

Anomaly B-Value Detection and Exclusion of GBAS Based on Wavelet Multi-Resolution Analysis

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Abstract

Multiple Reference Consistency Check (MRCC) based on maximum likelihood estimation is widely used for Ground Based Augmentation System (GBAS) ground reference station anomaly B-value detection and exclusion to ensure the reliability of the integrity data. But B-value slowly deviating under certain conditions is a time consumption and effectiveness challenge. An anomaly B-value detection and exclusion method based on wavelet multi-resolution analysis (WMRA) technology is proposed to distinguish the fault sources effectively. The simulation results indicate that WMRA technology shortens the detection time and can determine the fault characteristics of the ground reference station which improves the detection accuracy.

Keywords: GBAS; wavelet multi-resolution analysis; B-value; fault detection and exclusion

1. Introduction

Ground Based Augmentation System (GBAS) is used to support aircrafts precision approach and landing operations with high accuracy and integrity. With 3~4 ground reference receivers, GBAS ground facility calculates and broadcasts differential corrections and integrity data of the nearby GNSS satellites to solve the non-intuitive impact of their faults on aircraft operational capability, which helps the airborne GBAS receiver outputs meeting the approaching requirements [1]~[3].

The integrity monitoring is an important means of the onboard GBAS Landing System (GLS) to determine the reliability of navigation parameters. GBAS integrity monitoring consists of ground facility system-level integrity monitoring and GLS user-level integrity monitoring.

The ground facility system-level integrity monitoring is implemented by the GBAS ground station. GBAS ground facility monitors the GNSS satellites signal-in-space performance, receiver measurements data performance and data processing progress to ensure the safety-critical navigation system meet the accuracy and integrity requirements [3]. Examples of GBAS ground facility integrity monitoring include the signal deformation monitor, the ionosphere gradient monitor, differential corrections consistency monitor and loop check of broadcasted signal. Multi-reference consistency checks are executed before data broadcasting to ensure the consistency of corrections calculated by different reference stations. B-value of each reference station is calculated and compared with certain threshold, any reference station with B-value exceeds the threshold, its calculated differential corrections will be removed from the broadcasting message, which reduced GBAS differential and integrity information. So, accurate detection and exclusion of anomaly B-value is a significant challenge for GBAS integrity monitoring.

VHF data broadcast (VDB) facility broadcasts the integrity parameters including B-values and residual error data (sigma terms), which will be used for onboard GLS protection Level calculation.

GLS user-level integrity monitoring calculate the horizontal protection level and vertical protection level (HPL&VPL) using the residual error data and integrity information (B-values) broadcasted by VDB, which is used to determine its compliance with the routes navigation performance requirements.

To improve the accuracy of anomaly B-value detection and exclusion, some of the research focus

on threshold parameters inflation methods to enhance the availability considering noise probability density function compensate for distribution uncertainty or non-Gaussian tails [4-7], which can effectively exclude abnormal reference station data caused by faulty satellites, but it also resulted in a decrease of effective information at the same time. G,Yu et al[8] proposed a B-value calculation method based on Kalman filter with the assumption of a certain reference station receiver has zero probability of failure, which is generally difficult to hold in practice.

Considering that B-values inconsistence would be caused by reference station receiver fault, ionosphere gradient or multipath, which can commonly be described in a cluster of different ramp functions. An anomaly B-value detection and exclusion method based on wavelet multi-resolution analysis (WMRA) technology is proposed. By decomposing the B-value and components analyzing, anomaly B-value can be effectively identified with its characteristic and local. At the same time, the algorithm derived the effective signal directly during the decomposition process, reducing the detection time.

The rest of this article is organized as follows. Section II overviewed the differential correction and B-value estimation in the GBAS standard (RTCA DO245A). section III analyzed B-value anomaly source, WMRA for anomaly B-value detection and exclusion is explained and simulated, the simulation results are discussed. Section IV is the conclusion.

2. GBAS B-value estimation

According to ICAO annnex10, integrity is a measure of the trust that can be placed in the correctness of the information supplied by the total system. Integrity includes the ability of a system to provide timely and valid warnings to the user (alerts) when the system must not be used for the intended operation (or phase of flight) [9], which needs receiver positioning error estimation under certain probability on the user side. For GBAS, the aircraft subsystem makes the final integrity determination using information provided by the ground subsystem and a standardized protocol of how to apply that information.

The GBAS ground facility consists of two to four GNSS reference receivers with known site position and a monitor processing function, using its known position, a differential correction for each satellite in view is generated using measurements from each reference receiver. A typical four-reference facility architecture places the satellite signal receiving antennas at the four endpoints of a quadrilateral. A broadcast station consists of VHF data broadcasting (VDB) transmitter and antenna is used for data broadcast.

GBAS ground facility estimates the error components of each satellite in view pseudo-range measurement from each reference receiver and forms a differential correction for each satellite. The corrections from all the reference receivers for each satellite are averaged to form a composite pseudo-range correction, which is then uplinked to the airborne GBAS receiver. The airborne receiver then applies these pseudo-range corrections to its own measured pseudo-ranges improve its positioning accuracy.

The integrity of the pseudo-range corrections is monitored by the GBAS ground facility and a positive, real-time quality indication is provided to the airborne user. It monitors the ground and space segment system performance to enable the timely detection and exclusion of malfunctions in GBAS operation or other conditions that may cause normal use of the signals to be hazardous to the airborne user. A confidence bound referred to as a protection level on the positioning error is calculated based on estimated error parameters provided by the ground facility [10]~[12]. To ensure the integrity of the differential corrections, several monitor functions are utilized in the ground facility to detect and exclude the possible faults. These faults may include ranging source faults or faults in the ground reference receiver measurements.

