. The experimental results of WRaFES model metrics will be shown in section VI.

- $\Delta\Delta$ -Tests metrics describe the symmetry between the rising edge and falling edge that are around zero. Where M1 can reflect the symmetry above zero while M2 reflects the symmetry below zero.
- Symmetric Ratio Tests M3 to M9 can reflect the symmetry between the whole rising edge and the whole falling edge.
- Asymmetric Ratio Tests M10 to M23 can describe whether there is distortion for each selected point. They are often used in pairs, for example, M10 and M11.
- Symmetric Area Ratio Test denotes the ratio between the integration area of the left part (rising edge) and that of the right part (falling edge). It is a reflector of the whole chip symmetry, and it can affect the symmetry of correlation peak.
- In practical operation, evaluation criteria could be built according to the receiving condition to evaluate the difference between received signal and the theoretical signal.

5.2.2 Correlation Peak Metrics

The location of proposed correlator branches for a BOC(1,1) signal is shown in figure 8.





Fig. 8. Correlators adopted for BOC(1,1) SQM

The correlator branches are considered as a vector

 $R = [R_{-1}, R_{-0.5}, R_{-0.1}, R_{-0.05}, R_0, R_{0.05}, R_{0.1}, R_{0.5}, R_1]$. The outputs of those branches can be considered as Gaussian variables (Ali et al., 2015) with the mean $u_R = \sqrt{2(C / N_0)TR(d_I)}$, variance $\sigma_R^2 = 1$ and covariance value as $\sigma_{R1, R2} = R(d_{R1, R2})$. Where d_I denotes the distance from the center of the correlation function shown by $R(\bullet)$. And T is the coherent integration interval and $d_{R1, R2}$ represents the distance between R1 and R2 correlator_o

As a result, correlation metrics can be defined as follows:

$$P_{i} = \begin{cases} \frac{R_{-m} - R_{m}}{R_{0}} & i = 3, 4, 5, 6\\ \frac{R_{n}}{R_{0}} & i = 7, 8, \dots 14 \end{cases}$$
(12)

 $P_1 = P_4 - P_3 \quad \& \quad P_2 = P_5 - P_4$

In formula (14), the value of m is 0.05, 0.1, 0.5 and 1 respectively when i = 3, 4, 5, 6. And the value of n is -0.05, 0.05, -0.1, 0.1, -0.5, 0.5, -1 and 1 respectively when $i = 7, 8, \dots 14$.

Table 2 summarizes the theoretical means and variance of different correlation metrics based on the ideal BOC (1,1) correlation function.

Parameters	Means	Variances
P ₁	0	$0.6/2T(C/N_0)$
P ₂	0	$2.4/2T(C/N_0)$
P ₃	0	0.6/2T(C/N ₀)
P_4	0	$1.2/2T(C/N_0)$
P ₅	0	2.0/2T(C/N ₀)
P ₆	0	2.0/2T(C/N ₀)
P ₇	0.85	2.775/2T(C/N ₀)
Pg	0.85	2.775/2T(C/N ₀)
P9	0.7	0.51/2T(C/N ₀)
P ₁₀	0.7	0.51/2T(C/N ₀)
P ₁₁	-0.5	0.75/2T(C/N ₀)
P ₁₂	-0.5	0.75/2T(C/N ₀)
P ₁₃	0	1.0/2T(C/N ₀)
P ₁₄	0	$1.0/2T(C/N_0)$

Table 2: Theoretical means and variances of correlation metrics

Assuming that the normalized amplitude of code chip is 1, and there are 100 points for each chip, with 13 points for each rising edge or falling edge. So the stable part with amplitude of 1 during each chip is 87 points. Here we simulated 28 different cases to better analyze the effects of different waveform asymmetries: where number "1" to "13" represents the case when the absolute value of



each point in the falling edge is increased by 0.3. Number "14" represents the symmetric waveform just as waveform (2) described above, while "15" represents the asymmetrical waveform as waveform (4). The number "16" to "28" represents the case when the absolute value of each point in the rising edge is increased by 0.3.

Figure 9 shows some of the correlation peaks for ideal signal and several asymmetrical signals. And figure 10 presents the correlation metrics for different kinds of waveform asymmetries.



