frontiers | Frontiers in Physics

TYPE Original Research
PUBLISHED 16 March 2023
DOI 10.3389/fphy.2023.1076346

Check for updates

OPEN ACCESS

EDITED BY
Olga V. Khabarova,
Tel Aviv University, Israel

REVIEWED BY
Zhaowen Yan,
Beihang University, China
Ershen Wang,
Shenyang Aerospace University, China

*CORRESPONDENCE
Xiao Wei,
xiaowei12@nudt.edu.cn

SPECIALTY SECTION
This article was submitted to Space Physics, a section of the journal Frontiers in Physics

RECEIVED 21 October 2022
ACCEPTED 06 March 2023
PUBLISHED 16 March 2023

CITATION
Wenxiang L, Wei X, Xiaozhou Y, Manli Q, Zukun L, Xiangjun L and Xin Y (2023), Analysis of ranging biases of BOC signal threat based on non-ideal channel group delay characteristics.
Front. Phys. 11:1076346.
doi: 10.3389/fphy.2023.1076346

Analysis of ranging biases of BOC signal threat based on non-ideal channel group delay characteristics

Liu Wenxiang, Xiao Wei*, Ye Xiaozhou, Qin Manli, Lu Zukun, Li Xiangjun and Yang Xin

College of Electronic Science, National University of Defense Technology, Changsha, China

Satellite signal threat is an important kind of satellite signal anomaly, which will lead to ranging biases of user receiver. BOC modulation is used more and more widely in the field of satellite navigation system. In the existing literature, there is a shortage that the non-ideal characteristics of the channel are not taken into account in the ranging biases analysis of BOC signal threat. The non-ideal characteristic of the receiving channel is one of the main bias sources of navigation signal reception. In the process of receiving navigation signal, due to the jitter caused by channel noise and the non-ideal phase of the channel, ranging biases will be introduced. To solve this problem, this paper proposes the analysis model of ranging biases of BOC signal threat based on non-ideal channel characteristics, and analyzes the non-ideal group delay characteristics of BOC (1,1) signal incoherent ranging mode. From the analysis results of ranging biases under multiple threated signals, it can be seen that the non-ideal group delay characteristics will worsen the ranging biases of BOC signal threat in most cases. In the sense of minimum ranging biases caused by BOC signal threat, 0.3chip~0.35chip is the recommended parameter for non-coherent reception of BOC (1,1) early late code.

KEYWORDS

GNSS signal threat, binary offset carrier (BOC) signal, ranging biases, non-ideal channel, group delay characteristics

1 Introduction

Satellite signal threat is one of the faults of the satellite system that results in abnormal integrity. In history, GPS signals have been detected abnormal for many times [1–4]. The study of the effect of satellite signal threat is an important content of the study on integrity of satellite navigation system. After the signal threat of GPS PRN 19 satellite in 1993 [1], the International Civil Aviation Organization (ICAO) used the second-order step threat model to describe the threat characteristics of BPSK signal [5–7]. The second-order step threat model of BPSK signal is also called ICAO threat model. Although the modeling of ICAO threat model is derived from the approximation of GPS PRN 19 satellite signal threat characteristics, it describes the general impact on signal characteristics when the general digital and analog devices in the satellite signal generation unit are abnormal. Therefore, as the basic model of BPSK signal integrity research, this model has extensive research significance and application value.

With the wide application of BOC modulation in GPS modernization program, European Galileo system and Beidou system in China [8–10], experts at home and abroad have made in-depth research on parameter design of BOC signal and user reception algorithm [10–15] but the research on the integrity of BOC signal has just started [16, 17]. At present, the main research on the integrity of BOC signal is that the BOC signal threat results in the receiver ranging biases. Phelts et al. extended the ICAO threat model of BPSK signal to the BOC signal and expanded the ranging of threat parameters. The ranging biases of BOC threat signal to ideal infinite bandwidth receiver in the form of early late code incoherent tracking were simulated and analyzed [16]. Fontanella et al. extended the threat parameter ranging of ICAO model to a greater extent to describe the threat model of BOC signal, and finally simulated and analyzed the ranging biases of BOC threat signal to the ideal low-pass filter receiver [17]. Xiao et al. compared the differences of phase discriminator functions of several typical BOC tracking modes and gave suggestions on the design of receiver front-end filter bandwidth and correlator interval, but did not analyze the ranging biases performance of BOC threat signals through non-ideal receiving channels and different receiver algorithms [18, 19]. The influence of waveform threat on ranging performance was analyzed by He et al. The signal used was BPSK signal, which did not involve the analysis of IBOC signal [20–23]. Gabriel Wong et al. introduced the threat of different satellite signals and the ranging biases under different code intervals [24]. M. Jean Baptiste Pagot et al. established signal threat models for new GNSS signals such as Galileo E1C, E5a, GPS L5, and compared the effect of different front-end bandwidth on signal reception [3]. Therefore, the current research on receiver ranging biases caused by BOC signal threat does not take into account the non-ideal characteristics of the channel.

Channel is an important part of the signal link of navigation receiver. Its non-ideal group delay characteristics can lead to threat of signal correlation peak, which affects the receiver's ranging performance [25]. Chen et al analyzed the influence of receiver group delay on QMBOC signal correlation peak, but did not involve signal threat and final ranging biases [26]. Li et al have done a lot of research on channel characteristics of navigation signals, which can provide theoretical reference for channel model in this paper [27–35]. In order to reduce the influence of group delay on signal ranging performance in actual receiver channel design, it is necessary to study the effect of channel characteristics on ranging performance to guide receiver design.

