Parametric Performance Study of Advanced Receiver Autonomous Integrity Monitoring (ARAIM) for Combined GNSS Constellations

Markus Rippl, Alexandru Spletter, and Christoph Günther
German Aerospace Center (DLR)

BIOGRAPHY

Markus Rippl received his Diploma in Electrical Engineering and Information Technology from Technische Universität München (TUM) in 2007. Since then, he has been a research fellow with the Institute of Communications and Navigation (IKN) at the German Aerospace Center (DLR) in Oberpfaffenhofen near Munich. His field of work is the integrity of GNSS based navigation using receiver-side algorithms.

Alexandru Spletter (birth name: Alexandru Ene) received his PhD in Aeronautical and Astronautical Engineering from Stanford University in 2009, based on a doctoral dissertation with the title "Utilization of Modernized GNSS for Aircraft-Based Navigation Integrity". He conducted his doctoral research in the Stanford GPS Laboratory, developing novel multi-costellation GNSS integrity algorithms for civil aviation. He joined the German Aerospace Center (DLR) in 2010 to continue his research work in satellite navigation with a focus on software simulation in the area of combined GNSS signals, positioning error threat space and integrity.

Christoph Günther studied theoretical physics at the Swiss Federal Institute of Technology (ETH), Zurich, Switzerland. He received his diploma in 1979 and completed his PhD in 1984. He worked on communication and information theory at Brown Boveri and Ascom Tech. From 1995, he led the development of mobile phones for GSM and later dual mode GSM/Satellite phones at Ascom. In 1999, he became head of the research department of Ericsson in Nuremberg. Since 2003, he is the director of the Institute of Communications and Navigation at the German Aerospace Center (DLR) and since December 2004, he additionally holds a Chair at the Technische Universität München, Munich, Germany. His research interests are in satellite navigation, communication, and signal processing.

ABSTRACT

GPS, Galileo and GLONASS are preparing for the transmission of signals in two protected frequency bands (L1, and L5). The combined use of such signals and the verification of their consistency significantly improve the autonomous integrity of position estimates. Aviation applications benefit from this increase in performance, and the use of GNSS as primary means of navigation for precision approach, e.g. in the LPV-200 category, comes into reach.

Previously considered integrity architectures heavily depend on augmentation, and have to respond within the time-to-alert. Autonomous methods, such as the Advanced Receiver Autonomous Integrity Monitoring (ARAIM) considered here, do not suffer from the latter constraint. However the threat space is significantly inflated: Simultaneous satellite faults as well as constellation faults need to be considered. This can be addressed by an ARAIM algorithm employing the principle of Multiple Hypothesis Solution Separation (MHSS), and limiting the threat space to faults with large probability.

The present paper assesses the performance of this algorithm using combinations of future GNSS under different assumptions of satellite fault probability and constellation fault probability. Combinations of GPS, Galileo and GLONASS are investigated to determine the worldwide availability coverage using the integrity requirements defined in LPV-200: Vertical Protection Level (VPL), Effective Monitoring Threshold (EMT) and vertical positioning accuracy (Acc_v).

Based on the simulation results presented here, combinations of GPS and Galileo are shown to provide sufficient VPL-based performance for LPV-200 precision approaches at all runways worldwide. However there exist limitations on meeting the EMT requirement if a single satellite is unavailable. Minimal dependence on the probability of satellite fault is observed for both VPL and EMT. With fault probabilities higher than 10^{-3}/approach, the LPV-200 availability requirement is not met. This probability threshold corresponds to approximately 40 observed faults per year for a nominal 27-SV constellation, with a 6-hour latency after fault onset.

When using a triple GPS-Galileo-GLONASS constellation, the simulated performance becomes generally robust enough to handle even worst case scenarios without any degradation of the relevant performance metrics. However it is shown that assuming independent satellite fault events at high probabilities leads to high computational complexity with potential implications for the real-time capability of ARAIM. Thus, the current research results recommend a limitation on the total number of satellites used for processing integrity limits with MHSS ARAIM, possibly by employing a selection process to visible satellites from all available constellations.

I. Introduction

Today, airborne navigation already strongly relies on Global Navigation Satellite Systems (GNSS). As a primary means of navigation in a precision approach, classical Receiver Autonomous Integrity Monitoring (RAIM) approaches such as [1] have not been possible to use due to the stringent requirements on the 10^{-7}/approach integrity risk error bound associated with the vertical positioning error (VPE). Particularly, in order to emulate the performance of existing SBAS, RAIM algorithms would have to provide LPV-200 availability, for which the Vertical Alert Limit (VAL) is 35 m.

