Research on the Distortion Threat Model and Threat Space of BDS B1C and B2a Signals

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Abstract. Navigation signal distortion is a potential threat to navigation services. Modeling signal distortion is a necessary condition to ensure service safety and an important content of mandatory requirements in International Civil Aviation Organization (ICAO) standards. This paper studies the distortion threat model and threat space of BDS B1C and B2a signals. Based on the existing ICAO standard distortion model frame, a threat space determination method considering both satellite physical characteristics and distortion error characteristics is proposed. At the same time, the good ranging bias detection performance provided by the satellite onboard monitoring receiver on BDS satellite is well used to reduce the distortion parameter range threatening service, thus the threat space of B1C and B2a signals is determined and made smaller compared with the that of similar signals in other systems, and the requirement of signal quality monitoring performance will be reduced in theory. The research results can provide reference for the formulation and verification of the relevant contents of ICAO standards for BDS B1C and B2a signals.

Keywords: Navigation signal distortion · Threat model · Threat space · BDS B1C and B2a signals

1 Introduction

The satellite navigation signal may be distorted due to the non-ideality or failure of satellite onboard components. This distortion has actually occurred in GPS L1C/A signal [1, 2], which brings potential threat to navigation service [3, 4]. Especially for life safety services for civil aviation such as the Satellite-Based Augmentation System (SBAS) service and Ground-Based Augmentation System (GBAS) service, such distortion may lead to disastrous consequences [5–7]. So, some methods such as Signal Quality Monitoring (SQM) must be adopted to detect and alarm the distortion to ensure adequate protection for users.

Modeling the signal distortion and defining the specific distortion characteristics and distortion degree are the basis for the design and evaluation of SQM. In high integrity services such as civil aviation, the distortion threat model of navigation signal and the corresponding threat space are mandatory requirements in the International Civil Aviation Organization (ICAO) standard, and are the necessary conditions for satellite navigation system to be augmented by SBAS and GBAS to provide civil aviation services.

The signal distortion model research started firstly on GPS signal due to its actually occurred distortion cases. Based on the observation of the actual distortion, a reasonable compromise is made between fidelity and simplicity, and a distortion model for L1C/A signal is proposed, and the parameter range of the model is determined based on the state of the satellite, that is, the threat space [8]. This model has been written into ICAO standard [9].

Galileo system has also carried out signal distortion modeling research in the process of joining ICAO standard. Since Galileo in orbit satellite has not experienced obvious distortion, it directly adopts the distortion model framework of existing ICAO standards, and determines the threat space of E1C and E5a signals completely based on the theoretical characteristics of errors caused by distortion [10]. Because the actual characteristics of satellites are not considered in the modeling work, the threat space is obviously larger than that of GPS.

The BDS B1C and B2a signals plans to join the ICAO standards to be augmented by Dual-Frequency and Multi-Constellation Satellite-Based Augmentation System (DFMC SBAS). Therefore, it is necessary to define signal distortion threat model and threat space according to the requirements of the standard. This paper studies the distortion threat model and threat space for B1C and B2a signals.

Since there is no actual distortion in BDS in orbit satellite B1C and B2a signals currently, this paper takes into account the complexity, maturity and commonality with other GNSS, and adopts the general distortion model framework in the current ICAO standards. On this basis, this paper further proposes a threat space determination method considering both the satellite physical characteristics and distortion error characteristics and fully utilizes the good ranging error detection performance provided by the BDS satellite carrying the onboard monitoring receiver, then gives the threat space for B1C and B2a signals. Because more factors are considered in this paper comparing with that for other GNSS systems, the threat space obtained is significantly reduced comparing with that of similar signal in other GNSS systems, and the performance requirements of SQM will be also reduced in theory.

The results of this paper can provide reference for the formulation and verification of relevant contents of the ICAO standards for BDS B1C and B2a signals.

2 ICAO Threat Model and BDS Signal

2.1 Current Threat Model in ICAO

Threat model proposed by ICAO for the GPS and GLONASS signals has three parts, which are Threat Model A (TM-A), Threat Model B (TM-B) and Threat Model C (TM-C) [9].