This paper focuses on the influence analysis of receiver ranging biases caused by BOC signal threat. This paper reviews ICAO threat model and its extension on BOC signal, and establishes a theoretical analysis model of BOC signal threat ranging biases considering channel non-ideal characteristics. Considering the non-ideal characteristics of channel group delay, the relationship between the BOC(1,1) signal threat ranging biases and the design parameters such as the receiver's early late code interval is analyzed, and useful conclusions for the design of BOC receiver are obtained.

2 Signal threat model

Starting from the actual satellite signal generation process, the International Civil Aviation Organization (ICAO) uses a second-order step threat model to describe the BPSK signal threat. The traditional BPSK signal threat model can be extended to the BOC signal threat. In Figure 1, satellite signal generation components include digital devices and analog devices in two categories [5, 36–38]. The second-order step threat model is divided into three basic models based on the failure condition of each type of device: digital threat (Threat Model A, TM A), analog threat (Threat Model B, TM B), digital-analog threat (Threat Model C, TM C). Digital threat model corresponds to some digital faults such as satellite navigation data processing unit, analog threat model corresponds to some analog processing unit faults in the satellite signal generation process, and digital-analog threat model corresponds to the faults in the whole satellite signal generation process [2, 8].

2.1 Digital threat model (TM A)

The digital threat signal is caused by faults of the digital device (navigation data unit) in the satellite signal generation unit, which shows that the falling edge of the pseudo code is ahead of or behind the normal falling edge. The falling edge of pseudo code is represented by Δ. When Δ > 0, the falling edge of pseudo code is behind the normal falling edge; When Δ <0, the falling edge of pseudo code is ahead of the normal falling edge.

2.2 Analog threat model (TM B)

Analog threat signal is caused by faults of analog devices in the satellite signal generation unit, which exhibits a second-order damped oscillation in amplitude. The analog threat signal can be equivalent to the response of a normal pseudo code signal after passing through a second-order filter, which is mathematically described as the unit-step response:

$$e(t) = \begin{cases} 0 & t < 0 \\ 1 - e^{-\sigma t}\left(\cos\omega_d t + \frac{\sigma}{\omega_d}\sin\omega_d t\right) & t \geq 0 \end{cases}, \tag{1}$$

where σ is the decay frequency of the second-order damped oscillation, the value ranging is $0.8\text{Mneps/s} \leq \sigma \leq 8.8\text{Mneps/s}$, ω_d is the oscillation angular frequency of the second-order damped oscillation: $\omega_d = 2\pi f_d$。 f_d is the oscillation frequency of the second-order damped oscillation, the value ranging is $4\text{MHz} \leq f_d \leq 17\text{MHz}$.

2.3 Digital-analog threat model (TM C)

Digital-analog threat signals is caused by faults of digital and analog device in the satellite signal generation unit. The signal amplitude exhibits a second-order damped oscillation, and the pseudo code falling edge is ahead or behind the normal falling edge. The ranging of each threat parameter is $-0.12chip \leq \Delta \leq 0.12chip$, $0.8\text{Mneps/s} \leq \sigma \leq 8.8\text{Mneps/s}$, $7.3\ \text{MHz} \leq f_d \leq 13\text{MHz}$.

The top of the correlation peak between the receiver's local pseudo code signal and the digital-analog threat signal is flat and the whole correlation peak is threated. Figure 2 A1, B1 show digital threat signal and the correlation peak for the BOC(1,1) signal; Figure 2 A2, B2 show analog threat signal and the correlation peak for the

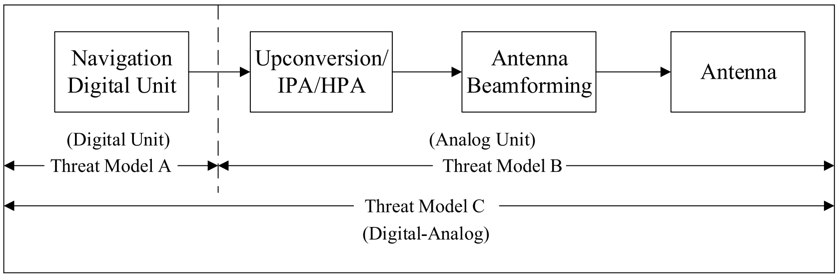

FIGURE 1
Corresponding relationship between signal threat model and fault of satellite signal generator.

BOC(1,1) signal; Figure 2 A3, B3 show digital-analog threat signal and the correlation peak for the BOC(1,1) signal:

3 Analysis model of ranging biases of BOC signal threat

From the perspective of the complete processing flow from generation to reception of BOC signal, BOC signal will go through the process of satellite generation, space propagation, ground user reception and measurement. The analysis of space propagation characteristics is relatively complex, including the influence of troposphere, ionosphere, multipath and interference, among which the troposphere propagation characteristics are mainly represented by the propagation delay independent of carrier frequency. If various factors such as multipath and interference are considered in the actual environment, the complete signal flow of BOC signal will be very complex. In order to simplify the analysis of the problem, this section temporarily does not consider factors such as multipath and interference, but mainly considers the influence of non-ideal channels such as signal generation filter, ionospheric propagation characteristics and receiver equivalent filter on BOC signal threat. Therefore, the BOC signal processing flow is simplified as shown in Figure 3.

