# A New Multiple Hypothesis RAIM Algorithm : Direct Estimation of a Fault Vector with an RRAIM Concept

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## ABSTRACT

In the next years, it is expected that dramatically improved capability for Global Navigation Satellite System (GNSS) will be available which will include multiple-frequency civil signals and multiple-constellations (Galileo, a renewed GLONASS, and Compass). To provide robust LPV-200 service worldwide, new Receiver Autonomous Integrity Monitoring (RAIM) algorithms are being developed by various research groups (GEAS, 2008), (Todd Walter et al, 2010), (Livio Gratton et al, 2010). Most of these algorithms assume single satellite failure condition. However the definition of failures would be changed, because the accuracy will be improved, the threshold for failure detection will be reduced. As a result, the prior probability of failures could be larger than what we used now. Furthermore, increased number of ranging sources due to new GNSS constellation makes it necessary to consider the possibility of simultaneous multiple failures.

This paper develops and analyzes a new RAIM algorithm as a candidate of future architecture of RAIM algorithm which can treat not only a single failure but also simultaneous multiple failures. A proposed algorithm uses measurements residuals and satellite observation matrices of several consecutive epochs for multiple Failures Detection and Exclusion (FDE). This new concept of FDE was firstly proposed by (Martini and Hein, 2006). It can detect multiple failures without limitation of number of faulty measurements. However the magnitude of Minimum Detectable Bias (MDB) is in the order of 5km with detection latency of 2 to 5 seconds, so that it is hard to be implemented in Safety Of Life (SOL) applications. This paper proposes a new FDE algorithm modified to have no detection latency by estimating the current error vector using the measurements of current and past epochs. In order to make the MDBs have smaller values so that it can be applied to practical application, we adopted Relative RAIM (RRAIM) scheme for navigation and protecting users against system failures. In this paper, we give detailed explanation of the FDE algorithms with rigorous mathematical expression. Simulation results show that proposed algorithm can detect and exclude the multiple failures of tens of meters depending on satellite geometry.

## 1. INTRODUCTION

This paper develops and analyzes a new RAIM algorithm as a candidate of future architecture of RAIM algorithm which can treat not only a single failure but also simultaneous multiple failures. A proposed algorithm uses range residuals and satellite observation matrices of several consecutive epochs for FDE. This new concept of FDE was firstly proposed by (Martini and Hein, 2006). It provides a test statistic to be compared with a threshold analogous to the conventional WLS algorithm, but is able to detect all kind of failures. However the magnitude of

Minimum Detectable Bias (MDB) is in the order of 5km with detection latency of 2 to 5 seconds, so that it is hard to be implemented in Safety Of Life (SOL) applications. A proposed algorithm combines the backward time differenced residual vectors and observation matrices, and directly estimate the error vector so that it can detect the failure(s) of range measurements with no latency. In order to make the MDBs have acceptable values so that it can be applied to practical application, we adopted Relative RAIM (RRAIM) scheme for navigation and protecting users against system failures. The paper gives detailed explanation of a new multiple hypothesis FDE algorithms with rigorous mathematical expression.And the simulation results are presented to assess the performance of the algorithm.

## 2. A NEW RAIM ALGORITHM CONSIDERING MULTIPE SIMULTANEOUS FAILURES.

To overcome the limitation of conventional WLS RAIM algorithm, (Ilaria Martini and Guenter Hein, 2006) have introduced a new idea of FDE algorithm that reconstruct its lost component. Fig. 1 shows a basic idea of a new FDE technique in 2D case.

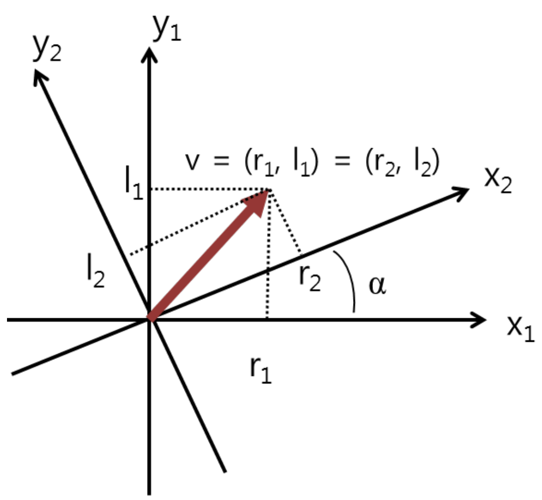



Fig. 1. Concept of a new FDE technique (2D case)

