Onboard Autonomous Integrity Monitoring using Intersatellite Links

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BIOGRAPHY

Robert Wolf studied Aerospace Engineering at the Technical University of Munich. In 1995 he received his diploma degree and entered the Institute of Geodesy and Navigation, University FAF Munich, as a research associate. He worked in the field of hybrid GPS / INS navigation and later on precise orbit simulation and orbit estimation. He contributed to German and European studies concerned with onboard satellite state estimation and inter satellite ranging. Since 1999 he is working for IfEN GmbH. He is currently involved in the development of the EGNOS CPF Check Set algorithms and integration into the EGNOS end-to-end simulator.

ABSTRACT

The integrity of the broadcast ephemeris and clock parameters plays an important role in the frame of the GNSS 2 design. In order to monitor integrity measurements have to be taken, statistically evaluated and compared to some decision thresholds. One important aspect, driving false alarm rate and misdetection (besides measurement accuracy) is the observation geometry. A way to enhance geometry is using ranging measurements between spacecrafts (intersatellite links).

Although these intersatellite links could be also processed on ground, they have a great potential for autonomous onboard processing. A conceptual design for an onboard orbit estimator has been proposed and implemented. The integrity processing algorithms have been embedded in a medium complex simulation environment. To evaluate performance of the design and algorithms, several types of non-integrity cases like unintended orbit manoeuvres or excessive clock drift have been simulated.

Although integrity is processed autonomously from ground, the onboard processors of each satellite are far from being independent. Induced by the intersatellite links, there is a coupling between the onboard processors of the satellites, additionally driven by the false alarm rate. In fact, as a major issue in a complete autonomous scenario it has been found that there is a threshold for the allowed simultaneous alarms, which - if exceeded – can cause the complete constellation to be "locked" at unhealthy.

This paper describes the integrity algorithms, presents results of a simulation scenario consisting of a complete constellation of autonomous monitored spacecrafts and points out problems and solutions.

INTRODUCTION

To utilize satellite navigation in civil aviation, integrity monitoring plays an important role. Systems like WAAS / EGNOS or LAAS monitor SIS integrity by using ground based measurements. Despite of the increased complexity added to the payload, onboard autonomous integrity monitoring could be a feasible way of providing reliable satellite status information with minimal time to alarm.

An autonomous integrity monitoring system using inter satellite links could look the following way:

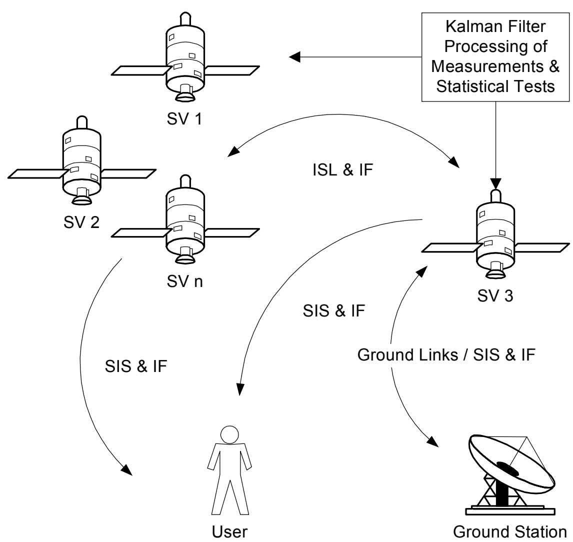

Figure 1 Onboard Integrity Monitoring Scenario

Each satellite is monitoring its own state and broadcasts the resulting integrity flag via signal in space (SIS) to the user as well as via inter satellite link (ISL) to the other space crafts. A scenario like this bears a potential hazard due to the usage of inter satellite links: the measurements to other satellite, which potentially could be faulty may impact the false alarm and misdetection probabilities of the onboard integrity monitor. In the algorithm design, a special countermeasure has been taken to overcome the problem.

In this paper, an autonomous onboard processing scenario is demonstrated using the Galileo constellation, consisting of 30 MEO satellites. It is assumed, that the broadcast ephemeris and clock parameters, valid for the next 24 hours, have already been determined in batch processing and uploaded. The broadcast ephemeris model used is a 15-parameter model derived from the GLONASS broadcast ephemeris.

$$\overline{X}_{Broadcast} = \left(x_0, y_0, z_0, \dot{x}_0, \dot{y}_0, \dot{z}_0, a_{x0}, a_{y0}, a_{z0}, a_{x1}, a_{y1}, a_{z1}, a_{x2}, a_{y2}, a_{z2}\right)$$

Whereas the residual acceleration in the GLONASS ephemeris computation is constant over the period of validity, this extended model uses a 2nd degree polynomial expression.

$$\begin{aligned}
\ddot{x}_{Res} &= a_{x0} + a_{x1}\left(t - t_0\right) + a_{x2}\left(t - t_0\right)^2 \\
\ddot{y}_{Res} &= a_{y0} + a_{y1}\left(t - t_0\right) + a_{y2}\left(t - t_0\right)^2 \\
\ddot{z}_{Res} &= a_{z0} + a_{z1}\left(t - t_0\right) + a_{z2}\left(t - t_0\right)^2
\end{aligned}$$

INTEGRITY ALGORITHM

Each satellite has an onboard processor, processing ground and intersatellite links. The onboard processor uses a Kalman filter with the following state vector.