Threat Model A consists of code that all the positive chips have a falling edge that leads or lags relative to the correct end-time. This model is associated with a failure of digital part of satellite, and has a single parameter Δ, which is the lead or lag of the falling edge expressed in µs or fractions of a chip.

Threat Model B introduces the amplitude modulation and models the degradation in the analog section of satellite. Specifically, it consists of the output from a second order linear system dominated by a pair of complex conjugate poles, which are $\sigma \pm j \cdot 2\pi f_d$, where σ is the damping factor in Mneper/s and f_d is the resonant frequency in MHz. The unit step response of the system is given as:

$$\mathrm{e}(t) = \begin{cases} 0 & t < 0 \\ 1 - e^{-\sigma t}\left[\cos(2\pi f_d) + \dfrac{\sigma}{2\pi f_d}\sin(2\pi f_d)\right] & t \geq 0 \end{cases} \tag{1}$$

Threat Model C consists of both the lead/lag and the amplitude modulation, and can be considered as a combination of the Threat Model A and Threat Model B.

2.2 BDS B1C/B2a Signals and the Processing Strategies

BDS B1C and B2a signals both consist of data channel and pilot channel [11, 12]. For civil aviation service, the pilot channel is used to get the ranging measurement. The pilot channel of B1C is QMBOC (6, 1, 4/33) modulated, which includes BOC (1, 1) component and BOC (6, 1) component in quadrature phase. For civil aviation service, only the BOC (1, 1) component of the pilot channel is used to get the ranging measurement. The pilot channel of B2a is BPSK (10) modulated, and for civil aviation service, it will be received by a BPSK (10) local replica.

Thus, the study of the threat model and threat space in this paper is for the BOC (1, 1) component of B1C pilot channel, and the B2a pilot channel in BPSK(10) modulation.

3   The Choice of Model Frame for BDS Signal

Currently, no obvious evil distortions have been observed on BDS B1C or B2a signals. Under this condition, we choose the model framework considering the following factors:

Firstly, the generation process of BDS signal on satellite includes digital 0/1 logic part and channel part (including digital channel and analog channel), which is basically consistent with the existing TM-A, TM-B and TM-C;

Secondly, according to reference [14], based on the continuous observation of GPS signal in recent years, the actual distortion characteristics may be very diverse and much more complex than what a specific model can characterize. The distortion models might only be an approximate of signal distortion, which should be compromised in the fidelity, complexity and maturity of application of the model.

As no obvious evil distortion appears yet for B1C and B2a signal, it is a reasonable choice to adopt a mature, simple and widely used model to approximate.

Therefore, the research on B1C and B2a signal distortion will be carried out in the framework of TM-A, TM-B and TM-C.

4 Threat Space Analysis

4.1 Analysis Methodology

Since no obvious distortion of B1C and B2a signals has been observed, based on this situation, we analyzed and determined the threat space (the parameter ranges of Δ, σ and f_d) by considering both the satellite status and the influence of the distortion on ranging measurement, including following principles:

Principle I: If the distortion parameter value has exceeded the physical realizability of the satellite, it will not be taken as the parameter range of the threat space.

Principle II: If the ranging error caused by the distortion parameter value is too large and easy to be detected, the distortion parameter value will not be taken as the parameter range of the threat space.

Principle III: If the differential error between the monitoring station receiver and the user receiver caused by the distortion parameter value is too small to affect the service performance, the distortion parameter value will not be taken as the parameter range of the threat space.

By using the three principles, some ranges of the parameters can be excluded. The remaining parameter ranges, which can be achieved by the satellite, not easy to detect and will lead to large differential error, are regarded as the threat space. The specific considerations for each principle are as follows.

