Postprint: User Algorithm and Performance Evaluation for SISA Parameters of the BeiDou-3 System

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Abstract

On the morning of July 31, 2020, the BeiDou-3 global satellite navigation system was officially commissioned. As the BeiDou system continues to be refined and its accuracy steadily improves, users are placing increasingly higher demands on the system's integrity. The BeiDou-3 system utilizes four parameters—SISAIoe, SISAIocb, SISAIoc1, and SISAIoc2—in the broadcast ephemeris to represent the accuracy of ephemeris and clock offset parameters. However, user algorithms for these four SISAI parameters have not yet been specified in the Interface Control Document (ICD), which prevents the practical application of the BeiDou-3 system's integrity service. This study investigates the level conversion algorithm and user algorithm for the basic integrity parameter SISAI of the BeiDou-3 system. Based on the integrity requirements for the Non-Precision Approach (ICNPA) phase as defined by the International Civil Aviation Organization (ICAO), and utilizing measured data from the global network of the International GNSS Monitoring and Assessment System (IGMAS) along with SISAI parameters from the BeiDou-3 satellite broadcast ephemeris, a preliminary verification and analysis of the integrity service performance of the BeiDou-3 system was conducted. The experimental results indicate that with the completion of the BeiDou-3 system constellation, and through the use of SISA parameter conversion and user algorithms, the BeiDou-3 system achieves 100% integrity service capability for the NPA phase.

Full Text

Preamble

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User Algorithm and Performance Evaluation of SISA Parameters for BDS-3

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Abstract

On July 31, 2020, the BeiDou-3 global satellite navigation system was officially commissioned. As the BeiDou system continues to improve and its accuracy increases, users are placing greater demands on system integrity. The BDS-3 system uses four parameters in its broadcast ephemeris—SISAIoe, SISAIocb, SISAIoc1, and SISAIoc2—to represent the accuracy of ephemeris and clock offset parameters. However, user algorithms for these four SISAI parameters have not yet been provided in the Interface Control Document (ICD), preventing the practical application of BDS-3 integrity services. This paper investigates the level conversion algorithm and user algorithm for the basic integrity parameter SISA of the BeiDou-3 system. In accordance with the integrity requirements for the International Civil Aviation Organization (ICAO) Non-Precision Approach (NPA) phase, we conduct preliminary verification and analysis of BDS-3 integrity service performance using data from the International GNSS Monitoring and Assessment System (IGMAS) global network and SISAI parameters from BDS-3 satellite broadcast ephemerides. Experimental results demonstrate that with the completion of the BDS-3 constellation and the adoption of the SISA parameter conversion and user algorithms presented herein, the NPA-phase integrity service capability of BDS-3 reaches 100%.

Keywords: BDS-3; integrity; SISA parameters; envelope

1 Introduction

The primary performance indicators of Global Navigation Satellite Systems (GNSS) include accuracy, integrity, continuity, and availability. Integrity refers to the ability of a navigation system to provide timely warnings to users when the navigation information fails to meet performance requirements—i.e., when system faults or excessive errors render the information unsuitable for navigation and positioning. Integrity is a crucial metric for evaluating the reliability of satellite navigation systems. As GNSS service accuracy continues to improve and applications expand, system integrity issues affecting user safety have garnered increasing attention, with all GNSS providers prioritizing integrity monitoring as a key system upgrade.

GNSS integrity monitoring techniques primarily include Satellite Autonomous Integrity Monitoring (SAIM), Ground Integrity Channel (GIC), and Receiver Autonomous Integrity Monitoring (RAIM). System operators mainly rely on GIC and SAIM for system-level integrity monitoring, while RAIM enables fault satellite identification through user receiver algorithms. GIC technology employs ground monitoring stations to collect navigation satellite observations, predict and monitor space signal accuracy of navigation messages, generate corresponding integrity messages, and broadcast them to users along with navigation messages. Users then employ these integrity parameters to assess satellite health status and the reliability of broadcast information. SAIM technology directly monitors signal anomalies onboard navigation satellites and broadcasts satellite signal health flags based on monitoring results, offering simple message parameters and high real-time alert capability, making it an important approach for next-generation GNSS integrity monitoring. RAIM technology processes redundant observations from multiple satellites using least squares or parity space vector algorithms to detect and exclude faulty satellites during positioning. However, RAIM generally only monitors single-satellite major faults, reduces system availability, and thus provides relatively weak integrity monitoring capability.