While RAIM algorithms that are currently in use for horizontal navigation (RNAV) cannot be employed with applications requiring vertical guidance, Advanced RAIM algorithms developed from the Multi-Hypothesis Solution Separation (MHSS) algorithm [2] can provide the necessary robustness to support LPV-200 based approaches. Advanced RAIM (ARAIM) is a new category of satellite navigation integrity algorithms that has been emerging over the past 5 years, along with the prospect of having multiple simultaneously operational GNSS constellations, each with enhanced multi-frequency navigation signals. The novelty that these algorithms bring over the classical RAIM algorithms, developed over the previous two decades, is that they are designed to handle any number of simultaneous satellite faults, which are inherent in a combined constellation scenario, as well as entire constellation faults. Additionally, ARAIM algorithms expect to take advantage of the anticipated multi-frequency signals in order to eliminate the unpredictable ionospheric delay, one of the most significant error sources for the earlier systems based on single-frequency GPS. With the possibility to use dual-frequency measurements on L1 and L5 and thus allowing users themselves to correct for the ionospheric delay [3], the residual nominal measurement errors will be low enough to allow for guidance of an approaching plane down to a decision height of 200 ft above the runway threshold.

Of the emerging category of ARAIM algorithms, the MHSS algorithm was the first one to be developed and it is the most widely known today in the satellite navigation and civil aviation communities. This ARAIM algorithm, originally developed at Stanford University [4], [5], has several variants today, as it is being further developed and validated by multiple research groups across the world. The results presented in this paper are based on an MHSS algorithm implemented at DLR and described in Section III. Previous studies have shown that a constellation of 30 modernized GPS satellites in geometry optimized orbits in combination with MHSS ARAIM onboard the aircraft can provide worldwide coverage at LPV-200 required integrity levels [6].

With Galileo becoming operational and GLONASS being modernized, users will be able to benefit from dual-frequency measurements originating from at least three different constellations. Given the larger number of ranging sources, it becomes necessary that the integrity concept providing robust navigation from the corresponding measurements has to consider multiple simultaneous satellite faults even at a relatively low probability of independent space vehicle (SV) faults (e.g. about 1 SV anomaly per year, causing errors in excess of the nominal model).

The grade of performance that can be obtained with an MHSS based RAIM algorithm depends on both assumptions of the magnitude of nominal measurement errors and on the probability that non-nominal measurement errors occur. An initial investigation of the dependence of VPL and availability on the signal-in-space (SIS) accuracy and biases affecting nominal measurement has been conducted in [7]. The fault probability dependence implies that with less confident ground monitoring, the performance of navigation integrity degrades for users of ARAIM.

When new GNSS constellations or modernized SV payloads based on novel hardware architectures such as precise onboard clocks are considered, ground monitoring cannot instantly guarantee a low probability of satellite fault (P_{sat}) due to limitations on the amount of already collected data. It can be assumed that with more observation data being collected from ground monitoring, the confidence in an estimate on the average satellite fault rate (i.e. the mean time between faults, or annual fault frequency of a constellation or a set of satellites based on the same hardware) increases. ARAIM users can then rely on lower fault probabilities, ultimately leading to less likely fault hypotheses, and better integrity performance.

This paper examines the dependence of ARAIM performance on different sets of prior probabilities, both related to individual satellite faults (P_{sat}) and to faults in one whole constellation (P_{const}). Service volume simulations give an estimation of the percentage of users that will be able to obtain LPV-200 compliant integrity performance under different assumptions on fault probabilities. Apart from the Vertical Protection Level (VPL), other requirements in the framework of LPV-200 include the Effective Monitoring Threshold (EMT) and the vertical accuracy (Acc_v). It has been observed that, depending on the assumed fault probability P_{sat}, the EMT may become a limiting factor for availability coverage instead of the VPL.

The remainder of this paper is organized as follows: Section II introduces the threat model used to describe the fault characteristics that ARAIM needs to mitigate. These characteristics include the statistical modeling of "nominal" ranging measurements and probabilistic modeling of the fault states for both individual satellites and complete GNSS constellations. Section III describes how MHSS RAIM is able to offer protection against threats contained in the previously described threat model. In Section IV, the simulation scenarios and parameters used to assess ARAIM performance are introduced, and the requirements that are defined by the LPV-200 performance framework are itemized as metrics that can be obtained from the simulation data. The Sections IV-B and V present the simulation results with respect to individual scenarios and as a comparison based on the variable parameter P_{sat}, followed by a succinct set of closing remarks summarizing the conclusions of the current study and proposed directions for future work.