$$\overline{x} = \begin{pmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta T \\ \Delta \dot{x} \\ \Delta \dot{y} \\ \Delta \dot{z} \\ \Delta \dot{T} \end{pmatrix}$$

And the following simplified transition matrix

$$\Phi = \begin{pmatrix}
1 & 0 & 0 & 0 & \Delta t & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & \Delta t & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & \Delta t & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & \Delta t \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{pmatrix}$$

At each epoch, the error state x and covariance matrix P are propagated by

$$\tilde{\overline{x}}_K = \Phi \cdot \hat{\overline{x}}_{k-1}$$

$$\tilde{P}_K = \Phi \cdot \hat{P}_{k-1} \cdot \Phi^T + Q$$

The process noise matrix Q is a diagonal matrix, adding a small amount of noise to each state.

To obtain the observations, the nominal ranges to the ground stations and satellites have to be computed.

$$\overline{r}_{LOS} = \overline{r}_{SV} - \overline{r}_{GS}$$

$$\overline{r}_{LOS,ISL} = \overline{r}_{SV} - \overline{r}_{SV,ISL}$$

The positions of the satellites are derived from the broadcast ephemeris and are therefore referenced in the earth-centred-earth-fixed frame. The range is derived from the magnitude of the line of sight vector

$$R_{GS}^{SV} = \left|\overline{r}_{LOS}\right|$$

The measurement vector z is derived from

$$\overline{z} = \begin{pmatrix} z_1 \\ z_2 \\ \dots \\ z_n \end{pmatrix}$$

where the i^{th} row consists of the measured range minus the computed range for one intersatellite link

$$z_i = R_{SV_i,ISL,measured}^{SV} - R_{SV_i,ISL,Computed}^{SV}$$

or the same value for one ground link

$$z_j = R_{GS_j,measured}^{SV} - R_{GS_j,Computed}^{SV}$$

The observation matrix H is

$$H = \begin{pmatrix} h_1 \\ h_2 \\ \dots \\ h_n \end{pmatrix}$$

with each row containing the partial derivative for the measurement with respect to the Kalman filter states

$$h_i = \begin{pmatrix} \frac{x^j_{i,LOS}}{R^j_i} & \frac{y^j_{i,LOS}}{R^j_i} & \frac{z^j_{i,LOS}}{R^j_i} & 1 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Before the Kalman filter routines are executed, the covariance matrix of the a priori residuals

$$\mathbf{E} = \bar{e}^T \cdot \bar{e}$$

with

$$\bar{e} = \bar{z} - H \cdot \tilde{\tilde{x}}$$

is tested to exclude faulty measurements. The i_{th} measurement, and therefore the i_{th} row of the observation matrix H would be excluded if the following relationship holds

$$T_{i,i} > 9 \Rightarrow \text{Measurement i excluded}$$

with

$T_{i,i}$ diagonal element of matrix T

$$T = E \cdot \left(H \cdot \tilde{P} \cdot H^T + R\right)^{-1}$$

which is the covariance matrix of the a-priori residuals times the inverse of the state covariance matrix P mapped into the residual domain inflated by observation noise. This formulation is close to the equation for the Kalman gain and is therefore proportional to the weight this particular measurement will have. The test is formulated in way that a measurement must not exceed 3 σ, which translates to approximately 99.86 % probability if a Gaussian distribution is assumed.

Exclusion of measurements can have 4 possible reasons:

1. sending SV is faulty
2. receiving SV is faulty
3. signal propagation path and local effects (biased measurement)
4. high measurement noise

A decision logic has to decide if only the measurements where faulty (noise / bias) or if there is a real satellite integrity problem. A majority logic proved to be the right criterion: if 50 % or more of the valid observations had to be removed, the onboard integrity monitor flags the satellite unhealthy.

$$\frac{N_{removed,meas}}{N_{valid,meas}} \geq 0.5 \Rightarrow \text{SV Integrity flag = "unhealthy"}$$

Note that in this simulation the information "SV n permanently removed by a number of k onboard processors" is not further exploited, but could also serve as an integrity indicator.

After removal of suspicious observations, the Kalman routines are executed. Note that the Kalman gain matrix has to be recomputed using the reduced Observation matrix H_{red}, if measurements have been removed.

$$K = \tilde{P} \cdot H^T_{red} \left(H_{red} \cdot \tilde{P} \cdot H^T_{red} + R\right)^{-1}$$

The updated estimates of covariance and state are then computed by

$$P = \left(I - K \cdot H_{red}\right) \cdot \tilde{P}$$

and

$$\hat{x} = \tilde{\tilde{x}} + K\left(\bar{z}_{red} - H_{red} \cdot \tilde{\tilde{x}}\right)$$

After the measurement update of the Kalman filter, a Chi-Square test is performed

$$\frac{s^2}{n \cdot \sigma^2} > \varepsilon \Rightarrow \text{SV Integrity flag = "unhealthy"}$$

with n being the number of valid observations and

$$s^2 = \sum_i \hat{e}_i^2$$

the sample variance of the a-posteriori residuals.

$$\hat{\bar{e}} = \bar{z} - H_{red} \cdot \hat{x}$$

The model variance is derived from the a-posteriori covariance matrix

$$\sigma^2 = \frac{1}{n} \operatorname{Trace}\left(H \cdot \hat{P} \cdot H^T\right)$$

The sample variance is assumed to be Chi Square distributed, thus ε is derived from a Chi Square distribution with n-1 degrees of freedom.

