Signal Quality Monitoring Algorithms of DFMC SBAS for Dual-Frequency Civil Signals of BDS

Xiang Wang[1], Xiaowei Cui[1](✉), Kefan Wei[3], Gang Liu[1], Yang Gao[4], and Mingquan Lu[2]

[1] Department of Electronic Engineering, Tsinghua University, Beijing 100084, China
cxw2005@tsinghua.edu.cn
[2] Beijing National Research Center for Information Science and Technology, Tsinghua University, Beijing 100084, China
[3] North Information Control Research, Academy Group Co. Ltd., Nanjing 211153, China
[4] Beijing Satellite Navigation Center, Beijing 100094, China

Abstract. The integrity of GNSS characterizes the ability to alert users in time when reliable services could not be provided as expected. BeiDou Satellite-Based Augmentation System (BDSBAS) is an important component of the generalized BeiDou Navigation Satellite System (BDS), and would provide Dual-Frequency Multi-Constellation (DFMC) augmented services for life-safety applications. Thus, users could be better protected against integrity risks with the first-order ionospheric error, which is the largest ranging uncertainty, removed and observation redundancy provided. The potential evil waveform (EWF) existing in iono-free combined signals is an important threat affecting the integrity performance. It is urgent to particularly and systematically design the signal quality monitors for DFMC SBAS to monitor the potential imperfections or failures on navigation signals. For BDSBAS, a hybrid Signal Quality Monitoring (SQM) algorithm based on both chip domain observables (CDO) and multi-correlator observables (MCO) is proposed in this paper on the basis of modulation characteristics of B1C and B2a signals, thus improves detection performances without significantly raising complexity in implementation. Configurations and procedures of the proposed hybrid SQM algorithm are expounded and detailed evaluation schemes are designed in this paper. In addition, the proposed algorithms are simulated and evaluated by applying the Threat Model and Threat Spaces of both signals lately adopted by ICAO. The results show that the DF civil signals of BDS could be well guaranteed to meet the integrity monitoring requirements of DFMC SBAS by this hybrid SQM algorithm.

Keywords: DFMC SBAS · Signal Quality Monitoring · BeiDou navigation satellite system · Chip domain observable · Multi-correlator

1 Introduction

Satellite-Based Augmentation System (SBAS), as is an important addition to Global Navigation Satellite System (GNSS), broadcasts differential corrections to improve

C. Yang and J. Xie (Eds.): *China Satellite Navigation Conference (CSNC 2021) Proceedings*, LNEE 773, pp. 75–91, 2021.
https://doi.org/10.1007/978-981-16-3142-9_8

precision of positioning, while at the same time, monitors metrics such as clock and ephemeris error, ionospheric delay, signal distortion, code-carrier divergence and so on by utilizing a series of monitors to protect users against Hazardous Misleading Information (HMI). Early SBAS's, including Wide Area Augmentation System (WAAS) in North America and European Geostationary Navigation Overlay Service, provided integrity monitoring on GPS L1 C/A signal only. While with the development of GNSS's, the next generation of SBAS would apply technology of Dual-Frequency Multi-Constellation (DFMC) to mitigate integrity risks for users, by eliminating the first-order ionospheric error, which is the largest ranging uncertainty, and providing observation redundancy [19, 23].

With the removal of ionospheric error, impacts on ranging accuracy of other anomalies or errors, including signal distortions, would become relatively significant. Signal distortion, or called Evil Waveform (EWF), is caused by the signal generating hardware on board a navigation satellite with imperfections or failures [15]. Owing to the fact that an EWF could be neither detected from observables nor eliminated by differential process, in addition, different characteristics of an EWF are exhibited on and different effects are caused on different signals, a series of techniques called Signal Quality Monitoring (SQM) have been developed, to monitor the potential EWFs in real time.

The third generation of BeiDou Navigation Satellite System (BDS-III) has been officially declared to provide global services, with B1C and B2a signals provided for civil aviation. BeiDou Satellite-Based Augmentation System (BDSBAS), as is an important component of BDS, is under development and will provide DFMC integrity augmentation services on B1/B2 frequencies for life-safety applications [3, 9, 11]. Therefore, a particularly and systematically design of SQM technique adaptive to BDSBAS is needed. In order to meet the integrity monitoring requirement in DFMC service of BDSBAS, a hybrid SQM algorithm based on both chip domain observables (CDO) and multi-correlator observables (MCO) is proposed in this paper on the basis of modulation characteristics of B1C and B2a signals, thus improves detection performances without significantly raising complexity in implementation. Considering the lower chip rate and higher ranging accuracy requirement for B1C signal (BOC(1,1) modulated), an SQM algorithm based on CDOs is suggested. While for B2a signal (BPSK(10) modulated), an SQM algorithm based on MCOs is suggested because of the higher chip rate and lower inflation factor on errors. In addition, the proposed algorithms are simulated and evaluated by applying the Threat Model and Threat Spaces of both signals lately adopted by International Civil Aviation Organization (ICAO). The results show that the DF civil signals of BDS could be well guaranteed to meet the integrity monitoring requirements of DFMC SBAS by this hybrid SQM algorithm.