II. Threat Model

This paper employs the same threat model and residual range error modeling described in [4], [5] for our implementation of the MHSS algorithm. In the current section, only a brief review of this threat model is offered.

ARAIM relies strongly on assumptions about both the probability of a fault onset, and on the maximum magnitude of measurement errors that may remain undetected. It is required that ground monitoring continuously observes the satellite measurements and alerts users if the measurement error magnitude for any user is likely to exceed the broadcast error overbound. The proposed Integrity Support Message (ISM) would contain fault probabilities and parameters characterizing the measurement error distribution that need to be provided to the user with a maximum delay of TTA_{ext} [8].

A. Fault Probabilities

The definition of a fault is characterized by a combination of a Gaussian overbound, URA, and a maximum bias, b_{max}. These two parameters describe a probability distribution for the ranging error of every satellite which is not to be exceeded by the actual distribution of error measurements. It is the responsibility of ground monitoring to determine URA and b_{max} such as to guarantee that the probability distribution of ranging measurement errors for all users in the service volume is below this estimate.

When ground monitoring guarantees such a level of performance and integrity of the observed satellites, a remaining risk exists for the user that a satellite fault may become effective during approach and ground monitoring will not be able to alert the user within the external time-to-alert (TTA_{ext}). Failure in alerting the user may either result from not detecting the fault on ground, or from not forwarding the alert event fast enough. It is important to emphasize the difference between the external time-to-alert, which describes the maximum timespan between a fault being detected by ground monitoring and the user being alerted, and global time-to-alert (TTA) as a requirement from LPV-200. While the TTA is required not to exceed 6 seconds, TTA_{ext} may be significantly larger. However, a large TTA_{ext} value implies that the probability of fault onset refers to a larger time span as well. The same ground monitoring system can thus only guarantee a larger value of P_{sat} as TTA_{ext} increases.

A second probability input to ARAIM addresses the likelihood of a constellation fault onset during the same timespan, denoted as P_{const}. The term "constellation fault" refers to those hypotheses containing multiple correlated satellite faults. An example of such a fault is a situation where due to erroneous navigation data, a single constellation position solution is consistent enough as to pass through classical RAIM FDE tests but results in a high position error for the user. This very specific situation may occur if all satellite positions are jointly rotated or shifted into the same direction with respect to what is broadcast as navigation data. Although it is very unlikely that this may occur due to individual fault events for every satellite, it is possible that the navigation data gets corrupted while being processed prior to uploading it to the SVs. Again, constellation faults can be detected by ground monitoring, but the user algorithm has to consider the remaining probability of experiencing this fault mode without being notified in time.

B. Nominal Error Model

A second characterization of the range measurement errors, URE and b_{nom}, is used to estimate the predicted behavior of the ARAIM algorithm without the necessity to have real measurements available. The previously introduced characterization of error, through URA and b_{max}, defines a probability distribution that overbounds the real measurement error distribution at its tails. This overbound is a conservative estimation of the real errors and can therefore be considered assessing the integrity of the system. The vertical difference between the full-set solution and a subset solution is called the solution separation. As the ARAIM VPL needs to be predicted in simulation, the behavior of the solution separation will be probabilistically estimated such that the continuity requirement is guaranteed to be met, and for every fault mode considered in the fault tree of computed hypotheses. The probability that any of the solution separations is under-estimated is therefore limited by the continuity risk, which is defined at $P_{\text{cont}} = 4 \times 10^{-6}$ for LPV-200 operations. Note that this requirement conservatively refers to a single epoch in this work, following a suggestion from [8].

Concluding the definition of the threat space, ARAIM assumes that the position error of a measurement is overbounded by a probability distribution defined by URA and b_{max} with a probability of $1 - P_{\text{sat}}$. Using this dependence, the next section will explain how the ARAIM algorithm determines combinations of satellite faults based on their prior likelihood, and how it computes the prediction of VPL used as the main metric in the availability study.