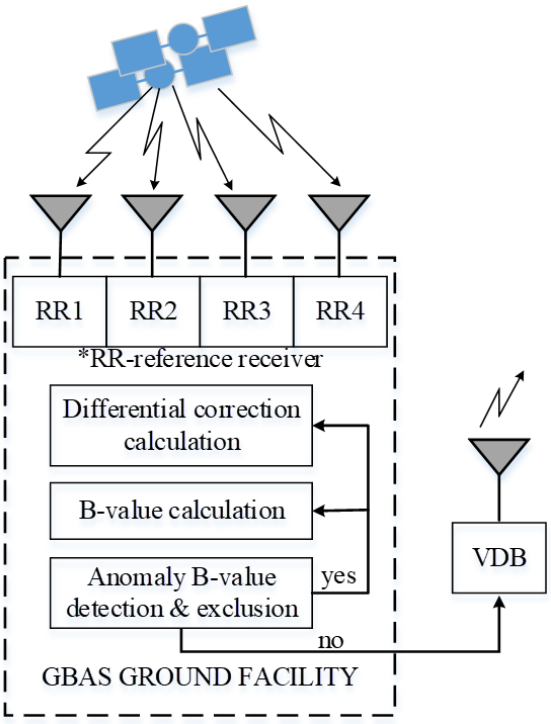


Figure 1 – GBAS integrity monitoring

A pseudo-range includes true range and a number of measurement errors. For reference station *M* and satellite *N*, the relationship between the true range to the satellite, the pseudo-range measurement, and the error sources can be described as [7]:

$$\rho_m^n = R_m^n + t^n + t_m + iono^n + tropo^n + n_m^n + \varepsilon^n \tag{1}$$

where, ρ_m^n is the pseudo-range between reference station M and satellite *N*.

R_m^n is the true distance between reference station *M* and satellite *N*.

t^n is the clock bias of satellite *N*.

t_m is the clock bias of reference receiver *M*.

$iono^n$ is the ionosphere error for satellite *N*.

$tropo^n$ is the troposphere error for satellite *N.*

n_m^n is the uncorrelated error between the airborne and ground system, which is the combination of receiver thermal noise, multipath, and any other errors which are not canceled by differential processing.

ε^n is the ephemeris error caused ranging error.

Each reference receiver computes the position of the satellites in view using the satellites broadcasted navigation message, and then, the distance between the phase center of the reference receiver antenna and the satellite, R_m^n. The differential correction is obtained by subtracting the computed range from the measured pseudo-range.

$$PRC_m^n = \rho_m^n - R_m^n = t^n + iono^n + tropo^n + \varepsilon^n + n_m^n + t_m \tag{2}$$

In standard GBAS calculation, the pseudo-range correction is considered to be composed by two different types, correlated errors and uncorrelated errors.

The reference receiver clock bias is correlated to all pseudo-range corrections from the same reference receiver but uncorrelated to other reference receivers. An effort is made to remove an estimated reference receiver clock bias as a practical matter, so that a cross comparison of the corrections from each reference receiver can be made.

Equ.2 implies that, there are limited differences among pseudo-range corrections of the same

satellite from different reference receivers if the uncorrelated errors between different reference receivers is kept in certain limit. Which means anomaly things happens such as reference receiver fault or processing errors, sudden ionosphere gradient or large multipath happens.

Differential corrections are monitored as one of the most important parts of the whole system integrity monitoring, which is usually achieved by cross comparison of the differential corrections derived for each individual reference receiver in the set of reference receivers. The GBAS ground facility computes the estimated error terms (B-values and sigma terms) for each pseudo-range correction, which are broadcasted and used by the airborne receiver.

The RTCA DO245A standard provides an MRCC algorithm based on the maximum likelihood estimation criterion. According to RTCA DO245A, ground reference station fault detection is accomplished by cross comparing each of the measurements. Assuming only one reference receiver fails at a time, calculate the B-value of each reference station by estimating the difference between the average of all the reference stations' differential corrections and the average of the corrections excluding the self-station.

The pseudo-range correction for satellite N is formed by averaging among the reference receivers, which is

$$PRC^n = \frac{1}{M}\sum_{j=1}^{M} PRC_j^n \tag{3}$$

where PRC_j^n (j=1, 2, ⋯M) is the differential correction value calculated by the j-th reference receiver. M is the total number of GBAS ground reference receivers.

The B-value is used to monitor the quality of the differential corrections as an important indicator of integrity [12]. It is compared with a threshold and any sufficiently large discrepancies are used to identify reference receiver failures or excessive measurement errors. Assuming only one reference receiver fails at a time, the magnitude of the hypothesized failure is the difference between the average of all the measurements and the average of the corrections excluding the hypothesized failure. To perform this, an estimated error term B-value is computed by

$$B_m^n = PRC^n - \frac{1}{M-1}\sum_{\substack{j=1,\\ j\neq m}}^{M} PRC_j^n \tag{4}$$

Where j means the j-th reference receiver, while n means the n-th satellite. B_m^n denotes the B-value calculated by the m-th reference station receiving the n-th satellite. M denotes the total number of GBAS ground reference receivers. From Equ.4, it is clear that, for fault-free conditions, B_m^n is composed of the residual reference receiver clock biases, the errors of the reference receivers uncorrelated between the ground receivers. A typical GBAS with four reference receivers contains four B-values: B_1, B_2, B_3 and B_4.