GNSS systems such as BDS, GPS, and Galileo broadcast integrity message parameters that include important information about the predicted accuracy of satellite orbit and clock errors in broadcast ephemerides. Due to different monitoring architectures and message designs, the integrity parameters broadcast by each GNSS system vary. Early implementations typically used a single integrity parameter to represent the combined radial prediction accuracy of satellite orbit and clock errors. As integrity monitoring capabilities improved, systems began to use different parameters to reflect the distinct error characteristics of orbit and clock errors. GPS uses the URAI (User Range Accuracy Index) in its legacy navigation message to reflect broadcast ephemeris space signal prediction accuracy. In the newly designed CNAV (Civil Navigation) message, GPS employs four parameters—URAed, URAned0, URAned1, and URAned2—to represent ephemeris in-plane prediction error, ephemeris radial and clock bias prediction error, clock drift prediction error, and clock aging prediction error, respectively. Galileo and BDS-2 (BeiDou regional system) use the SISAI (Signal In Space Accuracy Index) parameter and URAI to represent broadcast ephemeris space signal prediction accuracy, respectively. BDS-3 (BeiDou global system) has comprehensively upgraded its integrity monitoring architecture, using SISAIoe, SISAIocb, SISAIoc1, and SISAIoc2 to represent ephemeris in-plane prediction error, ephemeris radial and clock bias prediction error, clock drift prediction error, and clock aging prediction error, respectively. Table 1 compares the ephemeris and clock integrity message parameters broadcast by various GNSS systems.

Integrity service performance is typically expressed through alert limits, time-to-alert, and probability of Hazardously Misleading Information (HMI). Alert limits define the positioning error thresholds that ensure safe operation for specific flight phases, categorized as Horizontal Alert Limit (HAL) and Vertical

Alert Limit (VAL). Time-to-alert represents the maximum allowable delay from system fault occurrence to user warning reception. HMI probability refers to the risk probability of hazardous flight conditions when the current positioning value exceeds alert limits, generally required to be no greater than 10^{-7} per hour. Due to safety-of-life service requirements, aviation users impose the most stringent integrity requirements on satellite navigation systems. Table 2 presents ICAO integrity performance requirements for various flight phases.

As shown in Table 1, the integrity message parameters broadcast by GNSS systems through ephemerides are all index values. Users must convert these index values into specific space signal accuracy predictions according to the user interface control documents published by each GNSS system, and then apply them using user algorithms. BDS-3 began basic service based on 18 MEO satellites on December 27, 2018, and officially commissioned global service based on a 24MEO/3IGSO/3GEO constellation on July 31, 2020. Currently, BDS-3 has not provided the level conversion relationships for each SISAI index parameter in its ICD, nor has it provided user application algorithms for SISA parameters. This paper designs the level conversion algorithm and user application algorithm for BDS-3 SISAI parameters, investigates integrity assessment methods for SISA parameters based on the positioning domain, and conducts preliminary verification of the integrity performance of SISA parameters broadcast by BDS-3 using IGMAS global monitoring network data, comparing integrity service capabilities across different BDS-3 development phases.

2 BDS-3 SISAI Parameter Index Conversion Algorithm

Due to navigation message bandwidth limitations, GNSS systems broadcast space signal integrity parameters as level index values. In BDS-3 broadcast ephemerides, integrity parameters SISAI express the prediction accuracy of satellite orbit and clock errors in broadcast ephemerides. The index values broadcast via navigation messages include SISAIoe, SISAIocb, SISAIoc1, and SISAIoc2. Before using integrity parameters, users must convert these index values into specific prediction accuracy values. Currently, the BeiDou ICD has not published dedicated level correspondence tables for each parameter.

