PRECISION INCREASING AND INTEGRITY MONITORING OF NAVIGATION DATA FOR GPS/INERTIAL HYBRID SOLUTION

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Abstract

This paper mainly describes the global navigation satellite systems (GNSS) receiver autonomous integrity monitoring problem solutions based on a least squares method. The fault detection problem is formulated as that of the most rapid detection of satellite measurement biases with an assigned mean time before false alarm. For problem solving the modified cumulative sum algorithm is proposed. The advantages of proposed approach are demonstrated by simulation. Obtained expressions show as the satellite geometry influences on the characteristics of fault detection and isolation algorithms.

The increasing of precision and reliability of the airplane position determination, when GNSS and inertial data are jointly processed, is also shown.

I. Introduction

Air navigation concept is substantially changed now because of two global navigation satellite systems (GNSS) putting into operation in the nearest future. Standard position service will be implemented since 1993 by GPS network and 1995 by GLONASS network [1]. However, GNSS using as a sole-means navigation system for en-route navigation is planned some years later; using for terminal navigation, approach and precision approach is planned only in the next century [1]. So significant delay is caused by some reasons. One of the main of them is the necessity of integrity questions resolving. Integrity is defined as system's ability to provide timely warnings to users when the system should not be used for navigation [11,24]. Integrity problem solution is connected with two different approaches: receiver autonomous integrity monitoring (RAIM) and the ground-based satellite monitoring stations approach which is referred to as GNSS integrity channel (GIC) [1,24]. The GIC system will generally consist of a sparse network including ground monitors, a master station and, most likely, geostationary satellite repeaters. Thus, the GIC system is expensive and it's implementation will be required some years. According to RAIM approach, the verifications would be performed in the satellite navigation on-board receiver. It should be noted that RAIM method may be considered relatively independently from GIC. This paper is mainly devoted to the RAIM problem solution: the fault detection and isolation. The GNSS/inertial integrated configuration is examined primarily as for integrity problem too.

II. GNSS/Inertial Hybrid Solution

Enormous number of published works is devoted to joint GNSS and inertial data processing. Lately, considerable part of them is related to integrated GNSS and inertial navigation systems (INS) or GNSS and attitude heading reference systems (AHRS). These integrated systems are characterized by many benefits [2]. Most of the papers are related with precision and reliability increasing of output data. However, the all benefits are realized also by joint processing of output data of two systems: GNSS receiver and INS(AHRS). In this case the synchronization problem can be solved by the hybrid filter realization in INS (AHRS) or by inertial output data rate increasing and realizing of filter in home computer or GNSS receiver. Then the results of integrated system investigations also correspond to those of two systems joint data processing.

Inertial data are usually supplied by strapdown INS or AHRS. In case of AHRS, it is possible to provide the calculation scheme which is similar to that of INS due to high precision aiding from GNSS. AHRS errors are estimated by hybrid filter and their estimates are used in AHRS algorithm. As a result, nonlinear effects are diminished. Therefore, we don't distinguish the two mentioned above cases, except inertial measurement unit (IMU) precision.

GNSS receivers (separate or embedded) are very different. Five - six channel receivers and one - two channel receivers with fast-sequencing design including "all-in-view" implementation are widely used. Till quite recently receivers with scanning possibilities had been essentially cheaper, although less precise. However, the situation is being changed. On the one hand, impressible electronics achievements, specifically VLSI technology development, enable to increase the number of channels with moderate cost. Combined GPS/GLONASS VLSI are also designed. On the other hand, for civil aviation receivers it is quite desirable to get simultaneously 10-12 satellite measurements at any rate.

Published works show, that one network (GPS or GLONASS) redundancy is not sufficient for the whole integrity problem solving by means of RAIM technique. It is completely true for nonprecision and precision approach. Further, it is shown that fault isolation in the case of six - eight satellite measurements (it is typical situation for one satellite network) is very difficult. Joint processing of signals from two networks allows to solve this problem. The estimate of the relative system time drift is not needed because of the difference between the two system times is sufficiently stable. After appropriate coordinates transformation (with accounting the estimated or a priori network times shift) measured pseudoranges can be processed jointly. Thus GNSS receivers with 10-15 parallel GPS/GLONASS channels are expected to appear.