III. Integrity Determination with MHSS

The VPL is a limit on the VPE for the user and, together with its horizontal correspondent HPL and other requirements, is used to assess whether using the position solution for navigation is safe for a specific operation, e.g. precision landing. VPL is connected with the integrity risk P_{HMI} in a way that assures that the actual VPE can exceed the VPL with at most this probability. ARAIM splits the risk of excess positioning error among individual hypotheses, which are mutually exclusive and commonly exhaustive. Every hypothesis refers to a unique combination of faulted and nominal satellite measurements.

MHSS will allocate the available integrity risk to a set of mutually exclusive fault hypotheses using the approach originally developed in [2], with optimization strategies and algorithmic extensions introduced in [4] and [5]. Sections III-A and III-B provide a short review of the underlying algorithm that was used to produce the presented simulation results.

A. MHSS Fault Hypotheses

The guaranteed probability of fault for an individual satellite can be used to compute the probability of a unique combination of faults, using

$$P_j = {P_{\text{sat}}}^k \left(1 - P_{\text{sat}}\right)^{(n-k)} \quad , \tag{1}$$

where the total number of measurements in the hypothesis (j) is n and the total number of faulted satellites is k. This assumption is valid if the fault events addressed by this estimation are independent. One important fault type which is neglected by this approach is the constellation fault. These hypotheses are therefore considered additionally with a separate probability.

Assuming no fault modes other than independent faults of satellites with the probability P_{sat}, the total probability over all fault combination adds to one:

$$\sum_{\text{all } j} P_j = 1 \tag{2}$$

The state of each satellite is modeled as either "faulty" or "nominal", thus the resulting total number of hypotheses is:

$$J = 2^n \quad . \tag{3}$$

Naturally, with a low probability of single satellite fault, a combination of multiple satellites becomes more unlikely to occur. A large part of the higher order fault modes can therefore be accommodated in a small partition within the integrity budget, denoted P_{unknown}. With their total probability being only a fraction of P_{HMI}, these fault modes are considered unlikely to threaten the user position integrity, so no hypothesis VPL is computed. These higher order fault hypotheses are called the *unknown hypotheses*. All remaining estimated hypotheses, denoted *computed hypotheses*, will be considered determining the VPL in a later step. The remaining integrity budget is distributed in an optimal way between all computed hypotheses, and the resulting hypothesis VPLs are directly connected with the probability allocated to every hypothesis:

$$P_{\text{HMI}} - P_{\text{unknown}} = \sum_{\text{all computed } j} P_j \cdot P\{\text{HMI}|H_j\} \tag{4}$$

From the shown relationship between satellite fault probability and available integrity budget it becomes apparent that the number of computed hypotheses for a standard P_{HMI} of 10^{-7} becomes larger if the fault probability is high, including fault modes of more simultaneous faults. Table I shows the number of computed hypotheses for a 18 SV geometry and a 25 SV geometry along with the maximum number of simultaneous faults, d_{max}, for different values of P_{sat}. Here, the fault probability P_{sat} is connected with the satellite fault rate through the external alert time, TTA_{ext}.

TABLE I

SATELLITE FAULT PROBABILITY P_{SAT}, NUMBER OF COMPUTED HYPOTHESES PER EPOCH, AND NUMBER OF MAXIMUM SIMULTANEOUS SATELLITE FAULTS

P_{sat}	J (n=18)	d_{max} (n=18)	J (n=25)	d_{max} (n=25)
10^{-6}	19	1	26	1
10^{-5}	19	1	326	2
10^{-4}	172	2	326	2
10^{-3}	988	3	2626	3
$5 \cdot 10^{-3}$	12616	5	68406	5

B. Computation of Protection Levels

For every hypothesis j, the j^{th} predicted VPL can be computed from the vertical standard deviation of the subset solution, the vertical bias projection, and the predicted solution separation [8]:

$$\text{VPL}_{j,\text{pred}} = K_{md,j} \cdot \sigma_{v,j} + \sum_{i=1}^{N} \left| [S_j]_{3,i} \right| \cdot b_{\text{max}} + D_{ss,j} \tag{5}$$

The allocated partition of the integrity budget has been used to define the inflation factor $K_{md,j}$ for the Gaussian overbound of the vertical position accuracy $\sigma_{v,j}$ corresponding to the hypothesis j with N measurements.