Suppose to have the problem of finding a error vector $\mathbf{v}$. In this problem, the $\mathbf{r}$ is available at each epoch, but not the $\mathbf{l}$. In navigation problem, the residual vector at each epoch is equivalent to the $\mathbf{r}_1$ and $\mathbf{r}_2$, lost components are equivalent to the $\mathbf{l}_1$ and $\mathbf{l}_2$. The single measure of the $\mathbf{r}_1$ is not enough to estimate the vector $\mathbf{v}$, because the $\mathbf{r}_1$ has only one degree of information while the $\mathbf{v}$ contains two degrees of information. Therefore two independent observations are necessary in order to estimate the magnitude of vector $\mathbf{v}$. Collecting the information on two consecutives epochs and measuring the change of coordinate frame $\alpha$, the unknown vector $\mathbf{v}$ can be estimated. This problem can be expressed as following mathematical expression.

$$\mathbf{v} = (\mathbf{r}_1, \mathbf{l}_1) = (\mathbf{r}_2, \mathbf{l}_2)$$

$$\begin{cases} \mathbf{r}_2 = \mathbf{r}_1 \cdot \cos\alpha + \mathbf{l}_1 \cdot \sin\alpha \\ \mathbf{l}_2 = -\mathbf{r}_1 \cdot \sin\alpha + \mathbf{l}_1 \cdot \cos\alpha \end{cases} \tag{1}$$

where the unknowns are $\mathbf{v}$, $\mathbf{l}_1$, $\mathbf{l}_2$ and the observables $\mathbf{r}_1$, $\mathbf{r}_2$, and $\alpha$. The problem is then to reconstruct the vector $(\mathbf{r}_1, \mathbf{l}_1)$, with knowing the $\mathbf{r}_1$, $\mathbf{r}_2$, $\alpha$. Assuming the $\mathbf{v}$ is constant on two consecutive epochs, the $\mathbf{l}_1$ can be calculated as Eq. (2)

$$\mathbf{l}_1 = -\frac{\cos\alpha}{\sin\alpha}\cdot\mathbf{r}_1 + \frac{1}{\sin\alpha}\cdot\mathbf{r}_2 \tag{2}$$

In this problem two reference systems ($x_1Oy_1$ and $x_2Oy_2$) must be linearly independent (i.e. $\alpha \neq 0$).

Expanding this 2D problem to navigation case, the unknown vector $\mathbf{v}$ has dimension $N$, and it consists of bias component and noise component. The residual vector - error vector's projection on the null space of $H^T$ (a subspace of dimension $N-4$) - is observable. By using the residual vectors of consecutive epochs and taking advantage of the constellation geometry diversity, it can detect multiple failures without limitations on the number of $\mathbf{v}$ components affected by biases. Also it can monitors not only the norm of the residuals vector, but it can also reconstruct the lost component of the $\mathbf{v}$. However the constellation geometry changes slightly, with respect to the enormous distances between user and satellites. Therefore the algorithm is very sensitive with respect to the magnitude of error vector because the system is ill-conditioned. Due to this problem, previous research has about 5km magnitude of MDB with GNSS live signals so that this result cannot be applied to SOL service(Ilaria Martini et al, 2006). And detection latency is 2~5 seconds depending on the number of satellite. This latency problem can be a menace to satisfying 6 seconds of Time To Alert (TTA) requirement. This paper proposes a new approach which can provide acceptable magnitude of MDB with no latency. A proposed algorithm combines the backward time differenced residual vectors and observation matrices, and directly estimate the error vector $\mathbf{v}_k$ so that it can detect the failure(s) of range measurements with no latency. As shown in Fig. 3, the error vector $\mathbf{v}_k$ can be expressed as a sum of projected component and lost component.

$$\mathbf{v}_k = \mathbf{r}_k + \mathbf{l}_k = (\mathbf{I}_k - \mathbf{H}_k\mathbf{K}_k)\mathbf{v}_k + \mathbf{H}_k\mathbf{K}_k\mathbf{v}_k \tag{3}$$