GNSS receivers are usually used modified Kalman filter for autonomous navigation solution. It allows to increase the position precision. The fluctuations are first of all decreased by means of process dynamics and additional velocity information accounting. Particularly Kalman filter advantages are manifested when satellite information is not sufficient. The least squares technique is used, too, because of simplicity and robustness.

In practice, Kalman filter modifications are used for GNSS/inertial hybrid solutions. Position and velocity GNSS output data can be used for mutual processing. Particularly this concept is reflected in standard integration filter design [4] and the AHRS software [5]. The other approach is related with pseudorange and delta-pseudorange measurements processing. This approach can be realized, when embedded or separate GNSS receiver is used, due to mentioned parameters and satellite ephemeris are included in output data [6,7]. In spite of more difficult realization (high filter order, many measurements processed), the second approach is used frequently when GPS/inertial solution is designed. This approach allows to achieve more precise position, particularly when satellite information is not sufficient.

III. GNSS/Inertial Precision Increasing

GNSS/inertial solutions precision is shown in many papers (see, for example, [8,9,10]). If the satellite information is sufficient joint processing does not appreciably increase position precision. The fluctuation errors are mainly decrease, but the bias-type errors are characterized by greater values. The main gain is reached when brief periods with insufficient GNSS information or GNSS information absence take place. High - accuracy performance can be achieved for substantial periods of GNSS outages if IMU dominant errors have been calibrated earlier. Two GNSS networks putting into operation, the errors behavior is the utmost interest when satellite signals are absent during several seconds - several minutes. Taking into consideration this situation, simulation has been carried out. It includes two minutes section with four satellite measurements, four minutes section with three satellite and baroaltitude measurements where velocity does not estimate, and six minutes section with satellite outage. The second section contains 30^{o} turn. Two simulation series have been considered: corresponding to Kalman filter hybrid solution and resetting the IMU positions and velocities to the positions and velocities specified by the GPS receiver. Typical simulation results for low-cost IMU with gyro drift 0.3 deg/hour (*rms*) are demonstrated in fig.1. During the first 2-3 minutes with satellite outage, hybrid solution errors are increased insignificantly. After six minutes of prediction, the position error is about 300 m. In the second case, errors are increased significantly, just after ceasing of aiding. When IMU of commercial strapdown INS is simulated (gyro drift *rms* equals to 0.01 deg/hour), error increasing during all six minutes period is small (about 100m). However, the errors of the reset INS don't increase much more. Thus, positive effect of hybrid solution is the greatest when low-cost IMU is used. In this case during 1-3 minutes GNSS outage, position errors increasing is not significant.

IV. GNSS Receiver Autonomous Integrity Monitoring

RAIM Methods Brief Review

RAIM function in a narrow sense is defined as ability to provide timely warning to users when the system should not be used for navigation. In other words, RAIM function is to detect and indicate any degradations of satellite signals that decrease flight safety [12]. It is reasonable, however, to expend the interpretation of a RAIM by including additional functions which ensure fault tolerant data processing scheme. (We imply the fault tolerance is a system property to carry out its functions without essentially deterioration of its characteristics under appearing of faults.) Therefore, the fault isolation can be included in RAIM functions. In addition to, the estimation of the fault level can be also needed, especially when the isolation carrying out is difficult.

Many papers have been devoted to the RAIM problem. It is due to RAIM function significance [1] and RAIM implementation demanding [6,7]. In the papers known to the authors several different methods have been suggested. In some articles brief algorithm classifications are given. For example, in paper (13) all algorithms are grouped into two categories: snapshot and averaging. The second category combines only variety of algorithms based on Kalman filtering (14,15). Paper (15) points out that techniques of integrity monitoring are based on either a snapshot solution or a Kalman filter solution. We suppose that reasonable grouping of considered algorithms is as follows: a least squares solution and a Kalman filter solution (16). Then the based on data averaging a least squares solution need not consider as a snapshot solution. In spite of a modified Kalman filter being generally used for navigation solution obtaining in GNSS receiver, the most papers describe least squares RAIM techniques. It should be noted that a least squares technique allows better to feel the special features of considered monitoring problem. Further, with more understanding one can investigate this problem solution based on Kalman filtering. Four approaches are selected in (13), which are distinguished by applicable test statistics: maximum solution separation, range comparison, position comparison and least squares residuals. The first three algorithms are enough simple and straightforward, but their realization requires considerable calculations, because of needing to obtain user positions using all subsets of N-1 satellites. The used test statistics are: (*i*) maximum horizontal separation between any two calculated solutions; (*ii*) the differences between the predicted ranges from these solutions and the measured pseudo ranges; (*iii*) the differences between the position using N satellites and the subsets positions.

