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Leveraged fault identification method for receiver autonomous integrity monitoring

Sun Yuan, Zhang Jun *, Xue Rui

School of Electronic and Information Engineering, Beihang University, Beijing 100191, China

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Abstract Receiver autonomous integrity monitoring (RAIM) provides integrity monitoring of global positioning system (GPS) for safety-of-life applications. In the process of RAIM, fault identification (FI) enables navigation to continue in the presence of fault measurement. Affected by satellite geometry, the leverage of each measurement in position solution may differ greatly. However, the conventional RAIM FI methods are generally based on maximum likelihood of ranging error for different measurements, thereby causing a major decrease in the probability of correct identification for the fault measurement with high leverage. In this paper, the impact of leverage on the fault identification is analyzed. The leveraged RAIM fault identification (L-RAIM FI) method is proposed with consideration of the difference in leverage for each satellite in view. Furthermore, the theoretical probability of correct identification is derived to evaluate the performance of L-RAIM FI method. The experiments in various typical scenarios demonstrate the effectiveness of L-RAIM FI method over conventional FI methods in the probability of correct identification for the fault with high leverage.

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1. Introduction

Global positioning system (GPS) has become the core element of modern air traffic system by greatly enhancing the operational efficiency. To ensure the safety of flight, excessive ranging errors on any navigation signals broadcasted by GPS satellites that would cause unaccepted positioning error must be detected, identified and excluded. To achieve this goal, one effective method is called receiver autonomous integrity monitoring (RAIM), an augmentation to GPS which uses self-consistency check among measurements of navigation satellite signals to detect and identify potential excessive ranging errors arising from satellite hardware, signal propagation, and receiver, i.e. faults. RAIM is essential for safety-of-life applications and is a mandatory function embedded in aviation navigation receiver to support the air navigation for en-route, terminal, and non-precision approach (NPA) phases of flight.[1–3]

The key function of RAIM to identify faults is called fault identification (FI). Various RAIM FI methods were studied over the past decades and could be classified into three categories: maximum likelihood estimation fault identification

* Corresponding author. Tel.: +86 10 82338282.
E-mail address: buaazhangjun@vip.sina.com (J. Zhang).

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algorithm (MLE FI),[4] characteristic bias line fault identification algorithm (CBL FI)[5] and subset measurement fault identification algorithm (SM FI).[6] These three kinds of methods were proved to have equivalent FI performance but with different calculation costs.[5,7] Novel RAIM FI methods that identify faults among measurements from different navigation satellite constellations, e.g. GPS, Beidou and Galileo, have become hot spots in recent years.[8–10] In the event of simultaneous multiple faults, the identification process is repeated until no more faults are identified.[11,12]

In spite of different implementations, current RAIM FI methods are generally based on the same basic idea, which is to determine the satellite measurement that maximizes the likelihood of ranging error. However, the impact of ranging error on positioning error has not been considered in previous RAIM FI method. Actually, the ranging measurements from different satellites have different impacts on the positioning solutions. This effect is defined as "leverage" in regression theory.[13] The measurement with higher leverage has larger impact on position estimation than that with lower leverage. Therefore, faults on high leverage measurement tend to cause larger positioning errors. Whereas, the probability of correct identification using traditional RAIM FI methods may decrease in the presence of faults on high leverage measurements.

In this paper, a leveraged RAIM fault identification (L-RAIM FI) method considering the difference in measurement leverage is proposed. The theoretical probability of correct identification is derived. Based on this, the performance of L-RAIM FI method and traditional FI method in the probability of correct identification is compared and discussed. Experimental results with simulated and real data show that the L-RAIM FI method outperforms the traditional method in the probability of correct identification.

The remainder of this paper is organized as follows. In Section 2, the traditional RAIM FI method is described. In Section 3, the L-RAIM FI method is proposed which takes account into different leverage of the measurement. In Section 4, the probability of correct identification is derived to compare the performance of L-RAIM FI method with the traditional method. The experiments are conducted in Section 5 to demonstrate the performance of our approach. Finally the conclusions are shown in Section 6.

2. Traditional RAIM FI method

Because of the equivalence of traditional RAIM FI methods, only MLE FI method is described in this section as a baseline for further discussion.

The MLE FI method employs the maximum likelihood criterion to estimate fault bias. After that, the likelihood probability under the estimated bias is exploited to identify the fault measurements.

The basic linearized GPS measurement equation is described by an over-determined system.[14]

$$z = \boldsymbol{Hx} + \boldsymbol{e} \tag{1}$$

where $z \in \mathbf{R}^n$ is a vector of pseudorange measurement residuals, in which n is the number of satellites in view. $\boldsymbol{H} \in \mathbf{R}^{n\times 4}$ is the observation matrix consisting of line-of-sight vectors. $\boldsymbol{x} \in \mathbf{R}^4$ is a vector of estimated position and clock bias correction. $\boldsymbol{e} \in \mathbf{R}^n$ is Gaussian measurement errors with the covariance of σ^2.