The estimated state is used as further criterion to estimate the orbit and clock error. It must not exceed a predefined threshold, otherwise the satellite is flagged unhealthy.

$$x_i > e_i \Rightarrow \text{SV Integrity flag = "unhealthy"}$$

Because the position as well as the velocity error is estimated, the condition above can be evaluated also to detect a ramp error, i.e. a slow drift in the position and clock error states. In the simulations performed however, a ramp did not result immediately in an unhealthy status.

The following figure summarizes the process flow.

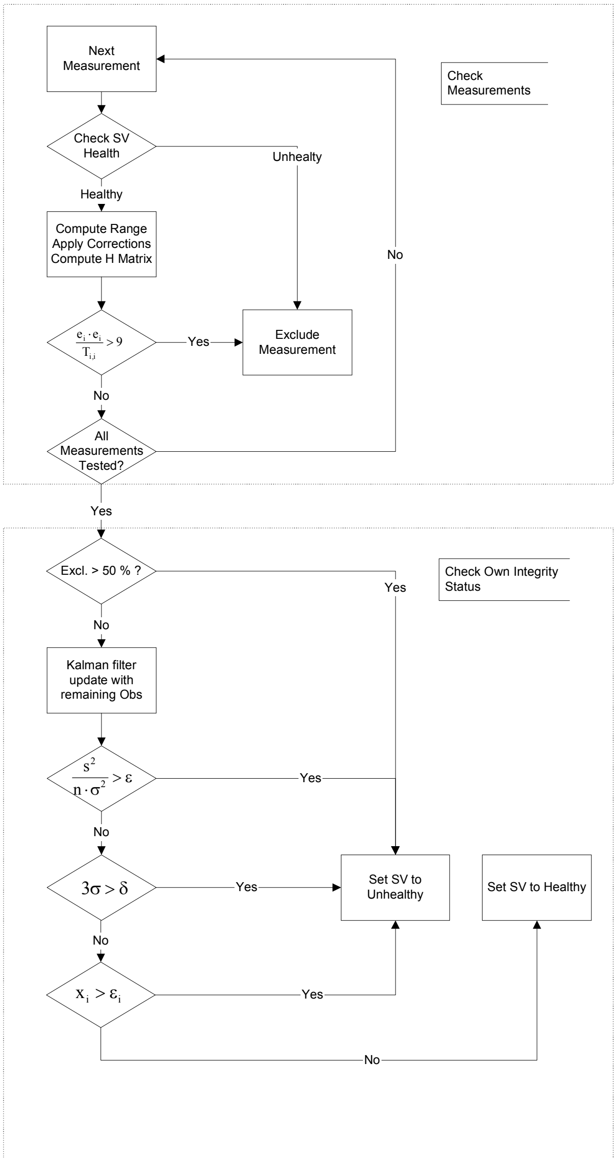

Figure 2 Process Flow of the Onboard Integrity Monitor

USER POSITION ERROR DUE TO NORMAL ORBIT AND CLOCK DEGRADATION

To evaluate the effect of orbit and clock degradation, a static user at Munich (Lat: 47° / Lon: 11°) has been assumed, which computes his position using all satellites in view. The satellites positions are computed using the broadcast parameters. The broadcast clock parameters have not been computed, but are assumed to be applied as well. Thus only the residual degradation effect has been modeled by random walk on the frequency and the resulting error has been added to the range.

In the following simulation, no integrity monitoring takes place. The predicted and uploaded broadcast ephemeris, as well as the clock are subject to degradation. The following two figures show examples of the simulated orbit and clock errors.