4.1.1 Specific Considerations for Principle I

Similar to the analysis in [8], as the parameters of satellite signal are determined by on-board devices, even in the case of serious distortion, the parameter range will not exceed the level allowed by hardware. This factor mainly refers to the transmission bandwidth of the signal. As the navigation signal power is very low near the ground, if the suppression of a certain frequency band by the on-board filter is more than 10 dB, the signal in that frequency band can be ignored for user receiver. According to the filter status on the BDS Satellite: the onboard filters have more than 10 dB suppression for frequency 30 MHz or more far away from the center frequency of B1C, and have more than 10 dB suppression for frequency 40 MHz or more far away from the center frequency of B2a. Therefore, the distortion parameters larger than these frequencies have no threat to users.

4.1.2 Specific Considerations for Principle II

Signal distortion may induce ranging bias in receivers ranging measurement comparing with that of nominal signal. When this bias is large enough, it will be easily detected and alarmed by various methods like RAIM, SQM and the satellite on board signal monitoring. Therefore, it will not threat the user. BDS satellites have on board receivers to monitor the B1C and B2a signal, which can get the ranging measurement of the two signals under high power, low noise conditions and without dynamic, multipath, ionosphere or other interference, which will provide much better ranging performance than that can be reached on the ground. So, the principle II consideration will be further specified based on this satellite on board monitoring method. According to the actual measuring data, the Carrier to Noise density ratio (C/N0) that the satellite on board

monitoring receivers achieved will exceed 60 dB-Hz, ranging standard deviation will be better than 0.3 m ($1\sigma_{noise}$). For the detection performance with missed detection probability $< 1.5 \times 10^{-7}$/test (corresponding to $5.26\sigma_{noise}$) and false alarm probability $< 1.5 \times 10^{-7}$/test (corresponding to $5.26\sigma_{noise}$), the minimum detectable bias is 0.3 m $\times (5.26 + 5.26) = 3.156$ m. To be conservative, the threshold value is doubled and rounded to 7 m, that is, if the ranging bias caused by signal distortion is higher than 7 m, it is considered that this distortion can be effectively detected by the satellite on board receiver, which is not taken as a threat. Here, the satellite receiver parameters are consistent with the ground monitoring receiving parameters, see Sect. 4.1.3 for details.

4.1.3 Specific Considerations for Principle III

As the reference station receiver and the user receivers have strict design constrains in ICAO standard, the maximum differential error between monitor station receiver and the user receivers induced by the distortion characterized by a group of parameters can be determined by finite simulations. For BDS B1C and B2a signals in DFMC SBAS service, reference station receiver and the user receiver constraints are as follows.

(1) The reference station receiver:

   (a) BOC (1, 1) local replica for B1C, BPSK (10) local replica for B2a;
   (b) 3 dB bandwidth is 24 MHz;
   (c) Use early minus late discriminator;
   (d) B1C correlator spacing is 0.1 chips;
   (e) B2a correlator spacing is 1.0 chips.

(2) The user receiver:

   (a) BOC (1, 1) local replica for B1C, BPSK (10) local replica for B2a;
   (b) 3 dB bandwidth between 12–24 MHz;
   (c) Differential group delay not greater than 150 ns;
   (d) Use early minus late discriminator;
   (e) B1C correlator spacing between 0.08 and 0.12 chips;
   (f) B2a correlator spacing between 0.9 and 1.1 chips.

Referring to the analysis conclusion of [10], the maximum error range residual of B1C/B2a dual-frequency pseudo range combination is set as 3.5 m in this paper, which is equivalent that the maximum allowable differential error of B1C is 1.55 m, and the maximum allowable differential error of B2a is 2.78 m. Refer to further conservative way in [10] for the relevant study, the differential error threshold is fixed to 1 m for both signals. That is to say, under the above-mentioned receiver conditions, the distortion parameters that cause the worst-case differential error on B1C or B2a to be less than 1 m do not constitute a threat.