As regards CPU processing load, the least squares residuals (LSR) method is preferable because for fault detection the position calculation in usual way is used and only minimal additional calculations are required. The test statistics is created by residual vector which is the difference between actual and expected measurements. Expected measurements are calculated from the position fixes (18). However, for fault isolation Parkinson and Axelrad again use residuals corresponding to all subsets of N-1 satellites.

In paper (19) the universal method of the fault detection and isolation not requiring subsets calculations is proposed. The fault detection algorithm is almost identical to that of previous paper.

The considered measurement equation is:

$$y = Hx + n + b \qquad (1)$$

where y is the N*1 vector of measurements; H is the N*M measurement matrix, rank(H)=M; x is the N*1 state vector; n is the N*1 vector of Gaussian measurement noise, E[n]=0 and cov[n]= $\sigma_n^2 I_N$, where I_N is the identity matrix of order N; and b is the N*1 vector of uncompensated measurement biases (faults). A failure of measurement source *i* is modeled by $b=b_i$, where b_i is an N*1 vector with ith element B and zeros elsewhere. If there are no faults, then b=0.

The fault detection algorithm based on the generalized likelihood test (GLT) is:
1) Calculate the fault (residual) vector,

$$r = y - \hat{y} = y - H\hat{x} = Sy, \qquad (2)$$

where $S=I_N-HH^*$. Matrix H^* is generalized inverse of H: $H^*=(H^TH)^{-1}H^T$
2) Calculate the decision variable,

$$D = r^T r$$

3) Based on the required probability of false alarm (P_{FA}), the number of redundant measurements, N-M, and the measurement noise variance, σ_n^2, calculate the threshold h.
4) If D>h, a fault has occurred.
The threshold h is calculated from chi-square distribution with N-M degrees of freedom, using the equalities E[r] = Sb, cov[r] = σ_n^2S.

The fault isolation algorithm was derived from maximum likelihood estimation (MLE) approach. It is as follows:
1) Calculate the quantities r_i^2/S_{ii} for i=1,...,N, where S_{ii} is the ith diagonal element of S, r_i the ith component of r.
2) Find the maximum r_i^2/S_{ii}. Then the ith satellite corresponding to the maximum value is declared as faulty.
It should be noted that for RAIM M equals 4.

Author considering the problem of detection and isolation in 10 s (the present integrity requirement for nonprecision approach (12)), the measurements are averaged over 10 s interval *to reduce the contribution of* white noise sources.

Suggested approach

LSR algorithm considered has the two special features which can reduce the fault detection effectiveness. The first feature is that the residual vector behavior information is reduced to one decision variable D. The second feature is that information for the fault detection comes during fixed time interval (10 s). Practically it may be preferable to use the algorithm based on the criterion of optimality which minimizes the mean time delay $\bar{\tau}$ of fault detection. For this aim cumulative sum algorithm (CUSUM) (16,21,22,23) is proposed. CUSUM is intended for changing detection of average value of Gaussian white sequence w(k). If there is no fault, then $E[w(k)]=0$, $cov[w(k)]=\sigma_w^2$, $(k<k_o)$. A failure results in appearing of shift: $E[w(k)]=\pm\delta$ $(k\geq k_o)$. CUSUM is described as follows:

$$k_a = \inf\{k\geq 1:\ (g\geq h)\vee(g^{\#}\geq h)\};$$
$$g(k)=(g(k-1) + \frac{w(k)}{\sigma_w} - \frac{\delta}{2\sigma_w})^{+};$$
$$g^{\#}(k)=(g^{\#}(k-1) - \frac{w(k)}{\sigma_w} - \frac{\delta}{2\sigma_w})^{+}; \quad (3)$$
$$g(0)=g^{\#}(0)=0;\quad \delta>0;\quad z^{+} = \max(z,0),$$