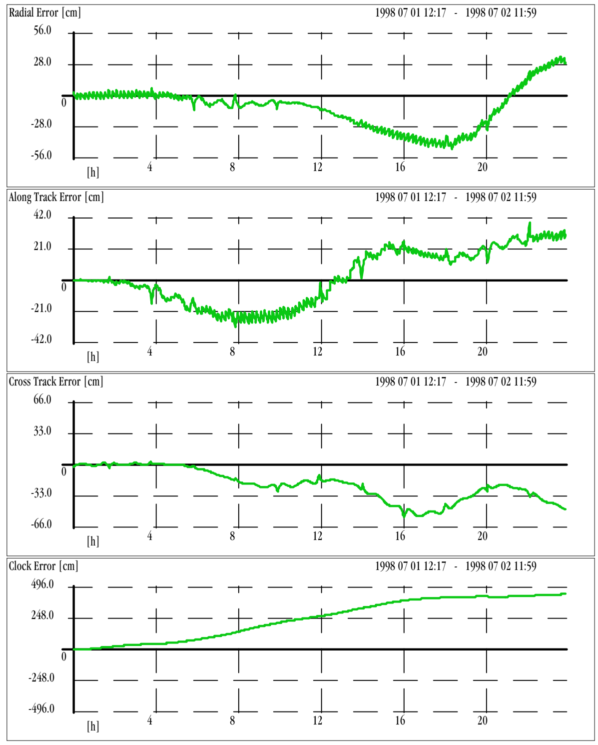

Figure 3 Orbit and Clock Degradation of SV 26

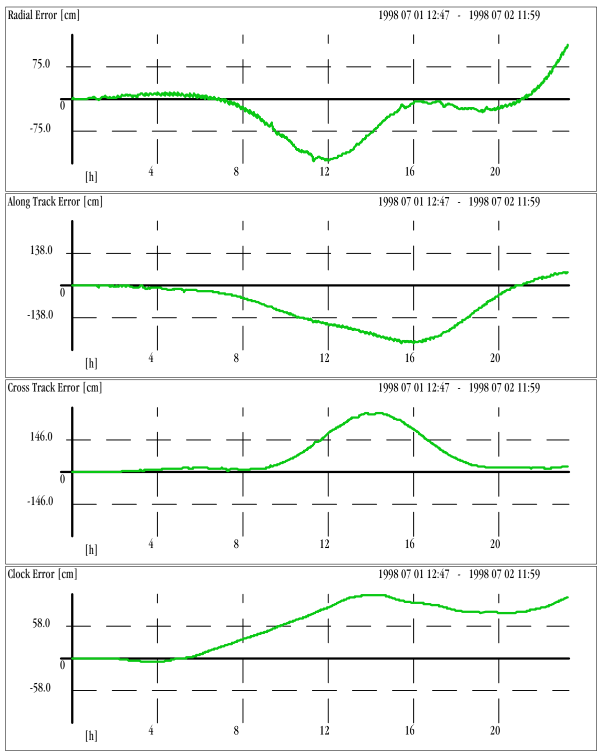

Figure 4 Orbit and Clock Degradation of SV 10

If a user computes the satellite positions using the broadcast parameters, his positioning performance will decrease due to the degraded orbit and clock parameters. Remember, the broadcast ephemeris have been derived from a predicted trajectory. In the same way, the clock parameters would have also been derived from prediction. The following figures show the users positioning error over time, and in the horizontal plane.

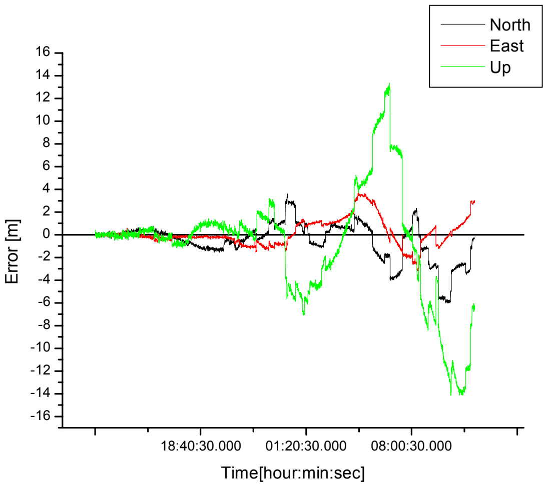

Figure 5 User Position Error over Time

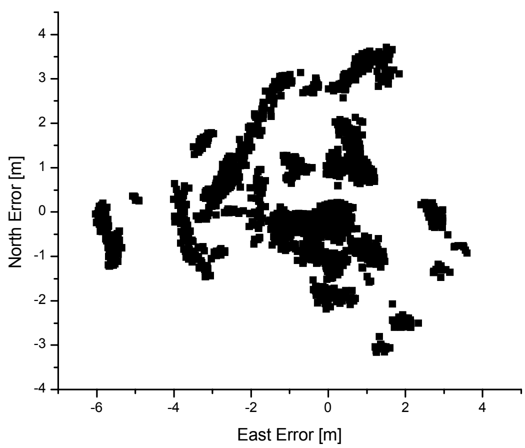

Figure 6 User Horizontal Position Error

After nearly 24 hours, the users vertical error can be up to 15 meters, mostly due to the SV clock error. However, to overcome the problem in normal system operation, the orbit and clock parameters would be updated at a higher rate than 24 hours, say every 6 hours, to prevent excessive positioning service degradation. This would keep the position error below 2 meters.

USER POSITION ERROR DUE TO SATELLITE FAILURE

But not only the normal orbit degradation impacts the user position. If something happened with the satellite clock, say an excessive increase in frequency (clock drift), this could not be overcome by frequent parameter updates. Especially if the integrity requirement on the satellite position and clock is high, as would be the case in airborne navigation, the user can not rely on predicted orbits only. In the following simulation, one 2 Newton thruster of the orbit control system of SV 26 is fired, resulting in a small 0.1 m/s velocity increment. At the time the event takes place, the satellite is in view of the user position.