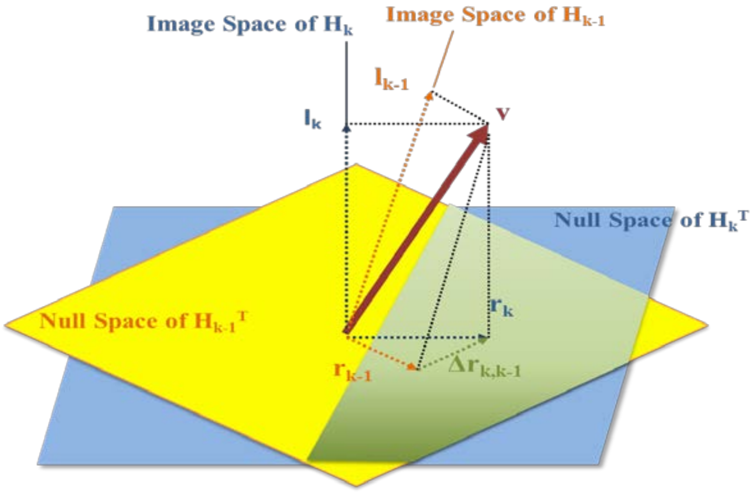



Fig. 2. Composition of the error vector

Assuming the bias component of the error vectors at current and past two epochs are same, that is $\mathbf{v}_k \cong \mathbf{v}_{k-1} \cong \mathbf{v}_{k-2} = \mathbf{v}$, a new formulation is derived.

$$\begin{aligned}\mathbf{r}_k + \mathbf{H}_k \mathbf{K}_k \mathbf{v} &= \mathbf{r}_{k-1} + \mathbf{H}_{k-1} \mathbf{K}_{k-1} \mathbf{v} \\ \mathbf{r}_k + \mathbf{H}_k \mathbf{K}_k \mathbf{v} &= \mathbf{r}_{k-2} + \mathbf{H}_{k-2} \mathbf{K}_{k-2} \mathbf{v}\end{aligned} \tag{4}$$

$$\begin{bmatrix} \mathbf{r}_k - \mathbf{r}_{k-1} \\ \mathbf{r}_k - \mathbf{r}_{k-2} \end{bmatrix} = \begin{bmatrix} -\mathbf{H}_k & \mathbf{H}_{k-1} & \mathbf{O} \\ -\mathbf{H}_\mathbf{k} & \mathbf{O} & \mathbf{H}_{k-2} \end{bmatrix} \begin{bmatrix} \mathbf{K}_k \mathbf{v} \\ \mathbf{K}_{k-1} \mathbf{v} \\ \mathbf{K}_{k-2} \mathbf{v} \end{bmatrix} \tag{5}$$

By some definitions, Eq. (5) can be simplified as Eq. (6)

$$\Delta \overline{\mathbf{r}} = \mathbf{C} \cdot \mathbf{a} \tag{6}$$

where $\Delta \overline{\mathbf{r}} \triangleq \begin{bmatrix} \mathbf{r}_k - \mathbf{r}_{k-1} \\ \mathbf{r}_k - \mathbf{r}_{k-2} \end{bmatrix}$, $\mathbf{C} \triangleq \begin{bmatrix} -\mathbf{H}_k & \mathbf{H}_{k-1} & \mathbf{O} \\ -\mathbf{H}_\mathbf{k} & \mathbf{O} & \mathbf{H}_{k-2} \end{bmatrix}$ and $\mathbf{a} \triangleq \begin{bmatrix} \mathbf{K}_k \mathbf{v} \\ \mathbf{K}_{k-1} \mathbf{v} \\ \mathbf{K}_{k-2} \mathbf{v} \end{bmatrix}$.

From Eq. (6), the unknown vector $\mathbf{l}_k$ (lost component of $\mathbf{v}_k$) can be estimated utilizing the change of observation matrix and projections on them. Finally the error vector can be reconstructed using Eq. (8). This algorithm uses measurements of current and past two epochs, thus it can estimate the error vector without latency.

$$\hat{\mathbf{a}} = \left[ \left( \mathbf{C}^T \mathbf{C} \right)^{-1} \mathbf{C}^T \right] \cdot \Delta \overline{\mathbf{r}} \tag{7}$$

$$\begin{aligned}\hat{\mathbf{l}}_k &= \mathbf{H}_k \cdot \hat{\mathbf{a}}_k \\ \hat{\mathbf{v}}_k &= \mathbf{r}_k + \hat{\mathbf{l}}_k\end{aligned} \tag{8}$$

where $\hat{\mathbf{a}}_k$ consists of first four components of $\hat{\mathbf{a}}$.