2 BDS Signals for Civil Aviation and Threat Models

2.1 B1C and B2a Signals

B1C and B2a signals are both composed of data and pilot components, as listed in Table 1 [1, 2].

Table 1. Structures of B1C and B2a signals

Signal	Signal components		Carrier frequency (MHz)	Modulation		Phase	Power ratio	Symbol rate (sps)
B1C	data	$s_{\mathrm{B1C\_data}}(t)$	1575.42	BOC(1,1)		0	11/44	100
	pilot	$s_{\mathrm{B1C\_pilot\_a}}(t)$		QMBOC(6,1,4/33)	BOC(1,1)	90	29/44	0
		$s_{\mathrm{B1C\_pilot\_b}}(t)$			BOC(6,1)	0	4/44	
B2a	data	$s_{\mathrm{B2a\_data}}(t)$	1176.45	BPSK(10)		0	1/2	200
	pilot	$s_{\mathrm{B2a\_pilot}}(t)$		BPSK(10)		90	1/2	0

The pilot component of B1C signal could be expressed as the product of code and sub-carrier [1]:

$$s_{\mathrm{B1C\_pilot}}(t) = \frac{\sqrt{3}}{2} C_{\mathrm{B1C\_pilot}}(t) \cdot sc_{\mathrm{B1C\_pilot}}(t) \tag{1}$$

Where, the sub-carrier is combined with orthogonal BOC(1,1) and BOC(6,1) sub-carriers, the power ratio between whom is 29 to 4. According to specifications of ICAO, ranging observations on airborne receivers are obtained only from pilot_a component modulated by BOC(1,1) sub-carrier.

The pilot component of B2a signal only contains code [2]:

$$s_{\mathrm{B2a\_pilot}}(t) = \frac{1}{\sqrt{2}} C_{\mathrm{B2a\_pilot}}(t) \tag{2}$$

According to specifications of ICAO, ranging observations on airborne receivers are obtained from the pilot component (BPSK(10) modulated).

2.2 Threat Models

The threat model of a navigation signal characterizes the modeled approximations of EWFs it would be able to produce. Since GPS SVN-19 Event in 1993, the first observed EWF occurrence [15], several threat models on EWFs were proposed to precisely describe the anomalies in SVN-19 Event. In 2000, ICAO adopted 2nd-Order Step Threat Model (2OS-TM) into Standards and Recommended Practices (SARPs), and specified corresponding threat spaces for GPS and GLONASS [8]. The systems of Galileo and BDS are developing and researches on the applicability of 2OS-TM to new signals have been carried out. The threat spaces of both systems, having been submitted to ICAO [4, 18], would also be adopted into SARPs, indicating that the DF signals of both systems could meet the requirements of life-safety and be able to provide integrity augmentation services globally.

EWF threats are categorized into threat modes by 2OS-TM, described by:

(1) Digital Deformation Mode (TM-A): indicates the occurrence of failures on digital components of signal generating hardware. One parameter, Δ in length of chip (T_C), is used corresponding to the ratio of a lead or lag amount to a nominal chip on each falling edge of ideal code sequence which has been modulated by nominal sub-carrier BOC(1,1).

(2) Analog Deformation Mode (TM-B): represents the existence of failures on analog components. Two parameters used are f_d in Megahertz (MHz), corresponding to the damped frequency of oscillation on each transition of ideal code sequence, and σ in Meganeper per second (MNp/s), corresponding to the damping factor, respectively.

(3) Combination Mode (TM-C): means a combination of digital and analog failure, and uses all the three parameters above.

To date, although there is not any EWFs observed on either B1C or B2a signal, relevant researches have been moved on domestically. To guarantee applications with high accuracies and high integrities, it is necessary for DFMC SBAS to apply a set of threat model with proper threat space to describe potential EWFs in signals. Reference [4] suggested that the analyses and selections of Threat Model frames and corresponding Threat Spaces of BDS B1C and B2a signals, should be based on thorough considerations about factors of characteristics of signal generating hardware onboard, abilities on distortion detections on board, ranging biases and differential errors induced by distortions, etc. The Threat Model frames are also suggested to be aligned with ICAO Threat Model, basing on the facts that the signal generating hardware on board BDS satellites is similarly consist of digital and analog components with GPS and GLONASS satellites, and it would be reasonable and feasible to apply a mature, simple and widely used model for an emerging signal. The related further simulations were carried out in Reference [5]. Reference [20] clarified digital failures into three categories for BOC signals, namely PRN code failure, subcarrier failure and combination digital failure. Reference [25] proved that distortions on pilot_b signal could not affect code tracking, thus TM-A of BDS B1C signal was defined as a lead/lag on the falling edge of BOC(1,1) sub-carrier.

