Ensuring the GNSS Onboard Integrity Function Under Adverse Conditions: Feasibility and Flight Test Results

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1 Abstract

With an increasing system and technology performance of satellite navigation components, the Global Navigation Satellite Systems (GNSS) conquer more and more fields of military and civil applications. Due to the undisputed high level of accuracy and its marginal needs of terrestrial infrastructure, satellite navigation is in principle the most suitable candidate for positioning tasks under adverse environments where conventional radio navigation aids fail. Considering this background, the Institute of Flight Guidance and Control participated recently in a flight test program in Lugano, Switzerland supported by the Swiss Federal Office of Aviation (FOCA).

Flight tests were performed under highly dynamic and adverse conditions with the additional use of low-cost inertial information. The landscape in which these test were realized leads to the risk of extensive shadowing of the space vehicles, thus increasing the probability that the GNSS is not available in order to compute a position solution. Additionally, the mountains provide a reflecting surface of the radiofrequency signals. Hence, the possibility of multipath reception is given here as well.

This paper deals with the current means that are used to achieve the accuracy and the integrity that is necessary for high-precision and safety-critical procedures. The methods are discussed briefly and flight test results are presented.

2 Introduction

Satellite navigation systems are very accurate means of determining the user position with passive and comparatively inexpensive user equipment. Since the American satellite navigation system GPS has been declared fully operational, the service of a navigation system is available, which is more accurate than any other medium- or long-range navigation system.

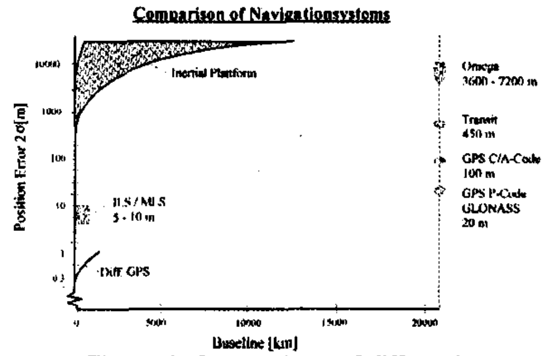

Figure 1: Comparison of different Navigation Systems

As figure 1 shows, satellite navigation systems have the potential to become the most versatile navigation system for short- and long-range navigation applications. In order to fully utilize this potential, a number of factors have to be taken into account which influence the accuracy and the integrity of this system.

3 Satellite Navigation

3.1 Measurement

The position determination with satellite navigation systems is performed by using the 'propagation time measurements' of electromagnetic waves which originate from satellites in specified orbits. These measurements are converted into distances using the speed of light as the known speed of propagation. Basically three types of measurement variables are available : the code-pseudorange, the carrier phase and the doppler-frequency (a derivative of the carrier phase).

The figure 2 illustrates the basic principle of the user position calculation using three measurements. Since the time-scale of the user receiver can not be synchronized with the time scale of the satellites without the help of a high-precision atomic clock, four satellite measurements instead of three are necessary to calculate the 4D user solution (3D position and time).

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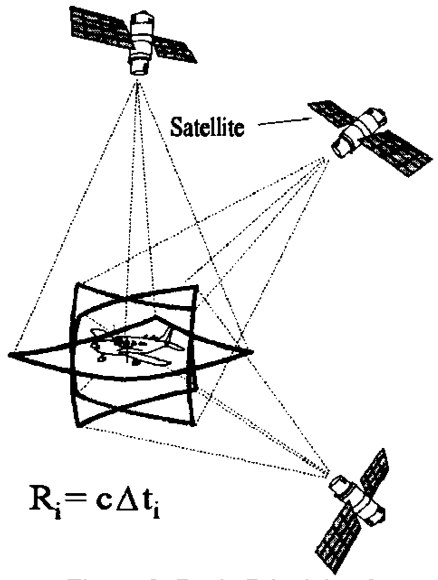

Figure 2: Basic Principle of Position Determination

3.2 Accuracy

To achieve a certain level of accuracy, ground-based differential augmentation systems are needed for the satellite navigation system. These subsystems monitor the navigation signal and broadcast appropriate range corrections to the user by the means of a dedicated data channel (see figure 3).