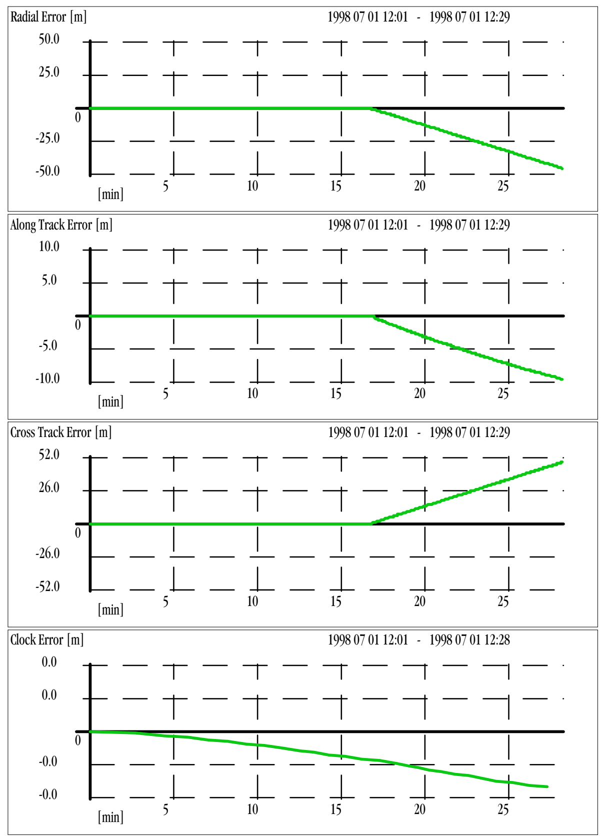

Figure 7 SV 26 Orbit Error due to 2N Thrust / 0.1 m/s Delta V

The user computes the satellites position now with orbit information, which is not applicable any more. If the user does not monitor the integrity of his position computation using RAIM, an increasing position error will be the result.

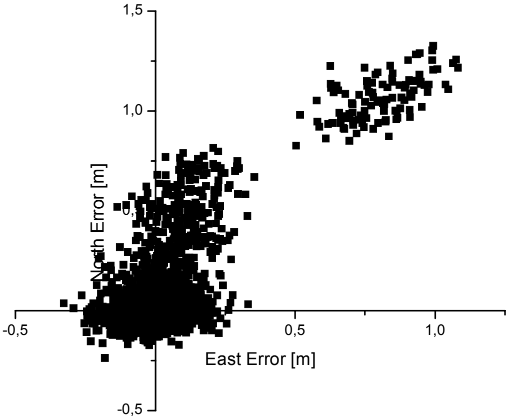

Figure 8 User Position Error in Horizontal Plane

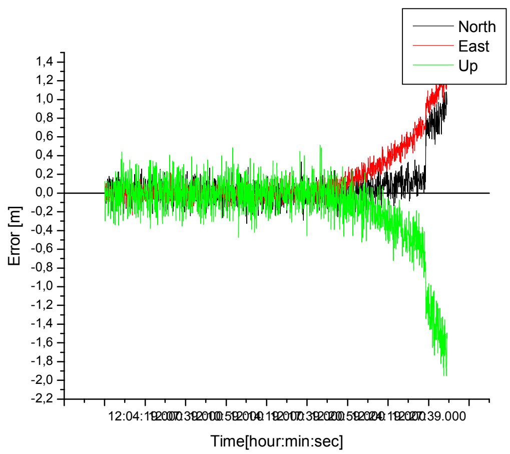

Figure 9 User Position Error over Time

USER POSITION ERROR WITH ONBOARD INTEGRITY MONITORING

The next four simulations have been conducted using the onboard integrity monitor described above. This means, there are 30 Kalman filters running in parallel. The simulation has been set up in a way that each integrity monitor is processing only measurements and information available at the satellite. It is assumed that the satellites broadcast their integrity status via ISL to the other satellites, as well as to the user via SIS, which then becomes available in the next epoch. This translates to a system latency of 1 second. If a user receives an "Unhealthy" flag from a satellite, this SV is excluded from the position solution. The same applies to the satellites monitoring their own status using ISL's. A received unhealthy flag leads to exclusion of this particular link.

In the simulation, a non integrity case is assumed, if the resulting worst case ranging error exceeds 1 meter. The alarm threshold values for the state vector limit test have been chosen the following way:

State	Alarm Threshold	Result
X, Y and Z Estimated Position Error	1 Meter	Integrity flag is set to UNHEALTHY
Clock Offset	1 Meter	Integrity flag is set to UNHEALTHY
VX,VY,VZ Estimated Velocity Error	2 cm/s	Warning Only
Clock Drift	2 cm/s	Warning Only

Table 1 Alarm Threshold for State Vector Limit Test Detector

Strong Orbit Manoeuvre

The first simulated non-integrity case is an orbit manoeuvre with 50 Newton thrust, producing a velocity increment of 0.5 m/s in the along track direction. The affected satellite is again SV 26, which is visible to the user at a medium elevation. The resulting orbit error over time is depicted in the figure below.

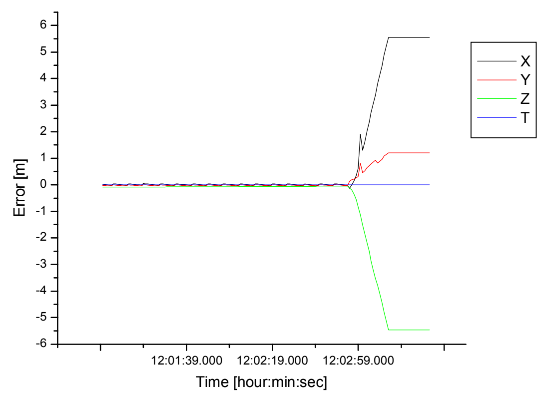

Figure 10 Absolute Orbit Error of SV 26

In the Kalman filter, the orbit error is estimated. The following figure shows the relative orbit error of satellite, i.e. estimated versus true error.

