Study on an optimized grouping RAIM method

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Abstract. Receiver Autonomous Integrity Monitoring (RAIM) method is widely used in the field of aviation navigation for its advantages of fast response, low cost and wide coverage. The performance of traditional RAIM is not as good as that of fault detection, and the calculation is complex. With the development of multi-constellation integrated positioning technology, the number of visible satellite is gradually increasing. Although the performance of traditional RAIM method has been improved, but it is not large, and the amount of calculation has increased greatly. In order to solve the above problems, an optimized grouping RAIM method is proposed. Through uniform grouping, fault detection can be directly used to complete fault identification, which reduces a lot of calculation and improves the efficiency and performance. The simulation results of graphics and data show that the algorithm is feasible and effective.

Keywords: RAIM, multi-constellation, fault detection, fault identification.

1. Introduction

Integrity refers to the ability to timely report to the user when the navigation error of the current navigation system exceeds the allowable error and is not competent for the specified work[5]. At present, there are three main integrity detection methods for navigation satellite system: Satellite Autonomous Integrity Monitoring (SAIM), Ground Integrity Channel technology (GIC) and Receiver Autonomous Integrity Monitoring (RAIM)[4]. RAIM does not need external information, only uses redundant observation information to identify and eliminate faulty satellites in navigation satellites, so it has a rapid response, and does not need to build a large number of ground monitoring stations like GIC technology, so it is widely used in the field of aviation navigation. RAIM method mainly includes two aspects: fault detection and fault identification. RAIM method also has certain requirements for the number of visible satellites. Fault detection needs \( (m+4) \) satellites, and fault identification needs \( (m+5) \) satellites, where \( m \) is the number of navigation systems. At present, scholars at home and abroad have done a lot of research on single satellite fault identification methods, among which the better identification methods are pseudo range comparison method, odd even vector method and least squares residual method, which are proved to be equivalent[3]. In [1], a subset comparison method is proposed,
in which one satellite is removed from all satellites at a time, and then fault detection is carried out on the remaining satellites. Fault detection is directly used to complete fault identification, but the randomness of this method is too strong. In [9], the performance of several snapshot RAIM algorithms is compared and analyzed. The simulation results show that the computation complexity of the parity vector method is smaller than that of the other two RAIM methods. According to the above ideas, this paper proposes an optimized grouping RAIM method. Firstly, the parity vector method is used for fault detection of satellites. If a fault is detected, the satellites are evenly grouped, and then the parity vector method is used for detection to complete the identification of faulty satellites.

2. odd even vector method

Assuming that the number of visible satellite of the navigation system at a certain time is n, the pseudo range observation equation after linearization is expressed as follows:

$$y = Hx + \varepsilon$$  \hspace{1cm} (1)

Where: $y \in \mathbb{R}^N$ represents the pseudo range observation vector, that is, the difference between the observation pseudo range and the approximate calculation pseudo range; $H \in \mathbb{R}^{N \times M}$ represents the observation matrix, where: $M = m + 3$, $m$ represents the number of constellations; $x \in \mathbb{R}^{Mn}$ represents the state vector, and the elements include the user coordinate position and clock error. $\varepsilon \in \mathbb{R}^N$ is the pseudo range observation noise.

The observation matrix $H$ is decomposed into QR to get two matrices: orthogonal matrix $Q$ and triangle matrix $R$, and the following can be obtained:

$$H = QR$$  \hspace{1cm} (2)

Take the last $(N - M)$ rows of the transposed orthogonal matrix to form the matrix $Q_p$, and construct the parity vector $p$:

$$P = Q_p y = Q_p \varepsilon$$  \hspace{1cm} (3)

Among them, $Q_p$ is called odd even space matrix, which has the characteristics that row vectors are orthogonal to each other and intersect with the columns of observation matrix $H$. Even and odd space vectors also directly reflect the pseudo range error information, so $p$ can be used to detect and identify faulty satellites. The test statistics are as follows:

$$R_N = \sqrt{\frac{p^T P}{N - M}} = \sqrt{\frac{SSE}{N - M}}$$  \hspace{1cm} (4)

Secondly, according to the false alarm rate $P_{fa}$ given by the system, the detection limit $T$ of $\frac{SSE}{\sigma^2}$ can be calculated:

$$P_r \left( \frac{SSE}{\sigma^2} < T^2 \right) = \int_0^{T^2} f_{\chi^2(N-M)}(x) \, dx = 1 - P_{fa}$$  \hspace{1cm} (5)

Where: $P_r \left( \frac{SSE}{\sigma^2} < T^2 \right)$ is the probability of $\frac{SSE}{\sigma^2} < T^2$, $f_{\chi^2(N-M)}(x)$ is the probability density function of $\chi^2$ distribution with degree of freedom $(N - M)$, and $\sigma^2$ is the variance of pseudo range observation noise.