To solve Eq. (7) two important problems must be considered. The first problem is ill-conditioned system matrix. The satellite geometry changes slightly because of enormous distance between user receiver and satellites. Therefore the matrices $\mathbf{H}_k$, $\mathbf{H}_{k-1}$, and $\mathbf{H}_{k-2}$ have similar components each other, consequentially the system matrix **C** becomes difficult to be inverted. Ill-conditioned system leads to sensitivity of the algorithm with respect to variation of the error vector $\mathbf{v}$. As mentioned above, the magnitude of the error vector $\mathbf{v}$ can be considered as a sum of bias component and noise component of range measurements. Assuming the bias components at (k-2) ~ k-th epochs as constant vectors, then only the noise components affect to the error vector estimation. Ill-conditioned system amplifies the noise level of range measurements when the system matrix is inverted. Therefore too large noise level can cause a wrong estimation of error vector. If range measurements are acquired more precisely, the solution will be more robust and its noise level of error vector estimation will be reduced. Smaller measurement noise contributes to smaller value of MDB as well as robustness of the algorithm. Next section describes a new formulation of the algorithm adopting RRAIM concept for lower noise level of the range measurements

Another problem is the linear dependency of the system. Similarly with 2D case, in order to estimate a valid $\mathbf{l}_k$, the subspaces of different epochs in Fig. 3 should be linearly independent.

That is the null spaces at epoch k and epoch k-1 should be independent. The same must be valid for the image spaces. However the image spaces of each observation matrix shares the same subspace which is spanned from column $\begin{bmatrix}-1 & -1 & \cdots & -1\end{bmatrix}^T$. Due to this column, image spaces and null spaces of each observation matrix do not satisfy the property of linearly independence from epoch to epoch. The column $\begin{bmatrix}-1 & -1 & \cdots & -1\end{bmatrix}^T$ is involved in calculating receiver clock error and do not affect the position solution. Thus this common component is not critical for the integrity monitoring. Thus the receiver clock error is estimated independently from the main FDE process and assumed as common component. Due to ill-conditioned system problem, it needs precise receiver clock estimation as well as precise range measurement. For precise receiver clock estimation, kinematic Kalman filter is used with pseudorange and time differenced carrier phase measurements (Junghan Kim, 2005). It estimates the receiver clock errors with several millimeters of accuracy. The receiver clock error is regarded as common component, and then the proposed algorithm can calculates the lost components without effect of the common component. In this case, residual vector and P matrix is re-definded as following equations.

$$\mathbf{r}'_k = \mathbf{z}_k - \mathbf{H}\hat{\mathbf{x}}'_k$$
$$\mathbf{P}'_k \triangleq \mathbf{H}_{k,1:3} \cdot \mathbf{K}'_k \triangleq \mathbf{H}_{k,1:3} \cdot \left[\mathbf{H}_{k,1:3}{}^T \mathbf{R}_k{}^{-1} \mathbf{H}_{k,1:3}\right]^{-1} \mathbf{H}_{k,1:3}{}^T \mathbf{R}_k{}^{-1} \tag{9}$$

where $\hat{\mathbf{x}}'_k$ is composed of $3\times1$ user position estimation vector and 1 receiver clock estimation which is calculated from independent clock estimation filter. $\mathbf{H}_{k,1:3}$ is $N\times3$ observation matrix which consists of first three columns of $\mathbf{H}_k$.

## 3. RRAIM ADOPTED ALGOTITHM FORMULATION

As mentioned in previous section, in order to obtain reliable estimation of the error vector , we need precise range measurement so that it can minimize the effect of ill-conditioned system matrix. The most common way of getting precise GNSS ranging measurement is using carrier phase measurement as a ranging source. Carrier phase measurement has a much lower noise level compared with pseudorange measurement. Therefore it is applied in the fields that requiring high positioning accuracy such as surveying and Precise Point Positioning (PPP). However, as carrier phase measurement contains a constant unknown integer ambiguity, it cannot directly used as a ranging source. Resolving carrier phase integer ambiguity is another challenging problem. In order to resolve carrier phase integer ambiguity, user would be heavily dependent on data from ground facility. Heavy dependency on ground channel can be a threat of satisfying a TTA requirement due to a limited data transfer rate of ground facility. In order to make the best use of precise carrier phase measurement without resolving integer ambiguity, RRAIM concept is adopted for the proposed algorithm.

