Applicability Analysis of DFMC SBAS Receiver Design Constraints to BDS B1C and B2a Signals

Henglin Chu[1], Yang Gao[1](✉), Kefan Wei[2], and Xiaowei Cui[3]

[1] Beijing Satellite Navigation Center, Beijing, China
bikong_001@aliyun.com
[2] North Information Control Research Academy Group Co. Ltd., Nanjing, China
[3] Department of Electronic and Engineering, Tsinghua University, Beijing, China

Abstract. Receiver design constraints are mandatory requirements in the International Civil Aviation Organization (ICAO) Dual Frequency and Multi Constellation Satellite-Based Augmentation System (DFMC SBAS) service standard. In this kind of service, the Global Navigation Satellite Systems (GNSS) should adopt uniform or similar constraints as far as possible, so as to simplify the terminal design and promote the joint use of multiple GNSS. BDS B1C and B2a signals plan to be augmented signals of DFMC SBAS service. This paper evaluates the applicability of ICAO currently planning DFMC SBAS receiver design constraints for B1C and B2a signals. Under the constraints, by adopting signal quality monitoring (SQM) baseline method, based on B1C and B2a signal distortion model, threat space and signal power, the system end design requirements needed by service providers and performance margin are analyzed for the first time. The results show that the planning DFMC SBAS receiver design constraints are applicable to B1C and B2a signals and the performance margins are 5 dB and 15 dB respectively according to the coherent use of SQM data from three monitoring stations. The conclusion of this paper can provide reference for the formulation and verification of the relevant contents of ICAO standards for B1C and B2a signals.

Keywords: Dual-frequency and multi constellation satellite-based augmentation system · Receiver design constraints · BDS B1C and B2a signals · Applicability analysis

1 Introduction

Navigation satellite signal may produce distortion due to various unexpected reasons [1–3], which may bring a potential threat to differential service users [4–6]. In high integrity services related to life safety such as Satellite-Based Augmentation System (SBAS) service for civil aviation, service providers usually use receiver design constraints and Signal Quality Monitoring (SQM) methods together to avoid the impact of signal distortion on integrity [7–9]. The receiver design constraints are important contents of the International Civil Aviation Organization (ICAO) standard, which should ensure that the user receiver is within is within the protection range provided by the

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SQM, that is, the intolerable differential error between the user receiver and the monitoring station receiver caused by signal distortion can be detected and alerted by SQM in time [10].

At present, ICAO is developing the Dual Frequency and Multi-Constellation Satellite-Based Augmentation System (DFMC SBAS) service standards, which will augment the four global navigation satellite systems (GNSS). The DFMC SBAS receiver constraints for each GNSS is an important part of the developing standard, and the same or similar design constraints should be adopted as far as possible to simplify the user design and promote the joint use of multiple GNSS in DFMC SBAS services. GPS, Galileo and GLONASS have preliminarily defined most of the parameter ranges in the constraints [11], including code discriminating method, code discriminating space, filter bandwidth, in band differential group delay, etc., and the same design constraints are adopted. BDS B1C and B2a signals, which are interoperability signals with other GNSS and plan to be augmented in DFMC SBAS, also need to define the receiver design constraints under the consistent principle.

However, due to the differences in signal modulation mode, signal power and distortion model, the applicability of receiver design constraints needs to be carefully evaluated to determine whether it can provide sufficient protection for users.

In this paper, the applicability of ICAO currently planning DFMC SBAS receiver constraints for BDS B1C and B2a signals is evaluated. Under the constraints, by adopting signal quality monitoring (SQM) baseline method, based on B1C and B2a signal distortion model, threat space and signal power, the system end design requirements needed by service providers and performance margin are analyzed for the first time.

The results show that under the planning DFMC SBAS receiver design constraints and the minimum power condition of B1C and B2a signals, requirements of civil aviation services can be satisfied and the user can be fully protected by using only one monitoring station SQM data. Under the conditions that three monitoring station SQM data are coherently accumulated, performance margins are 5 dB and 15 dB for B1C and B2a respectively. Therefore, BDS B1C and B2a signal can adopt the same receiver design constraints as other GNSS in DFMC SBAS service. The conclusion of this paper can provide reference for the formulation and verification of the relevant contents of ICAO standards for B1C and B2a signals.