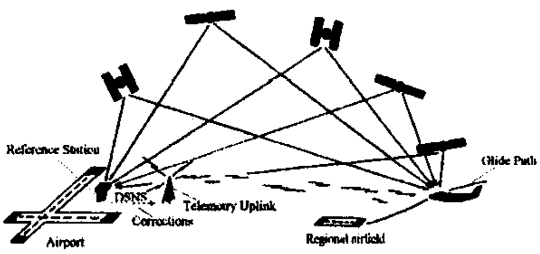

Figure 3: Ground-based Differential Augmentation Systems

Another method to enhance the resolution of the code-base navigation solution is known as carrier-smoothing. Furthermore the carrier-phase relationship between the received and the internally generated signal can be measured and used to increase the position accuracy of the satellite navigation systems

3.3 Integrity

In the context of navigation, the integrity is defined as the 'ability of the navigation system to provide the user with navigation signals that are within specifications or with a notification that the user should not use certain navigation signals' [2]. Thus, the integrity monitoring of the satellite navigation systems is concerned with the quality control of the radionavigation signals. One possible approach is to externally transmit information about the state of the system to the user by means of a dedicated data channel. The other possible approach to integrity monitoring is to perform the monitoring onboard the aircraft.

Since the ground integrity monitoring is not able to detect errors that arise in the vicinity of the user, the onboard integrity monitoring is of essential importance to the satellite navigation system.

3.4 Failure Modes

The errors incurred on the measurements of the satellite navigation system can be divided into three areas. Errors due to the space segment are satellite clock errors and satellite position errors. Further errors occur while the signal travels from the satellite to the receiver (propagation errors). The receiver-antenna combination is the last source of errors (multipath, loss of line-of-sight due to shadowing, interference and jamming).

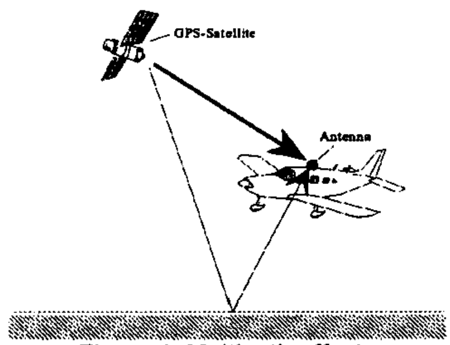

Figure 4: Multipath effects

Unresolved issues are the influence of multipath effects on the achievable position accuracy, in particular in the vicinity of reflecting surfaces (see figure 4), the interference and the deliberate jamming of radiofrequency signals.

4 Integrated Navigation Systems

The basic concept of an integrated satellite-/inertial-navigation system is illustrated in figure 5. The overall accuracy performance of such a system is determined by the satellite subsystem. Sensor errors of both the satellite- and the inertial-subsystem are estimated on-line.

The inertial sensors are an ideal complement to GNSS due to their good dynamic properties, although they can be characterized by a long-term drift as a result of misalignment and gyro errors. Since the inertial-subsystem can be calibrated by the satellite-subsystem and as long as the inertial error properties can be sufficiently modeled, the integrated system can keep the overall position accuracy even during outages of the satellite navigation system.

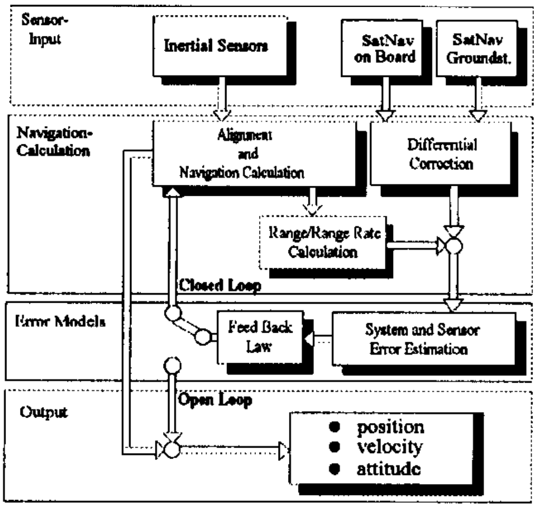

Figure 5: Concept of an Integrated Navigation System

5 Accuracy Aspects of GPS

5.1 Differential GPS

The differential GPS technique is based on a comparison between a precisely determined stationary reference position and a GPS standalone navigation solution for the user position. In this comparison, the errors of the satellite clock, the satellite position and the effects of the atmospheric errors can be determined. Transmitting these error correction information to the user, it is possible to compensate for all the above mentioned errors.

For approach and landing procedures, where there exists a direct line-of-sight between the reference station and the user aircraft, a Local Area DGPS with a customized ultra-high frequency data link can be used. However, for low-level flight tests in valleys and in mountainous areas, this technique is not adequate because the availability of the telemetry UHF data link is reduced due to terrain formations. In these situations, the correction DGPS-signal has been provided via a low-frequency transmitter that has been established by the Institute of Applied Geodesy (IfAG, Germany). The low-frequency data are broadcasted in a format recommended by the Radio Technical Commission for Maritime Services (RTCM).

A parameter affecting the achievable accuracy while applying the differential corrections to the user standalone GPS navigation process is the baseline length, i.e. the distance between the transmitter of the reference station and the user aircraft.