Because satellite orbit and clock errors exhibit different characteristics and affect users at different positions differently, the in-plane and cross-plane orbit prediction accuracy is expressed by the SISAIoe parameter, while the radial orbit and clock error prediction accuracy is expressed by the SISAIoc parameter. Furthermore, based on the quadratic model characteristics of clock errors, the SISAIoc parameter is subdivided into SISAIocb, SISAIoc1, and SISAIoc2. The SISAIocb parameter comprehensively represents satellite clock bias and radial orbit errors, SISAIoc1 represents satellite clock drift error, and SISAIoc2 represents satellite clock aging error.

The SISAIoe index ranges from -16 to +15, with different index values representing parameter ranges as shown in Table 3 . The SISAIocb index also ranges from

-16 to +15, with parameter ranges identical to SISAIoe and thus not repeated here. The SISAIoc1 and SISAIoc2 parameters range from 0 to 7, representing eight levels without dedicated correspondence tables.

For SISAIoe and SISAIocb parameters, this paper designs a conversion method that obtains the level conversion value corresponding to an index by taking the standard deviation within the index value range, as shown in Equation (1):

$$SISA_{oe/ocb} = \begin{cases} 2^{(1+N/2)} & (N \leq 6) \\ 2^{(N-2)} & (N > 6, N < 15) \\ 2.8; 5.7; 11.3 & (N = 1; 3; 5) \end{cases}$$

where N is the index parameter value in Table 3. When N is less than 0 in Equation (1), the corresponding precision for each index value in Table 3 is used.

For SISAIoc1 and SISAIoc2 parameters, the index level conversion is shown in Equation (2):

$$SISA_{oc1} = 2^{-(SISAI_{oc1}+14)} SISA_{oc2} = 2^{-(SISAI_{oc2}+28)}$$

Using Equations (1) and (2), the SISAI level index values broadcast in navigation messages can be converted into specific accuracy representations.

3 SISA Parameter User Application Algorithm

After receiving the index values of integrity parameters in broadcast ephemerides, users must first convert them into specific accuracy values. For satellite clock error prediction errors, which are represented by three parameters, the prediction accuracy must be calculated using the converted SISAocb, SISAoc1, and SISAoc2 parameters according to the clock prediction model, as shown in Equation (3):

$$SISA_{oc} = \begin{cases} SISA_{ocb} + SISA_{oc1}(t - t_{op}) & t - t_{op} \leq 93,600 \\ SISA_{ocb} + SISA_{oc1}(t - t_{op}) + \frac{SISA_{oc2}(t - t_{op} - 93,600)^2}{t - t_{op}} & t - t_{op} > 93,600 \end{cases}$$

where t is system time and t_{op} is the ephemeris reference time, both in seconds.

After obtaining the SISAoe and SISAoc parameters, users must calculate the comprehensive SISA parameter to reflect the space signal accuracy of broadcast ephemeris based on error characteristics. According to the approximate projection of orbit plane errors and radial/clock errors in the worst-case user direction, the comprehensive SISA parameter is expressed by Equation (4):

$$SISA = \sqrt{(SISA_{oe} \cdot \sin 14°)^2 + SISA_{oc}^2}$$

Users employ the integrity parameters broadcast by the system to calculate positioning protection levels that reflect the reliability of position solutions derived from observations. System integrity service performance can be expressed through three parameters: Position Error (PE), Protection Level (PL), and Alert Limit (AL). Position error refers to the deviation between the user-calculated position using observation data and broadcast ephemeris and the true position. Protection level represents a conservative estimate of positioning error calculated by users using system-broadcast integrity parameters. Alert limit is the warning threshold for positioning error; if the calculated protection level exceeds the alert limit, the navigation service is considered "unavailable." Alert limits are determined by navigation positioning service industries, with ICAO providing different requirements for various flight phases as shown in Table 2. The relationship between PE, PL, and AL is illustrated in Figure 1 [Figure 1: see original paper].

In practice, users (especially real-time dynamic users) typically do not know their true position and thus cannot calculate their navigation positioning error. They can only compute the corresponding positioning protection level as a conservative estimate of positioning error using integrity parameters. Satellite navigation systems must ensure that the protection level calculated using system-broadcast integrity parameters exceeds the user's true positioning error. If the calculated protection level is less than the user alert limit but the user's true positioning error exceeds the alert limit, an integrity risk event occurs. One of the most important integrity performance metrics for satellite navigation systems is the integrity risk probability.