4.2   Threat Space Analysis for B1C

4.2.1   Parameter Range for TM-A

TM-A have only one parameter Δ, which is the lead or lag of the chip falling edge. As [10] depicts, the misleading information threat is identical for lead and lag, thus only the lag situation is studied here. Specifically, principle II is considered here, and the following Fig. 1 shows the simulation results, which is the relationship between the ranging bias of the satellite on board receiver and the Δ value.
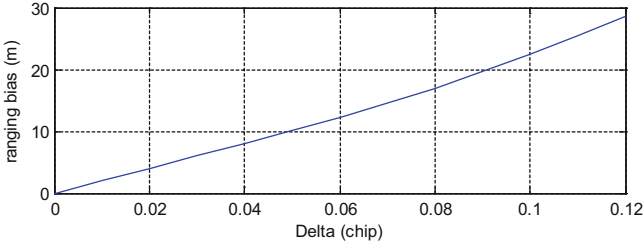

Fig. 1. Relationship between the ranging bias of the satellite on board monitoring receiver and Δ for B1C signal in TM-A

As Fig. 1 shows, the ranging bias will be larger as Δ increases, when Δ is 0.05 chip, the ranging bias is already higher than 7 m. So, the maximum of Δ could be 0.05 chip. Thus, the TM-A parameter range of B1C is: $0.05 \leq \Delta \leq 0.05$ (chip).

4.2.2   Parameter Range for TM-B

4.2.2.1. Parameter Range Analysis for f_d

The upper bound of f_d is associate with the signal transmit bandwidth [8], as analyzed in Sect. 4.1.1, the maximum value of f_d will not exceed 30 MHz, as higher frequency will be filtered out by the satellite filter. The upper limit value of f_d can be further reduced, see Sect. 4.2.2.2 for specific analysis.

Lower bound of f_d can also be analyzed based on principle II. Specifically, we simulate the ranging bias of the satellite on board receiver under various of f_d and σ, as Fig. 2 shows.

In Fig. 2, the variation of ranging bias (in meters) with f_d and σ is given in the form of contour lines. The results shows that, for $f_d \leq 1.5$ MHz, the ranging bias is higher than 10 m, which can be detected by the satellite. Thus the 1.5 MHz is selected as the lower bound of f_d.

4.2.2.2 Parameter Range Analysis for σ

The lower limit of the damping factor σ can approach to 0 theoretically. However, as the actual device cannot make σ really reach 0 and $\sigma = 0$ cannot be used in simulation assessment. Therefore, in the process of model definition and simulation, refer to the general practice [10], $\sigma = 0.1$Mnepers/s is used as the lowest value. It can be also seen
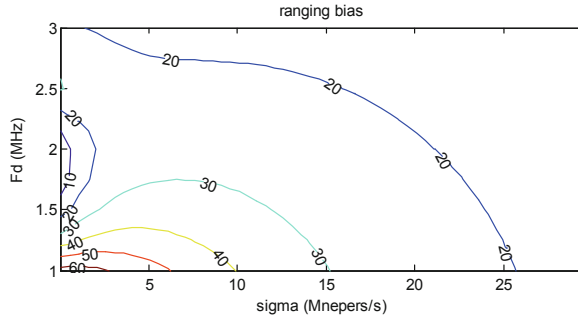
Fig. 2. Relationship between the ranging bias of the satellite on board receiver and the parameters in TM-B for B1C signal

in Fig. 2 that the ranging bias is in the order of tens of meters when $\sigma = 0.1$Mnepers/s, which is a conservative estimation.

Furthermore, its upper limit is considered. It can be seen in Fig. 2 that with the increase of σ, the ranging bias tends to decrease, so the upper limit value of σ can not be defined by the analysis of ranging bias Here, we use differential error analysis (Principle III).