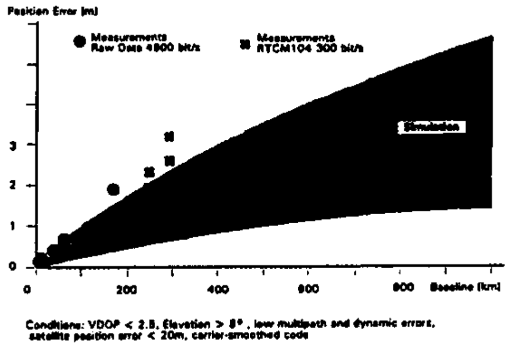

Figure 6: Accuracy of Differential GPS

However, using the low-frequency data link, another parameter becomes important. Since the transmission rate of the differential corrections is significantly lower, the age of the correction data has an influence on the achievable accuracy. This is shown in figure 6, where the accuracy that has been achieved with Local Area Differential GPS and with Wide-Area Differential GPS using the RTCM data format is shown.

5.2 Carrier-Phase Solutions

With standard algorithms for DGPS processing like carrier-phase smoothed code measurements, it is possible to achieve an accuracy in the m-range. However, with the application of GPS phase ambiguity resolution techniques, the achievable accuracy can be increased down to a cm-level. With this level of accuracy, it is possible to use the satellite navigation system as a reference system for flight inspection purposes.

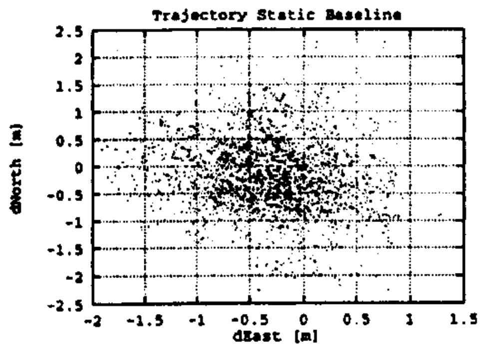

Figure 7: Carrier Phase Position Solution

Figure 7 illustrates the potential of the carrier phase navigation solution in a static test environment. The figures 8 and 9 show the standard deviation of the carrier phase solution for the latitude, longitude and altitude, respectively in a flight test.

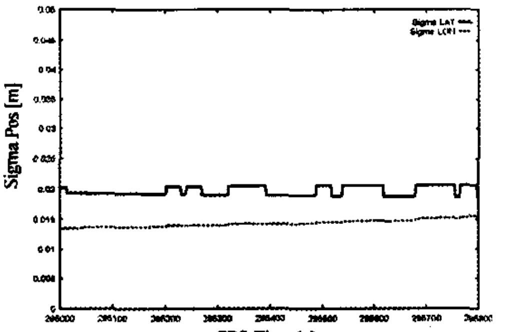

Figure 8: Standard Deviation of Position Solution with Carrier Phase (Latitude and Longitude)

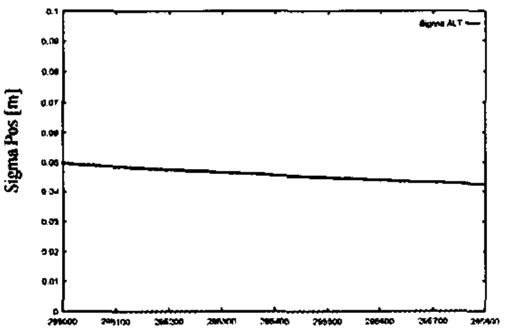

Figure 9: Standard Deviation of Position Solution with Carrier Phase (Altitude)

Since the accuracy of the carrier phase solution approaches the cm-level, the technique of using carrier phase information of satellite navigation systems can be used as a reference system during flight inspection procedures.

Some of the current algorithms for the resolution of the integer ambiguities use static techniques for the initial determination of the ambiguities, and furthermore, rely on continuous satellite tracking during the flight. Yet, it is not feasible for an aircraft to stand on a taxiway and wait, until the search space has been narrowed down to a sufficient level to solve for the ambiguities. Additionally, no continuous tracking of all received satellites can be guaranteed, since the flight path is provided by the ground controllers with aspects of air traffic flow.

Thus, the satellite navigation carrier phase techniques must be able to resolve the ambiguities 'on-the-fly' during the flight. It is very important that these integer ambiguities are solved correctly, since wrong combinations would cause position errors which are sufficiently large to violate the accuracy requirements for precision landings.

In many ambiguity resolution techniques, the pseudorange-residuals of a solution are used as a measure of the quality of the solution. However, in order to generate residuals, a redundancy of at least one satellite is necessary. Thus, a minimum of at least five satellites is needed for the ambiguity resolution techniques.