In conclusion, the Threat Model and Space for BDS B1C and B2a signals applied in this paper are based on the work of Reference [4]. Digital, analog and combined distortions are modeled by TM-A(Δ), TM-B(f_d, σ) and TM-C(Δ, f_d, σ), respectively. The Threat Models and Threat Spaces are listed in Table 2.

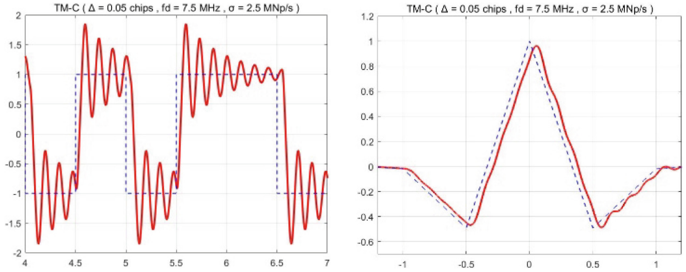
Table 2. Threat models and spaces for B1C and B2a signals

Signal	TM-A	TM-B	TM-C
B1C	$-0.05 \le \Delta^{\mathrm{B1C}} \le +0.05$	$1.5 \le f_d^{\mathrm{B1C}} \le 18$ $0.1 \le \sigma^{\mathrm{B1C}} \le 20$	$-0.05 \le \Delta^{\mathrm{B1C}} \le +0.05$ $1.5 \le f_d^{\mathrm{B1C}} \le 18$ $0.1 \le \sigma^{\mathrm{B1C}} \le 20$
B2a	$-0.5 \le \Delta^{\mathrm{B2a}} \le +0.5$	$4 \le f_d^{\mathrm{B2a}} \le 18$ $0.1 \le \sigma^{\mathrm{B2a}} \le 18$	$-0.5 \le \Delta^{\mathrm{B2a}} \le +0.5$ $4 \le f_d^{\mathrm{B2a}} \le 18$ $0.1 \le \sigma^{\mathrm{B2a}} \le 18$

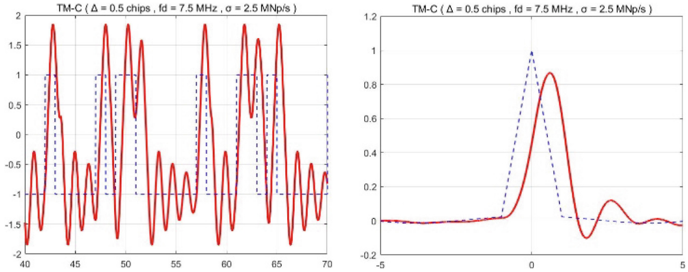
Figure 1 shows distorted chip shapes and correlation peaks (red curves) of B1C signal under TM-C ($0.05T_C$, 7.5MHz, 2.5MNp/s) and B2a signal under TM-C ($0.5T_C$, 7.5MHz, 2.5MNp/s), comparing to those of ideal signals (dash curves).

3 Progress of Signal Quality Monitoring Techniques

The basic concept of SQM is to obtain observations from the monitored signal and then form a set of detection metrics. While at least one bias between a pair of real-time and nominal metrics exceeds corresponding threshold, EWF would be judged to exist in the monitored signal. In terms of observables, there are mainly 3 types of SQM techniques, namely based on pseudo-range observables, MCOs and CDOs.



(a) Deformation of B1C Signal (PRN-5)



(b) Deformation of B2a Signal (PRN-5)

Fig. 1. EWF Manifestations on Codes and Correlation Peaks

3.1 SQM Techniques Based on Pseudo-Range Observables

The acquisition and tracking of GNSS signal receivers are conventionally achieved by utilizing the good auto-correlation characteristics of Pseudo Random Noise (PRN) codes. EWFs might make correlation functions deformed, causing different pseudo-range values obtained from different receivers with different tracking correlator spacings, from which larger differential pseudo-range errors might be induced. As a result, early methodology of SQM tended to judge the existence of EWFs by checking the relative biases among all the measured pseudo-ranges from different tracking correlator spacings.