In RRAIM concept, the receiver uses carrier smoothed pseudorange measurements that have been validated by the GIC and propagates these measurements forward in time by adding the difference between current and past carrier phase measurements.

$$\hat{\rho}_k = \rho_{k-M} + \Delta\phi_{k,k-M} \tag{10}$$

In Eq. (10), $\hat{\rho}_k$ is measurement at current epoch ‘k’ propagated from the past GIC-corrected, ionosphere-free, and carrier smoothed pseudorange at 'k-M' ( $\rho_{k-M}$ ), and the difference in carrier phase measurements between epoch k and k-M( $\Delta\phi_{k,k-M}$ ). The propagated range measurement can be related to the true range, r, between the user and the satellite as Eq. (11)

$$\hat{\rho}_k = r_k + \tau_k + \delta\rho_{k-M} + \delta\Delta\phi_{k,k-M} \tag{11}$$

where $\tau$ is the receiver clock bias, $\delta\rho_{k-M}$ is the error in $\rho_{k-M}$ , $\delta\Delta\phi_{k,k-M}$ and is the error in $\Delta\phi_{k,k-M}$ . $\delta\rho_{k-M}$ is defined to be normally distributed with variance specified by Eq. (12).

$$\sigma^2_{\rho,j} = \sigma^2_{clk\_eph,j} + \sigma^2_{DF\_air,j} + \sigma^2_{tropo,j} \tag{12}$$

$\sigma^2_{\rho,j}$ means a variance of the j-th line of sight for $\delta\rho_{k-M}$ . The error in $\rho_{k-M}$ (i.e. $\delta\rho_{k-M}$ ) is assumed as a sum of three independent error components. $\sigma^2_{clk\_eph,j}$ is variance of residual error in the GIC-generated range correction (accounting for satellite clock and orbit errors), $\sigma^2_{DF\_air,j}$ is variance of carrier-smoothed code receiver noise and multipath, and $\sigma^2_{tropo,j}$ is variance of residual tropospheric error. The error term $\delta\Delta\phi_{k,k-M}$ , in Eq. (11) is also the sum of three independent error components: the change in carrier phase receiver noise and multipath over time interval M, the change in tropospheric error over the time interval, and the satellite clock drift over the time interval. These errors are also modeled as a zero mean normal distribution with standard deviations $\sigma_{\Delta(n+mp)}$ , $\sigma_{\Delta trop}$ , and $\sigma_{\Delta clk}$ .

$$\sigma^2_{\Delta\phi,j} = \sigma^2_{\Delta(n+mp),j} + \sigma^2_{\Delta trop,j} + \sigma^2_{\Delta clk,j} \tag{13}$$

The methods for specifying each standard deviation in Eq. (12) and (13) are well described in (GEAS, 2008).

The error covariance matrix associated with $\delta\rho_{k-M}$ for $N$ satellites in view is $\mathbf{R}_{\delta\rho} = diag\left(\sigma^2_{\rho,1},\cdots,\sigma^2_{\rho,N}\right)$. And the same for $\delta\Delta\phi_{k,k-M}$ is $\mathbf{R}_{\delta\Delta\phi} = diag\left(\sigma^2_{\Delta\phi,1},\cdots,\sigma^2_{\Delta\phi,N}\right)$. The total error associated with the propagated ranging measurements, $\hat{\rho}_k$ , in Eq. (10) for $N$ satellites is then described by the covariance matrix $\mathbf{R}_{\delta\hat{\rho}} = \mathbf{R}_{\delta\rho} + \mathbf{R}_{\delta\Delta\phi}$ .

RRAIM measurement and its covariance matrix in this section can be related to equations in the previous section. Observation equation can be rewritten adopting RRAIM measurement model as Eq. (14).

$$\begin{bmatrix} \hat{\rho}_{k,1} \\ \vdots \\ \hat{\rho}_{k,N} \end{bmatrix} = \mathbf{H}\begin{bmatrix} \mathbf{x}_k \\ \tau_k \end{bmatrix} + \begin{bmatrix} \delta\hat{\rho}_{k,1} \\ \vdots \\ \delta\hat{\rho}_{k,N} \end{bmatrix} + \boldsymbol{\beta} \tag{14}$$