2 BDS Signals and the Threat Model

2.1 B1C/B2a Signals and the Processing Strategies

The BDS B1C and B2a signals are new signals to provide global satellite navigation service, and they are also interoperability signals with other GNSS systems. Both signals include data channel and pilot channel [12, 13]. In civil aviation applications such as DFMC SBAS, only the pilot channel is used for ranging.

B1C pilot channel adopts QMBOC(6,1,4/33) modulation, including BOC(6,1) and BOC(1,1) components [14]. In civil aviation applications, only BOC(1,1) component is used for ranging. The pilot channel of B2a signal adopts BPSK(10) modulation, which is used for ranging in civil aviation application.

Therefore, the following research only focuses on BOC(1,1) component of B1C pilot channel and BPSK(10) modulated B2a pilot channel.

2.2 B1C/B2a Signal Threat Model

As BDS B1C and B2a signals have not been obviously distorted yet, the distortion model adopts the general distortion model framework in ICAO standard [15], including Threat Model A (TM-A), Threat Model B (TM-B) and Threat Model C (TM-C). According to the study of satellite state and distortion error, the parameter ranges (the threat space) are shown in Table 1.

Table 1. 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	$-0.05 \le \Delta \le 0.05$	$0.1 \le \sigma \le 20$ $1.5 \le fd \le 18$	$-0.05 \le \Delta \le 0.05$ $0.1 \le \sigma \le 20$ $1.5 \le fd \le 18$
B2a	$-0.5 \le \Delta \le 0.5$	$0.1 \le \sigma \le 18$ $4 \le fd \le 18$	$-0.5 \le \Delta \le 0.5$ $0.1 \le \sigma \le 18$ $4 \le fd \le 18$

3 DFMC SBAS Receiver Design Constraints

3.1 User Receiver Design Constraints

The signals to be augmented by DFMC SBAS service include: L1C/A and L5 of GPS, L1OC and L3OC of GLONASS, E1C and E5a of Galileo, B1C and B2a signals of BDS [16, 17]. Multi GNSS interoperability requirements are considered at the beginning of design for most of the signals, aiming to jointly provide better services for users. At present, the proposed and planning used receiver constraints for DFMC SBAS users include:

(1) The 3dB front-end bandwidth is 12 ~ 24MHz;
(2) The in band differential group delay is no more than 150ns;
(3) E-L discrimination method is used;
(4) The discrimination space is 0.08 ~ 0.12 chip for L1C/A, L1OC and E1C
(5) The discrimination space is 0.9 ~ 1.1 chip for L5, L3OC and E5a.

In order to facilitate the interoperability of multiple GNSS, B1C signal should use the same or similar constraints with E1C, L1C/A; B2a signal should use the same or similar constraints with E5a, L5, etc.

3.2 Monitoring Station Receiver Recommendation

The design of the monitoring station receiver is not mandatory in civil aviation standards. However, in order to minimize the differential error and facilitate SQM design, the monitoring station receiver design is usually close to that of the user receiver. According to reference [11], the recommended design conditions for the monitoring station receiver are as follows:

(1) The 3dB front-end bandwidth is 24 MHz;
(2) The in band differential group delay is less than 150ns;
(3) E-L discrimination method is used;
(4) The discrimination space is 0.1 chip for L1C/A, L1OC and E1C
(5) The discrimination space is 1.0 chip for L5, L3OC and E5a.

Similar to Sect. 3.1, B1C signal should use the same or similar design E1C, L1C/A, etc.; B2a signal should use the same or similar design suggestions with E5a, L5, etc.

4 Constraints Applicability Analysis

4.1 Analysis Method

According to the requirements of civil aviation integrity service, the analysis of the applicability of the receiver design constraints to B1C and B2a signals will be carried out under the following conditions:

(1) The user receiver adopts constraints in Sect. 3.1;
(2) B1C and B2a signals are under the minimum signal power promised by ICD;
(3) The distortion of B1C and B2a signals is in the range of distortion model in Sect. 2.2.

