Design of Signal Quality Test Module for Ground Verification System of Satellite Based Augmentation System (SBAS)

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Abstract

The satellite-based augmentation system (SBAS) transmits correction data through satellites, and navigation receivers utilize this correction data to improve the accuracy of the Global Navigation Satellite System (GNSS). In order to implement the SBAS, ground equipment that generates correction signals is required. If a ground verification system is developed, it can be utilized to verify the performance and function of the system on the ground before the full construction of the augmentation system, and check the transmission and reception status of test messages. The ground verification system includes a signal generator. A module that performs signal quality test must be installed in the system to check the quality status of the signal generated by the signal generator. In this study, a signal quality test algorithm required for the ground verification system of the satellite-based augmentation system was designed. The test was performed using the SBAS signal to confirm the possibility of module development. The developed module can be applied to a ground verification system and used to verify the generated signal.

Keywords

Augmentation System, Signal Generation, Quality Monitoring

1. Introduction

Global Navigation Satellite Systems (GNSS) provide position and time information to users using navigation satellites. GNSS have been used in military and transportation applications that require position information. Their applications have gradually expanded. Currently, GNSS have become essential components in a wide range of technologies such as Internet of Things and smart devices[1, 2]. GNSS signals contain errors that are induced during measurement and transmission processes. The satellite positions and timing information provided by navigation satellites contain error elements, and additional errors are induced as signals pass through the ionosphere and troposphere during transmission. GNSS calculates users' positions and time based on information such as system time synchronization, navigation satellite positions, and signal transmission times. As error elements are always included in GNSS signals, the accuracy of the calculated user position decreases. While various correction techniques are applied to minimize measurement and transmission errors, perfect elimination of these errors is difficult. Satellite-based Augmentation System (SBAS) uses satellites to transmit correction information to satellite navigation receivers to improve positioning accuracy by reducing position errors in GNSS. The correction information includes satellite position errors, clock errors, and ionospheric errors, which receivers can use to improve positioning accuracy. Unlike conventional navigation satellites, satellites used in SBAS cannot generate signals on the satellite itself. Instead, correction information signals are generated on the ground, and the augmentation satellite serves as a relay. Therefore, ground systems must control signals so that receivers can receive correction

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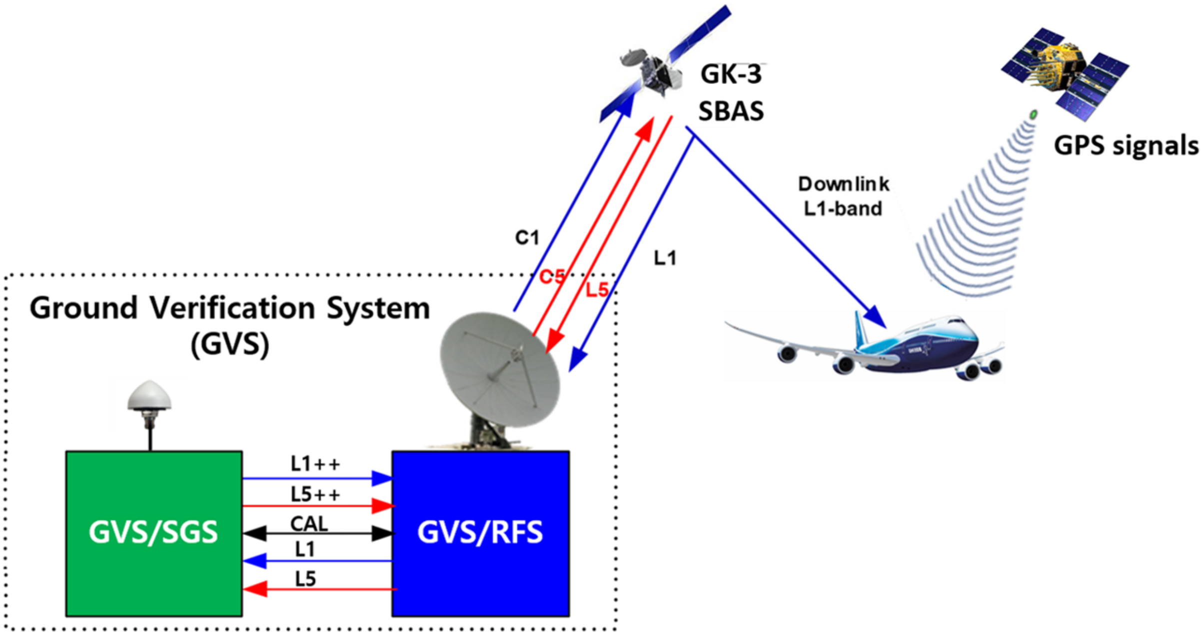