Range measurement $\mathbf{z}$ is carrier-propagated code measurement which is validated from GIC, and the error vector $\mathbf{v}$ is expressed as a sum of noise component $\delta\hat{\rho}_k$ and unknown bias component $\boldsymbol{\beta}$. Measurement noise can be reduced easily by adopting the RRAIM concept. However when updating the pseudorange measurement at the end of coasting time, pseudorange noise causes a problem in FDE process. Because the noise level of pseudorange measurement is very large compared with that of carrier phase measurement, a noise of a new pseudorange measurement affects like range bias during whole coasting time. In other words, if pseudorange is updated at k-th epoch, then nominal bias due to pseudorange noise in $\hat{\rho}_k$ becomes different from that of $\hat{\rho}_{k-1}$ and $\hat{\rho}_{k-2}$. This nominal bias change occurs with every pseudorange update at each end of coasting time. And this nominal bias change breaks the assumption that error vector is constant at consecutive 3 epochs. Therefore the FDE algorithm raises a false alarm during 2 epochs after every pseudorange updates. From (k+2)-th epoch to next pseudorange update, $\hat{\rho}_k, \hat{\rho}_{k+1}, \cdots, \hat{\rho}_{k+M}$ have same nominal bias, thus false alarm due to a change of pseudorange noise doesn't occur. With single test statistics, continuous FDE cannot be conducted due to the false alarms. This problem can be solved using 2 test statistics in parallel. Fig. 3 shows the concept of the parallel test statistics.

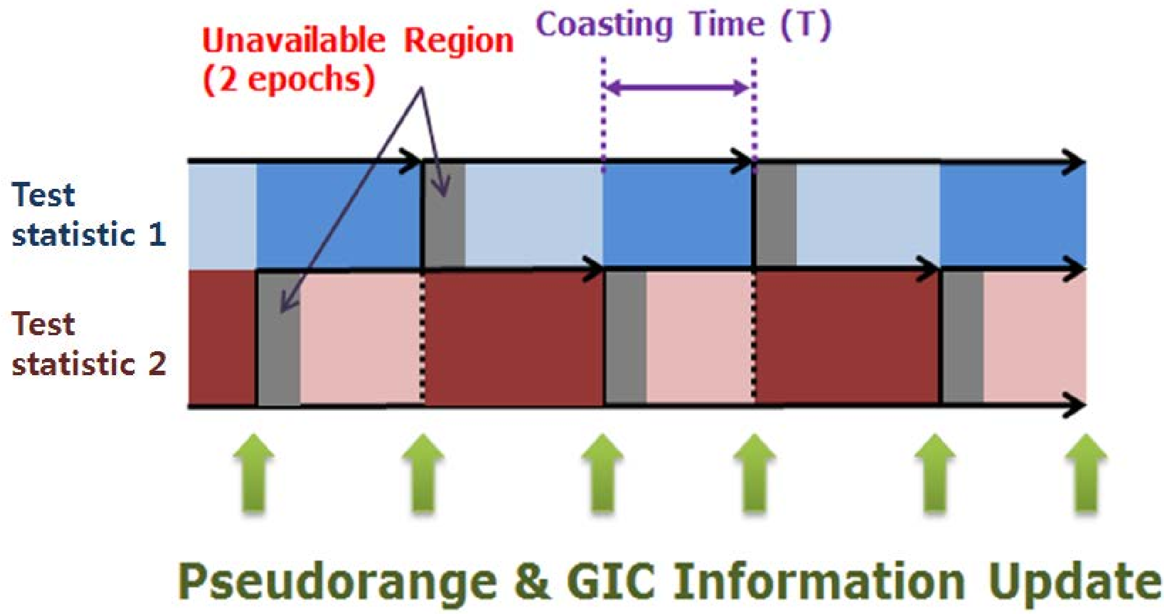



Fig. 3. Concept of parrallel test statistics

If GIC information and pseudorange is updated at every 'T' seconds, the test statistic are unavailable at every T to T+1 second (gray region). One measurement updates the pseudorange and GIC information at 1T, 3T, ··· , (2n-1)T seconds, and the other one updates the information at 2T, 4T, ···, (2n)T seconds (where an 'n' is positive integer number). By doing this, at least one test statistic is available at all time (dark blue and dark red region).