If all the error sources are characterized by Gaussian distributions with zero means, the standard deviation is assumed to be a function of satellite elevation angle. Hence, the expected value of the B terms is zero as shown in the following equation.

$$E\left[B_m^n\right] = 0 \tag{5}$$

$$Var\left[B_m^n\right] = \sigma_{pr-gnd}^2\left(\frac{N-1}{(M-1)MN}\right) \tag{6}$$

where σ_{pr_gnd} is the variance of the uncorrelated measurement error from a single reference receiver which is an approximate expression of the pseudo-range correction error boundary based on a zero-mean Gaussian distribution. It is the standard deviation of the fault-free measurement error (i.e., uncorrelated errors) for each pseudo-range correction. This value describes the variance of a Gaussian distribution that bounds the total uncorrelated error contributions. σ_{pr_gnd} is used for protection level calculation of onboard receivers.

For fault detection, a detection threshold is calculated according to the desired probability of fault-

free detection. As for Gaussian distribution with zero mean, the detection threshold is equal to a scaling factor multiplying the standard deviation, where the scaling factor is determined by the tail of the Gaussian probability density function. Each B_m^n is compared with the corresponding detection threshold, for B-values larger than the threshold, a fault is declared. The corresponding measurement is excluded from the calculation of the averaged pseudo-range correction, B-value and σ_{pr_gnd} are recalculated.

The estimated error terms (B-values) and standard deviation of the fault-free measurement error (sigma)for each pseudo-range correction calculated by the ground monitor function are provided to the airborne equipment. If there is no fault detected by the ground monitoring function, the pseudo-range correction, the estimated error terms are sent to the airborne equipment for position solution and integrity monitoring. If there is a faulty one, the pseudo-range correction will be formed by averaging the corrections from all the reference receivers that are believed fault-free after fault detection and exclusion.

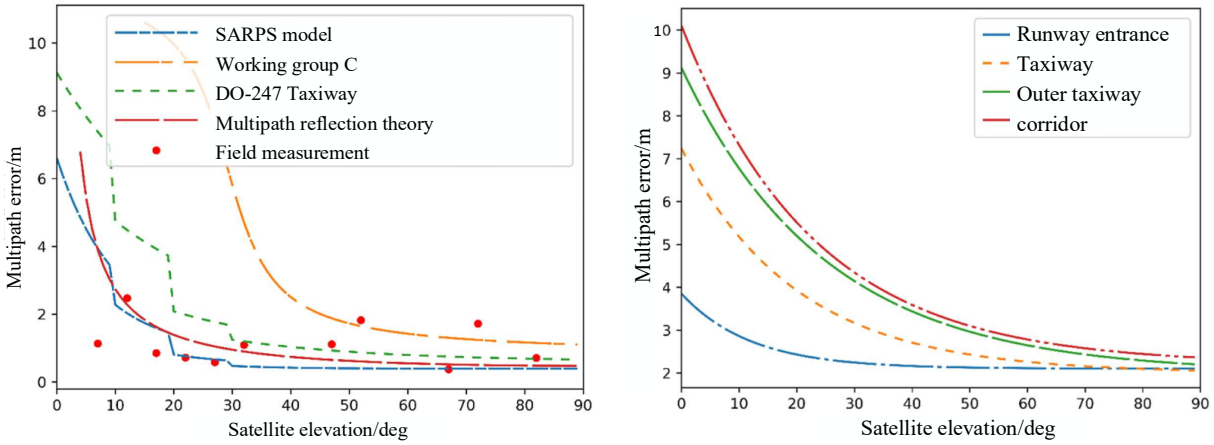
3. Anomaly B-value detection and exclusion

3.1 Model of B-value anomalies

Fault detection and exclusion should account for the statistical distribution of all the error sources that affect the B-value. There are two possible causes of anomaly B-value.

One cause comes from the contribution of the sudden step or impulsive errors of GNSS signal-in-space of the reference receiver measurements. According to Equ.2, the main elements of the B-values are the uncorrelated errors between different reference receivers such as multipath and the difference of the correlated errors which possibly caused by ionosphere gradient or satellite ephemeris failure. The other possible cause is the ground reference receiver fault [13]~[14].

Generally, each GBAS ground facility contains 3~4 ground reference receivers whose antenna are sited on different place. Because of the near buildings, moving vehicles and aircraft, each reference receiver would produce different and time-varying multipath errors. Figure2 depicts multipath errors at different sites near the airport according to different model, which is nearly ramp variation with satellite elevation.



(a) multipath errors based on different models (b) multipath errors at different site

Figure 2 – Receiver multipath errors at different site

According to DO-245, very large ionosphere temporal and spatial gradients have been discovered during ionosphere storms. During these storms, spatial gradients of ionosphere vertical delays on the order of several hundred millimeters per kilometer of separation were observed, which are far greater than typical values. In most cases, these gradients appeared to move rapidly (several hundreds of meters per second) with respect to the Earth's surface [7], but in some cases, the gradients appeared to remain stationary or near stationary for some period of time.