Under the above conditions, if SQM can effectively detect the distortion that causes intolerable differential error between the user receiver and the monitoring receiver according to the specified detection performance, it indicates that the system can provide effective protection for users, that is, the constraint conditions are applicable. In this paper, the specific process is as follows:

Step 1: for B1C and B2a signals, the whole Threat Space in Sect. 2.2 will be tested in a certain step to cover all the parameter combinations.

Step 2: for each group of distortion parameters, based on the design constraints of Sect. 3.1 and Sect. 3.2, the maximum differential errors between the monitoring station receiver and all user receivers are calculated, and the monitoring data of the distorted signal by SQM method are simulated. The maximum differential error and SQM monitoring data under each distortion parameter are recorded.

Step 3: for the distortion that causes the differential error to exceed the error tolerance, the minimum Carrier to Noise ratio (C/N0) condition that SQM need to satisfy the specified detection performance is estimated.

Step 4: calculate B1C and B2a signal actual C/N0 based on the minimum powers, and according to which, estimate the SQM design requirement and performance margin.

4.2 Simulation Conditions

4.2.1 Threat Space Test Points

Under TM-A, TM-B and TM-C model in Sect. 2.2, the whole Threat Space is tested in a certain step. To be conservative, the range of parameters is extended appropriately, as Table 2 shows.

Table 2. Simulation step for B1C and B2a Threat Space

signal	TM-A parameter range in simulation Δ(chip)	TM-B parameter range in simulation σ (Mnepers/s) f_d (MHz)	TM-C parameter range in simulation Δ (chip) σ (Mnepers/s) f_d (MHz)
B1C	– 0.12: 0.01: 0.12	0.1: 0.5: 20 (σ) 1: 1: 21 (f_d)	– 0.12: 0.01: 0.12(Δ) 0.1: 0.5: 20 (σ) 1: 1: 21 (f_d)
B2a	– 0.9: 0.1: 0.9	0.1: 0.5: 20 (σ) 2: 1: 20 (f_d)	– 0.9: 0.1: 0.9(Δ) 0.1: 0.5: 20 (σ) 2: 1: 20 (f_d)

4.2.2 Receiver Conditions

4.2.2.1 Monitoring Station Receiver

The monitoring station receiver adopts parameters in Sect. 3.2, where, B1C discrimination space is 0.1 chip, B2a discrimination space is 1.0 chip, the filter 3 dB bandwidth is 24 discrimination space MHz, the amplitude frequency response is that of 6th order Butterworth filter, and in band differential group delay is 0 ns.

4.2.2.2 User Receivers

The user receiver traverses the parameter range of Sect. 3.1. Specifically, B1C discrimination space includes 0.08, 0.10 and 0.12 chips; B2a discrimination space includes 0.9, 1.0, 1.1 chips; filter bandwidth includes 12, 14, 16, 18, 20, 22, 24 MHz Three kinds of filters are selected for each bandwidth, which are 0 ns, 30 ns, 150 ns of in band differential group delay, and the amplitude frequency response is that of 6-order Butterworth filter.

4.2.3 SQM Parameter

4.2.3.1 The Metric Design

Three metrics are used in the simulation, which are

(1) Simple ratio metric:

$$metric_x = \frac{I_x}{I_0}$$

(2) Difference ratio metric:

$$metric_{-x-x} = \frac{I_{-x} - I_{+x}}{I_0}$$

(3) Sum ratio metric:

$$metric_{-x+x} = \frac{I_{-x} + I_{+x}}{I_0}$$

where, I is the output of correlator, subscript $\pm x$ is the position where the correlator is located, negative sign is leading and positive sign is lagging, I_0 is output of the prompt correlator.

4.2.3.2 The Correlators Design

A baseline SQM method with many correlators is selected to analyze the theoretical feasibility:

(1) Correlators for B1C: There are 51 correlators for B1C, including 1 prompt correlator, 25 early correlators with space of 0.01 chip and range from -0.25 ~ -0.01chips, and 25 late correlators with space of 0.01 chip and range from + 0.01 ~ + 0.25 chips. All the correlators can be written as: $I_{-0.25}, I_{-0.24}, \ldots, I_{-0.01}, I_0, I_{+0.01}, I_{+0.02}, \ldots, I_{+0.25}$.