Then, according to the detection limit $T$, the detection threshold $T_r$ of $R_N$ can be obtained:

$$T_r = \sigma \times \frac{T}{\sqrt{N - M}}$$  \hspace{1cm} (6)

Finally, the detection threshold $T_r$ is compared with the test statistic $R_N$. If $R_N > T_r$, the fault is detected; otherwise, no fault is detected.

When it is detected that the navigation system contains faulty satellite, the fault identification is carried out. It can be seen from (3) that the odd and even vectors generated by the fault deviation of each satellite will be located on a straight line, and the slope of this straight line is related to the parity space matrix. This straight line is defined as the characteristic deviation line, and each satellite corresponds to
a different characteristic deviation line. Therefore, fault identification can be carried out according to whether the characteristic deviation line of each satellite is collinear with the odd and even vectors. In order to enlarge the observability of the deviation as much as possible, the parity vector $p$ is projected into the column of $Q_p$ and standardized, the test statistic of the $i$th satellite is obtained as follows:

$$r_i = \frac{P^T Q_{P,j}}{|Q_{P,j}|}$$  \hspace{1cm} (7)

Where: $Q_{P,j}$ is the column vector corresponding to the $i$th satellite in $Q_p$. Whether two vectors are collinear or not can be determined by calculating $r$:

$$r = \frac{\hat{a} \cdot \hat{b}}{|\hat{a}||\hat{b}|}$$  \hspace{1cm} (8)

Where: $r \in [0,1]$. When $\hat{a}$ and $\hat{b}$ are collinear, $r = 1$; when $\hat{a}$ and $\hat{b}$ are perpendicular, $r = 0$. The satellite with the maximum value of $r_i = \frac{P^T Q_{P,j}}{|Q_{P,j}|}$ is the faulty satellite.

3. RAIM method for optimizing grouping

The principle of detection and recognition of single satellite fault by subset comparison method is: assume that all the visible satellites are $n$ currently. When the fault detection method is used to detect the fault of the current visible satellites, one satellite is removed from the $n$ satellites at a time, and then the remaining $(n-1)$ satellites are detected. If the $(n-1)$ satellite fails to detect the fault, it can be judged that the satellite eliminated is the fault satellite; if the remaining satellite still detects the fault, remove one of the $n$ satellites again and continue to carry out grouping detection until the fault satellite is found.

Through the research and analysis of the subset comparison method, it is found that the algorithm is too random, it may find the fault satellite by one packet detection, or it may need to detect different groups to find the fault satellite, so the calculation is too large. In view of the above disadvantages, this paper proposes an optimized grouping RAIM algorithm, the specific steps are as follows:

Assuming that the current number of visible stars is $n$, the parity vector method is used to detect the fault of all visible satellites. If the fault is detected, the next step is performed.

The $n$ satellites were divided into two groups. If $n$ is odd, then one group is $\frac{n+1}{2}$ and the other group is $\frac{n-1}{2}$.

The two groups of satellites are detected again. If a group detects a fault, the group of satellites will return to step 2 to continue grouping.

Repeat steps 2 and 3. If the faulty group of satellites cannot be equally divided, that is, the number of satellites corresponding to the group with the least number of satellites is less than $s$ ($s$ is the minimum number of satellites required for RAIM detection). Record the number of satellites in this group as $m$ and proceed to the next step.

$s$ satellites are selected from $m$ satellites, which are called basic set, and the remaining $(m-s)$ satellites are called test set. Then detect whether there are faulty satellites in the basic set:

If there is a fault, one of the satellites in the basic set is replaced by the fault free satellite removed before, and then the fault detection is carried out on the basic set. If the fault satellite is not detected in the basic set, the replaced satellite is the fault satellite.