The threat of the BOC signal is mainly manifested in the threat of the correlation peak function, which leads to the biases of the receiver when tracking the BOC signal and measuring the pseudo range. The factors that cause the threat of correlation peak function include: threat of BOC signal, non-ideal characteristics of satellite signal generation filter (including non-ideal amplitude frequency response and non-ideal group delay), ionospheric propagation characteristics and non-ideal characteristics of receiver equivalent filter. In order to simplify the analysis, the non-ideal characteristics of satellite signal generation filter, ionospheric propagation characteristics and receiver equivalent filter are collectively referred to as channel non-ideal. It is worth pointing out that the threat of BOC signal correlation peak leads to the biases of receiver measurement (mean shift of measurement biases), which is independent of noise [27, 28]. Therefore, the influence of thermal noise is not considered in the analysis of ranging biases of BOC signal threat.

In this way, if the channel is not ideal, the equivalent analysis model of ranging biases of BOC signal threat is shown in Figure 4.

The original BOC signal generated on the satellite is set as $s(t)$, the BOC threat signal is set as $\tilde{s}(t)$, the BOC signal after passing the ideal low-pass filter and the channel non-ideal equivalent filter is $\tilde{s}_{LN}(t)$. The local signal $s_R(t)$ generated at the receiver is correlated with the received BOC signal $\tilde{s}_{LN}(t)$ to obtain the correlation function $\tilde{R}_{LN}(\tau)$, and then the ranging biases of BOC signal threat is obtained according to the correlation function and tracking discrimination function analysis.

According to the conversion relationship between the time domain cross correlation function and the frequency domain cross power spectrum of the two signals, we can get:

$$\begin{aligned}&\tilde{R}_{LN}(\tau)\\&=\int_{-\infty}^{\infty}\tilde{S}(f)H_L(f)H_N(f)S_R^*(f)e^{j2\pi f\tau}df\\&=\int_{-\infty}^{\infty}G_{TM}(f)H_L(f)H_N(f)e^{j2\pi f\tau}df\end{aligned} \tag{2}$$

Where, $H_L(f)$ is the frequency domain response function of the ideal low-pass filter, $H_N(f)$ is frequency domain response function of channel non-ideal equivalent filter, $\tilde{S}(f)$ is the spectrum of the BOC threat signal $\tilde{s}(t)$, $S_R^*(f)$ is the spectrum of the local signal $s_R(t)$, $G_{TM}(f)$ is the cross power spectrum of the BOC threat signal and the BOC ideal signal.

The definition of ideal low-pass filtering can be written as:

$$H_N(f)\triangleq A(f)e^{j\varphi(f)} \tag{3}$$

Where, B_n is the one-sided cutoff bandwidth for ideal low-pass filtering.

The definition of the channel non-ideal equivalent filter can be written as:

$$H_N(f)\triangleq A(f)e^{j\varphi(f)} \tag{4}$$

Where, $A(f)$ and $\varphi(f)$ are the amplitude frequency response and phase frequency response of channel non-ideal equivalent filter, the group delay is defined as [9]:

$$\tau_g(f)\triangleq-\frac{1}{2\pi}\frac{d\varphi(f)}{df} \tag{5}$$

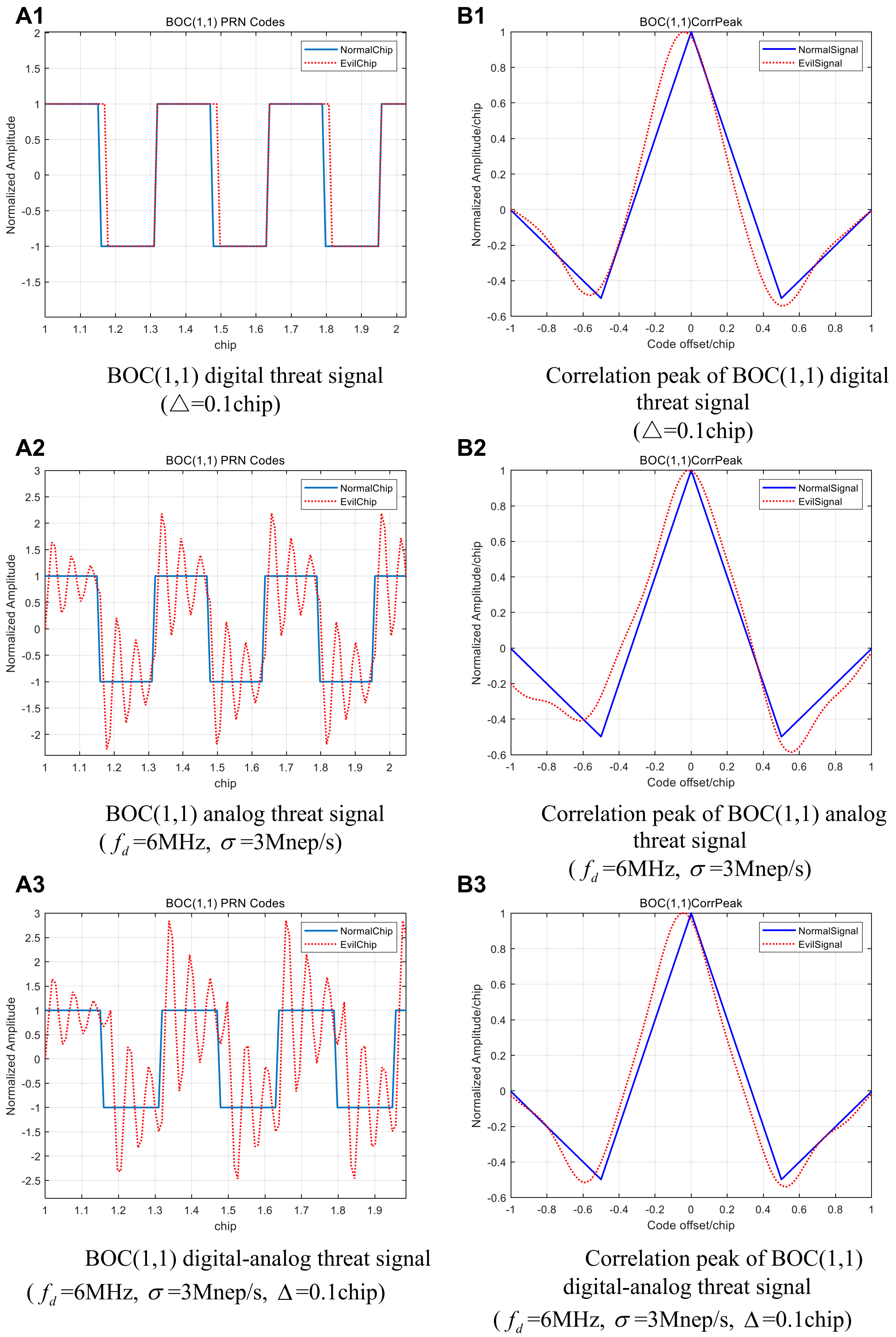

FIGURE 2
Time domain waveform and correlation peak of BOC (1,1) signal threat.

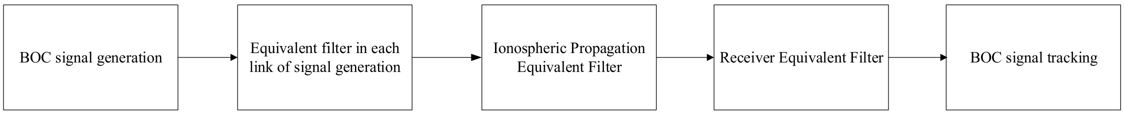

FIGURE 3
Simplified process of BOC signal generation and reception.

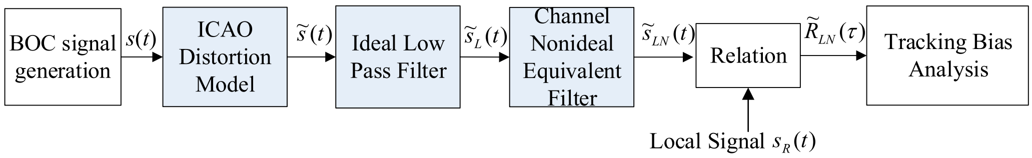

FIGURE 4
Equivalent analysis model of ranging biases of BOC signal threat based on non-ideal channel.

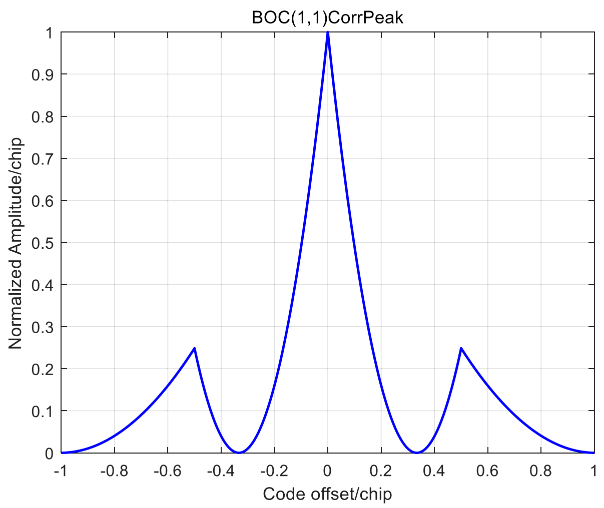

FIGURE 5
Correlation function by BOC (1,1) Bump-jump method under ideal condition.

4 BOC(1,1) signal threat ranging biases based on non-ideal channel group delay

The equivalent analysis model in Figure 4 can be used to analyze the BOC signal threat ranging biases based on the non-ideal group delay characteristics. The non-ideal group delay characteristics are the typical non-ideal channel effect [27, 28]. This section analyzes the influence of BOC signal threat under the non-ideal group delay characteristics. Let $A(f) \equiv 1$, $\tau_g(f)$ takes different functions to analyze the correlation function characteristics and ranging biases of BOC signal under the non-ideal group delay. Next, under the quadratic curve group delay characteristics, the influence of threated signals on ranging biases is analyzed for BOC (1,1) signals.

Assuming that $B_n = 3$MHz, the non-ideal filter is quadratic curve group delay characteristic:

$$\tau(f) = kT_c(f/B_n)^2 \tag{6}$$

Where T_c is a chip width of the PN code of the BOC(1,1) signal, the normalized coefficient is taken as 3.