However, one receiver channel conventionally has only one code tracking loop. It is hardware and budget consuming to locate large amount of receivers ergodic toward the whole user receiver configuration space with different correlator spacings and different pre-correlation bandwidths. Therefore, it is implausible to implement SQM based on pseudo-range observables [15].

3.2 SQM Techniques Based on Multi-Correlator Observables

The restriction of implementation complexity on multiple pseudo-range observables could be mitigated by putting the observation source forward to correlation function. Therefrom it becomes mainstream for SQM to be implemented on monitoring receivers with multiple correlator pairs.

To implement SQM techniques based on MCOs, several pairs of Early (E) and Late (L) correlators are set symmetric about the Prompt (P) correlator to consecutively obtain multiple correlator values to form a series of detection metrics, which are used to measure slopes and symmetries of various parts of or the overall shape of correlation peak. Although a bit of hardware complexity is induced by multiple correlators, this SQM technique was widely used by early SBAS's because of its simple design. SQM techniques based on MCOs can be mainly divided into two categories in terms of metric forms. The first one uses particular correlator values to form local metrics, e.g. Δ-test and ratio-test, which are applied by SQM2b monitor receivers on current EGNOS reference stations [14]. The second one uses all the correlator values to form overall metrics, e.g. α-metric once applied by NovAtel G-II monitor receivers on WAAS reference stations [16, 17].

SQM techniques based on MCOs have been used in WAAS and EGNOS for decades, which however reached pure performances not that satisfactory [21]. A lower performance bound of this type of SQM is indicated mainly on the fact that some local EWFs might be averaged down by correlation process, making it hard to detect. While toward SQM in DFMC SBAS, problems come from two aspects. On one hand, Binary Offset Carrier (BOC) modulation is applied on most emerging and modernized GNSS signals, of which the shapes of correlation functions are quite different from traditional Binary Phase Shift Keying (BPSK) modulated signals, changing manifestations of EWFs on correlation functions. On the other hand, any biases on each single-frequency observables of iono-free combination measurements should be inflated, e.g. B1/B2 combination, by 2.26 and 1.26 times respectively [20], strongly challenging the detection performance of existing techniques.

3.3 SQM Techniques Based on Chip Domain Observables

In order to overcome the problems of modulation applicability and low performance of detections on correlation peak, the observation source of SQM should be further advanced to chip-shape. Mitigation on the attenuation of local EWFs by correlation process and the restriction of applicability by modulations could be achieved by measuring several CDOs from code waveform to form detection metrics. Furthermore, Maximum Undetected Differential Error (MUDE) would be reduced to meet requirement of ranging accuracy based on the raised detection sensitivity [13, 17].

The concept of CDO was first introduced by NovAtel Inc. for development of Vision Correlator [7], aiming at providing effective mitigation of multipath. Reference [16] compared the performances of SQM based on both technical paths before NovAtel G-III receivers were equipped at WAAS reference stations, on which Vision Correlators are applied. Further, Reference [22] derived the computation of CDOs and tested on some scenarios for GPS L1 C/A signal, applying a parabolic dish and omnidirectional antennas. Basing on this, Reference [12] gave a comparison between the visualizations of nominal distortion in both correlation and chip-shape domains on GPS L1 C/A signal with parabolic dishes. Also with a high-gain antenna, Reference [10] presented a method for assessment of signal quality using chip measurement. The hardware complexity of SQM techniques based on CDOs is raised by introducing Vision Correlator technology.

In summary, the general trend of observation source for SQM is forward with the development of hardware and software technology, being able to avoid the limitations on the original information of signals by follow-up processing, to achieve better detection performance. However, the more front the observation source is put, the more original and sufficient could the information obtained be, and the higher implementing complexity would be needed for an individual receiver. Each type of SQM technique has its own types of applicable signals because of the particular compromise between processing characteristics and implementing complexity. As a result, a hybrid SQM algorithm based on both CDOs and MCOs is proposed in this paper on the basis of characteristics of B1C and B2a signals.

4 Hybrid SQM Algorithm and Evaluation

4.1 Hybrid SQM Algorithm

A detailed hybrid SQM algorithm of BDS DF civil signals for DFMC SBAS is introduced in this section, where a chip-shape detection algorithm based on CDOs is applied to B1C signal, and a correlation-shape detection algorithm based on MCOs is applied to B2a signal. Configurations of the proposed algorithms are listed in Table 3.