Fig. 9. Correlation peaks for simulation dataset



Fig. 10. Correlation metrics for simulation dataset

As can be seen from simulation results that:

(1) Chip asymmetry between rising edge and falling edge will lead to correlation asymmetry: the right part of the correlation curve will be higher than the left part when the integration area of the chip's right part (falling edge) is higher than that of the left part (rising edge), and vice verse;

(2) Chip asymmetry between rising edge and falling edge will lead to a left or right shifting on its correlation peak;



(3) As for the correlation metrics:

- P_3 , P_4 , P_9 and P_{10} are more sensitive to waveform asymmetry, while P_{13} and P_{14} are less sensitive to this kind of deformation;
- P_1 is sensitive only to the asymmetries that occur in both ends of the rising edge or/and the falling edge. The more the integration area of the chip's right part (falling edge), the higher of P_1 value;
- Contrary to P_1 , P_3 is more sensitive to the asymmetries that occur in the middle part of the rising edge or/and the falling edge. The more the integration area of the chip's right part (falling edge), the higher of P_3 value;
- P_4 is sensitive to the asymmetries that occur in the whole part of the rising edge or/and the falling edge. The more the integration area of the chip's right part (falling edge), the higher of P_4 value;
- P_7 and P_9 are more sensitive to the asymmetries that occur in the latter half part of the rising edge or/and the falling edge. The more the integration area of the chip's right part (falling edge), the higher of their value;
- Contrary to P_7 or P_9 , P_2 , P_8 and P_{10} is more sensitive to the asymmetries that occur in the former half part of the rising edge or/and the falling edge. The more the integration area of the chip's right part (falling edge), the lower of their value.

5.2.3 S curve bias

S-curve represents discriminator outputs. As a consequence, a zero-crossing of the S-curve represents a point at which the tracking loop can be locked. In this sense, a zero-crossing of this S-curve represents the potential synchronization error once the tracking loop has converged. In theory, the zero-crossing point of the discrimination function of a DLL should be in the point where there is no tracking error(Wesson et al., 2013; Manfredini et al., 2014; Gamba et al., 2013). However, due to the non-ideal transmission channel such as channel distortion and multipath, the tracking loop may false lock onto a wrong point (He, 2013), thus causing a serious tracking error.



Fig. 11. S curve biases for simulation dataset

S curve biases of different kinds of waveform asymmetries are shown in figure 11. The first picture shows the S curve biases of evil waveforms with the absolute value of one point in the falling edge higher than that of the rising edge. The second one shows the S curve biases of evil waveforms with one point in the rising edge higher than the falling edge.

As can be seen from figure 11 that different kinds of waveform asymmetries can lead to different S curve biases:

- For correlator distance 0.15Tc < d < 0.9Tc, the more the integration area of the chip's falling edge, the lower the SCB value.
- In addition, different waveform asymmetries can lead to different variances of S curve biases: For correlator distance d < 0.15Tc and d > 0.9Tc, the higher the difference between the integration area of the rising edge and that of the falling edge, the higher the variance of S curve bias.



6. Test Results

China successfully launched two new generation satellites –named M1-S satellite and M2-S satellite--for its global navigation and positioning network on July 25, 2015. The successful launch marked another solid step in building BDS into a navigation system with global coverage.

In order to better observe and receive GNSS signals, the measurement equipment included a 40meter parabolic dish antenna (owned and operated by National Time Service Center (NTSC), Chinese Academy of Sciences) located at Haoping Radio Observatory (HRO), Shaanxi Province, China. This was used to take low-noise, low multipath measurements of the B1Cd codes transmitted by the current BDS M1-S satellite.

Due to the fact that there is a smooth transition period between the regional BDS and the global BDS, M1-S B1 signal, consisting of both the regional B1I and global B1, adopts POCET method to make its envelop constant. As a result, we need to separate each component before we evaluate its performance. At first, we need to strip the carrier and navigation message from the received signal using software receiver, and then we will get the baseband signal. Resample it to make sure that each chip contains the same integer number of sampling points. Taking advantage of the periodic repetition of PRN code, the good orthogonality between two different PRN codes and the randomness of noise, the algorithm averages over many PRN code periods. The SNR (signal-to-noise ratio) of the baseband signal is improved through many accumulations. In theory, after N times averaging, the noise power is reduced to 1/N, while signal power is invariant. It is evident that SNR is improved by 10*log(N) times after accumulation.

Taking the M1-S B1 signal for example, the separated B1Cd baseband waveform is as shown in figure 12.



Fig. 12. Separated baseband signal of BDS M1-S B1Cd

Figure 13 and figure 14 show the statistical WRaFES metrics and correlation metrics of BDS M1-S B1Cd signal. Having the mean and variance of each correlation metric and assuming a Gaussian distribution for them (in the presence of high C/N0 values), it is possible to determine a detection threshold based on a desired false alarm probability (PFA).