In mountainous areas such as the Lugano airport, the visibility is obviously limited to an even greater degree than with most other situations. A rigorous preplanning of the measurement times and a placement of the reference station for optimal satellite visibility becomes an issue of even more importance than it is with the differential techniques.

5.3 Integrated Navigation System

In the integrated navigation system an optimal estimator is used as an observer of the navigation process. In the observer, the appropriate error states of both the inertial navigation process and the satellite navigation process are used to estimate the system- and the sensor-errors of the integrated navigation system. The different error-models of the sensors are weighted accordingly to the user dynamic.

Through the use of appropriate error models, the navigation solution (position and velocity) is robust and a high degree of accuracy is achieved. Even with the total short-term loss of the satellite navigation, the achievable level of accuracy using the integrated navigation system is only slightly decreased. This is shown in figure 10, where for a period of 120 seconds, all satellites are masked. If an appropriate error modeling of the errors of the inertial sensors is performed, even 'low-cost' inertial sensors can be used in combination with the satellite navigation system.

6 Lugano Flight Tests

The performance of different onboard integrity monitoring approaches is evaluated using data of the flight test program that has been carried out in Lugano, Switzerland. The Lugano-Agno airport is situated within an extremely mountainous region on the southern side of the Alps. The airport has one concrete runway (RWY 03/21), running approximately north-south with a length of 1350 meters. It is surrounded by mountains as tall as 4000 m. The figure 11 demonstrates the view from an aircraft approaching from the north.

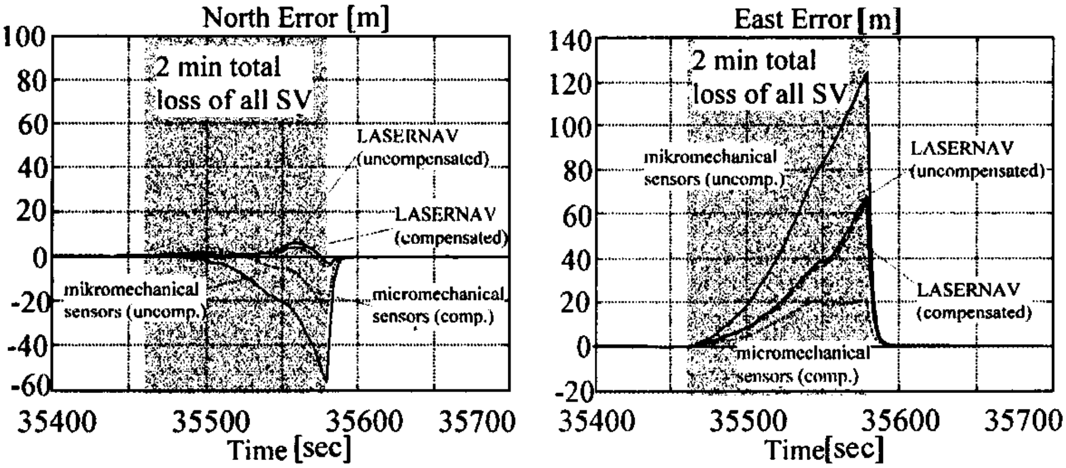

Figure 10: Loss of position precision due to total masking of satellite navigation

Due to mountainous terrain to the north of the airport, the approaches currently take place from the south. A DGPS approach procedure was developed that would save about 10 minutes flight time for aircraft approaching from the north. In the figure 12 the DGPS approach procedure is displayed.

Figure 11: View from an aircraft approaching Lugano-Agno from the north

6.1 Accuracy

6.1.1 Flight Tests

To get an advance estimate of terrain blocking for the ground station, data from a terrain model had been evaluated for a position on the airport runway by the Technical University of Zurich (ETH). This elevation-azimuth blockage diagram is shown in figure 13 overlayed with actual tracking data from a static test.

Each of the vertical lines shows ascent or descent of a satellite. Overlaps with the terrain contour indicate visibility below the model value, blank areas (visible especially between 30 degress and 90 degrees and at 300 degrees of azimuth) indicate hills not included in the model due to model resolution limitations. The high elevation mask that can be experienced at the location of the reference station due to the mountainous landscape is quite obvious.