Table 3. Configurations for the proposed hybrid SQM algorithm

Items		Configurations	
Name		SCSQM8r	SRPQM3
Signal		B1C	B2a
Correlators	Observable	CDO	MCO
	Quantity	8	7
	Locations	± 0.0875, ± 0.0625, ± 0.0375, ± 0.0125	± 1.0, ± 0.5, ± 0.1, 0
Integration (seconds)		1	
Detection metrics	Quantity	8	12
	Smoothing (seconds)	100	——
Stations for smoothing		2	——
Probability of false alert		1.5×10^{-7} per test	
Probability of miss detection		1×10^{-3} per test	
Minimum C/N$_0$ (dB-Hz)		35.5	37.3
MERR (meters)		1.61	2.89

The SQM algorithm for B1C signal on monitoring receivers of DFMC SBAS reference stations is called Signal Chip-Shape Quality Monitoring toward 8-CDO rising-edges Algorithm, taking SCSQM8r as the abbreviation [24]. Algorithm configurations refer to the typical distribution of multi-correlator in ICAO SARPs [8] for device versatility and concept acceptability. The distribution of 8 CDOs on code waveforms is shown in Fig. 2.

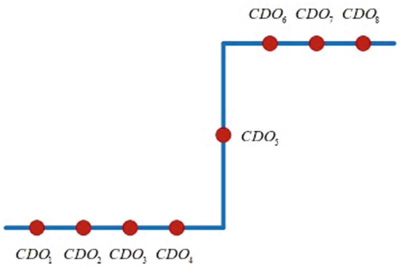


Fig. 2. Illustration of CDOs on a rising edge

The detection metrics of SCSQM8r algorithm are directly defined as the CDOs from one period of integration that are normalized by the original estimated signal amplitude, given by:

$$metric_i = CDO_{i,nml}\ ,\ 1 \le i < 8 \tag{3}$$

The SQM algorithm for B2a signal on monitoring receivers of DFMC SBAS reference stations is called Signal corRelation-Peak Quality Monitoring with 3-MCO pairs Algorithm, taking SRPQM3 as the abbreviation. The distribution of P-correlator and 3 pairs of E-L correlators is shown in Fig. 3.

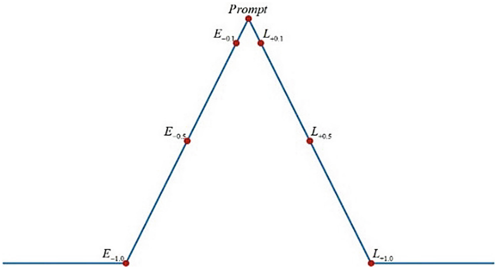


Fig. 3. Distribution of multi-correlators for B2a SQM

Twelve detection metrics of SRPQM3 algorithm, including 6 simple-ratio, 3 symmetric diff-ratio and 3 symmetric sum-ratio metrics, are formed from 7 correlator values, given by:

$$\begin{cases} M^{x} \equiv I_x \big/ I_{\mathrm{P}} \\ M^{[-x]-[x]} \equiv (I_{-x} - I_x) \big/ I_{\mathrm{P}} \\ M^{[-x]+[x]} \equiv (I_{-x} + I_x) \big/ I_{\mathrm{P}} \end{cases} \tag{4}$$

Where, I_x is the E/L correlator value x times of chip length far from P correlator, and I_{P} is P correlator value. Reference [14] proved that the approximately best performance of SQM algorithm based on MCOs could be reached by applying this formation scheme of metrics.

Thresholds of the algorithms are functions of corresponding nominal standard deviations of detection metrics, σ_{test}, given by:

$$\text{Threshold} = K_{\text{ffd}} \cdot \sigma_{\text{test}} \tag{5}$$

Where, $K_{\text{ffd}} = 5.26$ is calculated from the probability of fault-free detection requirement of Category I precision approach (CAT-I) in Table 3, and σ_{test} is calculated from the minimum Carrier-to-Noise ratios (C/N$_0$) on ground [5].

The procedure of proposed hybrid SQM algorithm is as follows:

(1) Monitoring receiver on reference station outputs a set of real-time measured CDOs/MCOs from the monitored B1C/B2a signal per 1-s integration to form real-time measured metrics respectively;
(2) By long-time observing nominal B1C/B2a signal to obtain nominal metrics and corresponding thresholds respectively in the same way, which should be pre-stored for SQM;
(3) Detection execution: for each signal, get differences between each pair of real-time measured and nominal metrics and then compare them against corresponding thresholds. The several ratios obtained are called Figures of Merit (FoM). The Figure of Detection (FoD), defined as the maximum one of FoMs, represents the result of this detection, given by:

$$T^{\text{EWF}} = \max_i \left\{ \frac{\left| metric_i^{\text{EWF}} - metric_i^{\text{nom}} \right|}{\text{Threshold}_i} \right\} \tag{6}$$

(4) Judgement: as long as $T^{\text{EWF}} \geq 1$, the monitored signal should be considered containing EWFs.