See Sect. 4.1.3 for reference station receiver conditions. The user receivers are selected in the parameter range of Sect. 4.1.3 and the specific parameters are as follows: the front-end bandwidth of B1C receiver is 12, 14, 16, 18, 20, 22, 24 MHz, and three filters are used (spectrum response is 6-order Butterworth filter, group delay is 30 ns, 0 ns, 150 ns respectively); B1C discriminating spaces are 0.08, 0.10, 0.12 chip; For every combination of f_d and σ, the maximum differential error between all user receivers and the reference station receiver is calculated. The calculation results are shown in Fig. 3.
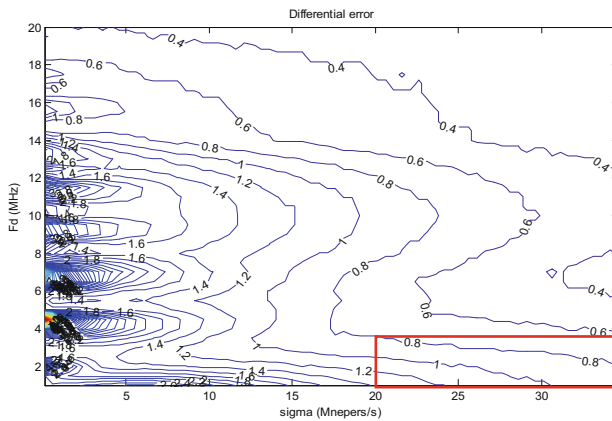

Fig. 3. Maximum differential error in TM-B for B1C signal

Figure 3 shows the variation of the differential error (in meters) with f_d and σ in the form of contour lines.

It can be seen that, when $\sigma \geq 31$Mnepers/s, the maximum differential error is less than 1 m, so 31Mnepers/s can be the σ upper limit. Furthermore, this upper limited can be further decreased as follows. As show in Fig. 3, in the area with red rectangle where 35Mnepers/s $\geq \sigma \geq$ 20Mnepers/s and 4 MHz $\geq f_d \geq$ 1 MHz, there are some part that the maximum differential error is higher than 1 m. In this area, the ranging bias (based on principle II) is shown in Fig. 4.
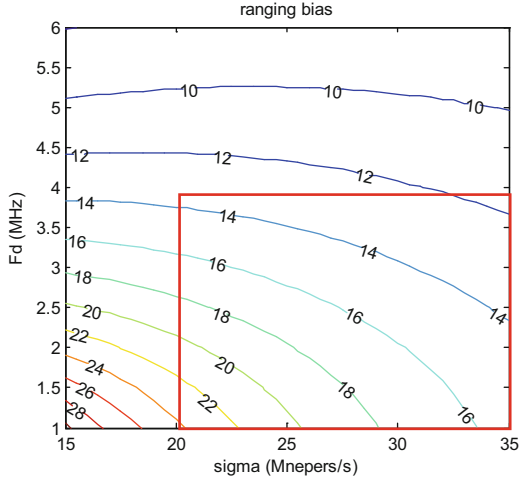

Fig. 4. Ranging bias induce by the distortion in the area where 35Mnepers/s $\geq \sigma \geq$ 20Mnepers/s and 4 MHz $\geq f_d \geq$ 1 MHz

As Fig. 4 shows, in the same red rectangle area with that in Fig. 3, although the differential error caused by this region is greater than 1 m, the ranging bias caused by the distortion is higher than 10 m, which can be detected, thus this area will not constitute a threat. Therefore, the upper limit of σ can be reduced to 20Mnepers/s.

It also shows in Fig. 3, that when $f_d \geq 18$ MHz, the maximum differential error is less than 1 m. Thus, the upper limit of f_d can be reduced to 18 MHz instead of 30 MHz determined in Sect. 4.2.2.1.

Based on the above analysis, the parameter range of TM-B for B1C signal can be determined as: $0.1 \leq \sigma \leq 20$ (Mnepers/s), $1.5 \leq f_d \leq 18$ (MHz).

4.2.3 Parameter Range for TM-C

The parameters of TM-C are the combination of that of TM-A and TM-B. Thus, parameter ranges of TM-C are the same with that of TM-A and TM-B [10].