where k_a is a stopping time, g and $g^{\#}$ are cumulative sums. This algorithm being intended for detection both positive and negative biases, that is referred to as two-sided CUSUM (TSCUSUM). Parameter δ/σ_w is an expected signal-noise ratio (SNR) of the stepwise jump and defines indifference region ("dead zone") in both cases. Threshold h fully defines $\bar{\tau}$ and $\bar{T}$ under fixed δ [21,23]. CUSUM has asymptotic optimal properties (when $\bar{T} \longrightarrow \infty$) *point of view "worst case"* $\bar{\tau}$ [22], but that is actually able stable to detect the shift beginning from $\delta/2$.

In case of RAIM based on LSR we have the residual vector. We can suppose that without selective availability (SA) noise the residuals are Gaussian white sequence with zero mean. Therefore, for the fault detection we use TSCUSUM for each component of residual vector. It seems naturally, if the isolation algorithm is based on suggested detection algorithm. For example, if $TSCUSUM_l$ ($TSCUSUM_l$ processes the lth component of residual vector) detects the fault, then the lth satellite is regarded as faulty. Really, the input of $TSCUSUM_j$ is the value $f_j/\sigma_j = f_j/\sigma_n\sqrt{S_{jj}}$. If a shift B appears in the ith component of measurement, SNR_j satisfies to $SNR_j = |BS_{ji}|/\sigma_n\sqrt{S_{jj}}$, and SNR_i is the greatest because S is non-negative defined matrix and

$$SNR_i/SNR_j = |\sqrt{S_{ii}S_{jj}}/S_{ji}| \geq 1.$$

If B is sufficiently big increasing rate of appropriate CUSUM from $TSCUSUM_i$ is approximately determined by $SNR_i = |B|\sqrt{S_{ii}}/\sigma_n$. If the parameters δ/σ_w and h are the same for all TSCUSUM, the average speed of fault detection is maximized for $TSCUSUM_i$. If $|S_{ij}|\cong\sqrt{S_{ii}S_{jj}}$, however, the average rates of appropriate cumulative sums from $TSCUSUM_i$ and $TSCUSUM_j$ are approximately equal. Selected h can ensure assigned $\bar{T}$ but be insufficiently big for obtaining appropriate characteristics of fault isolation. Increasing h improves these characteristics. However, the better characteristics are obtained if the results of paper [19] are used. From MLE approach, maximum of r_i^2/S_{ii} or $|r_i/\sqrt{S_{ii}}|$ for all i corresponds to the fault satellite. The changes being considered in time, we form new statistics as sum of appropriate values:

$$DL_i(k) = \sum_{k=k_b}^{k} r_i(k)/\sqrt{S_{ii}(k)} \quad i=1,\ldots,N \quad (4)$$

The value k_b can be chosen as equal to k_a. However, if $k_b=k_a-d$ is selected, where d is typical value of $\bar{\tau}$, the mean time delay of isolation decreases. In the case it need keep d last values $r_i/\sqrt{S_{ii}}$, $i=1,\ldots,N$. For determination of fault satellite it need provide essential differences between the maximum DL_i and the other. Relative values can be used as test statistics, but we use absolute difference:

$$|DL_{max1}(k)| - |DL_{max2}(k)|\geq h_I \quad (5)$$

where $|DL_{max1}(k)|$ and $|DL_{max2}(k)|$ are the two maximum values of $|DL_i(k)|$, $i=1,\ldots,N$, h_I is a threshold. Inequality (5) is checked when $k\geq k_a$. The probability of misisolation (P_{mi}) and mean time delay of isolation ($\bar{\tau}$) depend on h_I.

Obtained expressions show as the satellite geometry influences on the characteristics of fault detection and isolation algorithms. Under fixed and equaled δ/σ_w and h for all TSCUSUM, the mean time of the ith measurement bias detection depends on value of $B\sqrt{S_{ii}}$; the characteristics of isolation depend on $1 - |S_{ji}|/\sqrt{S_{ii}S_{jj}}$, $j=1,\ldots,N$. If the first and second components of the vector x are two horizontal position errors, and the third component is vertical position error, the bias B of the ith satellite measurement results in additional horizontal bias position error

$$HPE_i = B\sqrt{H_{1i}^{*2} + H_{2i}^{*2}}, \quad (6)$$

and vertical position error

$$VPE_i = B\,H_{3i}^{*},$$

where H_{ij}^{*} is the element of H^{*}.