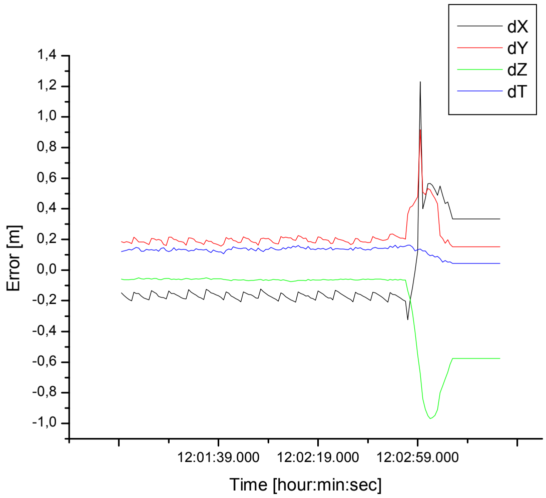

Figure 11 Estimated vs. True Error for SV 26

As can be seen from the figure above, the state is not estimated very well, due to the high process noise required to keep the filter adaptable to fast changes. The error estimate of such a Kalman filter is far too noisy to be used as a correction value, but it is sufficient to detect orbit errors. To evaluate the reaction of the onboard processor to the injected fault, the error log of all satellites has been recorded. Due to the lengthy format, the error logs of all simulations have been omitted in this paper. An example is shown below. It has the following format

<Year> <Month> < Day> <hour:min:sec> SV <ID> <Error Mess.>

```
1998 07 01 12:02:59.000 SV 26 Ramp Detected [Position]
1998 07 01 12:03:00.000 SV 26 Ramp Detected [Position]
1998 07 01 12:03:00.000 SV 26 Non Detected Position Error =
1.351 m
...
1998 07 01 12:03:03.000 SV 26 Ramp Detected [Position]
1998 07 01 12:03:03.000 SV 26 Limit Exceeded [Position]
1998 07 01 12:03:03.000 SV 26 Check Result: UNHEALTHY
1998 07 01 12:03:04.000 SV 00 Removed Unhealthy SV ID 26
1998 07 01 12:03:04.000 SV 01 Removed Unhealthy SV ID 26
1998 07 01 12:03:04.000 SV 02 Removed Unhealthy SV ID 26
...
1998 07 01 12:03:04.000 SV 26 Chi Square Test Failed
1998 07 01 12:03:04.000 SV 26 Ramp Detected [Position]
1998 07 01 12:03:04.000 SV 26 Limit Exceeded [Position]
```

Figure 12 Example of simulation message log

The event takes place at 12:02:55. Four seconds later, a position drift is detected (the ramp detector has a threshold of 2 cm/s). At this time, the satellites position is still within the 1x1x1 meter cube and therefore still considered to be integer. Another second later, the integrity limit of one meter is exceeded by 0.3 meters, but the estimated error is still within the limit. This is the first time a real non-integrity case exists, because the user has a hazardous misleading information. He would still use SV 26 although the orbit parameters are not correct anymore. The position error remains undetected for another two seconds and grows to nearly 2 meters, before the estimated position error is large enough to trigger an UNHEALTHY. From now on, the user is alarmed and will discontinue to use SV 26.

In the next epoch, all other satellites will exclude SV 26 from their integrity processing. One second after the state limit check has detected the error, the Chi Square test also raises an alarm.

As a result of the simulation, the user has been alarmed 3 seconds after occurrence of the non-integrity situation, which is an acceptable time to alarm event for a CAT I landing (6 seconds limit). The maximum range error has been 1.8 meter (0.8 meter above the limit), but the error in the user position has been negligible (see figure below).

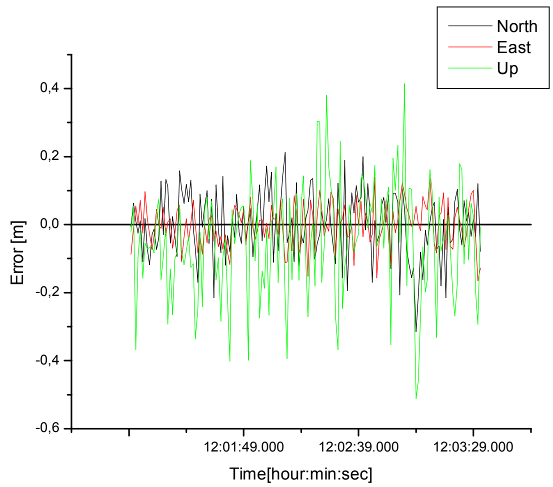

Figure 13 User Error during Manoeuvre

Weak Orbit Manoeuvre

In the next simulation, a weak thrust of 2N results in a velocity increment of 0.1 m/s in the cross track direction. Affected satellite is again SV 26. The next two figure show again true and estimated versus true error of the satellites onboard processor.

