A Novel Analog Threat Analysis of BDS Signal and Effect on Ranging Performance

Meng Wang, Chengyan He, Xiaochun Lu, Ji Guo and Li Kang

Abstract Satellite navigation analog threat generate unit abnormal will lead to signal distortion, navigation signal analog threat will directly affect the ranging, positioning performance and other user experience. In this paper, the analog threat signal of BDS are researched and analyzed. Firstly, the large-diameter antenna receiving system is used to obtain the off-line satellite navigation signal data. Using the cumulative average method to process the baseband waveforms. Then, the standard chip correlation technique is used to obtain the optimal symbol waveform. Secondly, the optimal symbol is modeled based on the 2OS model to determine the initial value of the σ (damping factor) and f_d (damped frequency) of oscillation. The two-dimensional search is used to search σ and f_d respectively. The mean of the difference between ideal signal and the real signal waveform are based for the σ and f_d of oscillation values. Finally, the simulation and experimental data are used to verify, the estimation method of the analog distortion parameters of the navigation signal and its influence on the ranging performance are given in detail.

Keywords BDS signal · Analog threat · Ranging performance

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J. Sun et al. (eds.), *China Satellite Navigation Conference (CSNC) 2018 Proceedings*, Lecture Notes in Electrical Engineering 498,
https://doi.org/10.1007/978-981-13-0014-1_12

1 Introduction

The SQM (signal quality monitoring) is an important indicator to detect the normal orbiting satellites, and the normal orbiting satellites also occur subtle distortion [1]. As a result, the cross-correlation function curve of the local signal and the ground receiving signal will be deteriorated, and the zero crossings of the S curve will occur move, thus causing ranging error [2]. The failure of the satellite payload in the satellite navigation system will lead to distortion of the navigation signal, thus affecting the user's ranging performance [2]. Since 1997 GPS-SV19 satellite failure, the satellite signal failure model analysis has drawn people's attention [3–5]. The foreign scholars Alexanhder Michael Miteman, Robert Eric Phelts, P Enge and soon on, have studied the evil signal model in dept [5]. The most typical research about the chip distortion model is the 2nd-order step (2OS) model proposed by Robert Eric Phelts. The model summarizes three possible fault signal models: TMA (digital distortion), TMB (analog distortion), and TMC (mixed distortion) [3, 5]. ICAO Annex 10 sets the parameters of the 2OS distortion model for GPS and GLONASS navigation signal [5]. For GPS and GLONASS systems, chip distortion model has been quite successful, qualitative and quantitative analysis have achieved remarkable results. In this paper, the digital threat and analog threat models in the 2nd-order step (2OS) model are introduced, and the analog threat model is introduced in detail. The second section introduces the chip extraction method, from the collection of raw data to the finally selected optimized chip. The third section is based on the 2nd-order step (2OS) model, the analog threat model of the measured BDS signal is established, and the two-dimensional accurate search method is proposed to obtain the precise parameter values of the simulation distortion. In the fourth section, the measured signals and the simulated signals with determined parameters in the third section are respectively used for verification. The locking points bias are given. It is further confirmed that the method to determine the simulated distortion parameters in Step 3 is feasible and effective. In conclusion, the determination of the simulated distortion parameters plays a supporting role in the signal quality assessment and has important reference significance for the BDS signal analysis.

2 2OS (2nd-Order Step)

2.1 Digitial Threat (TMA)

Digital threat occurs inside the NDU (navigation data unit), independent analog threat, this failure as either an advance or delay in the falling edge of C/A code chip [3], the positive and negative chip waveform width inconsistencies, correlation peak expansion [2, 6]. This kind of distortion mode generates the dead-zones in the correlation peak. Figure 1 depicts a delay of 0.3 chips of a chip period, and its effect on the correlation peak like Fig. 2. We can be get from the Figs. 1–2, the chip is