BOC signal tracking adopts the structure of Bump-jump early late code non-coherent tracking. In the Bump jump method, the correlation function of energy can be obtained by computing the square sum $(VE^2 + P^2)$ of the correlation output values of far instant and leading paths. Based on this correlation function, the unambiguous BOC signal can be captured. The output of the instant and leading correlation function obtained by the Bump jump method are [9]:

$$R_p(\varepsilon_\tau) = \frac{1}{T_p}\int_{t_d-T_p}^{t_d} s_f'(t-\tau)r_p(t-\hat{\tau})dt \tag{7}$$

$$R_{VE}(\varepsilon_\tau) = \frac{1}{T_p}\int_{t_d-T_p}^{t_d} s_f'(t-\tau)r_{VE}(t-\hat{\tau})dt \tag{8}$$

$$r_p(t-\hat{\tau}) = c(t-\hat{\tau})sc_I(t-\hat{\tau}) = c(t-\hat{\tau})sc(t-\hat{\tau}) \tag{9}$$

$$r_{VE}(t-\hat{\tau}) = c(t-\hat{\tau})sc_Q(t-\hat{\tau}) = c\left(t-\hat{\tau}-\frac{T_{sp}}{4}\right)sc\left(t-\hat{\tau}-\frac{T_{sp}}{4}\right) \tag{10}$$

Figure 5 shows the correlation by BOC(1,1) Bump-jump method under ideal condition$R_p(\varepsilon_\tau)$ and $R_{VE}(\varepsilon_\tau)$ are the correlation functions of the filtered received BOC signal and the local BOC signal respectively, $r_p(t-\hat{\tau})$ and $r_{VE}(t-\hat{\tau})$ are the local BOC signals. $s_f'(t)$ is the received BOC signal.

The ranging biases of BOC (1,1) signal under three threat models of digital threat (TM A), analog threat (TM B) and digital-analog threat (TM C) are analyzed.

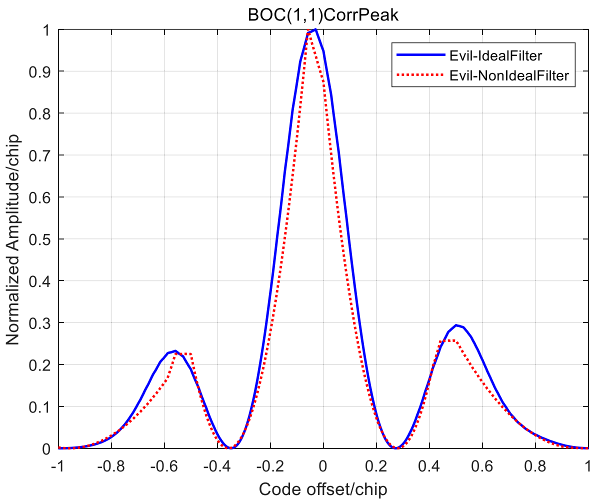

FIGURE 6
Correlation function of Bump-jump tracking method for BOC (1,1) signal TMA with non-ideal channel.

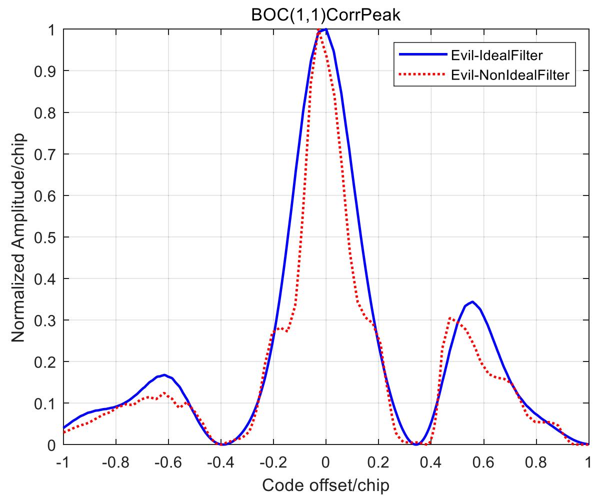

FIGURE 8
Correlation function of Bump-jump tracking method for BOC (1,1) signal TMB with non-ideal channel.

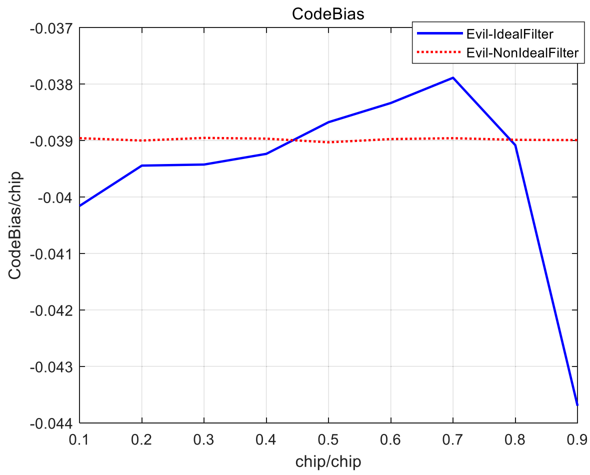

FIGURE 7
Ranging biases of Bump-jump tracking method for BOC (1,1) Signal TMA with non-ideal Channels.