The deformed correlation peak caused by distorted B1C signal might have greater impact on ranging accuracy because of the low chip rate. Concurrently, the inflation factor to biases on B1C signal induced by DF iono-free combination measurements is high as 2.26. Therefore, by detecting deformations on chip rising edges to raise detection sensitivity and equivalently reduce MUDE, it is proper to apply SQM algorithm based on CDOs, e.g. SCSQM8r, on B1C signal under simpler smoothing conditions, i.e. shorter time for metric-smoothing and/or fewer stations for reference-smoothing, to meet DFMC SBAS performance requirement.

For B2a signal, SQM algorithm based on MCOs is enough to meet requirements because of the fact that distorted signals have weaker impact on ranging accuracy for the high chip rate, and the DF inflation factor is merely 1.26. Meanwhile, the rising edge density of B2a signal is much higher than that of B1C signal, resulting in much limited effective length of chip for CDO obtention. On the other hand, situations of longer, e.g. at least 5, continuous positive chips are rare, which limits Signal-to-Noise Ratios (SNR) of CDO and performance of algorithm. In other word, the needed smoothing conditions or hardware complexity should be significantly raised if we apply an SQM algorithm based on CDOs to B2a signal and want to reach a performance as good as to B1C signal. Therefore, it is proper to apply SQM algorithm based on MCOs, e.g. SRPQM3, on B2a signal.

4.2 Evaluation on Hybrid SQM Algorithm

Two rounds of examinations should be included in evaluation on performance of an SQM algorithm, which needs to be carried out within specified threat model and threat space of the monitored signal.

The first examination is the detections on the monitored signal of the SQM algorithm itself. The more EWFs within the threat space could be detected, the more robust the algorithm would be, and the better users should be protected against integrity risks. The detections run as Eq. (6), of whom the thresholds are set as the Minimum Detectable Errors (MDE). An MDE is also a function of the standard deviation of nominal noise on corresponding detection metric, σ_{test}, given by:

$$\text{MDE} = (K_{\text{ffd}} + K_{\text{md}}) \cdot \sigma_{\text{test}} \tag{7}$$

Where, $K_{\text{md}} = 3.09$ is calculated from the probability of miss detection requirement of CAT-I in Table 3.

The second examination is determined by requirements of DFMC SBAS with judgement of whether the MUDE resulted from the first examination exceeds Maximum Error Range Residual (MERR), in order to make sure whether the signals potentially with undetected EWFs are safe to users. MERR is such a value of Maximum Differential Pseudo-Range Error (maxPRE) that is obtained with the worst satellite geometries but without resulting an HMI to the user. Any biases present on each single frequency signal of an iono-free combination measurement would be amplified by a pair of inflation factors decided by the combined carrier frequencies. Taking $\text{MERR}_{\text{DF}} = 3.64$ meters as the maximum allowable ranging error of DFMC SBAS, MERRs for both signals are listed in Table 3.

The evaluation on an SQM algorithm is essentially an examination on the detection ability toward the whole threat space, which hence needs to be properly discretized. Table 4 lists the discretized threat spaces of B1C and B2a signals, which are enlarged beyond the ranges in Table 2 for conservativeness. Note that threat space of TM-C could be divided into two sub-spaces corresponding to positive or negative values of parameter Δ, and each pair of symmetric EWF points from the two sub-spaces respectively would make symmetric deformation effects on correlation peak. Thus, the positive sub-space of TM-C is selected for B2a signal simulations. However in chip domain, the deformation effects on code waveform caused by the pair of EWF points could not be considered symmetric, because a rising edge on code waveform is not centrosymmetric about the prompt point. As a result, both sub-spaces are needed for B1C signal simulations.

The whole procedure of the evaluations on the proposed hybrid SQM algorithm in this paper is shown in Fig. 4 and listed as follows:

a. Select an EWF point within the discretized threat space of B1C/B2a signal, and insert the signal with the selected EWF parameters into pre-correlation filter of reference station;

Table 4. Discretization schemes of Threat Parameters for B1C and B2a signals

Signal	Threat parameters	Discretization schemes
B1C	$\Delta^{\text{B1C}}(T_C)$	0.12: 0.01: -0.01, 0.01: 0.01: 0.12
	f_d^{B1C}(MHz)	1: 1: 20
	σ^{B1C}(MNp/s)	0.1, 1: 1: 25
B2a	$\Delta^{\text{B2a}}(T_C)$	0.1: 0.1: 0.9
	f_d^{B2a}(MHz)	2: 1: 20
	σ^{B2a}(MNp/s)	0.1, 1: 1: 20