Figure 1: Functional Concept Diagram of GVS

information signals under the same conditions as other navigation satellites. Signal control accounts for the fact that the signal passes through the atmosphere twice during uplink and downlink transmission, requiring adjustment of code and carrier frequencies. When developing a SBAS, it is advisable to develop a ground verification system in the early stages to perform signal generation and validation on the ground, and subsequently expand to include satellite transmission and reception checks [3]. The ground verification system integrates signal generation, transmission, and reception processes to facilitate signal generation and validation. To ensure the quality of generated signals, it is necessary to inspect received signals to verify whether they meet the requirements for correction signals. In this study, we analyzed the requirements for a signal quality test module to inspect the quality of signals generated in the ground verification system of a SBAS, derived test techniques based on these requirements, and designed a signal quality test module for the ground verification system of a SBAS.

2. Signal Generation System for SBAS Ground Verification System

2.1. Functions and Configuration of the Ground Verification System

The ground verification system verifies the functionality and performance of relay equipment for the augmentation system to be mounted on satellites, and validates algorithms of the ground station for the augmentation system. Figure 1 shows the functional concept diagram of the ground verification system. As shown in Figure 1, the ground verification system includes a Signal Generation Subsystem (SGS) that generates augmentation signals and a Radio Frequency Subsystem (RFS). The SGS is responsible for generating test correction messages and controlling signal timing according to GPS time, while the RFS performs the function of connecting the geosynchronous equatorial orbit (GEO) satellite with the ground verification system, transmitting the generated signals to the satellite. The SGS for the ground verification system must have the capability to generate test correction messages and to generate and receive L1/L5 signals, which serve as augmentation signals. As shown in Figure 2, which illustrates the system architecture proposed in [3], the SGS performs the functions of correction message generation, signal generation, and transmission, while ensuring appropriate signal adjustments to satisfy signal characteristics similar to GPS. For signal generation and control, the SGS must control the code and carrier of L1/L5 signals individually to ensure that L1/L5 signals are synchronized based on GPS time at the phase center of the satellite's transmitting antenna. Furthermore, signals must be adjusted so