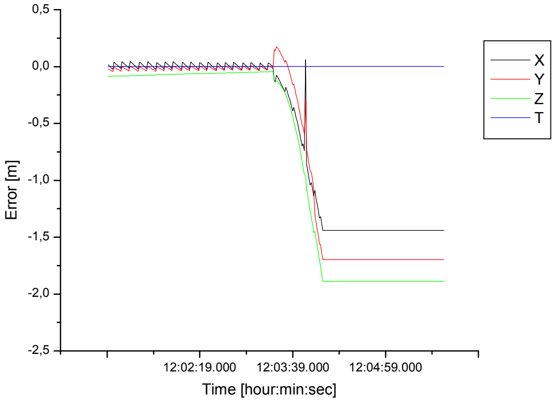

Figure 14 Absolute Error SV 26

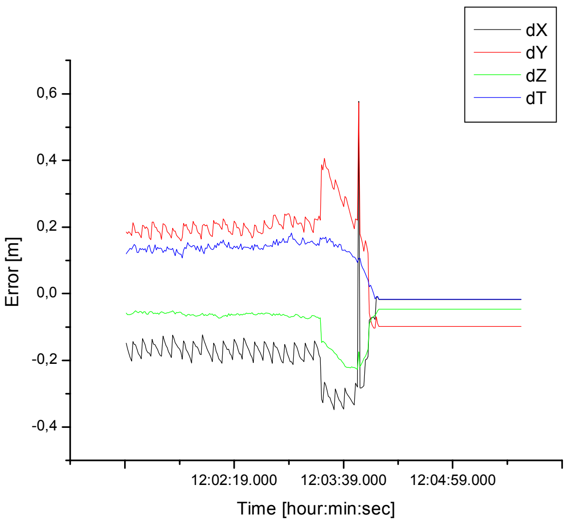

Figure 15 Estimated vs True Error SV 26

The event starts at 12:03:22. Twenty seconds later, the ramp detector is triggered the first time. First occurrence of a non-integrity event is at 12:03:53, the UNHEALTHY Flag due to position limit excess is raised at 12:03:55, yielding 2 seconds time to alarm. Impact on the user is negligible, as can be seen in the figure below.

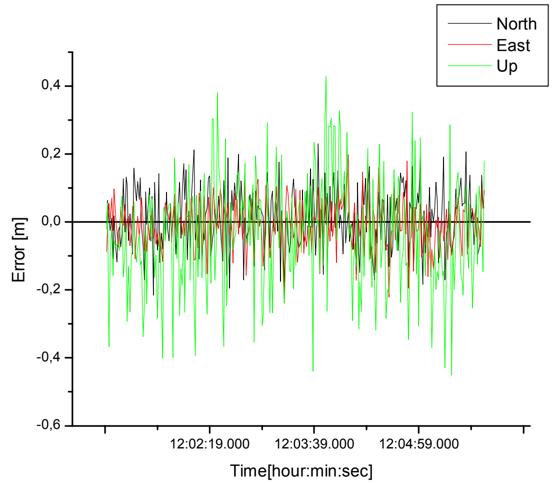

Figure 16 User Position Error during Manoeuvre

Clock Drift

The third case simulates a sudden excessive drift of 10^{-10} sec/sec in the clock of SV 04, which is visible to the user at a high elevation. The figures below indicate true and estimation error of the onboard processor.

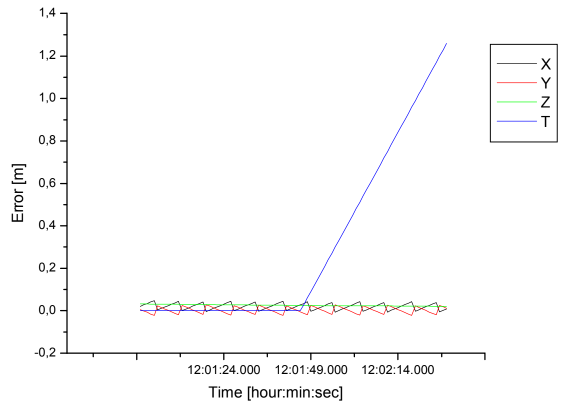

Figure 17 Absolute Clock Error SV 04

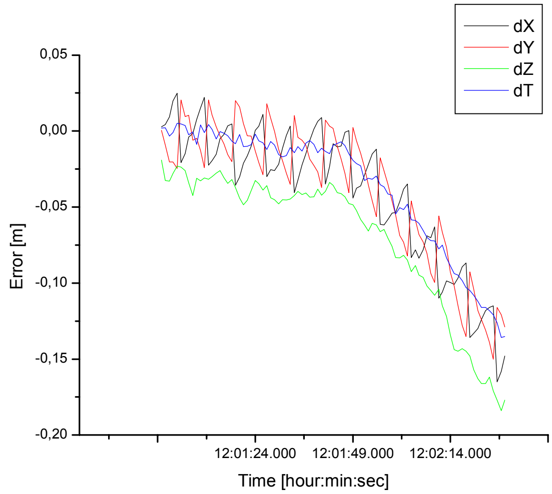

Figure 18 Estimated vs True Error SV 04

The error log summarises the sequence of events: the event takes place at 12:01:47. Four seconds later, the Chi Square test raises an UNHEALTHY, although the true error has not exceeded it's limit yet. The other satellites (as well as the user) immediately exclude the observations to the faulty satellite. In this case, the alarm has to be evaluated not as false alarm, but as an early detection. Although the limit has not been exceeded yet at the time the alarm has been raised, this will however be the case only 15 seconds later. Due to the very early alarm, no error in the user position is caused.