Using GPS and GLONASS networks jointly results in problem statement generalization for the case of unequal measurements: $cov[n]=\sigma_n^2 W$, where W is diagonal positive defined matrix. Then, it is reasonable to introduce the new measurements $\tilde{y}=W^{-1/2}y$. This is equivalent introducing $\tilde{H}=W^{-1/2}H$. Obtained expressions are transformed by substituting H and y on $W^{-1/2}H$ and $W^{-1/2}y$. As suggested measurement noise was Gaussian white noise.

SA noise being available the residuals are not white noise sequence. For decreasing of correlation we are using simple decorrelation algorithm:

$$\tilde{r}(k) = r(k) - \alpha r(k-1) \quad (7)$$

Since correlation in time is not removed fully, there is correlation between components $\tilde{r}$, for the determination of detection and isolation algorithm parameters we must carry out the simulation.

To summarize, suggested method is as follows:

1. Preliminary, based on the characteristics of GNSS receiver and SA, number of satellites, desirable characteristics of detection and isolation algorithms, obtain the parameters of α, δ/σ_w, h, h_I by simulation.
2. Calculate the residual vector, r (see (2)).
3. Carry out the decorrelation of residual vector (see (7)).
4. Process the components of vector $\tilde{r}$ by TSCUSUM (see (3)).
5. If a fault has not occurred, repeat step 2, 3, and 4 for each new measurement vector.
6. If a fault has occurred, calculate the quantities DL_i, i=1,...,N (see (4)).
7. Find two maximized quantities $|DL_{max1}|$ and $|DL_{max2}|$ from DL_i, i=1,...,N.
8. If $|DL_{max1}| - |DL_{max2}| < h_I$, begin the calculation from step 2.
If $|DL_{max1}| - |DL_{max2}| \geq h_I$, then declare that a fault is isolated. The number of fault satellite corresponds to the value max1.

As mentioned above the isolation algorithm can slightly become complicated due to the formation of quantities DL_i before the fault detection.

<u>Simulation Results</u>

During simulation we considered a stationary user situated in Moscow and the initial conditions for the 21 Primary Satellite Constellation (21+3 active spares)[20]. After preliminary simulation we considered a stationary satellites, too, because of required large time CPU. The influence of this simplification does not essentially decrease the precision of obtained estimates of $\bar{\tau}$, $\bar{\tau}_i$, and $\bar{T}$. Although an antenna mask angle of 7.5 deg in our situation provides 8 visible satellites (PDOP=1.7), the main simulation was carried out in the presence of 6 satellites (PDOP=3.8), which yields difficult conditions for the fault detection and, first of all, isolation (fig.2). The measurements of pseudorange was assumed to receive each second. The range errors were simulated by fast SA model[15] and white measurement noise. The SA had *rms* of 30 m with time constant of 3.5 min. The white measurement noise had *rms* of 10 m. Decorrelation of the residual was realized with α=0.7 according to (7). For all TSCUSUM h and δ/σ_w were chosen equal; δ/σ_w=70 m. Characteristics of suggested algorithm (LSR CUSUM) and described in paper[19] algorithm (LSR GLT) were compared by simulation.

Simulation results for N=6 on determining $\bar{T}$ with respect to threshold are shown on fig.2,3. The values $\bar{T}$ were calculated by 100 runs. One can see that for big $\bar{T}$ $ln(\bar{T}) \sim \sqrt{h}$ for GLT and $ln(\bar{T}) \sim h$ for CUSUM, that is coincided with expected behavior[23]. Further, required $\bar{T}$ was established at 1000 hours. Since matrices S and $H(H^TH)^{-1}H^T$ are non-negative definite and are related one with the other by (3), then $0 \leq S_{ii} < 1$. The greatest and least S_{ii} are S_{11}=0.58 and S_{55}=0.10; it corresponds to fortunate and unfortunate satellite configuration respectively. The fault detection characteristics were obtained by bias simulating in 1 and 5 satellite measurements.