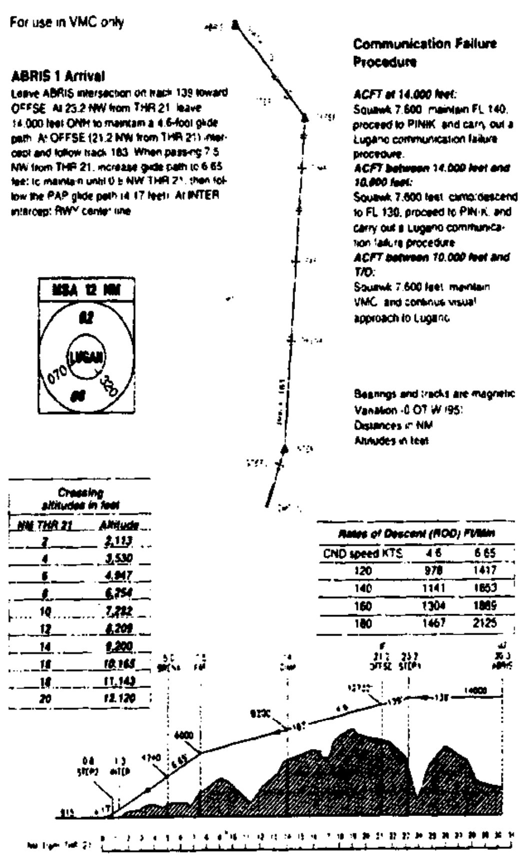

Figure 12: DGPS Approach Procedure

The figure 14 illustrates the ground track of the flight test that was used in the evaluation of the achievable accuracy.

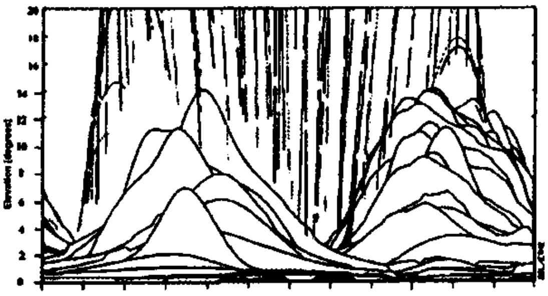

Figure 13 Elevation Mask at the reference station

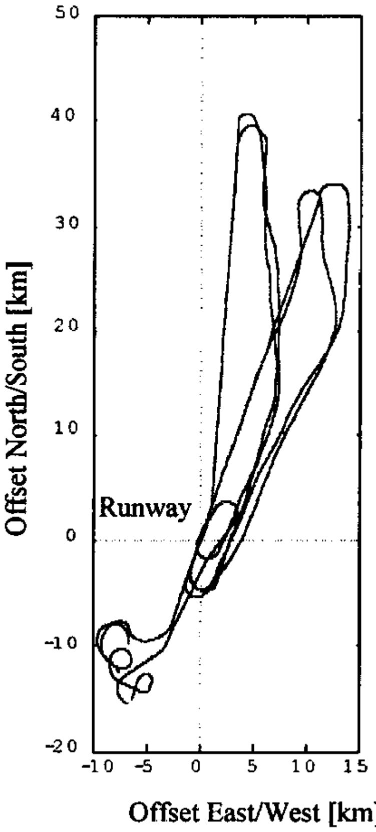

Figure 14: Ground Track of Flight Path

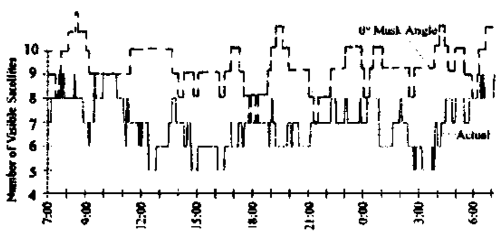

Figure 15: Number of received Satellites

To investigate the quality of the chosen position and reception of the satellite signals a 24h static test was performed. Figure 15 shows the number of satellites received in contrast to the satellites available without terrain masking. As expected, the mountains reduce the number of visible satellites significantly, down to five during several periods of the day.

6.1.2 Accuracy Results

For the one-week trials a GPS-reference station and a laser tracker were set up in the vicinity of the southern runway threshold and surveyed using known geodetic reference points. Two different GPS receivers were used, one of the guidance task at hand, the other as a reference to detect receiver specific errors. As reference systems, both laser tracker and an on-the-fly ambiguity resolution algorithm using pure GPS carrier phase measurements have been used.

As Figure 16a shows, approaches from the north were flown directly and with an offset, starting at FL140. Approaches from the south were planned, too, but interference problems of the GPS signals due to external transmitters in the area shown in the figure forced cancellation of this part of the tests. Figure 16b details the parts of the flight path where telemetry reception was stable, the range of more than 30 km at approach allowed a stable GPS/DGPS-transition.

