Chapter 14
Evaluation Method Research on GNSS Signal-in-Space Continuity

Yang Tang and Rui Li

Abstract As a statistical measure of the frequencies of satellite navigation system performance loss, continuity is an important embodiment of satellite navigation system reliability evaluation. In fact, the continuity index is initially developed from the demand of civil aviation users and mainly focus on the service layer. The signal-in-space continuity concept is not clearly put forward in GPS SPS PS document until 2008, relevant standard system is not yet mature and there are few results of the study on GNSS signal-in-space continuity evaluation. So this paper first studies the relationship between signal-in-space continuity and service continuity through analyzing the development of continuity index. And further analyzes specific connotation of signal-in-space continuity from the basic concept, index system. Then this paper studies the evaluation method of signal-in-space continuity based on the principle of basic reliability, and takes GPS for example to statistic all the unscheduled outages happened from 1999 to 2013 and calculates the mean time between failure to evaluate GPS signal-in-space continuity. The result is consistent with the performance standard announced by the GPS SPS PS (2008), which verifies the rationality and validity of this method. The method of evaluating signal-in-space continuity proceeded in this paper is to provide theoretical reference for the test and evaluation of BDS performance.

Keywords GNSS · Signal-in-space · Continuity · Unscheduled outage

14.1 Introduction

The formation and development of Global Navigation Satellite System GNSS including GPS as well as China's BeiDou is promoting the rapid progress of its applications in various fields. Meanwhile, the requirements of users' application

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J. Sun et al. (eds.), *China Satellite Navigation Conference (CSNC) 2015 Proceedings: Volume II*, Lecture Notes in Electrical Engineering 341,
DOI 10.1007/978-3-662-46635-3_14

also promote the research development of GNSS application performance. Incipiently, the integrity and continuity index were not taken into account. In essence, the application performance requirements of satellite navigation system in the civil aviation service led to the development of GNSS performance index, thus prompted the GNSS gradually to pay attention to integrity and continuity index. But originally the ICAO (International Civil Aviation Organization) focused on reliability of service, including integrity, continuity of service and availability. The signal-in-space continuity concept is not clearly put forward in GPS SPS PS (Global Positioning System Standard Positioning Service Performance Standard) document until 2008 and the related standard is not consummate. Also the research finding about signal-in-space continuity evaluation at home and abroad is very little.

Therefore, this article accounts for the essence of studying the signal-in-space continuity through analysing the development of continuity index, also analyzes the basic concept and standards of signal-in-space continuity and studies the evaluation method based on the principle of basic reliability. Then takes GPS for example, through measured data of nearly a decade to verify the correctness of the method. Mainly uses FAA (Federal Aviation Administration) failure report of every quarter to statistics mean time between failures, further analyzes GPS signal-in-space continuity, contrasting the result with GPS standard put forward by the GPS SPS PS to validate the effectiveness of the proposed method. Finally, this paper will provide theoretical references for the evaluation of BDS signal-in-space continuity.

14.2 Continuity Index Development Research

14.2.1 The Development of Continuity Index

Aviation demands for the performance of satellite navigation system has led to the development of GNSS performance index. As a system providing service to all customers within the airspace with continuous navigation service, the continuity often said of the satellite navigation system represents its ability of telling the user of system's normal and continuous work. But different users have different navigation performance requirements as well as definition of continuity, the concern level is also various.

At first, Aeronautical Telecommunications ANNEX 10 to the Convention on International Civil Aviation (Volume I) issued by ICAO illustrated the GNSS application performance requirements of civil aviation, including Accuracy, Integrity, Continuity of service and Availability. Also the performance standards for different phases of aircraft flight were presented. And the Continuity index was specifically referred as the Continuity of service, which is the capability of the system to perform its function without unscheduled interruptions during the intended operation.