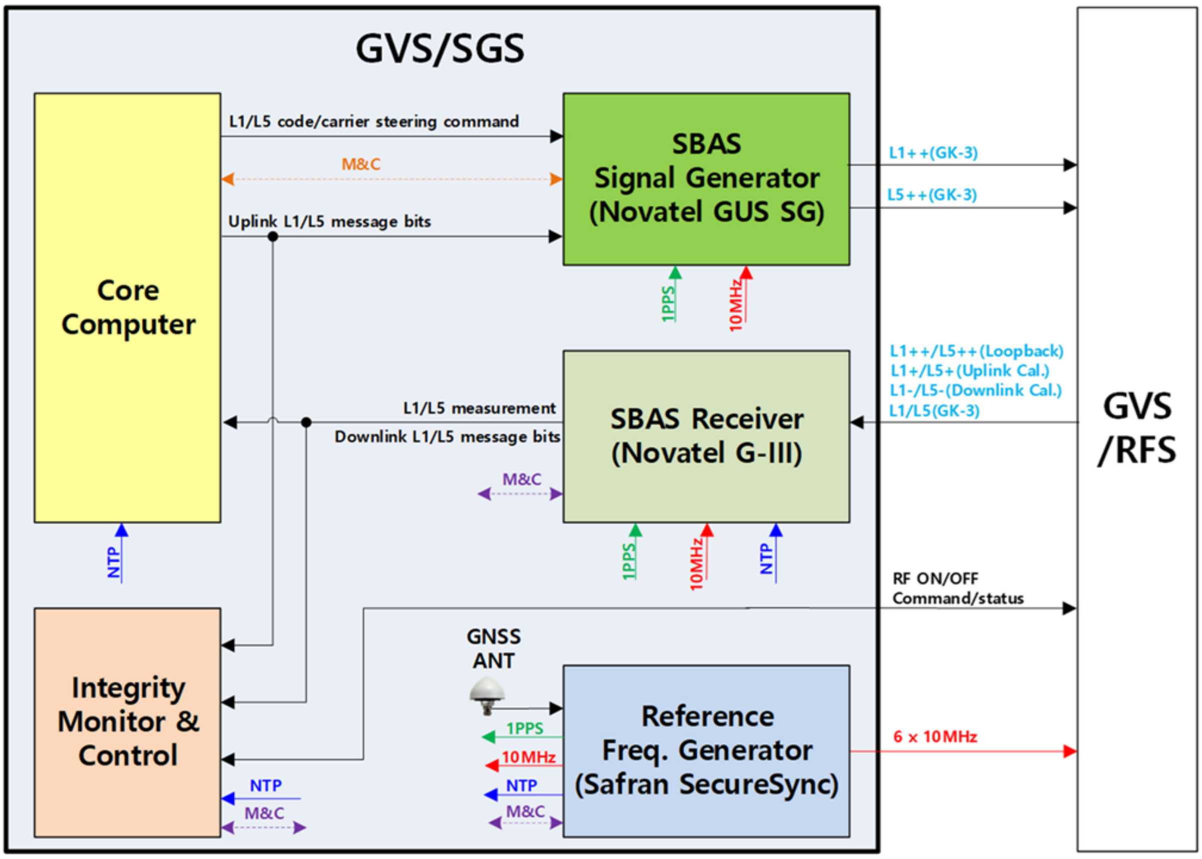

Figure 2: Configuration of Signal Generator Subsystem

that the code and carrier of the signals are synchronized both with each other and with the satellite navigation signals at the phase center of the satellite's transmitting antenna. Generated signals are transmitted to receivers through a ground loop or satellite loop. The signals received by the satellite navigation receiver are analyzed to inspect signal quality. Through the inspection results, the quality of signals generated by the SGS can be guaranteed.

2.2. Requirements for Correction Signal Quality Inspection

The SGS uses received measurement data to inspect GPS time synchronization offset errors, carrier frequency stability, and code/carrier coherency for verifying the quality of L1/L5 signals [4]. Signals generated by the signal generation system must be synchronized with GPS time within a certain error margin at the antenna phase center of the geosynchronous orbit satellite, with an offset error performance within 100 ns. The offset error must satisfy the requirement as a 3σ value for satellite navigation receivers to meaningfully use the range information of the satellite navigation augmentation system signal. The stability of the carrier frequency requires that the L1 and L5 frequencies at the antenna phase center are better than 5×10^{-11} over 1 to 10 seconds. When calculating the carrier frequency stability, the signal does not consider the ionosphere and Doppler effect. The requirement for short-term code carrier coherency is that the change in code phase and the change in carrier phase within a short time of less than 10 seconds should be within 5×10^{-11} based on 1σ. For short-term code carrier coherency, the divergence that occurs as the augmentation signal passes through the ionosphere is not considered, so the ionospheric delay in the measurement data must be corrected [5]. Finally, the requirement for long-term code carrier coherency is that the difference between the change in code phase and the change in carrier phase over a long period of 100 seconds should not exceed 1 cycle (1σ). Similar to the short-term code carrier coherency calculation, the divergence that occurs as the augmentation signal passes through the ionosphere is not considered, so for signals received from satellites, ionospheric delay must be corrected before calculating the difference [5].