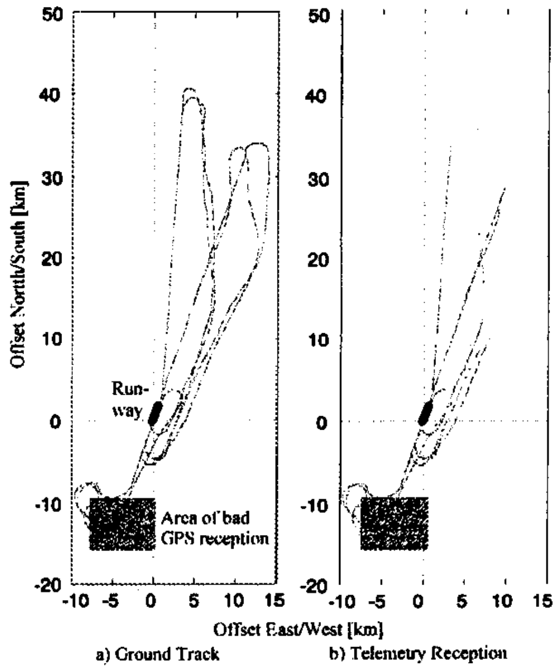

Figure 16: Flight Path with Area of bad GPS reception

As can be seen from figure 16, as well, interference caused loss of GPS L1 signal reception in a relatively large area south of the airport. Approaches from the south could therefore not be performed using GPS-based techniques. In this situation, the source of the

ground-based interference was determined to be constant for all the approaches. But often the interference source might as well be intermittent.
The achieved position accuracy was good (see figure 17), although the lower number of satellites due to the loss of the line-of-sight of low-altitude satellites to the east and to the west of the flown approach increased the error level. At a distance of 1.5 nautical miles from the runway threshold, a shadowing of one satellite by the aircraft caused a deviation in the along-track error.

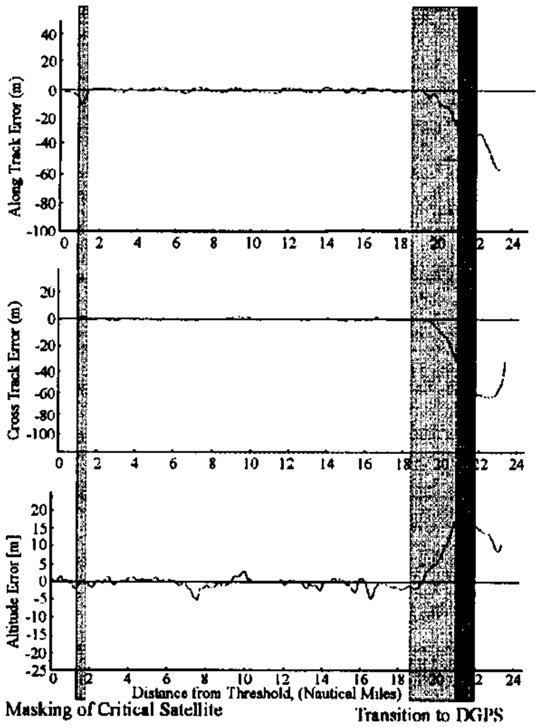

Figure 17: Accuracy during a typical approach

The number of satellites visible from the user station decreases as the aircraft descends toward the threshold. In this case, due to the positioning of the reference station, the number of satellites used for positioning after the transition to DGPS depends mainly on the number of corrections from the ground. Therefore the measurement redundancy needed to allow aircraft maneuvers with subsequent shadowing of further satellites is limited.

6.2 Integrity

6.2.1 Flight Tests

Since the integrity monitoring algorithms are evaluated using simulated errors that are introduced into the measurements, a part of the flight path has to be chosen that contains at least six received satellites (i.e. the minimum requirement for RAIM).

The figure 18 illustrates the horizontal flight path and in figure 19 the height above ground of the particular flight test that is used for the evaluation of the integrity monitoring is displayed.

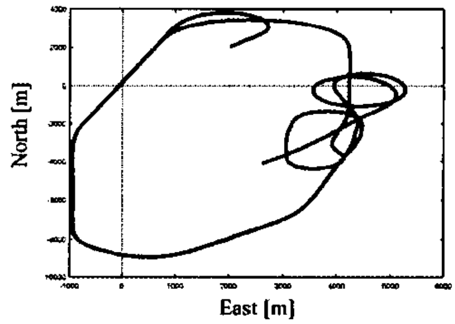

Figure 18 Horizontal Flight Path

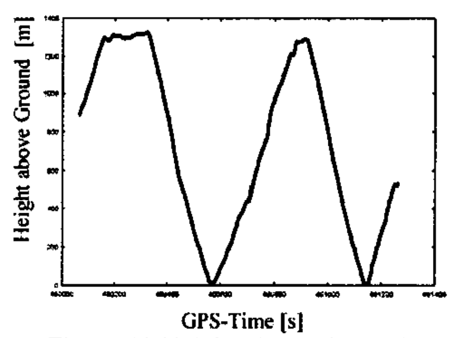

Figure 19 Height above Ground

The figure 20 displays the number of received satellites during that particular flight test. There is only a short time interval, in which six or more satellites are received. Only during this very short period, RAIM can be performed. Only a very small part of the flight test program is usable.