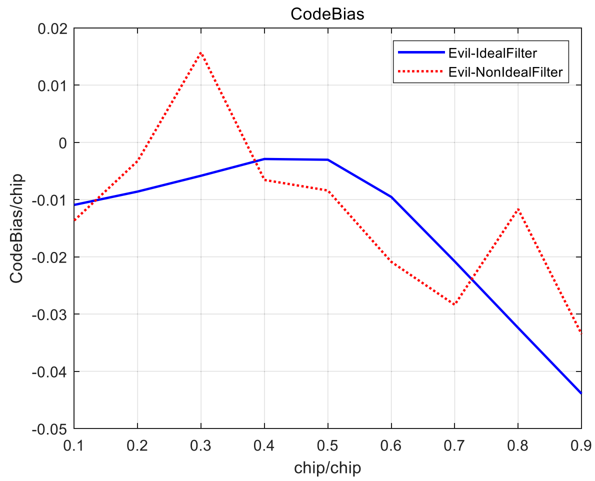

FIGURE 9
Ranging biases of Bump-jump tracking method for BOC (1,1) signal TMB with non-ideal channels.

4.1 The digital threat model (TM A) of $\Delta = 0.1chip$

Under the digital threat model (TM A) of $\Delta = 0.1$chip, considering the quadratic curve group delay characteristics of the non-ideal filter, the correlation peak result of the BOC signal Bump-jump early late code non-coherent tracking is shown in Figure 6. The comparison between the ranging biases results under the group delay characteristics of the quadratic curve and the ranging biases results under the ideal low-pass filter is shown in Figure 7.

4.2 The analog threat model (TM B) of $f_d = 6MHz$, $\sigma = 3Mnepers/s$

Under the analog threat model (TM B) of $f_d = 6MHz$, $\sigma = 3Mnepers/s$, considering the quadratic curve group delay characteristics of the non-ideal filter, the correlation peak result of the BOC signal Bump-jump early late code non-coherent tracking is shown in Figure 8. The comparison between the ranging biases results under the group delay characteristics of the quadratic curve and the ranging biases results under the ideal low-pass filter is shown in Figure 9.

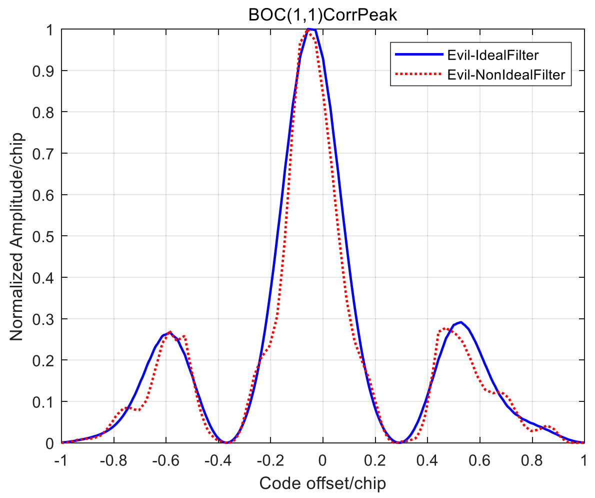

FIGURE 10
Correlation function of Bump-jump tracking method for BOC (1,1) signal TMC with non-ideal channel.

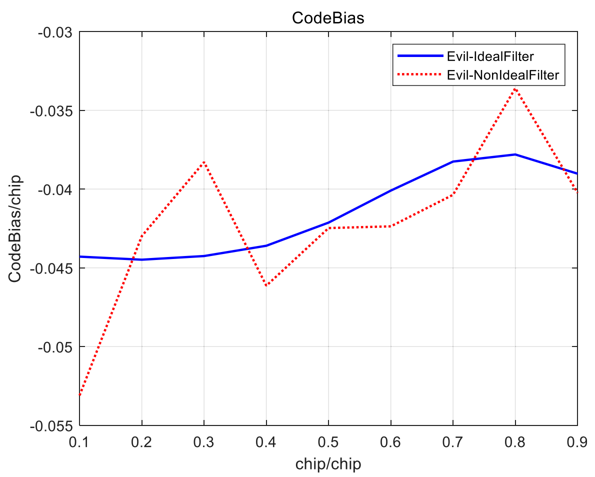

FIGURE 11
Ranging biases of Bump-jump tracking method for BOC (1,1) signal TMC with non-ideal channels.

4.3 The digital-analog threat model (TM C) of $f_d = 6MHz$, $\sigma = 3Mnepers/s$, $\Delta = 0.1$chip

Under the digital-analog threat model (TM C) of $f_d = 6MHz$, $\sigma = 3Mnepers/s$, $\Delta = 0.1$chip, considering the quadratic curve group delay characteristics of the non-ideal filter, the correlation peak result of the BOC signal Bump-jump early late code non-coherent tracking is shown in Figure 10. The comparison between the ranging biases results under the group delay characteristics of the quadratic curve and the ranging biases results under the ideal low-pass filter is shown in Figure 11.

Based on the above results, the following conclusions can be drawn: when the group delay characteristics of the channel are not ideal, the correlation peak shape of BOC signal threat will be further deteriorated under most of the early late code interval parameters, which will greatly increase the code tracking biases of BOC (1,1) signal. In addition, it is not difficult to find out from the above data results that, from the perspective of minimizing the ranging biases caused by signal threat, for the design of non-coherent reception of BOC (1,1) signal early late codes, if the early late code interval is selected between 0.3 chip and 0.35 chip, the ranging biases of BOC signal caused by the above three threat models under the ideal low-pass filter and non-ideal quadratic group delay channel characteristics are minimal or relatively small.