As each GBAS reference antenna is required to be separated from its adjacent antenna by a minimum of 100 meters, 155 meters is desirable, and much longer baselines are permissible, provided other system requirements are not violated [15]. Which means ionosphere gradient threat might make a problem. The gradient makes some reference receivers to be disturbed ones or quiet

ones, which means they are influenced by quite different ionosphere delays. Anomaly big B-value would appear under this condition, Figure3 depicts the ionosphere delay with no ionosphere storm, where we can find ionosphere errors vary in step or sharp ramp.

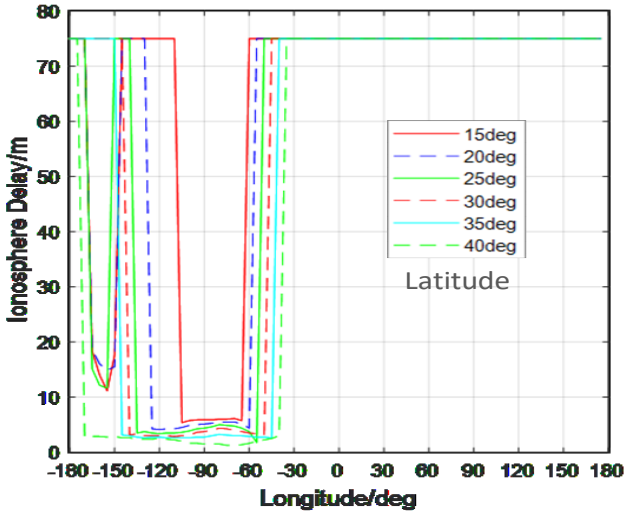


Figure 3 – Ionosphere delay at different IGP (14 Aug. 2024)

An ephemeris failure causing an error in the computed satellite position that is orthogonal to the satellite line-of-sight will cause an effective differential ranging error between the GBAS ground facility and aircraft. This will increase the magnitude of the n_m^n term in Equ.1. GBAS ground facility should have the ability to detect significant ephemeris discrepancies, satellite ephemeris error can be represented by a slow ramp.

All the above mentioned conditions exceed normal errors are considered as fault condition with different error sources [11] [16]. The GBAS ground reference receiver fault model is given in the latest research from Honeywell. Except the over-acceleration faults, the state of the ground receiver error can be described as a superposition of one or more ramp errors starting at the onset point as shown in Figure 4, where step faults can be considered as a ramp error with a rate of ∞. For GBAS ground facility, all the errors including faults are modeled as ramp clusters (0~∞) in this paper.

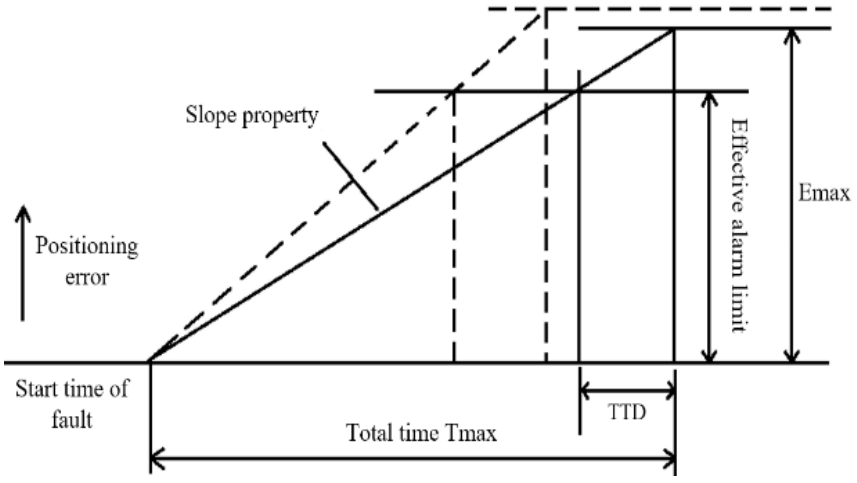


Figure 4 – The receiver failure ramp model

The ramp function of the fault model contains three elements: the fault start time, the change rate of error (ramp rate) and its duration $T_{\max}$. When the error is greater than the effective alarm limit (threshold), the system considers as fault happens and issues an alarm. As shown in Figure4, the maximum value of error, E_{max}, is relevant to the ramp rate and the detection time delay (TTD), which are directly related to the effectiveness of integrity detection.

Reference [11] summaries the parameters for the GBAS fault model in table 1 for lateral errors. The characteristics of the fault are functions of geometry screening parameters, Slat is the largest lateral

coefficient magnitude for any single satellite, and S_{lat2} is the largest sum of lateral coefficient magnitudes for any two satellites.

TABLE 1 Malfunction Transient Characteristics in the Lateral Direction [11]

Fault Type	Service Type	Ramp Rates (m/s)	Alarm limit(m)	Emax(m)	Effective Threshold (m)
Ranging Source Failures	GAST C	0~∞	40	Dependent	N/A
	GAST D	0~∞	1.6×S_{lat}	Dependent	0.75×Slat
Iono Anomaly	GAST C	0~2	N/A	40	N/A
	GAST D	0~2	N/A	2.75×S_{lat} 2.75×S_{lat2}	N/A
Single Ref Receiver Failure	GAST C	0~∞	40	Dependent	N/A
	GAST D	0~∞	35.9	Dependent	24.5

3.2 Multiple reference consistency check for B-value

MRCC is one of the commonly used methods for B-value anomalies detection. According to [22], The criteria for multiple reference consistency check of B-value is:

$$B_{i,j} \leqslant \frac{5.6\sigma_{pr_\lg f}}{\sqrt{N(N-1)}} \tag{6}$$

where $\sigma_{pr_\lg f} = 0.16 + 1.07e^{\theta_{i,j} \times 90.0/\pi/15.5}$, and $\theta_{i,j}$ is the elevation angle of the j-th satellite received by the i-th reference receiver.