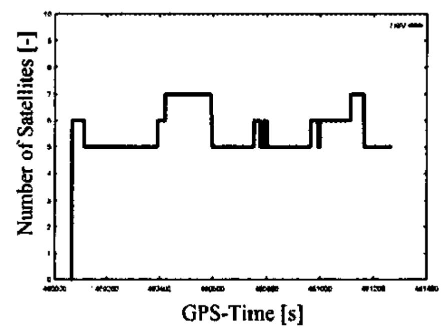

Figure 20: Number of Received Satellites

The errors that have been simulated onto the measured pseudoranges are selected according to the satellite constellation that is depicted in figure 21. The table 1 contains the parameters for the three simulations.

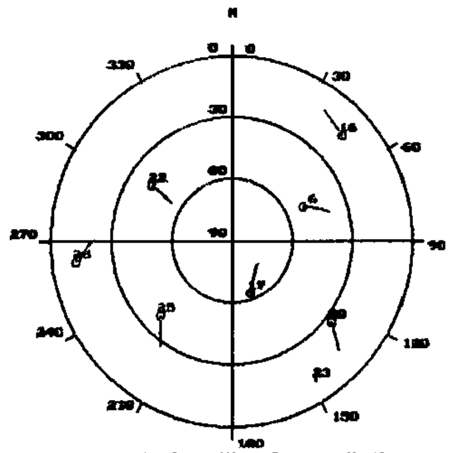

Figure 21: Satellite Constellation

Simulation 1		
Time [s]	SV	Error
460400.0 - 460450.0	22	ramp
460430.0 - 460450.0	25	ramp
Simulation 2		
460400.0 - 460450.0	6	ramp
460430.0 - 460450.0	16	ramp
Simulation 3		
460400.0 - 460450.0	7	ramp
460430.0 - 460450.0	20	ramp

Table 1: Error Simulations

6.2.2 RAIM Performance

The performance of RAIM has been evaluated using 2 approaches ([4],[9]). The detection and following identification of a faulty satellite is used as an observation of the integrity control algorithm, yet this observation is not used to exclude the identified satellite from the navigation solution. The pseudorange residuals are of prime interest for the RAIM algorithms. Yet, due to the way these residuals are calculated, the residuals are correlated among all channels that are used for GNSS navigation. The figure 22 illustrates this effect. Furthermore, the effect of the constellation change on the development of the pseudorange-residuals is noteworthy. A correct assignment of the error that are modeled onto the pseudoranges is not possible with this phenomenon.

Common to all the RAIM algorithms is the limitation that only one error source is detectable and can be identified. This leads to a situation (GPS-Time 460430), where the modeled errors cancel themselves out.

The figure 23 displays this limitation of all RAIM algorithms. A situation is identified where no error source is detected. The whole constellation is declared usable and no satellite must be excluded, yet errors of considerable amounts are introduced on two satellites.

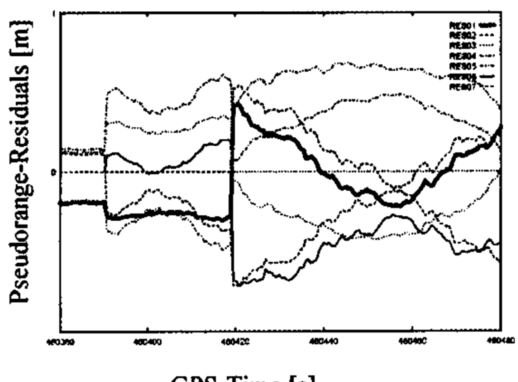

Figure 22: RAIM-Residuals

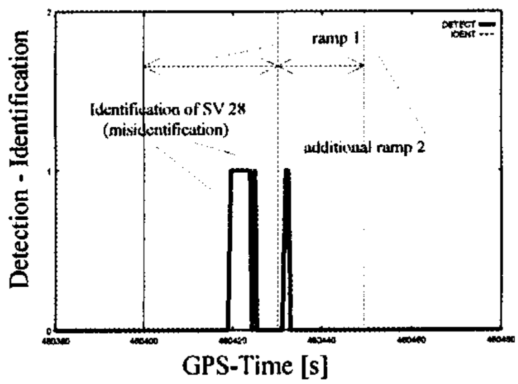

Figure 23: Identification Properties of RAIM

6.2.3 AAIM Performance

The other possible approach to onboard integrity monitoring of the satellite navigation systems is the use of information available from other, independent sensors onboard the aircraft. The performance of the AAIM algorithm is evaluated using the same satellite constellation and the same error-scenarios that have been used for the RAIM algorithms.