5 Conclusion

The non-ideal characteristics of channel group delay are not considered in the analysis of BOC signal distortion ranging deviation in the existing literature. This paper proposes an equivalent analysis model which is based on the assumption that the Bump-jump tracking method is used. And the range deviation of BOC (1,1) signal distortion under the time delay of the quadratic curve group is analyzed. The analysis results show that, the correlation peak of the BOC signal received through the non-ideal channel is deformed more than that of the BOC signal received through the ideal channel, and the ranging biases fluctuates significantly under different early late code intervals. Therefore, the characteristics of the non-ideal channel will worsen the ranging biases of the BOC signal threat in most cases. For the receiver, the early late code interval that is closer to the ranging biases of the ideal filter should be selected. It can be seen from the analysis results of ranging biases under multiple threated signals that in the sense of minimum ranging biases caused by BOC signal threat, 0.3 chip~0.35 chip is the recommended parameter for BOC (1,1) incoherent reception of early late codes. The analysis model in this paper can also be used to analyze the ranging biases of other higher-order BOC signals under different channel non-ideal characteristics when they are threated.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization: LW and XW; methodology and validation: XW and YEX; formal analysis and investigation: LW and QM;

resources: LZ; writing—original draft preparation: LW; writing—review and editing: LX and YAX.

Funding

This research was funded by the National Natural Science Foundation of China (U20A0193&62003354).

Acknowledgments

The authors would like to thank the College of Electronic Sciences for providing the test platform.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

1. Edgar C, Czopek F, Barker LB. A Co-operative Anomaly resolution on PRN-19. In: Proceedings of the 12th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 1999); September 1999; Nashville, TN (1999). p. 2269–71.

2. Barker B, Huser SJ. Protect yourself navigation payload anomalies and the importance of adhering to ICD-GPS-200. In: Proceedings of the 11th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 1998); September 1998; Nashville, TN (1998). p. 1843–54.

3. Jean-Baptiste P. *Modeling and monitoring of new GNSS signal distortions in the context of civil aviation*. Chromepet, Chennai: MITT (2016). p. 1–16.

4. Shallberg KW, Ericson SD, Phelts E. Catalog and description of GPS and WAAS L1 C/A signal deformation events. In: Proceedings of the 2017 International Technical Meeting of The Institute of Navigation; January 2017; Monterey, California (2017). p. 508–20. doi:10.33012/2017.14877

5. Phelts RE. *Multicorrelator techniques for robust mitigation of threats to GPS signal quality*. Stanford, CA: Stanford University PHD (2001). p. 1–17.

6. Eric P R, Karl S, Todd W. WAAS signal deformation monitor performance: Beyond the ICAO threat model. In: Proceedings of the ION 2017 Pacific PNT Meeting; May 2017; Honolulu, Hawaii (2017). p. 1–3. doi:10.33012/2017.15103

7. International Civil Aviation Organization. *ICAO international standards and recommended practices. Annex 10 to the convention on international civil aviation. Volume I radio navigation aids seventh edition: ISBN 978-92-9258-504-4[S]*. Montreal, Canada: International Civil Aviation Organization (2018).

8. Betz JW. Binary offset carrier modulations for radionavigation. *Navigation, J Inst Navigation* (2002) 48(4):227–46. doi:10.1002/j.2161-4296.2001.tb00247.x

9. Fine P, Wilson W. Tracking algorithm for GPS offset carrier signals[C]. In: Proceedings of U.S. Institute of Navigation NTM Conference; San Diego, CA (1999). p. 671–6.

10. Julien O, Cannon ME. A new unambiguous BOC(n,n) signal tracking technique. In: Proceedings of the European Navigation Conference; Rotterdam (2004). p. 1–3.

11. Ferrara NG, Bhuiyan MZ, Söderholm S, Ruotsalainen L, Kuusniemi H. A new implementation of narrowband interference detection, characterization, and mitigation technique for a software-defined multi-GNSS receiver. *GPS Solutions* (2018) 22(4):106. doi:10.1007/s10291-018-0769-z

12. Sun X, Zhou Q, Ji Y, Fu Q, Miao Q, Wu S. An unambiguous acquisition algorithm for BOC (n, n) signal based on sub-correlation combination. *Wireless Personal Commun* (2019) 106(3):1609–28. doi:10.1007/s11277-019-06232-1

13. Sun C, Zhao HB, Zhuang C, Feng W. The IFFT-based SQM method against digital distortion in GNSS signals. *GPS Solutions* (2017) 21(4):1457–68. doi:10.1007/s10291-017-0622-9

14. Guo Y, Wang X, Lu X, Rao Y, He C. Algorithm research on high-precision tracking of beidou-3 B1C signal. In: Sun J, Yang C, Yang Y, editors. *China satellite navigation conference (CSNC) 2019 proceedings. CSNC 2019. Lecture notes in electrical engineering, vol 562*. Singapore: Springer (2019). p. 1–4. doi:10.1007/978-981-13-7751-8_45

15. Lu M, Li W, Ya Z, Cui X. Overview of BDS III new signals. *Navigation* (2019) 66(1):19–35. doi:10.1002/navi.296

16. Phelts RE, Akos DM. Effects of signal deformations on modernized GNSS signals. *J Glob Positioning Syst* (2006) 5:2–10. doi:10.5081/jgps.5.1.2