Special care must be taken regarding the uncertainty of the true error distribution. The main sources of uncertainty are estimation errors caused by environmental changes as well as the fact that the tails of the true error distribution may not be exactly Gaussian. This uncertainty is normally accounted by inflation to cover all possible error distributions, which will decrease the continuity and availability performance of GBAS reference receiver.

Simulation is taken in order to analyze the impact on B-value of GBAS ground reference receiver fault, and to determine the effectiveness of the B-value anomaly detection algorithm, step fault and ramp fault are injected separately into the ground reference receiver measurements.

The simulation scenario is set as a typical GBAS ground facility with four reference receivers. The reference receiver is assumed setting in civil aviation university of China near Tianjin Binhai Airport. The distance between two receiver antenna is set as 150m, and satellites with elevation greater than 5° are selected as visible satellites.

Total simulation time is 10000s, with 1s sampling interval. Klobuchar model is used as the ionosphere error model and Hopfield model is used as the troposphere error model. The B-values of fault-free reference receiver (Figure 5) and B-values with an injection of step and ramp faults between 4000 and 6000 sampling period (Figure6 and Figure7) are simulated respectively.

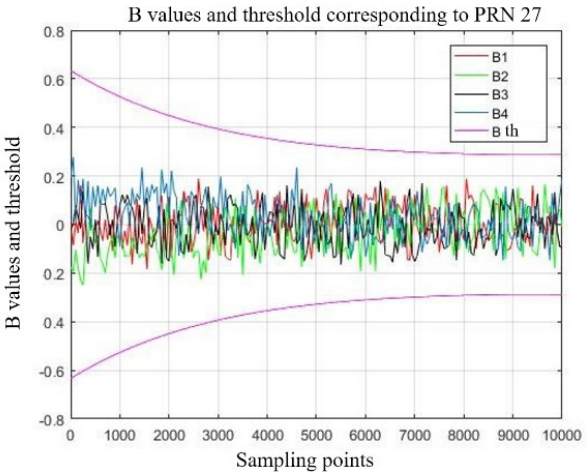


Figure 5– B-value with fault free receivers

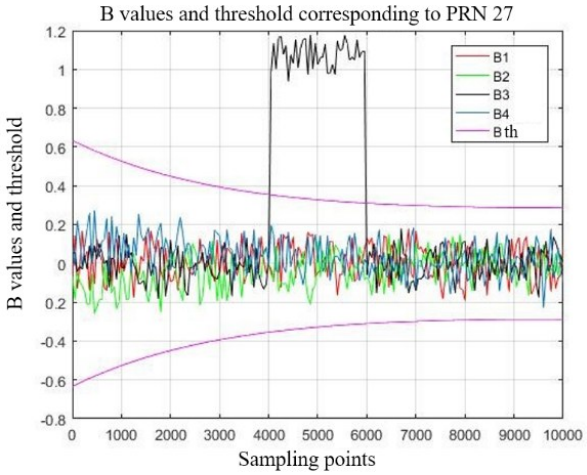


Figure 6 – B-value with a step fault in the receiver

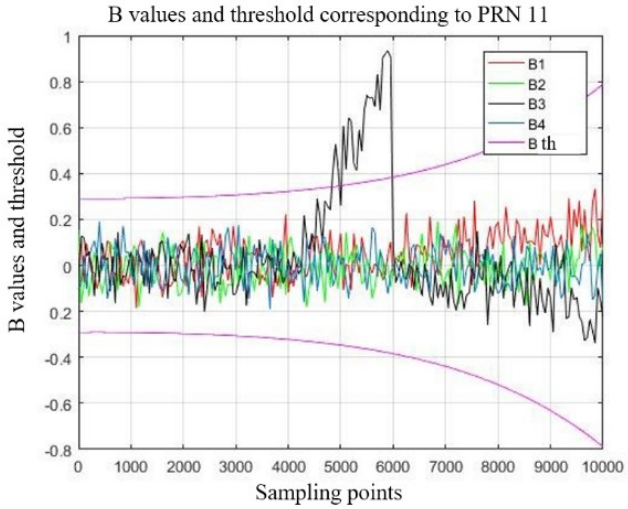


Figure 7 – B-value with a ramp fault in the receiver

When a ramp/step fault occurs in a ground reference receiver, the corresponding B-value of the faulty receiver suffers a sudden change also.

The simulation results show that, the MRCC detection method can detect the fault with almost no delay and issue an alarm when a step fault occurs. However, in the case of a ramp fault occurrence, the B-value anomaly is detected with a time delay of 5s, and the smaller the ramp rate, the longer the time delay, which introduces the potential integrity risk for critical flight phase. In addition, the MRCC detection method can't determine the type of B-value anomaly and the ramp rate of the error.

3.3 Anomaly detection of B-value based on Wavelet Multi-Resolution Analysis (WMRA)

3.3.1 Wavelet Multi-Resolution Analysis

Wavelet Multi-Resolution Analysis, also known as Multi-scale analysis, is a theory built on the concept of function space. WMRA is the decomposition of $L^2(R)$ into a sequence of subspaces with different resolutions, and the limit of the subspaces sequence is $L^2(R)$, where $L^2(R)$ denotes the set of all measurable functions defined on the interval R with $\int_R |f(x)|^2 dx < \infty$. The function *f* in $L^2(R)$ is described as the approximation limit of a series of approximation functions, where each approximation function is a smoothed version of the original function, with the approximation function getting finer as the parameters increase [18]~[20].