The subsets of satellites which exclude satellite 1 and 5 yield PDOP=3.9 and PDOP=8.1, respectively. Simulation results which were calculated by 1000 runs are shown on fig.4. One can see that TSCUSUM detects a bias B≥170 m (satellite 1) and B≥400 m (satellite 5) under $\bar{\tau} \leq 10$ s. Minimum levels of the detectable biases by GLT are 300 m and 700 m, respectively.

If equality (8) is numerically expressed for 1 and 5 satellites a failure is transformed into horizontal position error by coefficient 0.30 and 0.49 respectively. (Maximum coefficient is 0.95 for satellite 3.) Thus, the present integrity requirement for nonprecision approach - to detect a horizontal error (2drms) of 550 m[11] within 10 s - is satisfied. However, it need even now to be orientated towards maximum horizontal error of 200-300 m[24]. If LSR GLT is used the last requirement can not be satisfied under fault satellite 5.

Determined LSR GLT detection and isolation moments of fault satellite was equaled. Probability of the misisolation for satellite 1 with biases 300-150 m was 2.5-7 %, for satellite 5 with biases 700-350 m was 22-40 %. At first we considered the simplest LSR CUSUM isolation algorithm. It was that the number of fault satellite corresponds to the number of TSCUSUM which detects a fault and the isolation condition was the same that of LSR GLT. Probability of the misisolation of the LSR CUSUM is about 0-2 % and 2-18 %, respectively. Simulation results of suggested isolation algorithm are shown on fig.5.

Performances for satellite 5 are obviously unacceptable. This is stipulated by bad separation of the faults of satellites 4, 5, and 6. Indeed, the matrix $\tilde{S}$ that consists of the elements $S_{ij}/\sqrt{S_{ii}S_{jj}}$ is:

1.00	-0.55	0.69	-0.67	-0.32	-0.13
-0.55	1.00	-0.98	-0.25	-0.62	0.90
0.69	-0.98	1.00	0.07	0.47	-0.81
-0.67	-0.25	0.07	1.00	0.92	-0.65
-0.32	-0.62	0.47	0.92	1.00	-0.90
-0.13	0.90	-0.81	-0.65	-0.90	1.00

Underlined elements of S point out bad separation of a faults. It is clear that only satellite 1 is isolated well. For satisfactory isolation it need be used the satellites as much as possible. The configuration from 8 satellites has matrix $\tilde{S}$ as follows

1.00	-.31	.43	-.33	-.18	.03	-.36	-.39
-.31	1.00	-.05	-.03	-.75	.20	.08	-.39
.43	-.05	1.00	.11	-.50	-.85	.32	-.30
-.33	-.03	.11	1.00	.34	-.30	-.41	-.49
-.18	-.75	-.50	.34	1.00	.19	-.36	.33
.03	.20	-.85	-.30	.19	1.00	-.55	-.06
-.36	.08	.32	-.41	-.36	-.55	1.00	.68
-.39	-.39	-.30	-.49	.33	-.06	.68	1.00

The isolation condition is cardinally changed, however, separation of the fault of satellite 3 is still slightly difficult.

V. Inertial Measurement Unit Degradation Monitoring

If RAIM is available the GNSS information can successfully be used for monitoring of inertial measurement unit. The most difficulty is the detection of soft faults which are reduced to brought about the degradation of sensors: gyros and accelerometers.

Simple and effective method of the detection of IMU soft faults is to process the residuals of hybrid Kalman filter by CUSUM [16]. The more informative residuals about the fault are the velocity residuals. In designing the IMU monitoring, GNSS information being passed through RAIM can be assumed to be reliable. Parameter δ/σ_w for TSCUSUM is selected for typical level of sensor degradation which need be detected by simulation. Threshold h is set in accordance with $\bar{T}$ and δ/σ_w. Specifically, if IMU corresponds to an usual commercial strapdown INS it is desirable to detect the sensor degradation beginning from 6-8 nominal *rms* gyros error and 40-80 nominal *rms* accelerometers error [16]. Parameter δ/σ_w can be selected as starting with typical degradation levels which are twice greater than it's minimal fault levels.