The inflation $K_{md,j}$ is computed so that it represents the two-sided tail probability of HMI conditioned on the hypothesis j:

$$K_{md,j} = Q^{-1}\left(\frac{1}{2} P\left\{\text{HMI}|H_j\right\}\right) \tag{6}$$

The predicted solution separation $D_{ss,j}$ is an estimate on the vertical component of the difference between the all-in-view solution and the subset solution excluding the hypothetically faulted satellites. In this case the VPL would be predicted without knowing the actual set of pseudorange measurements, using the URE and b_{nom} assumptions. Because the predicted solution separation is computed in order to satisfy the continuity requirement, we do not need to employ the more conservative URA and b_{max} values used for the integrity calculations above.

$$\Delta S_j = S_j - S_0 \tag{7}$$

$$\sigma_{ss,j} = \left[\Delta S_j \cdot \Sigma \cdot \Delta S_j^T\right]_{3,3} \tag{8}$$

$$D_{ss,j} = K_{cont,j}\sigma_{ss,j} + \sum_{i=1}^{N} \left| [S_j]_{3,i} \right| \cdot b_{nom} \tag{9}$$

The VPL for the position solution including all computed fault hypotheses is then determined as the maximum of all $\text{VPL}_{j,\text{pred}}$:

$$\text{VPL}_{\text{pred}} = \max \text{VPL}_{j,\text{pred}} \quad . \tag{10}$$

The allocation of integrity sub-budgets to the set of computed hypotheses can be optimized such as that all VPL_j

become identical while the sum of the allocated probabilities does not exceed the remaining budget [9]. Further, [5] shows that while it is assured that the unoptimized predicted VPL_{pred} overbounds the real-time VPL at the pre-defined continuity risk, integrity allocation optimization results in a compression of the margin between the real-time and the predicted VPL.

Additional requirements defined by LPV-200 include the EMT and the (Acc_c). The EMT requirement is specifically assigned to the fault case, and it bounds the probability on vertical errors larger than 15m in the fault case to mitigate additional workload for pilots in final approach. The vertical accuracy in the fault-free case is required to be below 4m for 95% of the time. The system can be considered available only if a position solution can satisfy all of the requirements VPL, EMT and Acc_v. The EMT requirement is currently under discussion, and the final interpretation is not yet fixed. Within this work, the implementation of EMT follows the interpretation of [8]. For higher probabilities of satellite faults, the availability results of the simulations suggest that the EMT requirement becomes a limiting factor to availability besides VPL.

C. Specific implementation of the MHSS algorithm

The main characteristics which distinguish our implementation of the MHSS algorithm from other versions of MHSS RAIM are:

- In contrast to analyses in [6], [8], the present implementation completely assesses the threat space with respect to any number of concurrent satellite faults. It is assumed that single satellite faults are uncorrelated, thus their probability can be combinatorially determined. In addition, constellation faults are considered at a fixed, pre-defined probability which can be adjusted per constellation.
- No chi-squared test is needed for identifying faults, yielding a reduced probability of false detection of a fault in this MHSS version. Instead, a recursive fault detection and elimination (FDE) method helps to only eliminate those faults where a range measurement error translates into a hazardous positioning error.
- A specific fraction of the integrity budget is allocated to unlikely fault scenarios, whose Protection Levels do not need to be explicitly estimated. This significantly reduces the computational complexity of the algorithm. The size of this budget is a parameter of the algorithm, which allows making an efficient tradeoff between the processing time (or TTA) of the algorithm and availability. This configuration feature provides a much needed function in a scenario where the number of satellites in sight can be in the 15-25 range, as opposed to the 6-12 range for GPS alone.
- The VPL prediction algorithm makes another practical tradeoff: it optimizes integrity budget allocations between the possible fault modes, while using fixed, equal continuity allocations for the continuity budget. Past investigations [9] have found that this tradeoff leads to an insignificant deterioration of the VPL values, while potentially reducing the runtime of the MHSS algorithm significantly, in order to increase the timeliness of potential alert warnings to the aviation user.
- Finally, an original method is employed for evaluating both single satellite (uncorrelated) faults and entire constellation (or correlated multiple satellite) faults as hypotheses in the same framework. This allows more flexibility for the algorithm to handle complex real-life situations, while also optimizing the overall performance of the integrity algorithm.

IV. Simulation of predicted ARAIM performance

To assess how the performance of ARAIM depends on the satellite fault probability and constellation fault probability, a set of simulations has been run using a GPS and Galileo combined constellation, and a GPS, Galileo and GLONASS combined constellation. In the current simulations, the predicted VPL was computed along with the EMT and the vertical accuracy. From the resulting sets of data, the user location based availability with respect to the LPV-200 criteria has been determined.