If there is no fault, it means that the faulty satellite exists in the test set, and then select one satellite from the test set to replace one satellite in the basic set in turn, and then carry out fault detection on the
basic set. If the basic set detects a fault, it means that the satellite selected from the test set is the faulty satellite. The flow chart is as follows:

![Flow chart of optimized grouping RAIM method](image)

**Fig.1 Flow chart of optimized grouping RAIM method**

4. Simulation Analysis

In order to compare the differences between different RAIM algorithms, the following three performance indicators will be used to verify the performance of RAIM algorithm:

- **Fault detection rate**: the ratio of the number of the faulted satellites to the total number of the fault elements added.
- **Fault recognition rate**: the ratio of the number of all fault satellites to the total number of the fault elements added to the fault is correctly identified.
- **Calculation time**: the average time used to complete single epoch fault detection and identification.

In order to verify the effectiveness and reliability of the proposed method, the Beidou and GPS data received by the receiver of Xiangtan University on April 12 are used to simulate and analyze the parity vector method, subset comparison method and optimized grouping method. The total data duration is 12h, the sampling interval is 30s, and there are 1440 epochs in total. Take $\sigma = 6m$ as the equivalent ranging error, the satellite cut-off altitude angle is $10^\circ$, and the false alarm rate is $P_{fa} = 4 \times 10^{-6}$. Each epoch randomly selects a satellite to add a pseudo range observation error of 10m in steps from 1m to 100m. The fault detection rate and recognition rate results of the three algorithms are shown in Fig. 2 and Fig. 3, and the algorithm time consumption is shown in Table I.

Figure 2 shows the comparison of the fault detection rates of the three algorithms. It can be seen that the three methods can effectively detect the fault only after the pseudo range deviation reaches 20m. This is because the three methods detect the fault through the threshold decision method, and only when the test statistics exceed the 20m threshold can they be determined as the fault satellite. The fault detection performance of the three methods is almost the same, because the fault detection method of the subset comparison method is the least square residual method, which is equivalent to the fault detection statistics of the parity vector method, while the fault detection performance of the optimized grouping RAIM method is the parity vector method, so the fault detection rates of the three methods are almost the same.
Figure 3 shows the comparison of the fault recognition rate of three algorithms. It can be seen that the worst performance of the three methods is parity vector method. When the pseudo distance deviation is 40 m, the fault detection rate is close to 80%, but the recognition rate is only 50%, which proves that the fault identification rate of traditional RAIM method is lower than the fault detection rate. The fault recognition rate of the optimization grouping method and subset comparison method is almost the same, because both methods directly use fault detection to complete fault identification, and the fault detection performance of the two methods is consistent, so the performance of fault identification is consistent.

Table 1 shows the time-consuming comparison of three different algorithms for fault recognition. It can be seen that the parity vector method takes the least time and has higher efficiency. The time consumption of subset comparison method is much higher than that of the other two methods, which is almost 10 times that of parity vector method. Although this method improves the performance of fault recognition, it consumes too much resources. Although the optimized grouping method is time-consuming, it can shorten the time by nearly 80% compared with the subset comparison method, and can improve the fault recognition performance by 30% on the basis of the parity vector method.
Table 1. Time consuming comparison of three algorithms

| Algorithm type          | Fault detection time / ms | Fault recognition time / ms | Total time / ms |
|-------------------------|---------------------------|-----------------------------|-----------------|
| Parity vector method    | 0.5834                    | 0.396                       | 0.9796          |
| Subset comparison method| 0.5705                    | 8.824                       | 9.394           |
| Optimized grouping method| 0.5834                   | 0.625                       | 1.2084          |

To sum up, although the parity vector method has high efficiency, it has poor fault recognition performance; although the subset comparison method has good fault identification performance, it has too much calculation and high resource consumption; while the optimized grouping method can ensure the fault identification performance, it also greatly reduces the calculation and improves the efficiency, so it has high application value.

5. Summary
In this paper, an optimized grouping RAIM method is proposed. The results show that the method not only ensures the performance of fault identification, but also greatly reduces the amount of calculation and improves the efficiency, so it has high application value. However, the performance of this method is limited to fault detection performance, so the next step is to improve the fault detection performance of this method.

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