WMRA decomposes signals at different resolution levels, and the lower level signal obtained from decomposition is called a smoothing signal, which reflects the general characters of the signal. The signal that exists at a higher level and disappears at a lower level is called a detailed signal, which portrays the character of the signal. Signal decomposition can decompose a variety of mixed signals interwoven different frequencies into sub-signals of different frequency bands, and thus effectively

decompose and reconstruct complex signal, separate signal and noise, extract signal features, etc. [21], which is suitable for signal analysis with sharp information, such as boundary and edges.

WMRA enables time-frequency localized description of signals and can be utilized for signal singularity analysis. GBAS reference station B-value anomaly shows obvious multi-scale characteristics. there is a strong correlation between the B-value change and the fluctuation of the detail signal on each scale.

The signal singularity is generally divided into two cases. One is the amplitude or frequency sudden change in a certain moment which causes the intermittent point. The other is the smooth signal with no sudden change of amplitude while there are sudden changes and discontinuity in its first-order differential signal. The Lipschitz exponent is usually utilized to describe the local singularity of a function [22]~[25]. Using the wavelet singularity detection theory makes it possible to detect the abrupt B-value changes caused by GBAS reference receiver faults based on the local singularity information of the singular points.

Since the essence of WMRA is the approximation of the original signal. Using Vj denote the low-frequency subspace part of the j-th level of decomposition, and W_j denote the high-frequency subspace part of the same level of decomposition, which means that W_j is orthogonal complement to V_j at V_{j-1}, i.e.:

$$V_j + W_j = V_{j-1} \quad j \in Z \tag{7}$$

The subspace V_0 of WMRA can be approximated by a finite number of subspaces, with:

$$V_0 = V_1 + W_1 = \dots \quad \dots \tag{8}$$

The sudden-change point of the signal may be located at the zero point or the extreme value point of the wavelet transform. As the zero point is susceptible to noise interference, the WMRA decomposition usually employs module maximum for signal mutation points detection, which and control the noise effectively and locating the mutation points accurately.

The wavelet coefficients depend on the properties of the neighborhood of $f(x)$ at x_0 and the chosen scale of the wavelet transform. As for the dynamic systems, signal mutate quickly, its main characteristics are the signal sudden changes in time and space. Appropriate multi-resolution decomposition wavelet analysis method can take full advantage of its quick and accurate signal mutation detection.

The B-value and differential $\dot{B}$-value of GBAS reference receiver are chosen here for WMRA B-value anomaly detection. When a B-value anomaly happens, its wavelet transformed coefficients will have modulo-maximal values, module maximum detection is used to determine the type and the magnitude of the signal mutation and its occurrence time.

3.3.2 Anomaly detection of B-value based on WMRA

The anomaly information of B-values processed by WMRA reflects the characters of the receiver fault, which will be used to determine the receiver fault type and shorten the alarm time.

Different wavelet bases have different support lengths, attenuation properties, symmetry & regularity, and properties of the reconstructed signals. Therefore, the choice of wavelet basis is very important for B-value anomaly detection.

In wavelet bases selection, the factors should be considered more are orthogonality, tightness, symmetry and regularity. However, in practice, there is no “optimal” wavelet that can achieve the best results in all fields, so engineers must select the reasonable wavelet basis according to specific application requirements. Generally, the selection principle of wavelet basis is:

The symmetry of the wavelet basis is the first factor to be considered. Double orthogonal wavelets with symmetry generally have better compression performance, and can be appropriately selected in practice. Wavelets with higher regularity have good compression effect for smooth data, smooth images, etc. The db5/db3 wavelet bases in db wavelets are usually used to decompose and reconstruct the signal in signal anomalies analysis.

WMRA is used to decompose $\dot{B}$-values where decomposition levels of three and four are selected respectively under the same simulation condition as before. Comparative analysis of the detection

effects are done among db3, sym3, rbio3.1 and db5 wavelet basses [26]~[27].