A. Simulation Setup

While the ARAIM algorithm was independently implemented at the German Aerospace Center (DLR), it was integrated into the MAAST simulation platform [10] at a later stage to provide more comparability with other work in this field. As a baseline for the simulated space segments, a 27-SV GPS constellation with optimized slot distribution was simulated, and a nominal number of 27 satellites for Galileo, and 24 satellites for GLONASS. While GPS has exceeded its nominal state for years, the current total of 31 satellites [11] are currently distributed in 24 unique slots, with an adjustment of the constellation set-up being executed to use 27 different slots [12]. The geometrical diversity of a set of satellites is a more deciding factor to ARAIM performance than the number of visible satellites, and the simulated constellation of 27 geometry-optimized satellites provides a single-constellation geometry that closely resembles today's performance of the GPS segment with respect to the metrics evaluated. However it should be emphasized that multiple satellites in close formation still provide some redundancy of their measurements which can mitigate the geometry degradation if one satellite fails or is set into maintenance mode.

Galileo and GPS use inclination angles of $56°$ and $55°$ for their orbital planes. While Galileo uses only three orbital planes to accommodate 27 SVs, GPS distributes them on 6 planes. The average geometry for users is equally well-suited for navigation, though.

GLONASS provides 24 satellites only in its full nominal state, and the orbital inclination is at $65°$. The difference is that although there is a better coverage in high latitude regions, the equatorial and mid-latitude regions experience less densely distributed satellites, ultimately leading to a lower average number of satellites for the users. The mere decrease in ranging sources creates a significant degradation of positioning accuracy irrespective of the assumptions on the signal characteristics. It has been shown in [13] that the GLONASS constellation fails to provide enough ranging sources to allow LPV-200 compliant performance with ARAIM at any user location. In the cited study, the signal characteristics originate from legacy GPS assumptions [14] to account for the characteristic of a modernized signal transmitted by future GLONASS-K satellites.

With different space segments from multiple operators being simulated jointly, it is important to define how the relative orientation of the individual space segments should be assumed. The angular distance between individual orbital planes of a single GNSS is kept constant by the operator. However the Right Ascension of the Ascending Node (RAAN) parameter that defines the relative orientation of an orbital plane with respect to a fixed point in space changes slowly over time due to precession. The rate of change is a parameter that varies with the circumference of the satellite orbits, therefore the orbital planes of GPS and Galileo turn slowly with respect to each other. The same holds for any other combination of different GNSS using different orbital heights.

In the present study, an approximation of the worst case relative constellation phasing has been approximated by aligning the RAAN of the first orbital plane of every GNSS space segment simulated. Since Galileo and GPS use almost the same orbital inclinations, three of the GPS planes coincide with the Galileo planes. The GPS and GLONASS planes coincide only at the equator, since their orbital inclinations differ by nine degrees.

The essential satellite signal characteristics depend on the modulation scheme used in the SV payload, ground monitoring accuracy and other factors individual to every GNSS. An in-depth analysis of the ARAIM performance dependence on URA and bias assumptions was provided in [5]. However to show the connection between fault probabilities and VPLs, all assumptions regarding the satellite signals have been assumed identical in the framework of this study. For integrity purposes, in the VPL URA values of 1.0 m for all three constellations, and maximum bias magnitudes of 0.75 m are assumed. The Acc_v and EMT measures have been computed using a URE of 0.25 m and a nominal bias magnitude of 0.1 m.

The minimum elevation angle for all users has been set to $5°$ for GPS and GLONASS, according to the Interface Specification (IS) document [15]. For Galileo, the elevation mask has been set to $10°$ to correspond with current discussions on future Galileo IS. All simulations have been carried out for users separated around the globe on a $5°x5°$ degrees grid, including high latitude regions up to $85°$. A total duration of 10 days with 10-min. timesteps was simulated in order to include a full revolution of the Galileo constellation. The phasing effect between Galileo and GLONASS which has a total inter-constellation revolution time of 40 days [13] has not fully been covered in this study, since this combination of GNSS only appears in the triple constellation scenarios.

To simulate not only the nominal performance expected using full constellations, satellites have been excluded in an additional set of simulations. Under one degraded performance test scenario, every simulation was run with one fixed PRN number excluded. This scenario attempts to reproduce the conditions where scheduled maintenance of a single satellite is being performed, as well as other cases where its navigation data stream may be set unhealthy.