(2) Correlators for B2a: There are 21 correlators for B2a, including 1 prompt correlator, 10 early correlators with space of 0.1 chip and range from -1.0 ~ -0.1 chips, and 10 late correlators with space of 0.1 chip and range from + 0.1 ~ + 1.0 chips. All the correlators can be written as: $I_{-1.0}, I_{-0.9}, \ldots, I_{-0.1}, I_0, I_{+0.1}, I_{+0.2}, \ldots, I_{+1.0}$.

4.2.3.3 The Test and Alarm Design

Based on the above correlators and metrics, the test method is defined as:

$$Test_{metric} = \frac{|metric_{dist} - metric_{norm}|}{MDE_{metric}}$$

where, $metric_{dist}$ is some metric for distorted signal; $metric_{norm}$ is the corresponding metric for nominal signal; MDE_{metric} is the minimum detectable errors, which is dependent on noise power and detection performance, and can be written as:

$$MDE_{metric} = (K_{md} + K_{ffd}) \cdot \sigma_{metric}$$

where, K_{md} is the missed detection multiplier, according to [15], $K_{md} = 3.09$ is used as a typical value representing a missed detection probability of 1 × 10–3/test; K_{ffd} is fault-free detection multiplier, according to [15], $K_{ffd} = 5.26$ is used as a typical value representing a false detection probability of 1.5 × 10–7/test; σ_{metric} is the standard deviation of noise in the metric, which is related to the C/N0 of the signal, and Gaussian white noise is assumed in the simulation.

For one Threat Space point, if the test result of any one of $metric_x$, $metric_{-x-x}$, $metric_{-x+x}$ is greater than 1 ($Test_{metric} > 1$), then a distortion detection is declared.

In the simulation, 1 s integral time is used for one test, no additional smoothing is adopted.

4.3 Simulation Results

4.3.1 Simulation Result for B1C

The simulation result for B1C is shown in Fig. 1.

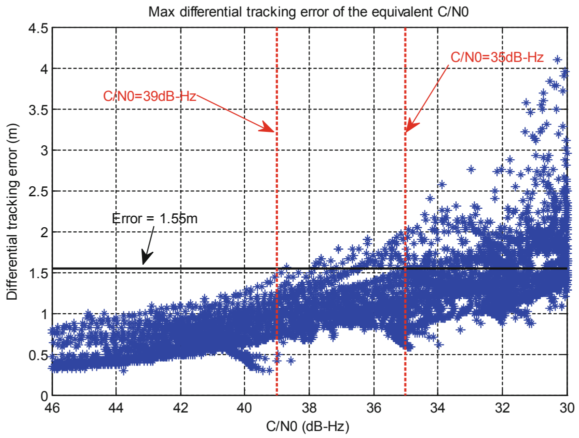

Fig. 1. Simulation results in distortion situation for B1C signal

Figure 1 use the expression way proposed in [11], the x-axis is C/N0, which means the position of $Test_{metric} = 1$ for the corresponding C/N0 value; the y-axis is the maximum differential error for every point. In this figure, for every C/N0 value in x-axis, all the points in left area of this C/N0 value are the ones that cannot trigger alarms, as there $Test_{metric} < 1$. While all the points in the right area of this C/N0 value are the ones that can trigger alarms, as there $Test_{metric} > 1$.

For B1C signals, according to [11], the maximum allowable differential error of B1C is 1.55m, which means, for a certain C/N0 value, if there are no point with error higher than 1.55 m in the left part, then the SQM performance meet the requirement under this C/N0. In contrary, if there are point with error higher than 1.55m in the left part, then the SQM performance does not meet the requirement under this C/N0. As shown in Fig. 1, to meet the SQM performance, the needed minimum C/N0 is 39 dB-Hz.