In specific applications, user positioning errors can be divided into Horizontal Position Error (HPE) and Vertical Position Error (VPE). Different users have varying accuracy requirements for horizontal and vertical directions, so alert limits are categorized as Horizontal Alert Limit (HAL) and Vertical Alert Limit (VAL). Correspondingly, protection levels calculated using integrity parameters can be divided into Horizontal Protection Level (HPL) and Vertical Protection Level (VPL). The specific calculation formulas for HPL and VPL are as follows:

$$HPL = K_H \sqrt{d_{east}^2 + d_{north}^2} VPL = K_U \sqrt{d_{up}^2}$$

where K_H and K_U are coefficients corresponding to confidence probabilities derived from horizontal risk probability P_{h,hmi} and vertical risk probability P_{v,hmi} according to system integrity service levels. Based on ICAO Annex 10, the integrity risk probability coefficients for different flight phases are: K_{H,NPA} = 6.18, K_{H,PA} = 6.0, K_{V,PA} = 5.33. In Equations (5) and (6), d_{ii} represents the projection of pseudorange domain line-of-sight residuals into the position domain using the spatial geometry projection matrix, expressed as:

$$\begin{bmatrix} d_{east} & d_{north} & d_{up} & d_t \end{bmatrix}^T = (G^T W G)^{-1} G^T W$$

where G is the observation matrix with row elements:

$$\begin{bmatrix} -\cos(Ele_i)\sin(Azi_i) & -\cos(Ele_i)\cos(Azi_i) & -\sin(Ele_i) & 1 \end{bmatrix}$$

The weight matrix W is a diagonal matrix expressed as:

$$W = \mathrm{diag}\left[\frac{1}{\sigma^2_{u,1} + SISA_1^2}, \cdots, \frac{1}{\sigma^2_{u,N} + SISA_N^2}\right]$$

where SISA_i represents the comprehensive SISA parameter for each satellite calculated by Equation (4), and σ__u represents propagation segment observation error:

$$\sigma^2_{u,i} = \sigma^2_{air,i} + \sigma^2_{tropo,i}$$

where user equipment error σ*{air,i} and tropospheric residual error* σ{tropo,i} are determined by user equipment and tropospheric models:

$$\sigma^2_{tropo,i} = 0.002 + \frac{0.12}{\sin^2(\theta_i)}\sigma^2_{air,i} = 0.15 + \mathrm{rand}(0.07)$$

where _i is the elevation angle.

4 SISA Parameter Integrity Assessment Method

The BDS-3 integrity service target is to meet civil aviation NPA-phase integrity requirements, which primarily focus on horizontal integrity service capability. Using IGMAS globally distributed monitoring data, we verify the integrity performance of BDS SISA parameters following the Stanford diagram method. As shown in Figure 2 [Figure 2: see original paper], the Stanford diagram assessment method categorizes system integrity service performance into four situations:

1. When positioning error is less than protection level and protection level is less than alert limit (HPE < HPL < HAL), integrity service is "available," represented by the white region in Figure 2.
2. When positioning error exceeds protection level but remains below alert limit (HPL < HPE < HAL), integrity service experiences "missed alert," represented by the blue region.

3. When positioning error exceeds alert limit while protection level remains below alert limit (HPL < HAL < HPE), integrity service experiences "serious integrity risk," represented by the red region.
4. When protection level exceeds alert limit (HPL > HAL), navigation service is "unavailable," represented by yellow and gray regions. The yellow region indicates no integrity missed alert, while the gray region indicates integrity missed alert.

Following the Stanford diagram assessment method, observation data from stations with known coordinates are selected for system integrity service evaluation. IGMAS station coordinates can be precisely calibrated using precise positioning methods. By calculating each station's position using BDS-3 broadcast ephemerides and comparing it with precise coordinates, navigation positioning errors for each station can be obtained:

$$POS_{err} = POS_{post} - POS_{nav}$$

where POS_{err} represents positioning error, POS_{post} represents post-processed precisely calibrated station coordinates, and POS_{nav} represents station coordinates calculated using navigation messages.