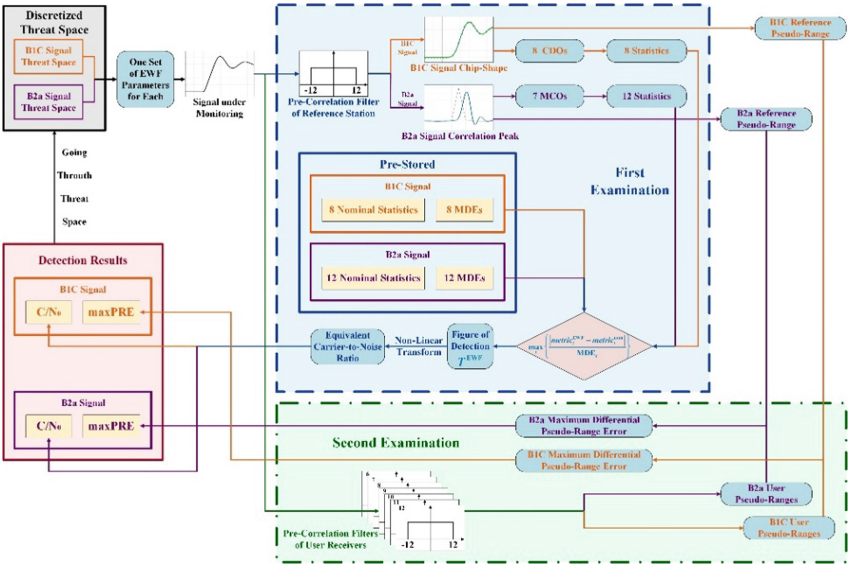


Fig. 4. General processing chart of performance evaluation of the proposed hybrid SQM algorithm

b. Obtain 8 CDOs/7 MCOs from the filtered code waveform/correlation function, and form 8/12 detection metrics of the monitored signal. Reference pseudo-range is measured concurrently;
c. Execute detections to the 8/12 real-time metrics after loading the 8/12 pre-stored nominal metrics and 8/12 corresponding MDEs, and the FoD is calculated, which is then non-linearly mapped to the output equivalent C/N$_0$;
d. Insert the monitored B1C/B2a signal synchronously into a series of user receivers with various configurations to measure a series of user pseudo-ranges. Then, use the reference pseudo-range value to calculate the output maxPRE;
e. Select a new EWF point into the loop until all the points within the discretized threat space have been examined.

5 Simulations and Analyses

Table 5. Configurations on reference and user receivers in simulations

Signal	BDS B1C		BDS B2a	
Receiver	Reference	Users	Reference	Users
Tracking	E-L, BOC(1,1) Local Replica		E-L, BPSK(10) Local Replica	
Correlator Spacings	0.10 chips	0.08, 0.10, 0.12 chips	1.0 chip	0.9, 1.0, 1.1 chips
Pre-Correlation Bandwidths (double-sided)	24 MHz	12, 14, 16, 18, 20, 22, 24 MHz	24 MHz	12, 14, 16, 18, 20, 22, 24 MHz
Filters	6th-order Butterworth	(1) 6th-order Butterworth (2) mixed Butterworth (3–6) 4 types of resonators	6th-order Butterworth	(1) 6th-order Butterworth (2) mixed Butterworth (3–6) 4 types of resonators

Simulation results of the proposed hybrid SQM algorithm on BDS DF civil signals are introduced in this section, within which SCSQM8r algorithm is applied to B1C signal and compared to performance of an algorithm based on MCOs, and SRPQM3 algorithm is applied to B2a signal. Receiver configurations of the simulations are listed in Table 5, where correlator spacings and pre-correlation bandwidths are set according to specifications in Reference [6]. The four types of resonator filters are with: 24/30 dB per octave gain roll-off and 0/150 ns differential group delay, respectively.

5.1 Simulations and Analyses on B1C Signal

The threat space of B1C signal is discretized to 13,024 EWF points according to Table 4. The red part of Fig. 5 shows the results of SCSQM8r algorithm simulation on B1C signal, indicating an equivalent C/N_0 not lower than 40.3 dB-Hz is needed to make sure 1.61-m MERR not exceeded by maxPRE induced by any EWF point within threat space across user receiver design space. Given 35.5 dB-Hz as the minimum C/N_0 for ground receivers, at least 4 dB gain obtained from 100-s metric-smoothing process [5], and about 3 dB gain provided by a double-station reference-smoothing process, the result could be written as:

$$35.5\ \text{dB - Hz} + 4\ \text{dB} + 3\ \text{dB} > 40.3\ \text{dB - Hz} \tag{8}$$

Which shows that the proposed SCSQM8r algorithm based on CDOs may sufficiently guarantee B1C signal for DFMC SBAS performance requirement.