3. Design of Signal Quality Test Algorithm

Inspection techniques for GPS time synchronization offset error, carrier frequency stability, short-term code/carrier coherency, and long-term code/carrier coherency were designed to test compliance with the requirements presented in Section 2. Each inspection technique uses pseudorange measurements, carrier phase measurements, and Doppler measurements of the augmentation satellite measured by satellite navigation receivers. The implemented signal quality test simulation processes user-defined inputs including measurement data, simulation time parameters, and signal quality requirements. The simulation generates output consisting of signal inspection results, visual graphs, and status indicators to determine whether tested signals meet the specified requirements. The test for GPS time synchronization offset error was performed using the precision of time difference between GPS and augmentation satellite signals. In satellite navigation systems, time is reflected in pseudorange measurements since distance between satellites and receivers is measured based on time. Therefore, the time difference was calculated by computing the difference between the expected pseudorange and the measured pseudorange of the augmentation satellite. Equation 1 shows the delay time calculation, which divides the difference in pseudoranges by the speed of light [6]. In Equation 1, τ is the delay time, ρˆ is the expected pseudorange, ρ is the measured pseudorange, and c is the speed of light.

$$\tau = \frac{\hat{\rho} - \rho}{c} \tag{1}$$

The standard deviation of the delay time was calculated and used in Equation 2. Based on the requirements in Section 2, the threshold value was set to 100 ns, and the standard deviation multiplied by 3 must remain under this value. When this threshold is met, the requirement of the GPS time synchronization offset error is satisfied, and the signal quality is determined to be good.

$$3\sigma(\tau) < 100\,\text{ns} \tag{2}$$

If a receiver provides pseudorange standard deviation in its output data, the standard deviation output by the receiver can be directly used for the GPS time synchronization offset test. The carrier frequency stability test examines Doppler frequency values against the reference carrier frequency. For testing frequency stability between 1 and 10 seconds, Allan deviation was calculated and compared with the requirement to determine whether signal quality meets the requirements. Equations 3 show the Allan Variance calculation for L1 and L5 frequency stability tests [6]. In Equations 3, $f_{D,L1}$ and $f_{D,L5}$ are Doppler frequencies for L1 and L5 signals. $f_{C,L1}$ and $f_{C,L5}$ are center frequencies for L1 and L5, which are 1575.42 MHz and 1176.45 MHz, respectively. In the frequency stability test, Allan deviation was calculated as in Equations 3, and the calculated Allan deviation must remain below the threshold value of 5×10^{-11} to confirm acceptable performance.

$$\begin{aligned} avar_{L1} &= \text{Allan Variance}\left(\frac{f_{D,L1}}{f_{C,L1}}\right) \\ avar_{L5} &= \text{Allan Variance}\left(\frac{f_{D,L5}}{f_{C,L5}}\right) \\ \sqrt{avar} &< 5 \times 10^{-11} \end{aligned} \tag{3}$$

The short-term code carrier coherency test used code measurements and carrier measurements to check whether the code and carrier generated over a short period of 1 to 10 seconds maintain coherency without divergence. The code frequency and carrier frequency were divided by their respective reference frequencies to create dimensionless values, and coherency was tested using the difference between these values. Equations 4 show how to calculate code and carrier frequencies. In Equations 4, f_c is the code frequency, f_{c0} is the base frequency of the code, Δf_c is the change in code frequency, c is the speed of light, and $\dot{\rho}$ is the time rate of change of pseudorange. Equations 4, f_φ is the carrier frequency, $f_{\varphi 0}$ is the base frequency of the carrier, Δf_φ is the change in carrier frequency, and $\dot{\varphi}$ is the time rate of change of carrier measurements.

$$\begin{aligned} f_c &= f_{c0} + \Delta f_c = f_{c0} - \frac{f_{c0}}{c}\dot{\rho} \\ f_\varphi &= f_{\varphi 0} + \Delta f_\varphi = f_{\varphi 0} - \dot{\varphi} \end{aligned} \tag{4}$$

As shown in Equation 5, the code and carrier frequencies are normalized by dividing by the base frequency of the code and the base frequency of the carrier, respectively. Their difference was compared to the threshold value (5×10^{-11}) to confirm acceptable signal quality.

$$\left| \frac{\Delta f_c}{f_{c0}} - \frac{\Delta f_\varphi}{f_{\varphi 0}} \right| < 5 \times 10^{-11} \tag{5}$$

The long-term code carrier coherency test checked coherency over a long period within 100 seconds, converting the frequency difference between code and carrier into carrier units. Signal quality was determined to be acceptable when the converted value does not exceed one cycle. Equation 6 shows the formula used for the long-term code carrier coherency test. The symbols in Equation 6 were used to represent the same parameters as those in Equation 5.