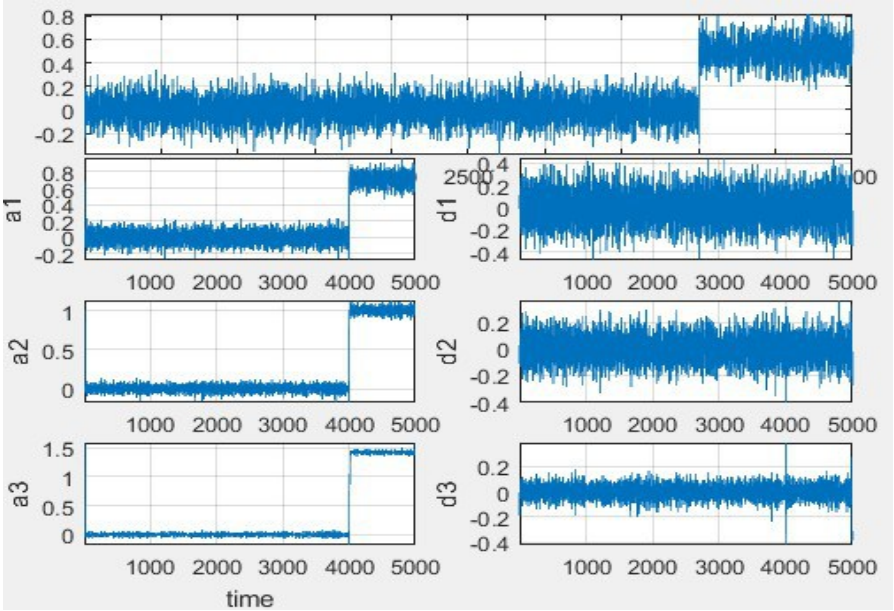


Figure 8 – Three layer decomposition of db3 wavelet basis for $\dot{B}$

The details of the third layer of decomposition after the three-layer decomposition using the db3 wavelet basis represents that the anomaly is a ramp fault occurring at the 4002nd sampling point with a 0.41 ramp rate of the fault function, as shown in Figure 9.

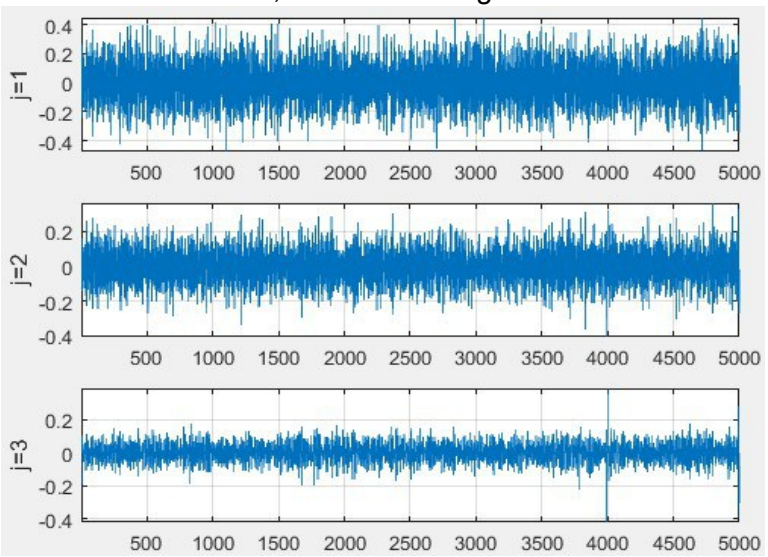


Figure 9 – The module maximum waveform of three layer decomposition of db3

The ramp rate of the fault function is detected as 0.43 by three-layer decomposition using sym3 wavelet basis, as shown in Figure 10.

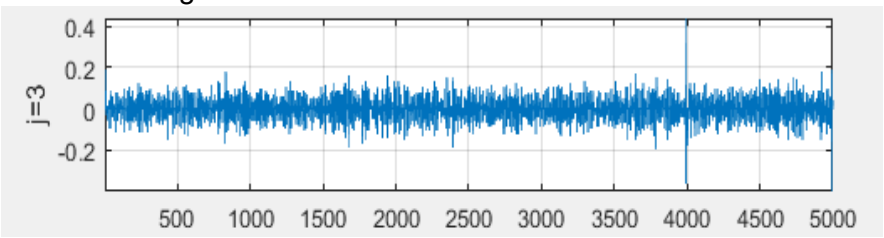


Figure 10 – The modulus maximum waveform of three layer decomposition of sym3

The ramp rate of the fault function obtained after three-layer decomposition using the rbio3.1 wavelet basis is 0.34, as shown in Figure 11.

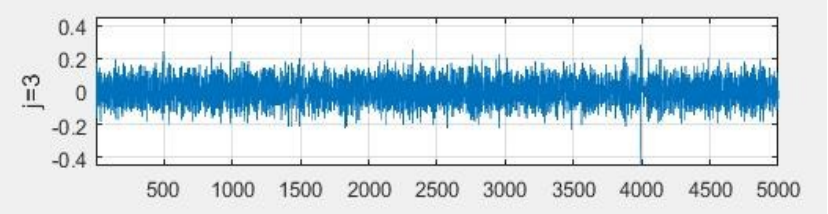


Figure 11 – The modulus maximum waveform of three layer decomposition of rbio3.1

The ramp rate of the fault function obtained after three-layer decomposition using the db5 wavelet basis is 0.45, as shown in Figure 12.

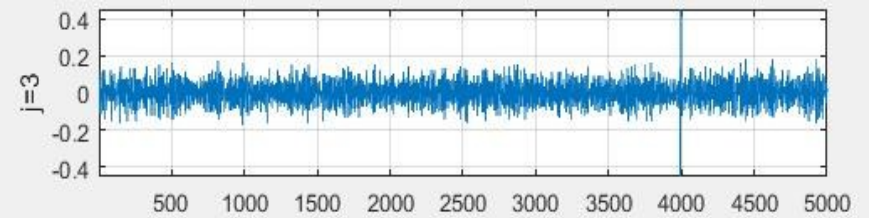


Figure 12 – The modulus maximum waveform of three layer decomposition of db5

TABLE 2 Comparison of three layer decomposition basis on different wavelet basis

Wavelet basis	Detection delay/s	Ramp rate of the detected fault	Ramp rate detection error
db3	2	0.41	0.09
sym3	2	0.43	0.07
rbio3.1	2	0.34	0.16
db5	2	0.45	0.05

According to the simulation results, the accuracy of the mutation estimate obtained from the homogeneous layer decomposition of the signal using different wavelet bases varies. The reason is the different properties of the wavelet bases.