According to [12], the minimum power of B1C on ground is -161 dBW with 5 degree elevation, and B1Cp-BOC (1, 1) component has 29/44 of the total power, thus the minimum C/N0 of B1C can be calculated as:

$$-162.8\text{dBW} + (-5.5\text{ dB}) - (-228.6\text{dBJ/K} + 24.8\text{dBK}) = 35.5\text{ dB-Hz}$$

here, -5.5 dB gain of the receiver antenna in 5° elevation and 300 K (24.8 dBK) thermal noise is assumed.

As 35.5 dB-Hz is lower than the need minimum C/N0 value, it cannot meet the requirement by using only 1 s integral time. Thus, smoothing of metrics is needed to increase the equivalent C/N0. According to [11], 100 s smoothing of metrics can be adopt in SQM, and the gain can be conservatively estimated as 4 dB considering the multipath influence in actual conditions. Therefore, the B1C equivalent C/N0 after smoothing can reach to 39.5 dB-Hz, which is higher than the 39 dB-Hz minimum C/N0, and will meet the requirement.

Further considering that the SBAS service itself requires at least three monitoring stations to be visible to satellites at the same time to carry out the differential information calculation, the coherent use of SQM data of three stations can introduce 4.7 dB gain, and the system design margin is about 39.5 dBHz + 4.7 dB-39.0 dBHz = 5.2 dB.

4.3.2 Simulation Result for B2a

The simulation result for B2a is shown in Fig. 2.

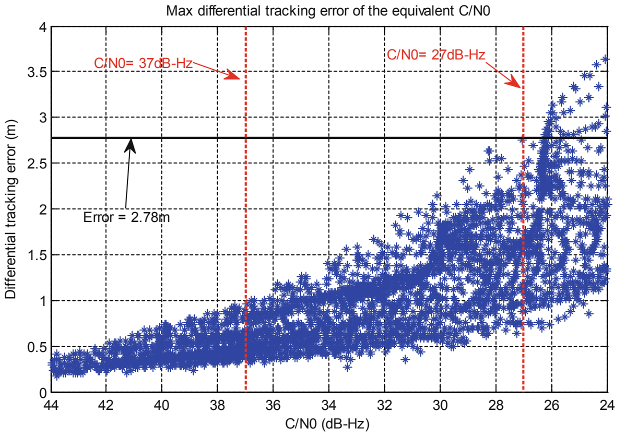

Fig. 2. Simulation results in distortion situation for B2a Signal

The expression way of Fig. 2 is the same with that of Fig. 1. For B2a signals, according to [11], the maximum allowable differential error is 2.78 m. As the results show, to meet the SQM performance, the needed minimum C/N0 is 27 dB-Hz.

According to [13], the minimum power of B2a on ground is -158 dBW with 5 degree elevation, and B2a pilot component has 1/2 of the total power, thus the minimum C/N0 of B2a pilot can be calculated as:

-161dBW + (-5.5dB) - (-228.6 dBJ/K + 24.8-dBK) = 37.3 dB-Hz

here, -5.5dB gain of the receiver antenna in 5° elevation and 300 K (24.8dBK) thermal noise is assumed.

As the C/N0 (37.3 dB-Hz) of B2a is higher than the needed minimum C/N0 (27 dB-Hz), it can meet the SQM performance requirement by using only 1 s integral time.

Further considering the coherent use of SQM data of three stations can introduce 4.7dB gain, and the system design margin is about 37.3 dB + 4.7 dB-27.0 dB = 15 dB.

5 Summary

To meet the requirements that BDS B1C and B2a signals used in SBAS and other civil aviation services, this paper analysed the applicability of DFMC SBAS receiver design constraints in the current ICAO standard draft for B1C and B2a signals for the first time. In this paper, based on B1C, B2a signal distortion threat model, signal power and other specific conditions, the minimum C/N0 that meets the requirements of SBAS service is simulated and obtained, and the system capacity margin is also evaluated. The results show that B1C and B2a signals can meet the user protection requirements by using the current DFMC SBAS receiver constraints. B1C signal has a margin of about 5dB, and B2a signal has a margin of 15 dB, which can further relax the constraints of receiver in theory. The conclusion of this paper can provide reference for the formulation and verification of the relevant contents of ICAO standards for B1C and B2a signals.

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