$$\left| \dot{\rho}\frac{f_{\varphi 0}}{c} + \dot{\varphi} \right| < 1 \text{ cycle} \tag{6}$$

4. Implementation and Testing of the Signal Quality Test Simulation

We applied the algorithms designed in Chapter 3 to test signals received from an actual satellite navigation augmentation system and signals generated by the SGS of the ground verification system to perform quality tests. Figure 3 shows the data collection environment used for the test. Two types of signals were collected: signals from the Korean Augmentation Satellite System (KASS) and signals generated by the SGS of the ground verification system. The KASS began test services in 2023 and has been providing full service since 2024. The KASS provides satellite-based augmentation services in the Korean Peninsula area. Both KASS signals and SGS signals were synthesized and simultaneously received by the satellite navigation receiver. The test data was collected for 10 hours. The collected data went through a decoding process to extract the measurements needed for testing. These extracted measurements were used as inputs for each test algorithm for analysis. Figure 4 shows the results of the GPS time synchronization offset error test using the L1 signal. The blue and red solid lines represent the GPS time synchronization offset error and the threshold derived from the requirements, respectively. Figure 4(a) shows the test results using KASS data, with an average value over 10 hours of 7.81 ns. Figure 4(b) shows the test results using SGS data, with an average value of 7.13 ns. Both KASS and SGS signal data maintained GPS time synchronization offset errors below the threshold value of 100 ns over 10 hours, satisfying the requirements and demonstrating good signal quality. KASS data includes error components during transmission from the augmentation satellite, while SGS data is input directly from the signal generator to the receiver, making SGS data more stable than KASS data. The GPS time synchronization offset error test results using the L5 signal also showed good signal quality, similar to the L1 signal test results. The average values were calculated as 8.51 ns for KASS data and 6.51 ns for SGS data. As with the L1 signal, SGS data was more stable than KASS data. Furthermore, the test results confirmed that the L5 signal was more stable compared to the L1 signal. Figure 5 shows the carrier frequency stability test results using the L1 signal. The blue and red solid lines represent the Allan deviation for the carrier frequency stability and the threshold, respectively. Test results using KASS data and SGS data are shown in Figure 5(a) and Figure 5(b). Analysis using Allan variance showed that both data sets met the threshold requirements. The test results confirmed that SGS data had more stable frequency compared to KASS data. Figure 6 shows the results of the short-term code carrier coherency test. The blue, black, and red solid lines represent the Allan deviations of L1