Then, a four-layer decomposition with the db5 wavelet basis yields 0.48 as the ramp rate of the fault (Figure13), which indicates that a more accurate ramp rate can be obtained with a higher-layer decomposition.

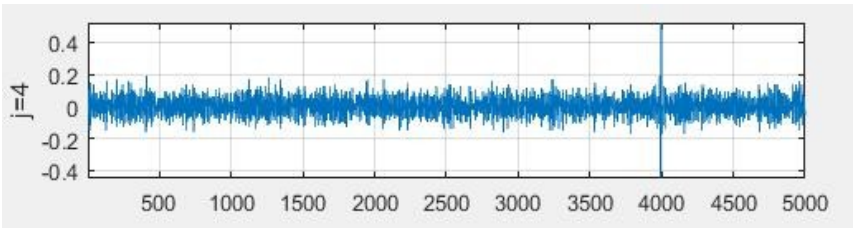


Figure 13 – The modulus maximum waveform of four-layer decomposition of db5

TABLE 3 Comparison of three layer decomposition and four layer decomposition basis on db5 wavelet basis

Decomposition layers with db5 wavelet basis	Detection delay/s	Ramp rate of the detected fault	Ramp rate detection error
Three-layer	2	0.45	0.05
Four-layer	2	0.48	0.02

According to the simulation results, higher decomposition layers brings more accurate ramp rate estimation of the B-value anomaly. More levels of decomposition lead to more similar details of the signal compared to the original signal. To conclude:

1) The WMRA of the $\dot{B}$-values can be used for GBAS ground reference station fault detection

effectively;

2) The simulation results proved that multi-resolution decomposition of more than three or four layers can reasonably and accurately detect the degree of B-value anomaly, and the more layers of decomposition leads to higher accuracy.

3) According to the simulation results, db5 is recommended to be used as the wavelet basis for B-value anomaly detection with comprehensively consideration of the selection factors of wavelet bases and properties of B-value's anomalies.

4. Comparison of B-value anomaly detection between WMRA detection and MRCC

In order to analyze the effect of B-value anomaly detection, a ramp fault is injected between 4000s-7000s with a 0.5m/s ramp rate of satellite PRN19 to No.3 reference receiver. The duration of simulation is 10000s, with sampling intervals of 50s.

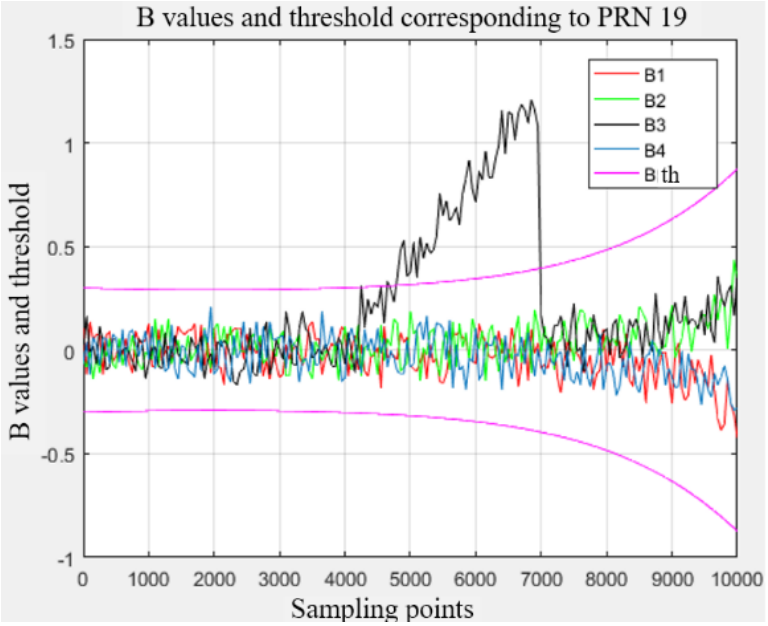


Figure 14 – MRCC detection result

WMRA detection using db5 wavelet basis for four-layer decomposition is used for verification. The results of B-value anomaly detection of MRCC and WMRA are listed in Table 4.

TABLE 4 Detection results of MRCC and WMRA

Means of detection	Faulty receiver	Fault type	Ramp rate of the fault	Alarm time (s)	Alarm delay (s)
MRCC	Receiver 3	—	—	4005s	5
WMRA	Receiver 3	ramp	0.48m/s	4002s	2

As shown in Table 4, compared with the conventional MRCC, the WMRA detection method can not only detect the type of faults and the ramp rate of the error, but also has a shorter alarm delay.

5. Conclusion

GBAS provides an efficient and cost-effective solution for aircrafts precision approach and landing operations using differential corrections and integrity enhancement services, which helps to increase the airport's capacity, improve the efficiency of airspace management and operation, and reduce air traffic noise. The integrity performance represented by B-value is the key criteria of GBAS ground facility.

An anomaly B-value detection and exclusion method based on WMRA is proposed according to the error characteristic of GBAS reference receiver, and compared with the MRCC method. Simulation results prove that WMRA using db5 wavelet basis can detect and exclude the anomaly B-value, provides the errors' characteristic parameters and scale which is helpful for more accurate and appropriate fault exclusion. With shorter time delay of fault detection and alarm, WMRA reduces the

risk of over time delay of alarm. However, more complex fault situations with multiple fault combinations have not been analyzed here, which would be researched latter.

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