Since the implemented algorithm uses differentially corrected GNSS pseudorange measurements, the clock offset of the GNSS user receiver is still included in the residuals that are used for integrity monitoring purposes. However, the residuals used here show no correlation between each channel (apart from the clock offset distribution). Thus, the erroneous pseudorange can easily be detected by simply inspecting the development of the residuals. Again, since there is no correlation between the channels of the GNSS receiver due to the process of the navigation solution, the residuals are different for each error-scenario investigated. This is shown in figures

24 and 25, where the residuals for the error simulation 1 and 2, respectively, are displayed.

Once the second introduced error ramp reaches a size that has to be detected, the identification of both the error sources is the correctly performed. This is shown in the figure 26 for the error simulation 1

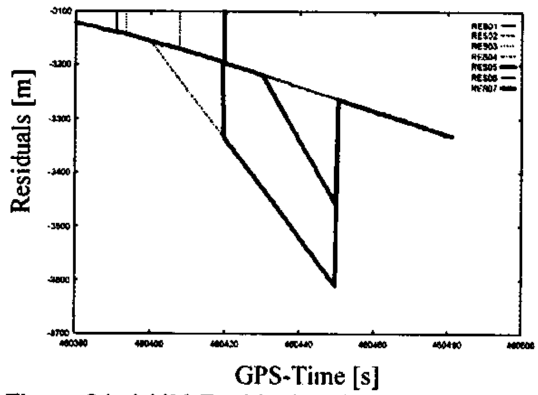

Figure 24: AAIM-Residuals, Simulation 1

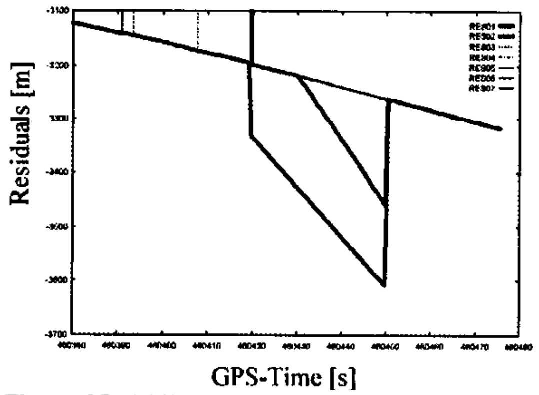

Figure 25: AAIM-Residuals, Simulation 2

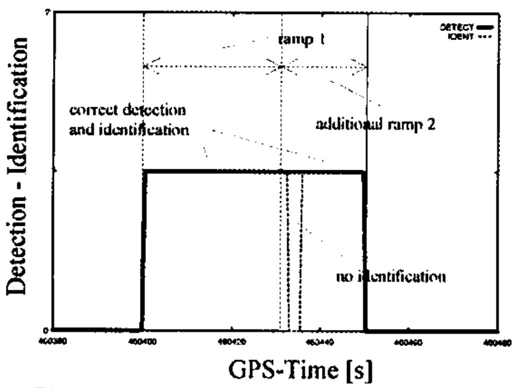

Figure 26: AAIM Identification Properties, Simulation 1

6.2.4 AAIM versus RAIM

The RAIM algorithms present extreme disadvantages and are, in general, not able to cope with multi-error scenarios. The identification scheme used for both algorithms shows tremendous insufficiencies, Additionally, the identification process is strongly influenced by the satellite constellation and its geometry.

Using the AAIM-algorithm, it is possible to identify erroneous satellites even in multi-error scenarios. The identification of the faulty satellites occurs earlier (i.e. with a smaller error introduced into the pseudoranges) and the identification properties do not depend that much on the satellite constellation and its geometry.

7 Conclusion

In order to comply with the accuracy as well as the safety requirements for safety-critical application, a continuous monitoring of the system status in its dynamic environment is essentially needed, in particular with GNSS.

Interference of local sources with satellite navigation signals has been detected and severely limits southern approaches to Lugano using satellite navigation systems. The average number of visible satellites is lower, this limits the amount of maneuvering allowable for the aircraft. In order to extend the limitations on satellite visibility it might be desirable to place the reference station in a less obstructed area.

The accuracy and integrity of integrated navigation systems seems adequate, but limited satellite visibility and telemetry loss must be taken into account in system design to assure continuous operation. Yet, pure satellite navigation solutions will not ensure sufficient integrity and accuracy. The combination of GNSS with self-supporting inertial information presents itself as an adequate solution.

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