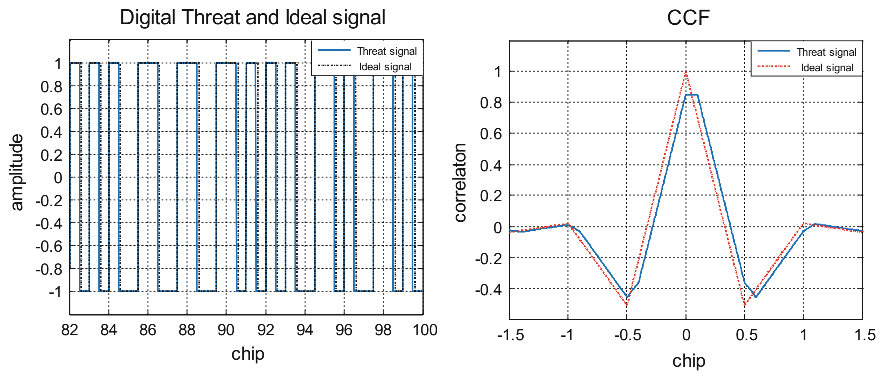


Fig. 1 Digital threat model

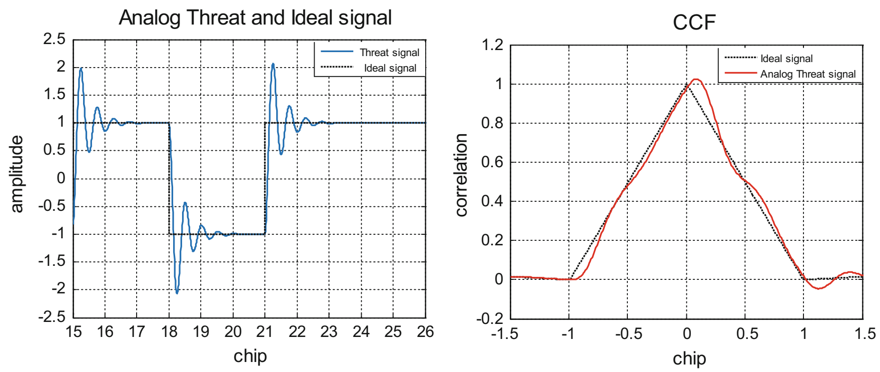


Fig. 2 Analog threat model

delayed (or advanced), the correlation curves also translates entirely backwards or forwards, and the correlation peak shows a dead-zones. The proposed range of single TMA parameter Δ, is ±0.12 of a code chip, since larger values produce waveforms that are easily detectable by multi-correlation signal quality monitors [6]. At present, a great deal of research has been done on the current BDS digital threat, so this article only briefly introduces and the follow-up no longer discussed in detail.

2.2 *Analog Threat (TMB)*

Analog threat (TMB) occurs in the satellite analog payload module, which is mainly caused by the on-board transmitter baseband filtering or radio frequency filtering anomaly [2]. As shown in Fig. 3, analog threat waveform like the

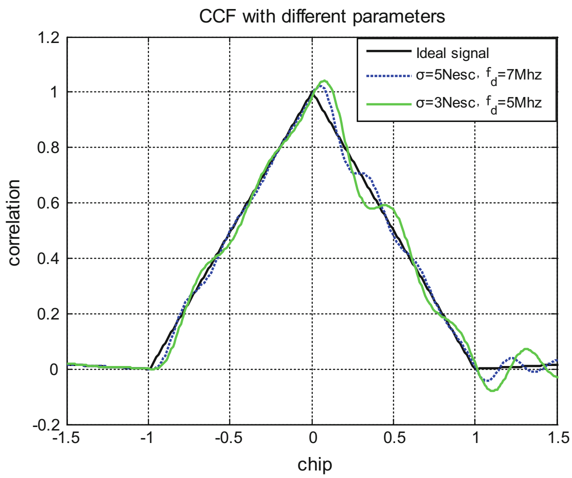


Fig. 3 Analog threat correlation curve with different parameters

amplitude modulation and ringing joint effect, independent of digital threat module [3]. The expression is the jitter of the time-domain chip waveform, the distortion of the correlation peak, left-right asymmetry, etc. [3, 5]. The analog threat signal can be regarded as the response of the ideal signal after passing through the second-order filter [3]. The mathematical expression is as follows:

$$e(t) = \begin{cases} 0 & t < 0 \\ 1 - \exp(-\sigma t)\left[\cos\omega_d t + \frac{\sigma}{\omega d}\sin\omega_d t\right] & t \geq 0 \end{cases} \quad (1)$$

From the above equation, the corresponding impulse response function is:

$$h_{(\sigma,f_d)}(t) = \frac{\sigma^2 + \omega_d^2}{\omega_d} e^{-\sigma t}\sin(\omega_d)u(t) \quad (2)$$

TMB signal that is:

$$x_{TMB}(t) = x_{nom}(t) \ * \ h_{(\sigma,f_d)}(t) \quad (3)$$

among them:

$$\omega_d = 2\pi f_d, x_{nom}(t) \text{is ideal signal;}$$

From Fig. 2 and Eq. (1), When σ is constant, the larger the f_d is, the higher the dithering frequency of the waveform is. When f_d is constant, the larger the σ is, the faster the waveform attenuation tends to the amplitude of the chip; thus, f_d affects the oscillation frequency of the waveform, While δ affects the oscillation amplitude of the waveform [3]. The second-order step (2OS) model proposed by Robert Eric Phelts gives the specific parameter values under different navigation system and threat models in detail. We can get from Table 1, For TMB, f_d range from 4 to

Table 1 .