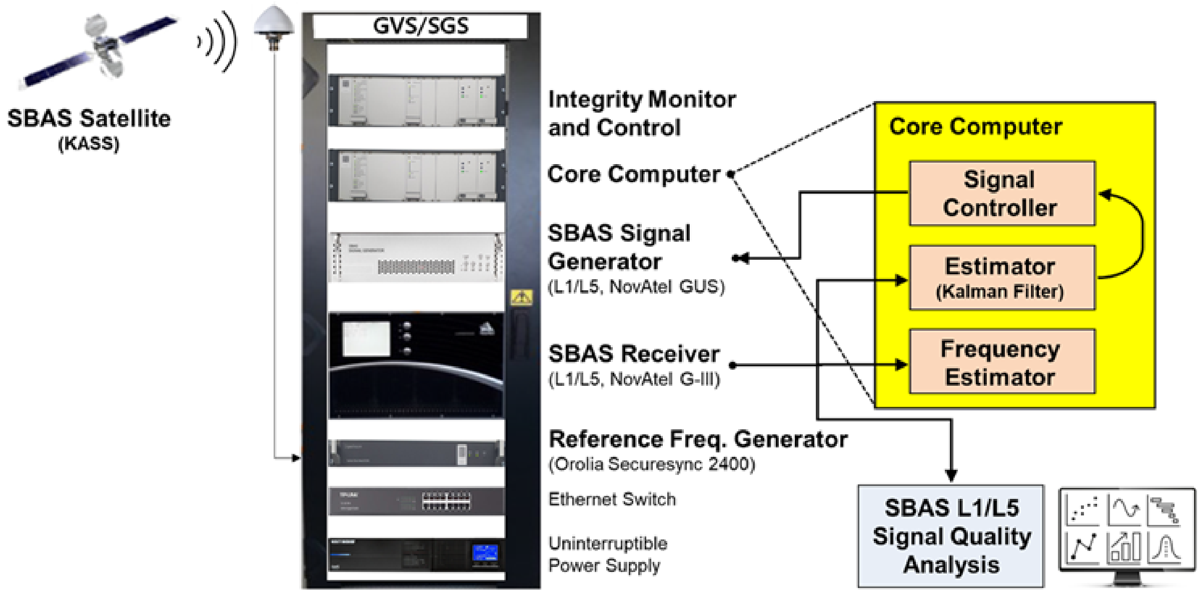

Figure 3: Test Data Acquisition Environment

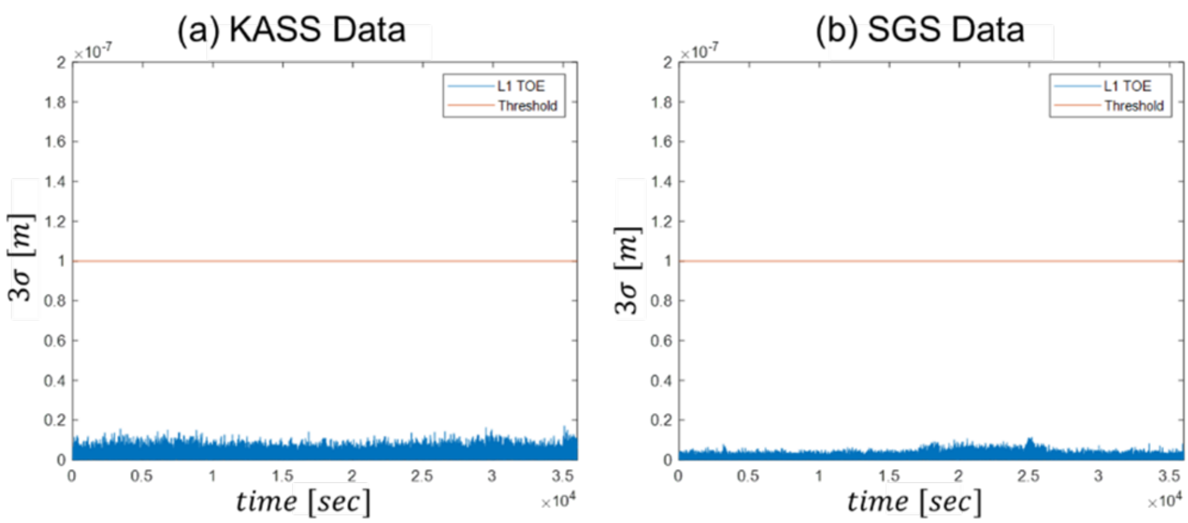

Figure 4: Test Result of GPS Time with an offset error

signals, the Allan deviations of L5 signals, and the threshold, respectively. Figure 6(a) and Figure 6(b) show the test results for KASS data and SGS data. Examining the Allan deviation, the L1 signal in both data sets exceeded the threshold value of 5×10^{-11} between 1 and 10 seconds, failing to meet the requirements. For the L5 signal, KASS data exceeded the threshold from 1 to 6 seconds, and SGS data exceeded the threshold from 1 to 3 seconds, failing to meet the requirements during these periods. After these periods, both data sets were below the threshold, meeting the requirements. Although SGS signals do not pass through the atmosphere and satellite, and both the GPS time synchronization offset error test and the carrier frequency stability test confirmed their stability, SGS signals still failed to meet the requirements in the short-term code carrier coherency test. The failure to meet short-term code carrier coherency requirements despite stable signal conditions confirms that requirements are very stringent. The short-term code carrier coherency requirement is one of the conditions necessary for using augmentation signals as additional navigation satellites, and even if the requirement is not satisfied, there is no problem with the function of transmitting augmentation information. However, additional research and analysis are needed to meet the requirements for using augmentation signals as