4.3 Threat Space Analysis for B2a

4.3.1 Parameter Range for TM-A

Based on the same consideration with that for B1C in Sect. 4.2.1, the relationship between the ranging bias of the satellite on board receiver and the Δ value for B2a is simulated and shown in Fig. 5.
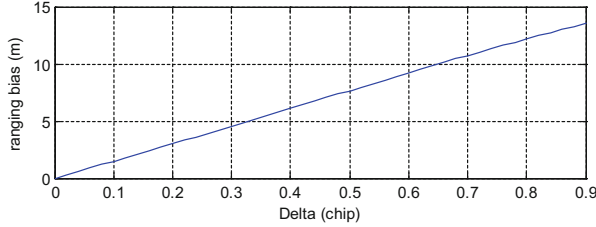

Fig. 5. Relationship between the ranging bias of the satellite on board receiver and the Δ value for B2a signal in TM-A

As Fig. 5 shows, the ranging bias will be larger as Δ increases, when Δ is 0.5 chip, the ranging bias is already higher than 7 m. Thus, the maximum of Δ could be 0.5 chip. The TM-A parameter range of B2a is: $-0.5 \leq \Delta \leq 0.5$ (chip).

4.3.2 Parameter Range for TM-B

4.3.2.1 Parameter Range Analysis for f_d
The upper bound of f_d is associate with the signal transmit bandwidth, as analyzed in Sect. 4.1.1, the maximum value of f_d will not exceed 40 MHz, as higher frequency will be filtered out by the satellite filter. The upper limit value of f_d can be further reduced, see Sect. 4.3.2.2 for specific analysis.

Base on the same consideration with that for B1C, lower limit of f_d for B2a is determined based on principle II, the ranging bias of the satellite on board receiver under various of f_d and σ are simulated and shown in Fig. 6.

The results shows that, for $f_d \leq 4$ MHz, the ranging bias is higher than 8 m, which can be detected by the satellite onboard receiver. Thus 4 MHz is selected as the lower bound of f_d.

4.3.2.2 Parameter Range Analysis for σ
Similar to the analysis in Sect. 4.2.2.2, the lower limit of σ is 0.1 Mnepers/s. Furthermore, its upper limit is considered. It can be seen in Fig. 2 that with the increase of σ, the ranging bias tends to decrease, so the upper limit value of σ can not be defined by the analysis of ranging bias Here, we use differential error analysis (Principle III).

See Sect. 4.1.3 for reference station receiver conditions. The user receivers are selected in the parameter range of Sect. 4.1.3 and the specific parameters are as follows: the front-end bandwidth of B2a receiver is 12, 14, 16, 18, 20, 22, 24 MHz, and three
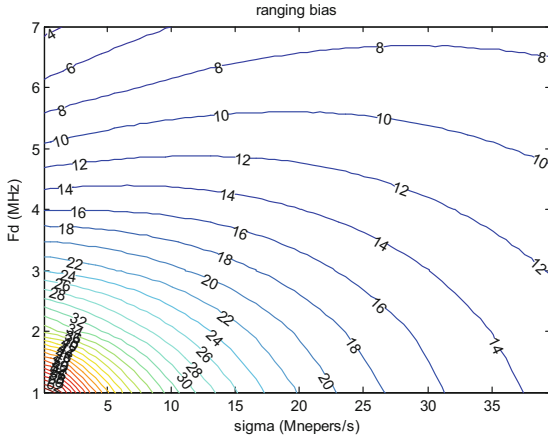
Fig. 6. Relationship between the ranging bias of the satellite on board receiver and the parameters in TM-B for B2a signal

filters are used (spectrum response is 6-order Butterworth filter, group delay is 30 ns, 0 ns, 150 ns respectively); B2a discriminating spaces are 0.9, 1.0, 1.1 chip; For every combination of f_d and σ, the maximum differential error between all user receivers and the reference station receiver is calculated. The calculation results are shown in Fig. 7.
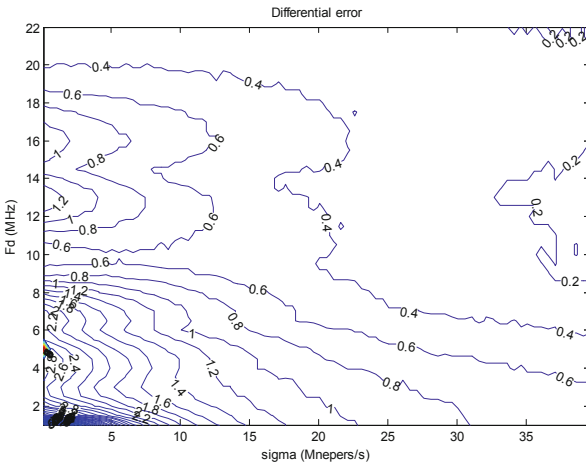