	GPS	GLONASS
TMA	-0.12 chip $\ll \Delta \ll 0.12$ chip	-0.11 chip $\ll \Delta \ll 0.11$ chip
TMB	$\Delta = 0$ 4 MHz $\ll$ fd $\ll$ 17 MHz 0.8 Nesc $\ll \sigma \ll$ 8.8 Nesc	$\Delta = 0$ 4 MHz $\ll$ fd $\ll$ 17 MHz 0.8 Nesc $\ll \sigma \ll$ 8.8 Nesc
TMC	-0.12 chip $\ll \Delta \ll 0.12$ chip 7.3 MHz $\ll$ fd $\ll$ 13 MHz 0.8 Nesc $\ll \sigma \ll$ 8.8 Nesc	-0.11 chip $\ll \Delta \ll 0.11$ chip 4 MHz $\ll$ fd $\ll$ 17 MHz 0.8 Nesc $\ll \sigma \ll$ 8.8 Nesc

17 MHz, and σ ranges from 0.8 to 8.8 M/s. f_d only extends as low as 4 MHz since lower frequencies would impact the military signal (P(Y)code), which is more closely monitored than the C/A code. Frequencies above 17 MHz would be difficult for the satellite signal hardware to generate. A lower σ would unrealistically result in unstable oscillations on the code chips, larger values of σ would not introduce additional constraints on the avionics since this would future attenuate the oscillations [6].

2.3 Analog Threat Model Correlation Function

The correlation function of analog threat is written as $R(\tau)$, TMB threat model:

$$\begin{aligned} \frac{\partial R(\tau)}{\partial \tau} &= u(\tau + T_c) - 2u(\tau) + u(\tau - T_c) \\ h_{2nd}(t) * \frac{\partial R(\tau)}{\partial \tau} &= e(\tau + T_c) - 2e(\tau) + e(\tau - T_c) \end{aligned} \quad (4)$$

Analog threat correlation peak function as follows:

$$R(\tau, \sigma, f_d) = h_{2nd}(\tau, \sigma, f_d) * R(\tau) = E\Big|_0^{\tau + T_c} - 2E\Big|_0^{\tau} + E\Big|_0^{\tau - T_c} \quad (5)$$

And E(t) is one-order response;

$$E(t) = \int_0^t e(\alpha)d\alpha = \begin{cases} 0 & t \leq 0 \\ t - \frac{2\sigma}{\sigma^2 + \omega_d^2} + \frac{\exp(-\sigma t)}{\sigma^2 + \omega_d^2}\left[2\sigma\omega_d t + \left(\frac{\sigma^2}{\omega_d} - \omega_d\right)\sin\omega_{dt}\right] & t \geq 0 \end{cases} \quad (6)$$

Analog threat correlation curve is affected by the sine and cosine function at the same time, which directly leads to the jitter and asymmetry of the correlation curve [3]. As shown in the Fig. 3, the correlation curves under different σ and f_d

parameters are simulate respectively. The smaller the f_d is, the smaller the frequency of the relevant curve jitter is. When f_d is constant, the smaller σ is, the smaller the jitter amplitude of the correlation curve is.

3 Optimal Chip Extraction

Using the 40-m large aperture antenna to obtain the original BDS signal data with high signal-to-noise ratio and low multipath interference. Firstly, use the software receiver to process the raw data to obtain the baseband signal Fig. 4a. Then, the baseband signal is processed with the averaging processing method, we can see that the baseband waveform amplitude envelope significantly neat. Figure 4c shown take the standard chip-correlation technology (signal waveform and code impulse sequence related) [7] to process the signal shown in Fig. 4b for chip recovery. Figure 4d shown the enlarged view of Fig. 4c. Figure 5 shows the optimized symbols extracted.