The blue part of Fig. 5 shows the simulation results of an SQM algorithm based on MCOs. Advantages of SCSQM8r algorithm are reflected by comparing the red and blue parts and listed as follows:

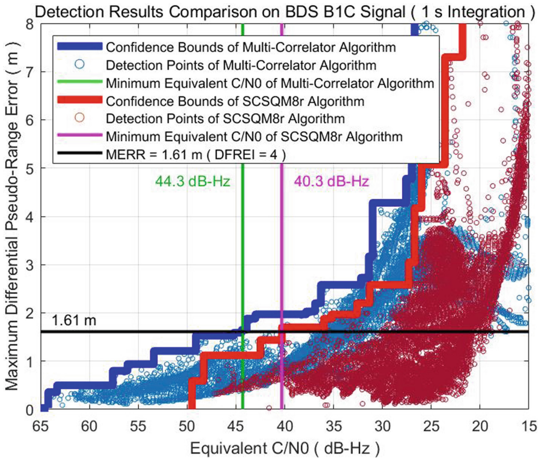


Fig. 5. Comparison of detection results of both SQM algorithms on B1C signal with 1-s integration

(1) SCSQM8r algorithm has a higher detection sensitivity, thus provides about 4 dB gain and better performance bounds to support DFMC SBAS protecting integrity for users better;
(2) The number of stations of SCSQM8r algorithm needed for reference stations is less than a half of that of traditional method under the same metric-smoothing conditions, indicating the requirement of DFMC SBAS may be met better.

To sum up, with the higher detection sensitivity, SCSQM8r algorithm shows high efficiency upon traditional method for steady-state SQM, where in fewer stations needed for reference-smoothing on B1C signals from GEOs, and in faster diagnosis on signals from IGSOs and MEOs. The latter one is particularly beneficial for transient SQM.

5.2 Simulations and Analyses on B2a Signal

The threat space of B2a signal is discretized to 3,999 EWF points according to Table 4. Figure 6 shows the results of SRPQM3 algorithm simulation on B2a signal, indicating an equivalent C/N_0 only not lower than 30.1 dB-Hz is needed to make sure 2.89 m MERR not exceeded by maxPRE induced by any EWF point within threat space across user receiver design space. Additionally considering 37.3 dB-Hz as the minimum C/N_0 for ground receivers, an MERR descending to 2.20 m is also satisfactory. Furthermore, an even low MERR of 1.38 m could be reached by taking at least a 4 dB gain contributed by 100-s metric-smoothing into account. So, B2a signal may be very well guaranteed by the proposed SRPQM3 algorithm based on MCOs for DFMC SBAS performance requirement.

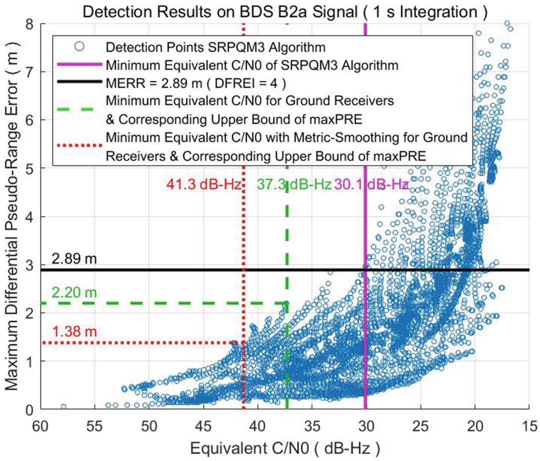


Fig. 6. Detection result of SRPQM3 algorithm on B2a signal with 1-s integration

6 Conclusions and Future Work

The academia and the industry of BDS have carried out in-depth research and made unremitting efforts to promote BDS DF civil signals meeting integrity requirements for life-safety users and being adopted into ICAO SARPs. Basing on existing achievement and the Threat Model and Spaces of both signals lately adopted by ICAO, a hybrid SQM algorithm based on both CDOs and MCOs is proposed in this paper, improving detection performances without significantly raising complexity in implementation.

a. An SQM algorithm based on CDOs is suggested for B1C signal. SCSQM8r algorithm proposed in this paper could provide about 4 dB gain in detection sensitivity and better performance bounds compared to traditional SQM method, and incorporate fewer stations in reference-smoothing process to more swiftly meet DFMC SBAS requirement efficiently.
b. An SQM algorithm based on MCOs is suggested for B2a signal, comprehensively compromising between algorithm performance and hardware overhead. SRPQM3 algorithm proposed in this paper could sufficiently meet requirement.

The hybrid SQM algorithm proposed in this paper could be considered as an effective candidate for DF SQM of the developing BDSBAS and other new generation DFMC SBAS's, providing better integrity performance for life-safety users such as civil aviation and self-driving vehicles.

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