But in the Appendix D of Aeronautical Telecommunications ANNEX 10 Volume I (2004), ICAO introduced aviation application performance for the main GNSS respectively at that time including GPS, GLONASS. Section 4.1 focused on the GPS and clearly pointed out that additional information about the GPS aviation application performance can be found in GPS SPS PS (2001) as well as the Interface Control Document (ICD)-GPS-200-c. This to some extent explains that the performance index of GNSS in the field of civil aviation is inseparable with the basic application service performance evaluation of concrete global satellite navigation system.

As for GPS, the US DoD (Department of Defense) successively presented four versions of the Standard Positioning Service Performance Standard document (US DoD, 1993, 1995, 2001, 2008) [2, 3]. Among them, the former 3 editions did not involve the concept of continuity, the latest version (2008) began to pay close attention to the continuity index and only provided the concepts and specific standards of signal-in-space (SIS) continuity. As a whole, the fourth edition of GPS SPS PS focused on SIS, which is also the obvious difference with the former 3 versions.

In a nutshell, the GNSS performance requirements in the aviation is more strict and comprehensive compared with other applications, so it almost leads GNSS performance development. For example, the GPS SPS PS released by U.S. DoD and FAA GPS measurement performance reports [4] mainly formulate the corresponding standards and analysis of the measured data based on the GNSS aviation applications performance requirements. Currently, GPS SPS PS documents basically dominate the satellite navigation system performance standards and the evaluation index system, which in fact becomes the GNSS performance evaluation standard.

14.2.2 The Analysis on Evolution of the Continuity of Service to SIS Continuity

Through the main official documents on the study of continuity index above, this paper argues that the reasons why GNSS focuses on SIS continuity mainly include the following two points:

A. Considering SIS performance is more direct and feasible for GNSS developers

According to the study of GNSS performance by ICAO, although it proposed the continuity of service standards for different typical civil aviation flight phase, it was in essence used as a starting point to derive GNSS signal-in-space performance requirements. Because for the developers or operation management departments of different satellite navigation systems including GPS as well as GLONASS, it is more direct to put forward the corresponding standards respectively according to their own satellite navigation products to make their products meet the demand of the terminal application. After all, the continuity of service for GNSS terminal application involves many uncertain factors including aviation equipment as well as transmission environment, which can't be guaranteed by GNSS developers. However, they can ensure the concrete performance of the satellite from their own product and thus considering SIS is more direct.

B. SIS continuity determines continuity of service in part

GNSS service continuity requirements by ICAO focus on service interruption frequency. In fact, for GNSS, interruption caused by single satellite fault and limited DOP because of insufficient visible satellite both can lead to a service interruption. So this paper argues that the service continuity was mainly affected by SIS continuity and DOP availability. For example, GPS constellation design of redundancy guarantees the DOP availability to some extent, also the SIS continuity for single satellite ensures the interrupt probability triggered by a number of satellites' failure in the constellation is very small, thus ensure the service continuity of the whole system to meet specific application requirements. This is also the reason this paper argues why the GPS PS SPS (2008) did not mention the service continuity but SIS continuity and PDOP availability index were given.

Therefore, according to the above analysis and the latest research trends of the current GPS SPS PS, this paper mainly studies the GNSS SIS continuity.

14.3 GNSS SIS Continuity Evaluation Method Research

14.3.1 GNSS SIS Continuity

The GPS SPS PS (2008) pointed out that SIS continuity for a healthy SPS SIS is the probability that the SPS SIS will continue to be healthy without unscheduled interruption over a specified time interval. Also the document argued that the standard positioning service SIS continuity is directly related to the SIS reliability.

The SIS continuity for BeiDou system public service [3] refers to the probability of a public health service signal continuously work without occur unscheduled interrupt in the required period of time, which also means that SIS continuity is closely related to the unscheduled interrupt.

GPS SPS PS (2008) provided the performance standard of SPS SIS continuity, as shown in Table 14.1. Also, it points out that an interruption is defined as a period in which the SIS from a satellite does not comply with the standards defined in this SPS PS. Among which, unscheduled interruption mainly results from system malfunctions or maintenance occurring outside the scheduled period and will be announced to the Coast Guard and the FAA as soon as possible, it includes unscheduled failure interruption and unscheduled maintenance interruption.