In simulation the velocity measurement noise (*rms*) was assumed to equal 0.1 m/s. The step size for the fault monitoring was equaled to 10 s. Required $\bar{T}$ was set to 10000 hours. If fault level of "horizontal" gyro equals to 15 nominal *rms* errors fault is mainly detected at 4-6 min. It should be noted that using special Kalman filter for IMU monitoring which differs by state vector from nominal hybrid filter can improve the characteristics of IMU monitoring.

VI. GNSS/Inertial Integrity Monitoring Considerations.

In previous sections GNSS and IMU monitoring (in the sense of soft fault) are considered separately. It was shown that the fault detection and, first of all, isolation under availability of 6-8 satellites can be insufficiently effective. This problem can be resolve by joint using the satellites of GPS and GLONASS networks. GNSS receiver must has a possibility to work with all-in-view satellites or at least with 10-12 of them. In addition to, hybrid GNSS/inertial system has additional reserves. It was shown that, when low precise IMU of AHRS class is used, the position determination precision of hybrid system without GNSS information is during 1-3 min maintained. This result can be used to improve the GNSS/inertial integrity monitoring. As been pointed out, the fault isolation can be needed much more time then the fault detection. Therefore, following ways can be useful to process the information after the fault detection:

1. GNSS/inertial hybrid solution is formed without GNSS information until the fault satellite is isolated.
2. After the fault is detected, several (2-4) satellites which probably contain a fault are defined at once or after a little delay. The decision variables can be the quantities DL_i (4). GNSS/inertial hybrid solution is formed without processing of the measurements of selected satellites up to the fault isolation.

Of course, it is assumed that the fault of one satellite and IMU does not occur simultaneously.

VII. Conclusions

GNSS/inertial hybrid solution has synergistic properties both owing to precision increasing and the integrity monitoring improving. The RAIM algorithm plays one of the main roles in GNSS/inertial system or GNSS receiver software. It is reasonable; the RAIM algorithms are grouped in two categories: least squares solution and Kalman filter solution. Suggesting method (LSR CUSUM) is based on recurrent processing the components of residuals vectors which are formed by the LSR. For the detection of shift in the satellite measurement

TSCUSUM is used; for the isolation of fault satellite the quantities which are the sum of normalized components of residual vector are used. In connection with necessity to take into consideration the SA the parameters of suggested RAIM algorithm are obtained by simulation. Simulation results show that the fault detection by the LSR CUSUM is better with respect to known LSR GLT. However, if a number of used satellites is small (N = 6-8), the fault detection and, especially, isolation characteristics can be unsatisfactory. Therefore, it is specially important that the GPS and GLONASS satellites are used. For civil aviation aims it would wait wide to use the GNSS receivers (and also embedded) with 10-15 channels, which can work both GPS and GLONASS networks.

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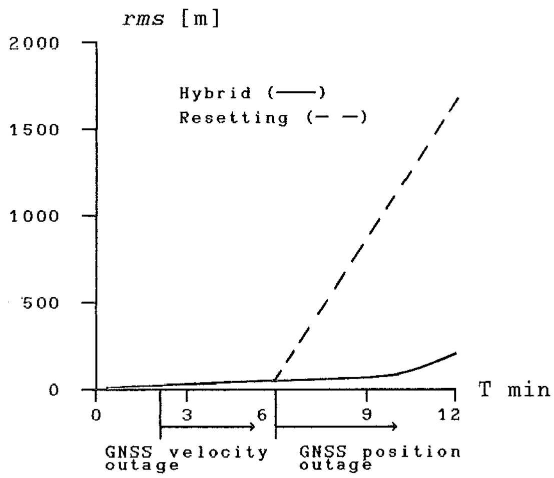

Figure 1. Comparison of GNSS/Inertial Hybrid (by Kalman Filter) and Resetting Solutions Precision