Fig. 7. Maximum differential error in TM-B for B2a

Considering that the lower limit of f_d has been analyzed and limited to 4 MHz in Sect. 4.3.2.1, thus only the region where $f_d \geq 4$ MHz in Fig. 7 is analyzed. As Fig. 7 shows, when $f_d \geq 4$ MHz and $\sigma \geq 18$Mnepers/s, the maximum differential error is less than 1 m. Thus, the upper limit of σ can be 18Mnepers/s.

It also shows in Fig. 7, that when $f_d \geq 18$ MHz, the maximum differential error is less than 1 m. Thus, the upper limit of f_d can be reduced to 18 MHz instead of 40 MHz determined in Sect. 4.3.2.1.

Based on the above analysis, the parameter range of TM-B for B2a signal can be determined as: $0.1 \leq \sigma \leq 18$ (Mnepers/s), $4 \leq f_d \leq 18$ (MHz).

4.3.3 Parameter Range for TM-C

The parameters of TM-C are the combination of that of TM-A and TM-B. Thus, parameter ranges of TM-C are the same with that of TM-A and TM-B [10].

4.4 Summaries for Threat Space

B1C and B2a signals adopt the distortion model framework of TM-A, TM-B and TM-C in ICAO standard, and the corresponding threat space can be summarized as Table 1.

Table 1. Summary of threat space for BDS B1C and B2a signals

Signal	TM-A parameter range Δ(chip)	TM-B parameter range σ (Mnepers/s) fd (MHz)	TM-C parameter range Δ (chip) σ (Mnepers/s) fd (MHz)
B1C	$-\ 0.05 \leq \Delta \leq 0.05$	$0.1 \leq \sigma \leq 20$ $1.5 \leq \text{fd} \leq 18$	$-\ 0.05 \leq \Delta \leq 0.05$ $0.1 \leq \sigma \leq 20$ $1.5 \leq \text{fd} \leq 18$
B2a	$-\ 0.5 \leq \Delta \leq 0.5$	$0.1 \leq \sigma \leq 18$ $4 \leq \text{fd} \leq 18$	$-\ 0.5 \leq \Delta \leq 0.5$ $0.1 \leq \sigma \leq 18$ $4 \leq \text{fd} \leq 18$

Here, the above results can be compared with similar signal in reference [10]. In reference [10], the threat space of signal similar to B1C signal modulation mode is as follows: $-0.12 \leq \Delta \leq 0.12$ (chip), $0.1 \leq \sigma \leq 26$ (Mnepers/s), $1 \leq f_d \leq 19$ (MHz). The threat space of signal similar to B2a signal modulation mode is as follows: $1.2 \leq \Delta \leq 1.2$ (chip), $0.1 \leq \sigma \leq 24$ (Mnepers/s), $1 \leq f_d \leq 19$ (MHz).

Compared with that, due to the comprehensive consideration of satellite physical characteristics and distortion error characteristics, and making full use of the good ranging error detection performance provided by the satellite onboard monitoring receiver in BDS satellite, the distortion space obtained is lower under the similar signals, and the performance requirements of SQM are more relaxed in theory.

5 Summary

This paper studies the distortion threat model and threat space of B1C and B2a signals. Considering the complexity, maturity and commonality of the model with other GNSS,

the general distortion model framework in the current ICAO standard is adopted; on this basis, a method for determining the threat space considering both the physical characteristics of the satellite and distortion error characteristics is proposed, and the good ranging bias detection performance provided by the onboard monitoring receiver in BDS satellite is fully utilized. Then, the threat space of B1C and B2a signals is given. The research results can provide reference for the formulation and verification of the relevant contents of ICAO standards for BDS B1C and B2a signals.

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