Table 14.1 GPS SPS SIS continuity standards

SIS continuity standard	Conditions and constraints
Unscheduled Failure Interruptions: • ≥0.9998 probability over any hour of not losing the SPS SIS availability from a slot due to unscheduled interruption	• Calculated as an average over all slots in the 24-slot constellation, normalized annually • Given that the SPS SIS is available from the slot at the start of the hour
Unscheduled Maintenance Interruptions: • No performance specified	• A future version of this SPS PS may establish a standard

14.3.2 Evaluation Method Analysis Based on the Reliability Theory

Based on the connotation of SIS continuity for GPS and BDS, SIS continuity in essence reflects unscheduled interrupt frequency for every single satellite. To some extent, the probability of system continuous operation without continuity loss (or unscheduled interrupt) described by SIS continuity is equivalent to the probability of system reliable operation. Therefore, SIS continuity is another way to present the reliability of satellite navigation system, therefore this paper in turn analyzes SIS continuity evaluation method based on the principle of reliability.

From the elementary reliability theory, if one can assume a constant hazard rate (probability of failure) for a system over time, then the probability of reliable operation (no failure) of that system in any given hour is:

$$P(\text{No Failure/h}) = e^{-(1/MTBF)} \tag{14.1}$$

Given that the system was operating at the start of the hour and that no interruptions are planned during that hour. The MTBF is Mean Time Between Failure as the average failure time interval, in hours.

Continuity is essentially a certain reliability, thus specific assessment of corresponding continuity can be obtained depending on the type of fault reflected by MTBF. So on reference to the principle of reliability, SIS continuity can be characterized by Mean Time Between Unscheduled Outages (MTBUO):

$$P_{SIS\_Con} = e^{-(1/MTBUO)} \tag{14.2}$$

$$P_{SIS\_C\_risk} = 1 - e^{-(1/MTBUO)} \tag{14.3}$$

where, P_{SIS_Con} is for the SIS continuity probability, $P_{SIS\_C\_risk}$ is for SIS continuity risk probability.

In fact, this model characterizes unscheduled interruption frequency through MTBUO and further characterizes SIS continuity. The smaller the MTBUO is, the more frequently the unscheduled interruption will occur, also the SIS continuity performance will be lower; Whereas the SIS continuity will be better.

14.4 The Verification by Statistics of Data

By the analysis above for SIS continuity evaluation model on the basis of reliability. The key for this method is to obtain MTBUO. However, to get MTBUO needs monitoring the long-term operational status of the GNSS. So this article uses the earliest actual operation GPS as analysis object and refers to corresponding standard in GPS SPS PS to verify the correctness and effectiveness of the proposed method.

14.4.1 Statistics of GPS MTBUO

As for GPS, MTBF for different types of fault provided by GPS SPS PS officially is just a rough value, can't reflect specific single satellite failure frequency. For the analysis of GPS SIS continuity, this paper statistics the actual mean time between unscheduled outages of each satellite for GPS. Mainly according to the GPS quarterly performance reports provided by FAA, this paper statistics all unscheduled interruption of per GPS satellite since 1999. But the basic fault reports mainly statistics satellite failure condition according to the satellite PRN number. For a specific single satellite, considering the status of changing satellites, this paper first statistics the corresponding SVN for each satellite PRN and the specific operation time since 1999. Part of the satellites did not occur unscheduled outages, and only one unscheduled interruption occurred for part of the satellites, as shown in Table 14.2.

Except for these satellites with no or just one unscheduled interruption, the distribution of MTBUO for other satellite is as follows in Fig. 14.1.

From the figure above, MTBUO approximately obeys the exponential distribution. On this basis, the paper statistics MTBUO for GPS satellites, with results shown as below in Fig. 14.2.