17. Fontanella D, Paonni M, Eissfeller B. A novel evil waveforms threat model for new generation GNSS signals theoretical analysis and performance. In: 2010 5th ESA Workshop on Satellite Navigation Technologies and European Workshop on GNSS Signals and Signal Processing (NAVITEC). Noordwijk, Netherlands: IEEE (2010). doi:10.1109/NAVITEC.2010.5708037

18. Xiao W, Liu W, Sun G. Modernization milestone: BeiDou M2-S initial signal analysis. *GPS Solutions* (2016) 20(1):125–33. doi:10.1007/s10291-015-0496-7

19. Han Q, Liu W, Xiao W. Equalization algorithm for GNSS receiver channel by FIR filters. In: 2017 Eighth International Conference on Intelligent Control and Information Processing (ICICIP). Hangzhou, China: IEEE (2017). p. 319–24.

20. He C, Guo J, Lu X, Wang X, Rao Y, Kang L, et al. A new evil waveforms evaluating method for new BDS navigation signals. *GPS Solutions* (2018) 22(2):37–13. doi:10.1007/s10291-018-0698-x

21. He C, Guo J, Lu X, Wang X, Liu F. The impact of carrier leakage and spectral asymmetry distortions on the performance of navigation signals. *China Satellite Navigation Conf* (2012) 161:147–60. doi:10.1007/978-3-642-29193-7_13

22. He C, Lu X, Guo J, Su C, Wang W, Wang M. Initial analysis for characterizing and mitigating the pseudo-range biases of BeiDou Navigation Satellite System. *Satellite Navigation* (2020) 1(1):3–10. doi:10.1186/s43020-019-0003-3

23. He C, Guo J, Lu X, Wang X. Measurements and offline analysis of bei dou GEO signal. In: *ION 2013* (2013). p. 28–30.

24. Gabriel W. *Impact of nominal signal deformations on satellite navigation systems*. Stanford, CA: Standford University (2014).

25. Coco DS, Clayton C, Dahlke S, Clynch J. Variability of GPS satellite differential group delay biases. *IEEE Trans Aerosp Electron Syst* (1991) 27(6):931–8. doi:10.1109/7.104264

26. Chen L, Zhao W, Xu Q, Zhang L. *The Effect Analysis of Filter group delay on QMBOC signal correlation peak*. Bacolod: CSNC (2022).

27. Li P, Huang Y, Zhou B, Ou G. *Research on all-pass network for wideband satellite receiver's RF front-end group delay equalization*. Virginia, USA: ION GNSS (2012).

28. Zhu X, Li Y, Yong S, Zhuang Z. A novel definition and measurement method of group delay and its application. *IEEE Trans Instrumentation Meas* (2009) 56(1):229–33. doi:10.1109/TIM.2008.927197

29. Lu Z, Chen F, Xie Y, Sun Y, Cai H. High precision pseudo-range measurement in GNSS anti-jamming antenna array processing. *Electronics* (2020) 9(3):412. doi:10.3390/electronics9030412

30. Song J, Lu Z, Xiao Z, Li B, Sun G. Optimal order of time-domain adaptive filter for anti-jamming navigation receiver. *Remote Sensing* (2021) 14(1):48. doi:10.3390/rs14010048

31. Wang F, Li P, Zhong S, Ni S. A fitting method of RF Channel Group delay characteristics for high precision navigation. In: IEEE 10th International Conference on Electronics Information and Emergency Communication (ICEIEC). Beijing, China: IEEE (2020). p. 26–30. doi:10.1109/ICEIEC49280.2020.9152281

32. Lu Z, Song J, Huang L, Ren C, Xiao Z, Li B. Distortionless 1/2 overlap windowing in frequency domain anti-jamming of satellite navigation receivers. *Remote Sensing* (2022) 14(8):1801. doi:10.3390/RS14081801

33. Wang F, Li P, Mou W, Zhong S, Ni S. Piecewise fitting technology of group delay difference based on fourier decomposition. In: IEEE 3rdInternational Conference on Information Communication and Signal Processing(ICICSP). Shanghai, China: IEEE (2020). p. 353–8. doi:10.1109/ICICSP50920.2020.9232113

34. Lu Z, Chen H, Chen F, Nie J, Ou G. Blind adaptive channel mismatch equalisation method for GNSS antenna arrays. *IET Radar, Sonar & Navigation* (2018) 12(4):383–9. doi:10.1049/iet-rsn.2017.0416

35. Lu Z, Nie J, Chen F, Chen H, Ou G. Adaptive time taps of STAP under channel mismatch for GNSS antenna arrays. *IEEE Trans Instrumentation Meas* (2017) 66(11):2813–24. doi:10.1109/TIM.2017.2728420

36. Liu WS, Xiao W. Performance analysis of GNSS signal distortions detection based on multi-correlators processing. *CSNC* (2022) 1:5. doi:10.26914/c.cnkihy.2022.000858

37. Phelts RE, Mitelman A, Pullen S. *Transient performance analysis of a multicorrelator signal quality monitor*. Beaumont, TX, USA: ION GPS (2001).

38. Li B, Qiao J, Lu Z, Yu X, Song J, Lin B, et al. Influence of sweep interference on satellite navigation time-domain anti-jamming. *Front Phys* (2013) 10:1–14. doi:10.3389/fphy.2022.1063474