The existing methods model the fault as measurement bias added to the measurement noise.[15] Then the measurement equation with fault can be expressed as follows:

$$\boldsymbol{z} = \boldsymbol{Hx} + \boldsymbol{e} + \boldsymbol{f} \tag{2}$$

where $\boldsymbol{f}$ denotes the fault bias vector.

Currently the satellite navigation system with RAIM can only be applied to the phases from en-route to non-precise approaches. For more stringent precise approach, specific standard for RAIM has not been developed yet. In this paper, only single fault is considered corresponding to the requirement for non-precise approaches. That means only one element in fault bias vector $\boldsymbol{f}$ is non-zero.[16] The vector $\boldsymbol{f}$ is determined by multiplying the fault bias magnitude b and fault mode $\boldsymbol{\mu}_i$, i.e.

$$\boldsymbol{f} = b\boldsymbol{\mu}_i \quad i = 1, 2, \ldots, n \tag{3}$$

where $\boldsymbol{\mu}_i$ is $n\times 1$ fault mode matrix. Corresponding to the fault on the ith satellite, the ith element of $\boldsymbol{\mu}_i$ is one and the other elements of $\boldsymbol{\mu}_i$ are zeros.

As the components of pseudorange measurement residual vector are not completely independent of each other, the state space is transformed to parity space to eliminate the correlation between the components. Using QR decomposition, matrix $\boldsymbol{H}$ can be decomposed as follows,

$$\boldsymbol{H} = \boldsymbol{UT} = [\boldsymbol{U}_1, \boldsymbol{U}_2]\begin{bmatrix}\boldsymbol{T}_1 \\ \boldsymbol{T}_2\end{bmatrix} \tag{4}$$

where $\boldsymbol{U}_1 \in \mathbf{R}^{n\times 4}$ and $\boldsymbol{U}_2 \in \mathbf{R}^{n\times (n-4)}$ constitute the unitary matrix $\boldsymbol{U} \in \mathbf{R}^{n\times \mathrm{n}}$. $\boldsymbol{T}_1 \in \mathbf{R}^{4\times 4}$ is the first four rows of matrix $\boldsymbol{T} \in \boldsymbol{R}^{n\times 4}$.

Then the parity vector $\boldsymbol{p} \in \mathbf{R}^{n-4}$ is defined as[4]

$$\boldsymbol{p} = \boldsymbol{U}_2^{\mathrm{T}}\boldsymbol{z} \tag{5}$$

The elements of parity vector are uncorrelated following joint Gaussian distribution with the expected value $b\boldsymbol{U}_2^T\boldsymbol{\mu}_i$ and the covariance $\sigma^2\boldsymbol{I}_{n-4}$. The probability density function of parity vector conditioned on bias magnitude and fault mode is[4]

$$p(\boldsymbol{p}|b, \boldsymbol{\mu}_i) = (2\pi\sigma^2)^{-(n-4)/2}\exp[-\boldsymbol{J}(b, \boldsymbol{\mu}_i)/2] \tag{6}$$

where $\boldsymbol{J}(b,\boldsymbol{\mu}_i) = (\boldsymbol{p} - b\boldsymbol{U}_2^{\mathrm{T}}\boldsymbol{\mu}_i)^{\mathrm{T}}(\boldsymbol{p} - b\boldsymbol{U}_2^{\mathrm{T}}\boldsymbol{\mu}_i)$. To describe the probability density distribution $p(\boldsymbol{p}|b,\boldsymbol{\mu}_i)$ with the changing of bias magnitude b corresponding to different fault mode $\boldsymbol{\mu}_i$, the expansion of $\boldsymbol{J}(b,\boldsymbol{\mu}_i)$ in Eq. (6) is given by[4]

$$\boldsymbol{J}(b, \boldsymbol{\mu}_i) = S_{ii}b^2 - 2b\boldsymbol{S}_i^{\mathrm{T}}\boldsymbol{z} + \boldsymbol{z}^{\mathrm{T}}\boldsymbol{Sz} \tag{7}$$

where $\boldsymbol{S}_i$ and S_{ii} are the ith column vector and the ith diagonal element of matrix $\boldsymbol{S} = \boldsymbol{I}_n - \boldsymbol{H}(\boldsymbol{H}^{\mathrm{T}}\boldsymbol{H})^{-1}\boldsymbol{H}^{\mathrm{T}}$ respectively.

In the process of the MLE FI method, the estimated bias magnitude $\hat{b}_i$ is calculated using MLE principle to maximize $p(\boldsymbol{p}|b,\boldsymbol{\mu}_i)$,[4] i.e.

$$\hat{b}_i = \frac{\boldsymbol{S}_i^{\mathrm{T}}\boldsymbol{z}}{S_{ii}} \tag{8}$$

If $p(b|\boldsymbol{\mu}_i)$ follows the uniform distribution, the $\hat{b}_i$ estimated by MLE and maximum a posteriori probability (MAP) is equivalent.[12] Then the ranging source $\mathcal{I}$ is identified as fault if

$$\mathcal{I} = \arg\max_i p(\boldsymbol{p}|\hat{b}_i, \boldsymbol{\mu}_i) \tag{9}$$

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