Under another simulation test scenario, for assessment of the worst case with respect to geometry, the satellite exclusion that resulted in the highest increase of VDOP was performed for each time step and user location, yielding the worst case degraded VPL. This was done both for the nominal "best case" scenario as well as for the "maintenance" scenario, resulting in a total of four levels of geometry degradation ('Nominal', 'Fixed PRN out', 'Critical PRN out', 'Fixed+Critical PRN out').

All scenarios result in data sets of VPL, EMT and vertical accuracy for every user and at every simulated time step. Several approaches have been taken to assess the performance of the different scenarios. First, the 99.5^{th} and 99.9^{th} percentile of the user VPL for every location has been computed from the results. This metric shows that even small, gradual changes to the scenario can significantly influence the VPL. The availability requirement for every individual user location was defined at 99.9 percent in this work, taking into account previous results which already showed good performance for dual constellation scenarios. The coverage figure is formed by weighting each location grid point according to its corresponding geographical area and taking the weighted sum, which represents the percentage of the global surface where the availability requirement is met. A coverage of 50% therefore means that 50% of the users can presumably use ARAIM with a maximum VPL of 35m at 99.9% of the time. Coverage can either be based on the VPL requirement (VPL $\leq$ VAL), the EMT requirement (EMT $\leq$ 15m), or on a combination off all requirements. The vertical accuracy requirement is not explicitly discussed since in our simulations, this requirement was always met.

The results from scenarios with different parametrization w.r.t. P_{sat} are presented in plots showing VPL percentiles against the fault probability, or coverage against probability.

B. Dual and Triple Constellation Performance

Baseline a priori assumptions that have been used in previous work on ARAIM [6] are a per satellite probability of fault $P_{sat} = 10^{-5}$ /approach and a per constellation probability of fault $P_{const} = 10^{-7}$ /approach. Figure 1 shows a plot of the 99.9^{th} VPL percentile at 2520 simulated user locations during 10 days of simulated time. This percentile represents the more stringent option for the availability requirements for LPV-200. The color coding shows only few areas where the metric comes close to the threshold, VAL = 35m. For most locations, the VPL is below 20m and there is enough headroom to compensate even for losses of satellites without losing availability. The VPL-based coverage is given in the subscript of the figure, and it is can be observed that this scenario achieves a 100% coverage for LPV-200.

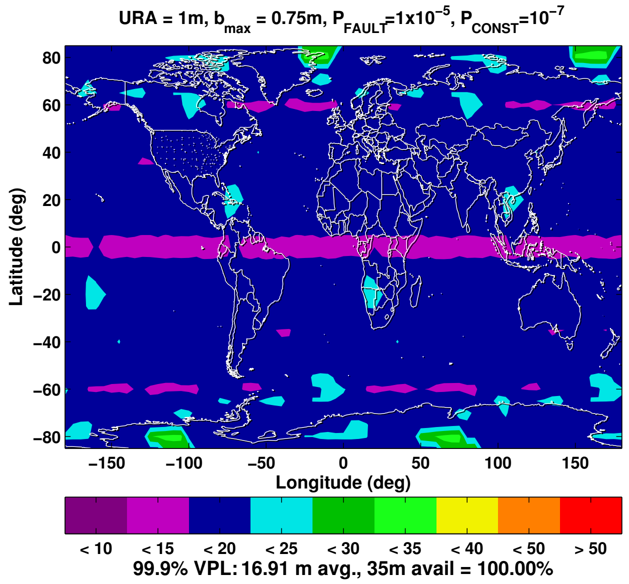

Fig. 1. Dual GPS+Galileo constellation VPL at $P_{\text{sat}} = 10^{-5}$. The VPL based coverage is at 100%, meaning that at all locations, LPV-200 compliant precision approach is possible.

The next result presented shows the availability of ARAIM with a worst-case probability of fault of $P_{\text{sat}} = 5 \cdot 10^{-3}$. If only little confidence might be obtained from recent observations of a newly activated GNSS, and the integrity supporting architecture makes it necessary to assume a large external alert time for ground observed faults, this scenario could probably still be seen as a worst case. However it is interesting to see how ARAIM performs under extremely pessimistic assumptions. The dual-constellation VPL-based availability is shown in Figure 2 illustrating that ARAIM performance can still meet the requirements.