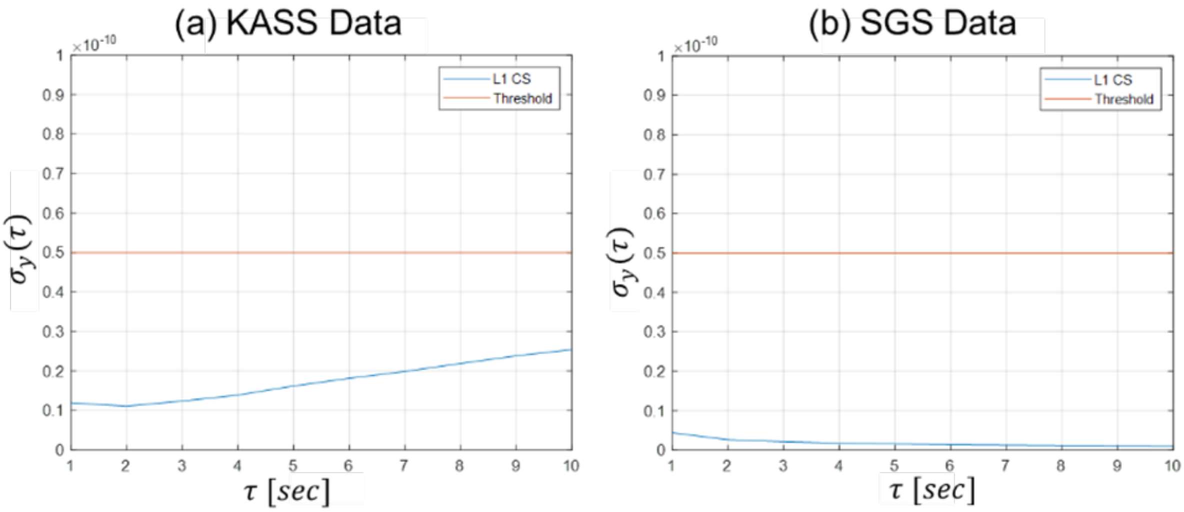

Figure 5: Test Result of Carrier Frequency Stability

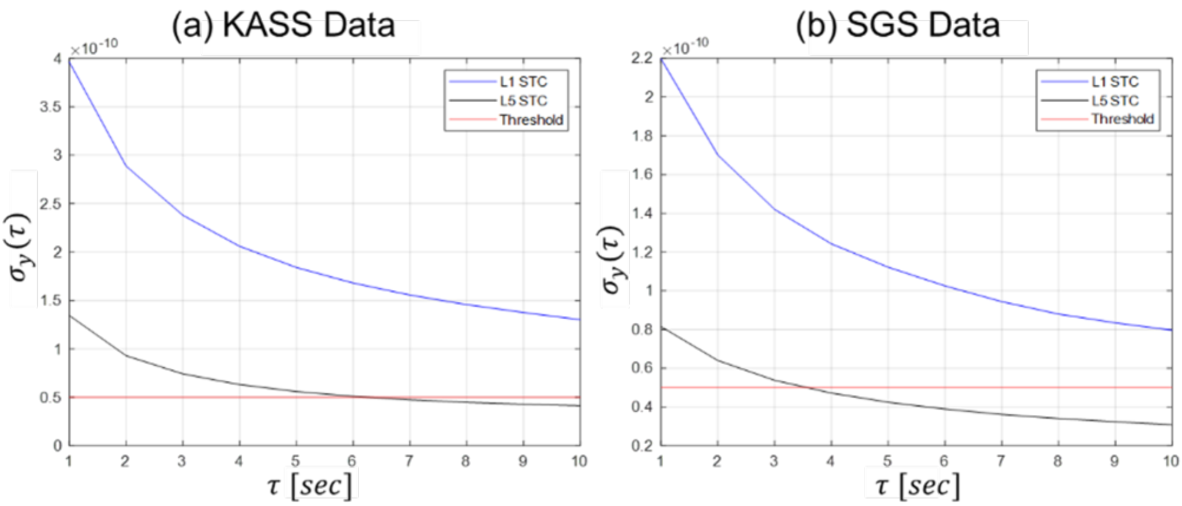

Figure 6: Test Result of Short-Term Code Carrier Coherency

pseudorange sources for additional navigation satellites. Figure 7 shows the results of the long-term code carrier coherency test. The blue, black, and red solid lines represent the Allan deviations of L1 signals, the Allan deviations of L5 signals, and the threshold, respectively. Figure 7(a) and Figure 7(b) show the test results for KASS data and SGS. Both data sets met the requirements with test results less than one cycle. The Allan deviation analysis from 1 to 100 seconds revealed that SGS data exhibited smaller values than KASS data, demonstrating superior signal quality. Similarly, the L5 signal showed smaller values compared to the L1 signal, indicating better signal quality. The test results show that the requirements for the long-term code carrier coherency test are more relaxed compared to the short-term code carrier coherency requirements. KASS data and SGS data have already been confirmed to have acceptable signal quality. Experimental results demonstrated that both data sets met most requirements when the designed signal quality test algorithms were applied. These experimental outcomes validated the applicability of the designed algorithms to signal quality testing of SBAS. The designed signal quality test algorithms effectively represented the characteristics of L1/L5 signals from both the currently used KASS and the SGS, enabling effective monitoring of signal quality status.

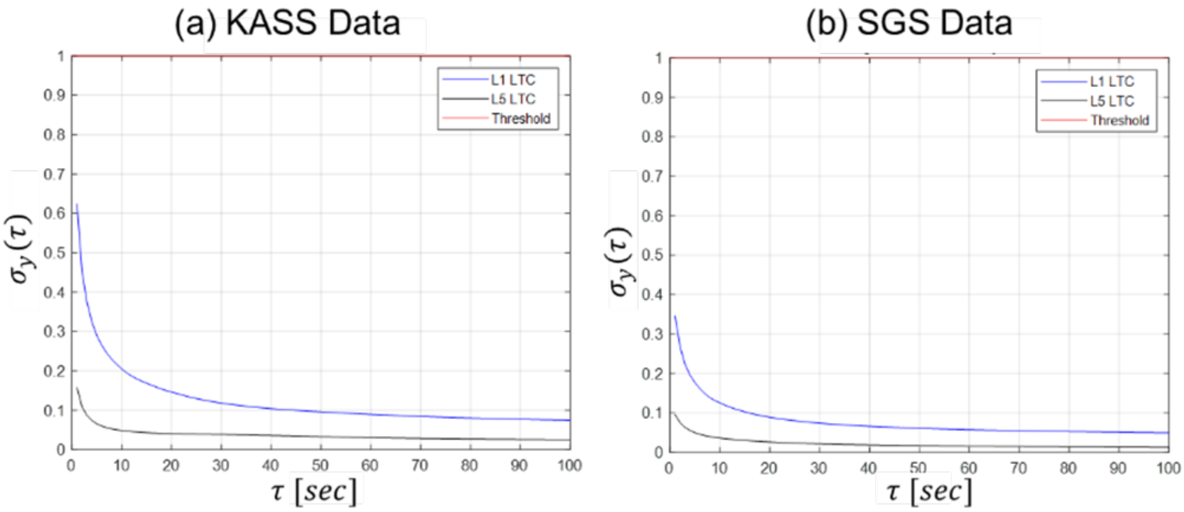

Figure 7: Test Result of Long-Term Code Carrier Coherency

5. Conclusion

SBAS provide correction information across wide areas, making them highly effective for improving navigation performance for numerous satellite navigation users. The development of SBAS represents a necessary field for continuously enhancing satellite navigation system performance. Developing a ground verification system as a preliminary step in the SBAS development process holds significant importance. The ground verification system must include functionality to inspect the signal quality of generated augmentation signals. This study designed signal quality test algorithms for ground verification systems. Signals from the Korean Augmentation Satellite System (KASS), currently in operational service, and signals from a signal generator were tested using the implemented algorithms to validate system application feasibility. The designed signal quality test algorithms demonstrate high utility potential for testing augmentation signals in future ground verification system implementations. Future work should expand beyond current augmentation signal requirements to develop additional inspection methods in terms of signal characteristics, measurement techniques, and data analysis. These enhancements would enable comprehensive signal quality assessment of ground verification systems from multiple technical perspectives.

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Declaration on Generative AI

Or (by using the activity taxonomy in ceur-ws.org/genai-tax.html):
During the preparation of this work, the authors used Claude-3.7 in order to: Grammar and spelling check. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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