## 4. SIMULATION RESULTS.

Simulations have been performed for verifying the feasibility of proposed algorithm. Satellite orbit was made from RINEX navigation files. In this simulation, it is assumed that GIC provides users with the correction messages and integrity messages at every 30 seconds. The user can obtain integrity assured measurements by applying the information from GIC. It is assumed that the ionospheric delay, tropospheric delay, satellite orbit and clock errors are eliminated with a help of GIC information. With this assumption, for each line of sight a random noise with a standard deviation modeled as a function of satellite elevation angle has been added to each geometrical range. In addition to this, various combination of biases have been inserted at t =

50~100s.

Fig. 4 is result of the proposed algorithm with using only pseudorange measurements in single failure case.

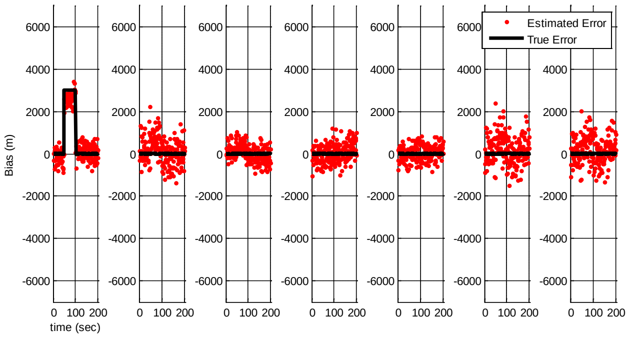
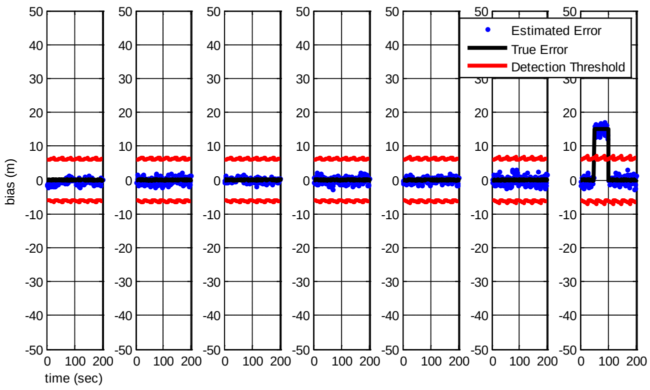


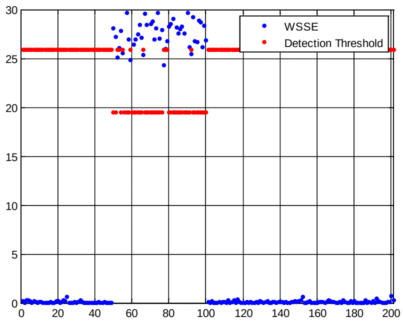

Fig. 4. Results of the algorithm when using only pseudorange measurements

The proposed algorithm can detect failures with magnitude in the order of several km, because it is very sensitive to measurement noise due to ill-conditioned system. Fig. 5.(a) and (b) are results of the proposed algorithm and conventional WLS RAIM algorithm each in a single failure condition. It is inserted the following bias.

**bias** = $[0\ 0\ 0\ 0\ 0\ 0\ 15]^T$ m



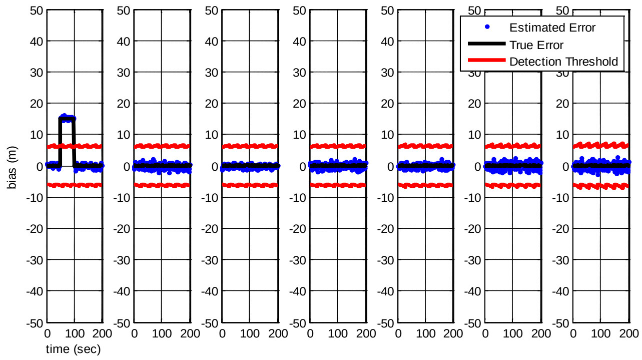

(a) Proposed algorithm



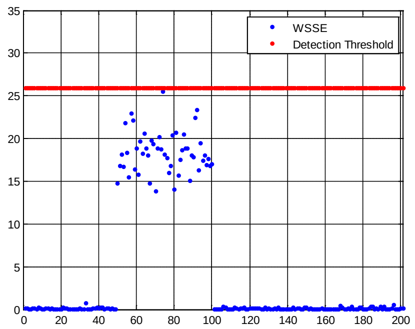

(b) Conventional WLS algorithm

Fig. 5. Results in case of bias = $[0\ 0\ 0\ 0\ 0\ 0\ 15]^T$ m

Comparing the results of Fig. 4 and Fig. 5 (a), magnitude of detectable bias decreases considerably when adopting RRAIM concept in range measurement. The magnitudes of MDBs have practical values by using carrier phase measurement as well as psuedorange measurement. The proposed algorithm detects and identifies the failures by estimating the individual component of errors directly, and then determine whether from individual probability density function. whereas WLS algorithm uses WSSE. Therefore the proposed algorithm has a smaller value of MDB and its identifying process is much simpler.