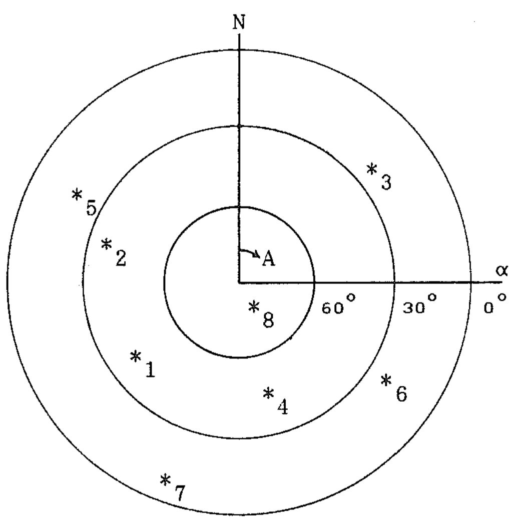

Figure 2. Satellite Positions

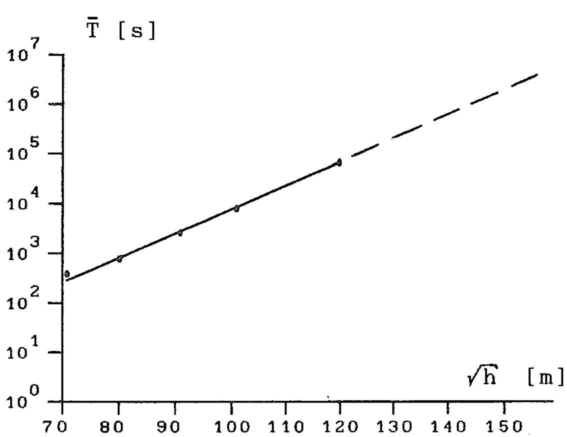

Figure 3. Mean Time before False Alarm versus Square Root of Threshold (GLT)

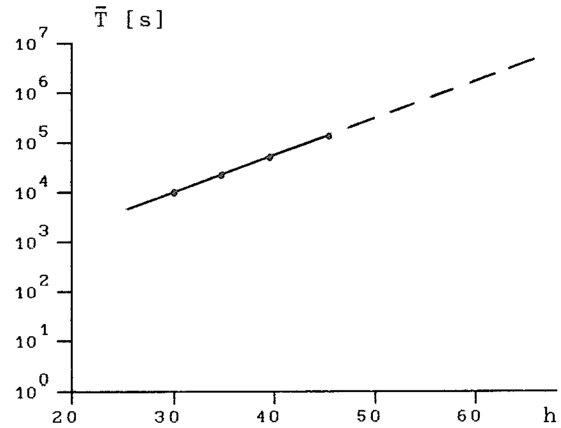

Figure 4. Mean Time before False Alarm versus Threshold (CUSUM)

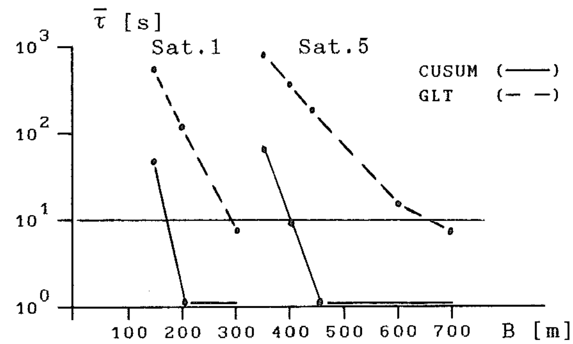

Figure 5. CUSUM and GLT Mean Time Delay versus Measurement Bias

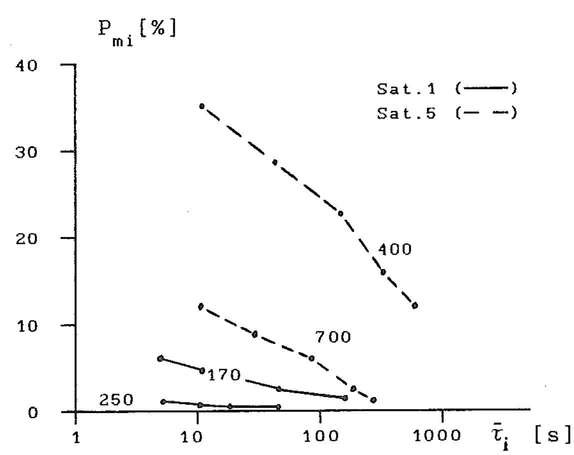

Figure 6. Probability of the Misisolation versus Mean Time Delay