Because of the periodic accumulation over multiple PRN code epochs, we could only get one epoch of separated B1Cd with high C/N0. So we calculate the WRaFES metrics of each chip over this epoch. Then we can obtain the mean and variance of each metric. You may have noticed that in figure 13 the order of WRaFES metrics have been adjusted according to their characteristics for better comparison. Test results show that:

- The rising edges and falling edges over one chip epoch are very stable, there is no obvious deformation;
- The symmetry of each pair of the rising edge and falling edge is pretty good, with slightly higher absolute value of the falling edge than the rising edge;
- The symmetry of each pair of the rising edge and falling edge around zero is very good, with slightly better asymmetry for the positive part than the negative part.





Fig. 13. WRaFES metrics of BDS M1-S B1Cd

Since, as already said, the outputs of those correlators can be considered as Gaussian distribution (Ali et al., 2016), the detection threshold corresponding to each correlation metric can be written as:

$$Thred_i = Mean_i \pm \sigma_i erf^{-1}(1 - P_{fa})$$
(13)

Where $erf^{-1}(\cdot)$ is the inverse of error function, P_{fa} is the desired false alarm probability, $Mean_i$ and σ_i are the expected mean and variance of the ith metric respectively. The mean values and detection thresholds are calculated based on theoretical analysis. However, in practical applications these values may slightly differ from this analysis. Therefore, an initial calibration is required in order to tune the theoretical values based on practical observations.

In this paper due to that fact that the test data were received and collected using high accuracy and high gain antenna of HRO, we use the theoretical means and variances of correlation metrics. Herein,



the false alarm probability P_{fa} is assumed to be $P_{fa} = 10$ -5and the C/N0 value is 65 dB-Hz. Figure 14 shows calculated correlation metrics along with their corresponding detection thresholds.



Fig. 14. Correlation metrics of BDS M1-S B1Cd

It is obvious that:

- Correlation asymmetry of the measured BDS M1-S B1Cd is pretty good.
- Correlation symmetry of the segment from $R_{0.1}$ to $R_{0.5}$ is a little better than that of the segment from $R_{0.05}$ to $R_{0.1}$, with the worst asymmetry occurs at around $R_{0.1}$
- The quality of the transmitted signal is within the specifications. There are neither major asymmetries in waveform nor major deformations in correlation peak.

7. Conclusion

In this paper, starting from the ICAO adopted threat model, a general extended TMA/TMB/TMC threat model suitable for new generation GNSS signals is proposed here in detail. The mathematical formulation has also been introduced in section II for new GNSS signals. The model has been applied to some present and possible future GNSS modulations. And it is shown to have good effectiveness.

However, as already said, no researches have been done on the symmetry between the rising edge and falling edge for a PRN code or baseband signal yet. It is shown that this kind of waveform distortion could also result in tracking errors, range biases, and position errors in GNSS receivers. A



novel WRaFES model determined for waveform asymmetry analyzing is proposed in this paper. And the effects of WRaFES model are analyzed in detail in terms of time domain, correlation peak and S curve bias. Here we assume that correlator outputs are Gaussian distribution, so it is possible to determine the detection threshold corresponding to each correlation metric. Simulation results show the good effectiveness and robustness of WRaFES model.

Finally, taking the first new generation satellite of BDS global system for example, B1 signal transmitted by the current BDS M1-S satellite was measured and collected with high accuracy, using a 40-meter parabolic antenna in Haoping Radio Observatory, China. In order to better analyze B1Cd signal, the carrier and navigation message should be stripped from the received signal at first. Then resample it to ensure an equal integral number of samples per chip. Taking the advantage of the periodic repetition and good orthogonality of PRN codes, it is possible to separate B1Cd component from the POCET modulated B1 complex signal. Then we can apply WRaFES model proposed in this paper to analyze the symmetry and its effects in detail in terms of time domain, correlation peak and S curve bias. Both simulation results and test results show that, WRaFES model is very effective not only in detecting waveform asymmetry with high accuracy, but also in analyzing the relationship between waveform asymmetry and tracking error. If used together with extended TMA/TMB/TMC, it is possible to better detect and analyze different kinds of evil waveform for new generation GNSS signals.

The next step of this research could focus on studying the influence on waveform deformation affected by different kinds of multipath and interference, and on designing specific SQM metrics to discriminate interference from multipath signals. In addition, the effectiveness of employing adaptive correlator space leading to flexible SQM metrics can be investigated to be an extension of this research (Progri et al., 2001; Progri et al., 2002; Progri et al., 2011). Due to modified correlator spacing, it is possible to reduce the time to detect a waveform deformation, which may lead to higher receiver awareness against distorted GNSS signals.

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