(a) Proposed algorithm




(b) Conventional WLS algorithm

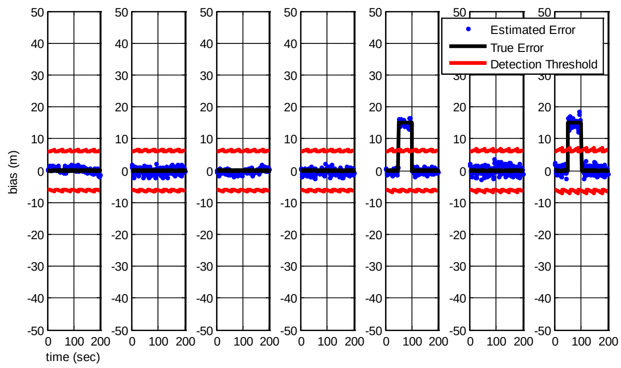
Fig. 6. Results in case of bias = $[15\ 0\ 0\ 0\ 0\ 0\ 0]^T$ m

Fig. 6 shows results of different case of a single failure. In this case, the magnitude of error vector is same as the case of Fig. 6 but direction of error vector is similar with direction of image space of **H** matrix. Although magnitude of bias was same as case of Fig. 5, WLS algorithm cannot detect a failure at all. In this case, impact of the bias on the test statistic could be negligible and the detection capability of WLS algorithm not sufficient to protect the user even in single failure cases. Detection capability of WLS algorithm depends on direction of error vector and satellite geometry, on the other hand the proposed algorithm utilizes not only range residual vector but also lost component, thus detection capability is not dependent on satellite geometry. It is observed that analogous results are valid also in cases of multiple failures.

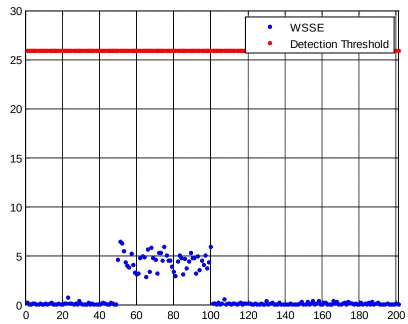
Fig. 7. (a) and (b) are results of each algorithm in case of multiple failures. In this simulation, in order to show the detection capability of each algorithm contrastively, the error vector is

placed near to the image space of **H** matrix so that its projection on the null space (i.e. residual vector) is near zero. The inserted biass are as following.

**bias** = $[0\ 0\ 0\ 0\ 15\ 0\ 15]^T$ m




(a) Proposed algorithm




(b) Cconventional WLS algorithm

Fig. 7. Results in case of bias = $[0\ 0\ 0\ 0\ 15\ 0\ 15]^T$ m

In this case, even two failures of same magnitude of bias have been inserted, the test statistics of WLS have smaller values with respect to the single failure cases. The error vector has been placed in image space of H matrix, resulting in most part of error vector is on lost component and only very small part of it is on projected component. Therefore the WLS algorithm could not detect any failure at all. And consequently the position errors will be increased without any alarm. On the other hand, the proposed algorithm estimated the error vector exactly and succeeded in detecting all the faulty measurements.

## 5. CONCLUSIONS.

RAIM plays a key role in protecting the user against various failure conditions. Conventional WLS RAIM algorithm can protect only against single failure. However prior probability of failures could be larger than what we used now due to improvement of accuracy, and reduction of the threshold for failure detection. Furthermore, increased number of ranging sources makes it necessary to consider the possibility of simultaneous multiple failures. This paper presented a new multiple hypothesis RAIM algorithm which detects the failures by monitoring the error vector directly instead of monitoring the projection of the error. The algorithm estimates the range errors using precise carrier phase measurements. Thus it is able to detect multiple failures with magnitude of several tens of meters, although the algorithm has to solve ill-conditioning problem.

The smaller MDB value compared with previous works makes it possible to use the algorithm in many of practical applications.

## ACKNOWLEDGEMENT

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