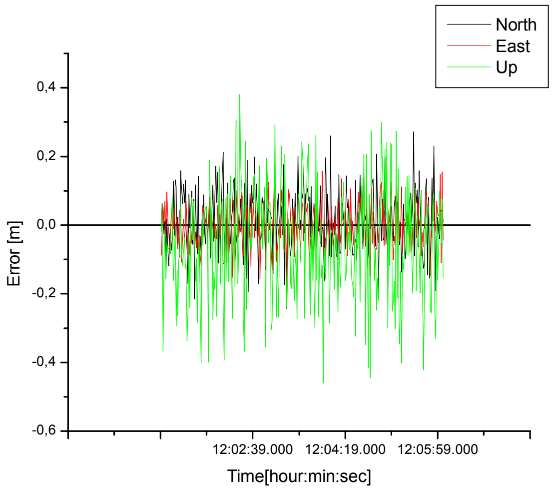

Figure 19 User Error

Clock Jump

The last non-integrity case simulated was a 10^{-8} s clock offset jump on SV 04.

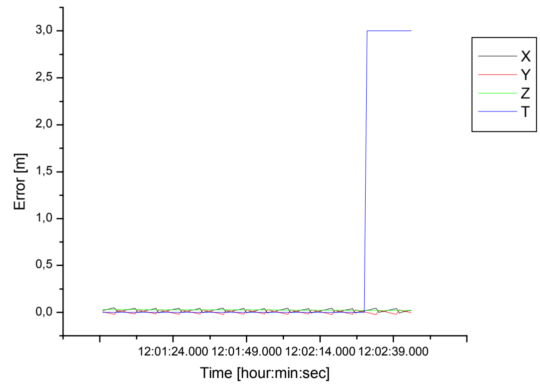

Figure 20 Absolute Error SV 04

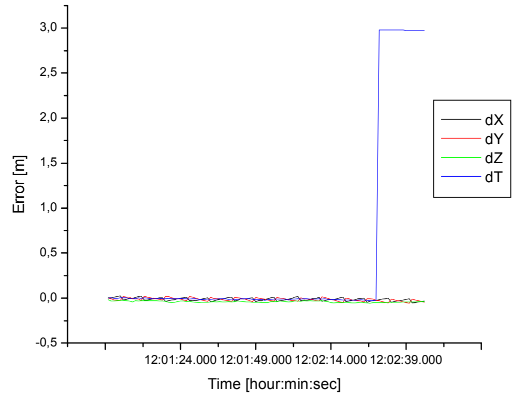

Figure 21 Estimated minus True Error

The event takes place at 12:02:29. The other satellites immediately remove the observation to SV 04 from their Kalman filter, due to a failed test of the a-priori residual. The onboard processor of SV 04 also removes the observations to nearly all other satellites as well as the ground links, due to failed tests of the a-priori residuals. After excluding more than 50 % of all observations, the onboard processor of SV 04 assumes an integrity problem, and raises the UNHEALTHY flag. In the next epoch, the other satellites - as well as the user - remove SV 04 due to the raised UNHEALTHY flag. Time to alarm: 1 second.

Note that the Chi Square test has raised no alarm, although the residuals are high. This is due to the fact that by removing nearly all observations, the covariance matrix P has high values. These are used to normalise the a-posteriori residuals. The Chi Square test is only a good detector, if enough measurements are available.

Due to the high elevation of SV 04, the clock jump of approximately 3 meters leads to a small spike in the altitude error of the user. But the overall impact on the user position error is negligible.

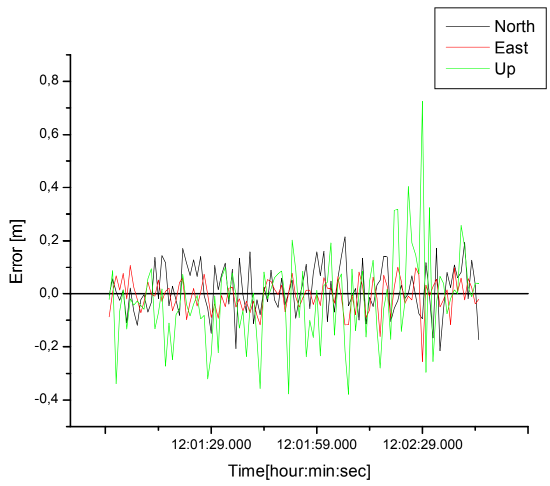

Figure 22 User Error over Time (Spike of Altitude Error at T = 12:02:30)

CONCLUSION

In this paper it has been shown that integrity is monitored best by a combination of 3 different tests:

1. An outlier test to exclude faulty/ noisy measurements combined with majority logic (number of excluded measurements > 50%).
2. A Kalman error estimator to detect slowly increasing errors in position and clock.
3. A Chi Square test to detect quickly increasing errors / jumps

The table below indicates failure type, test triggered first, ranging error and time to alarm.

Failure	Triggered Detector	WRE	TTA
Strong Orbit Manoeuvre	1.) Limit Test 2.) Chi Square Test (One epoch later) (Early Warning by Ramp Test)	1.82 m	3 s
Weak Orbit Manoeuvre	Limit Test (Early Warning by Ramp Test)	1.17 m	2 s
Clock Drift	Chi Square Test	< 1 m	1 s
Clock Jump	Majority Test	3 m	1 s

WRE Worst Range Error at alarm time
TTA Time to Alarm

The quick response of the integrity monitor is due to the high number of available measurements. Especially the inter satellite links contribute not only by adding a significant number of measurements, but also with an improved observation geometry.

The integrity monitoring algorithms do not necessarily need to be executed onboard, however data latency would become unacceptable long if the ISL measurement would have to be downloaded prior to processing by a ground facility.

ACKNOWLEDGMENTS

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