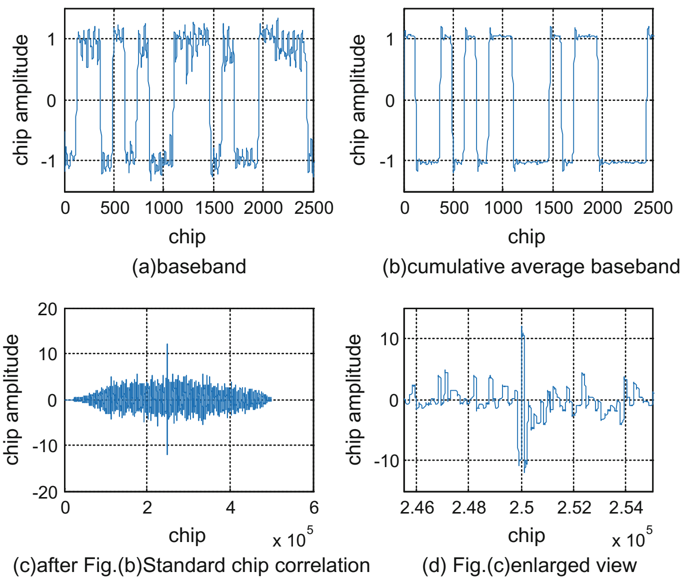


Fig. 4 Chip extraction process

4 Analog Distortion Model Parameters to Determine the Method

As shown in Fig. 5, the decay trend of the envelope curve is σ, and the difference between adjacent wave peaks is f_d. In order to obtain the initial values of σ and f_d, we first extract the special points such as the peak and trough of the optimal chip waveform. Then, the extracted data are fixed function interpolation fitting. According to the result of the fitting curve envelope, we obtain initial value about σ and f_d. In order to get more accurately estimate σ and f_d, the chart of the program structure is proposed as follows Fig. 6. After the pre-processing obtains the initial values of σ and f_d, the σ and f_d with 1000 Hz step search respectively. Based the mean of difference between the actual signal chip and ideal signal, the minimum mean difference is the needed ideal waveform, and the corresponding σ and f_d is finally determined precise parameter values. Figure 7 shown the minimum mean difference between the ideal signal and the actual signal chip waveform, we can see a good fit.

5 Ranging Performance

As shown in Fig. 3, Analog threat will produce the correlation curve fluctuation, jitter and lead to the left-right asymmetry situation, directly produce the ranging error. Ideally, the zero crossings of the receiver's loop phase curve (S-curve), code ring lock points, should be at a code loop tracking error of 0 [5]. Due to the influence of analog threat, the lock phase of the code phase detection phase will shift. Set the lead- lag correlator interval is d, the corresponding S-curve expression is:

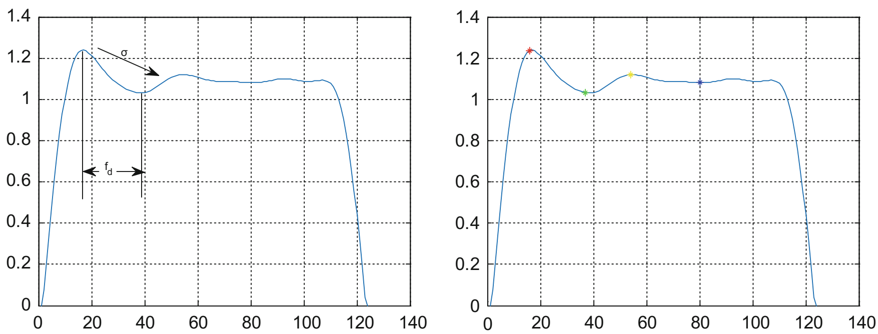


Fig. 5 Optimized symbol waveforms

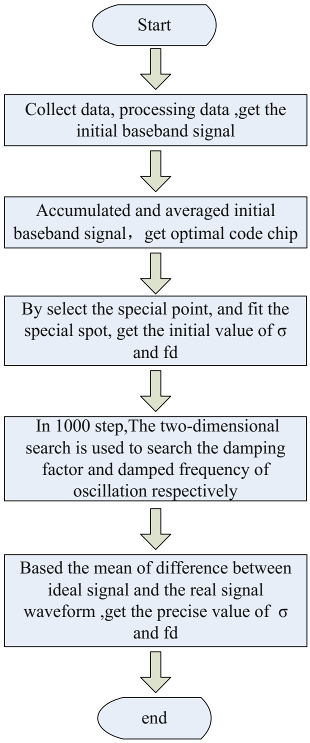


Fig. 6 Two-dimensional search flow chart

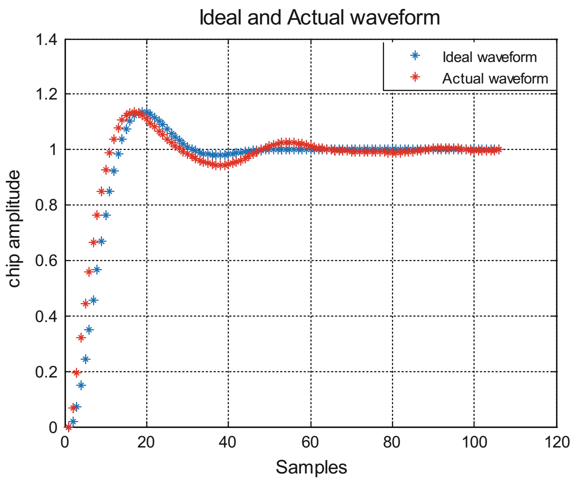


Fig. 7 Ideal and measured signal fitting plots

$$S_{Curve}(\varepsilon, d) = \left|CCF\left(\varepsilon - \frac{d}{2}\right)\right|^2 - \left|CCF\left(\varepsilon + \frac{d}{2}\right)\right|^2 \quad (7)$$

The locking point deviation ε_bias (d) is satisfied:

$$S_{Curve}(\varepsilon_{bias}(d), d) = 0 \quad (8)$$

As shown in the Fig. 8, it is the ranging error generated by the measured signal. As shown in the Fig. 9 which is the ranging error of the simulate signal calculated by the analog threat parameter adopted in this paper.

Fig. 8 Measured signal ranging error

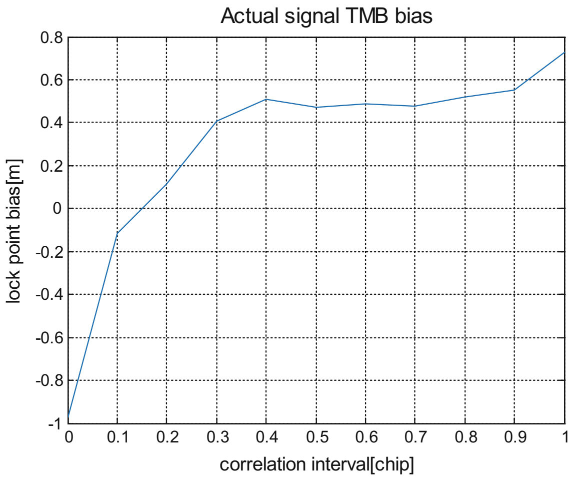
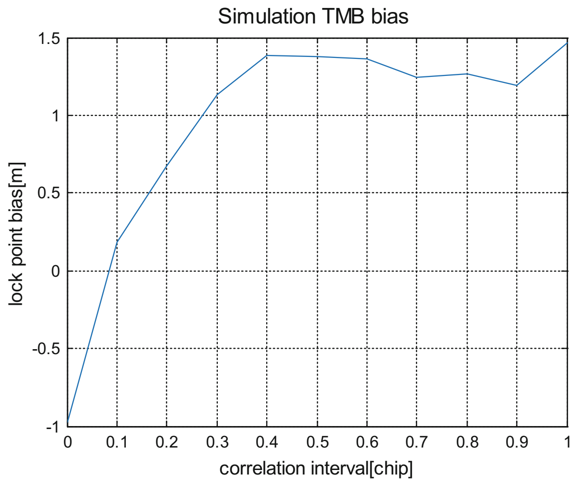


Fig. 9 Simulationsignal ranging error



6 Conclusion

In this paper, the model of BDS signal simulation distortion is discussed in detail, and the parameters of analog threat model are quantitatively deduced. The ideal signal obtained from the calculated σ and f_d parameters fits well with the measured signal. To a certain extent, this article provides support for the quantitative analysis of the simulated distortion parameters of BDS signals. Based on this, the effect of analog distorted signal on the ranging performance is verified. The results show that: (1) the analog threat calculated by the parameters are better fitted to the measured waveforms; (2) the higher the simulated distortion, the greater the impact on the ranging performance. These are of great importance to the subsequent BDS signal quality assessment.

Acknowledgements This study is funded by Youth Innovation Promotion Association of the Chinese Academy of Science (CN). This work is also supported by National Science Foundation of China (No. 61501430).

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