Using SISA parameters broadcast in navigation messages, horizontal protection levels (HPL) are calculated according to the method described in Section 3 to statistically analyze integrity service availability, missed alert rate, serious integrity risk probability, and service unavailability probability.

The NPA integrity service availability assessment method for BDS-3 is:

$$Availability = \frac{N(HAL > HPL > |POS_{errH}|)}{N_{all}}$$

The NPA integrity service missed alert probability analysis for BDS-3 examines the probability that horizontal positioning error exceeds horizontal protection level but remains below horizontal alert limit:

$$MIH = \frac{N(HAL > |POS_{errH}| > HPL)}{N_{all}}$$

The NPA integrity service integrity risk probability analysis for BDS-3 examines the probability that positioning error exceeds horizontal alert limit while protection level remains below horizontal alert limit:

$$HMIH = \frac{N(|POS_{errH}| > HAL > HPL)}{N_{all}}$$

The NPA integrity service unavailability probability analysis for BDS-3 examines the probability that protection level exceeds alert limit while positioning error remains below protection level, excluding missed alert cases:

$$H_{unavail} = \frac{N(|POS_{errH}| < HPL \wedge HPL > HAL)}{N_{all}}$$

In the above equations, N represents the number of samples meeting the conditions, and N_{all} represents the total number of statistical samples.

5 SISA Parameter Integrity Assessment Test Analysis

This paper analyzes the NPA-phase integrity service capability of BDS-3 and verifies the integrity performance of basic integrity SISA messages using BDS-3 basic integrity SISA messages and IGMAS global station observation data. According to NPA integrity service index requirements, we evaluate BDS-3 NPA integrity service availability and risk using Stanford diagram statistical methods.

Using BeiDou observation data from 11 globally distributed IGMAS stations, the system integrity service performance evaluation period spans from December 2018 to October 2020. IGMAS station distribution is shown in Figure 3 [Figure 3: see original paper].

Based on BDS-3 operational status, the test verification is divided into two phases: basic system phase and complete system phase. HPL and horizontal positioning error for IGMAS stations are calculated to analyze NPA integrity service availability, missed alert rate, and serious integrity risk probability across different BDS-3 development stages. No "serious integrity risk" events occurred during testing. Statistical results for integrity service availability (i.e., envelope capability) and missed alert rate at each station are presented in Table 4 . Figure 4 [Figure 4: see original paper] shows the comprehensive statistical results of NPA integrity service availability across all stations. Figure 5 [Figure 5: see original paper] displays the time series of horizontal error and horizontal protection level for IGMAS station canb in March 2020. The envelope capability of HPL calculated from SISA parameters for horizontal error reached 100% that month.

The evaluation results demonstrate that NPA integrity service availability gradually strengthens as the constellation improves. BDS-3 NPA service availability was 99.75% during the basic system phase and reached 100.00% during the full constellation complete system phase.

6 Conclusion

BDS-3 employs a completely new integrity design architecture, broadcasting SISAI parameters in ephemerides to reflect the prediction accuracy of broadcast ephemeris orbit and clock information. Due to the relatively short time since system commissioning, the publicly available BDS-3 ICD has not yet provided user algorithms for SISA parameters, hindering the promotion and application of system integrity services.

This paper designs a level conversion method for SISAI parameters and investigates user application algorithms for SISA parameters. Using IGMAS global observation station data and Stanford diagram analysis methods, we verify and analyze the integrity performance of SISA parameters. According to BDS-3 integrity service objectives and ICAO NPA-phase integrity service index requirements, we conduct a preliminary assessment of BDS-3 NPA integrity service capability. Experimental results show that BDS-3 integrity service capability strengthens as constellation deployment progresses, achieving 100% NPA-phase integrity service capability upon full constellation completion. The algorithms and experimental results presented in this paper provide important references for in-depth evaluation of BDS-3 integrity service capabilities.

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Note: Figure translations are in progress. See original paper for figures.