Table 14.2 GPS satellites of one unscheduled outage, 1999–2013

SVN	PRN	BLOCK	Unscheduled outage time
50	5	IIR-M	2009.9.5 22:28
67	6	IIF	2014.6.30 24:00
36	6	IIA	2006.6.29 11:05
17	17	IIR	2001.5.13 1:52
53	17	IIR-M	2007.9.15 12:50
18	18	IIR	2000.6.28 13:19
47	22	IIR	2006.1.8 19:31
60	23	IIR	2012.2.27 20:14

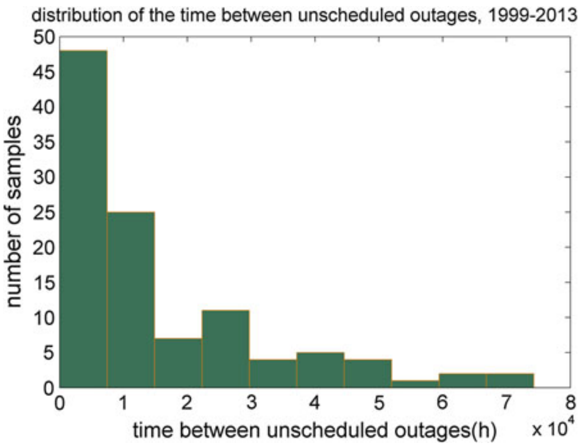

Fig. 14.1 Distribution of the time between unscheduled outages, 1999–2013

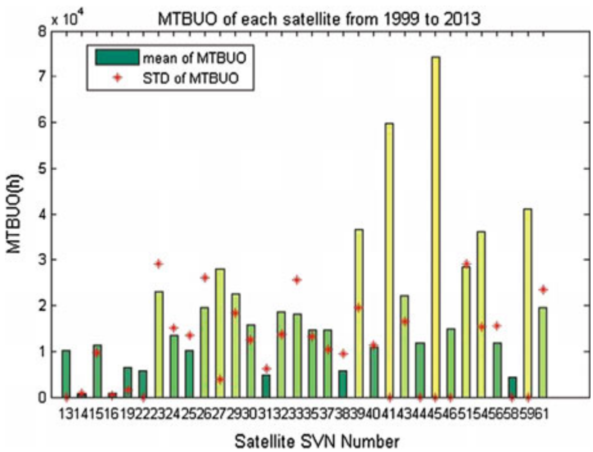

Fig. 14.2 MTBUO of GPS per satellite, 1999–2013

The figure shows that the MTBUO of BLOCK IIR\IIR-M satellite is bigger compared with the BLOCK II and IIA series. It is easy to understand, the SIS continuity is also improved with the launch and upgrade of GPS satellites. In addition to the SVN 41\45 satellites whose MTBUO is large (>50,000 h), the MTBUO for other satellites is of stationary distribution. On average, the mean MTBUO of BLOCK IIR\IIR-M satellites is 26590.85 h.

In addition, this paper statistics the GPS MTBUO of every year since 1999, shown as the following Fig. 14.3.

By above figure, the GPS MTBUO is basically at the trend of rising every year, which reflects that the system overall performance is in the continuous improvement.

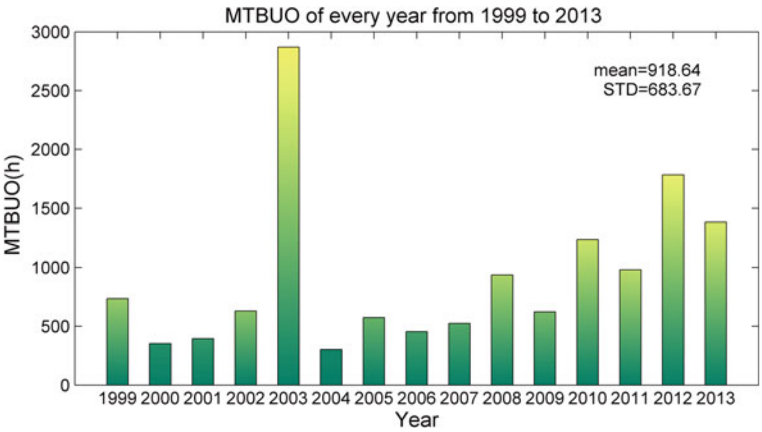

Fig. 14.3 MTBUO of every year for GPS, 1999–2013

14.4.2 SIS Continuity Analysis for Single Satellite

Based on the above evaluation model, this paper further researches GPS SIS continuity for each satellite using the measured average MTBUO, and the result is shown in Fig. 14.4.

As seen in Fig. 14.4, the probability of GPS satellite SIS continuity is not less than 0.9998/h except for the SVN 14 and SVN 16 which both belong to the retired

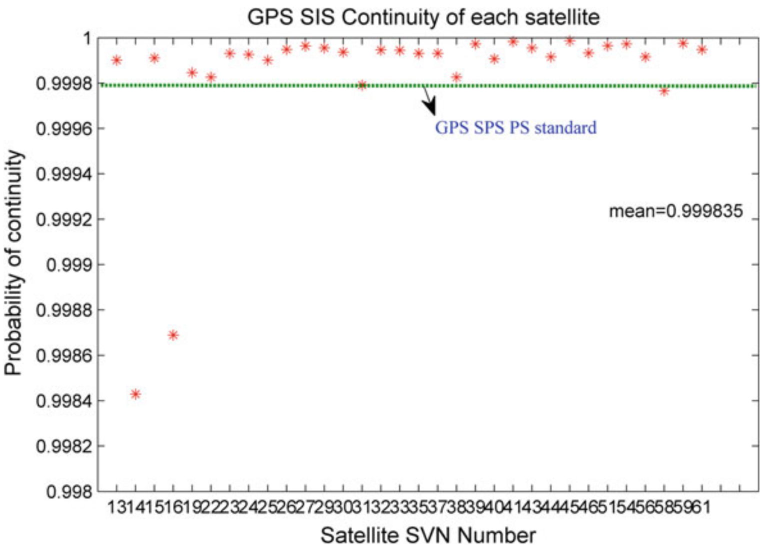

Fig. 14.4 SIS Continuity of GPS satellites, 1999–2013

BLOCK II. Therefore, the results comply with the SIS continuity standard given by GPS SPS PS (2008), which also proves the correctness and effectiveness of the evaluation method for GNSS SIS continuity discussed in this paper. And the average of SIS continuity for all the satellites in operation is 0.999938/h, far more than 0.9998/h.

In conclusion, the GNSS SIS continuity evaluation method based on the principle of reliability discussed in this paper is effective, expected to be applied to BDS SIS continuity analysis.

14.5 Conclusion

This article clarified the significance of the current study on GNSS SIS continuity through studying the evolution process of continuity index, further researched the definition and performance standards of GNSS SIS continuity. Then, studied SIS continuity evaluation model from the principle of reliability and analyzed GPS SIS continuity of each satellite according to the practical operation since 1999 based on the evaluation method. The results showed that the average GPS SIS continuity of each satellite is over 0.9999/h, consistent with the SIS continuity standards proposed by GPS SPS PS (2008), which verified the correctness and validity of this assessment method for GNSS SIS continuity expected to provide certain theoretical references for the evaluation and analysis of BDS SIS continuity.

Based on GNSS SIS continuity evaluation method research above which takes GPS as an example, this paper summarizes the following conclusions for BDS SIS continuity evaluation as a reference:

(1) The key of GNSS SIS continuity evaluation is to statistics all the unscheduled outages. For BDS, therefore, it is necessary to provide satellite failure reports periodically similar to GPS which is provided by FAA every quarter, listing all specific performance test of each satellite occured since launch to retirement.
(2) Improving GNSS SIS continuity is of great significance to promoting the reliability of the system. For BDS, the constellation layout is uneven and the redundancy is not so good as GPS. So in the case of DOP limited, to meet the demand of the service reliability of specific applications, improving the BDS SIS continuity is particularly important.

Acknowledgments The authors gratefully acknowledge the support of the National Basic Research Program of China (Grant No. 2010CB731805).

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