In this scenario, the massive increase in fault probability causes the algorithm to search for all combinations of as much as up to five simultaneous satellite faults. In consequence, the number of computed hypotheses is increasing depending on the number of ranging measurements, and the likelihood to obtain very weak geometries after excluding five satellites becomes larger. Nevertheless, the dependence on the fault probability is not excessively strong when VPL is analyzed as the primary constraint, the VPL-based coverage remaining close to 100% even under these worst-case assumptions.

The same $P_{\text{sat}} = 5 \cdot 10^{-3}$ scenario results in an EMT availability plot that is shown in Figure 3. Here, the results seem more inhomogeneous and some gaps in availability exist at various spots on the simulated earth surface. Availability for particular locations drops below 99%, illustrated as blue areas in the plot. Thus, the coverage area for the locations that meet the EMT is now limited to only 82%. In conclusion, the availability of the service is limited by EMT. It should be noted in this context that the exact definition of the EMT requirement

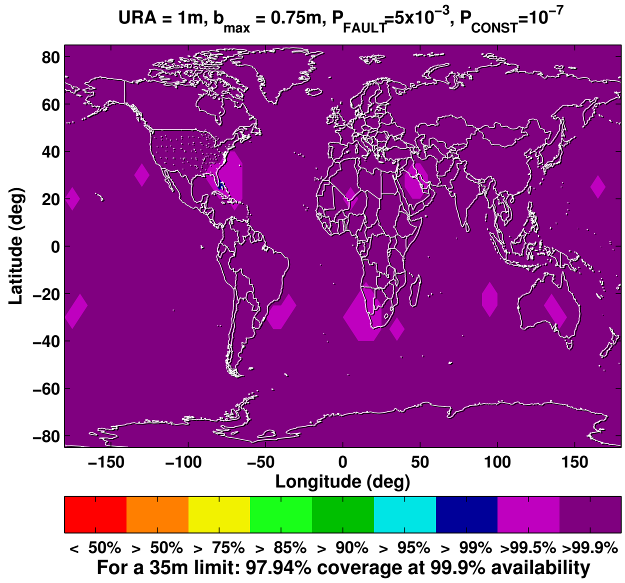

Fig. 2. Dual GPS+Galileo constellation availability based on VPL, at $P_{\text{sat}} = 5 \cdot 10^{-3}$. The availability coverage is close to 100% even at this high satellite fault probability, if only the VPL requirement is considered.

is still subject to interpretation. Additionaly, this result may be of secondary significance, since the limiting property of EMT becomes only visible if the probability of fault is excessively high.

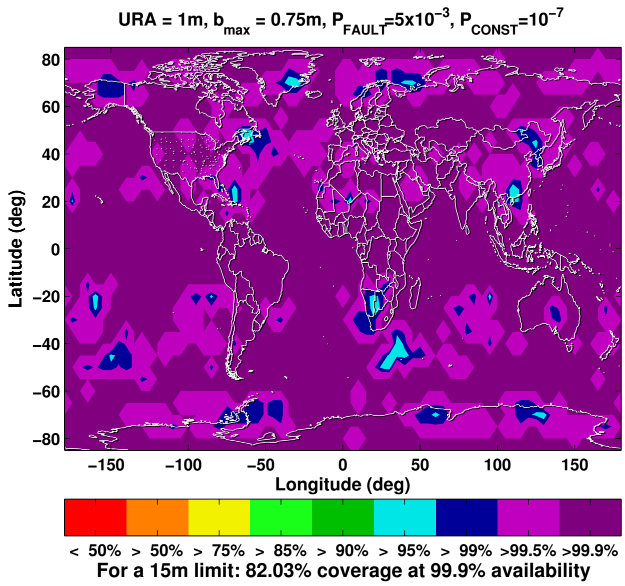

Fig. 3. Dual GPS+Galileo constellation availability for EMT at $P_{\text{sat}} = 5 \cdot 10^{-3}$/approach. Regions with low EMT availability result in the EMT-based coverage becoming significantly smaller. The overall availability is limited by the shown EMT availability, as depicted in Figure 8.

Next, the above worst-case scenario is directly compared to the triple constellation case using the 99.9^{th} VPL percentile. Figure 4 illustrates that the headroom between the VPL and the VAL for the dual constellation case has already significantly shrunken compared with the initially shown scenario in Figure 1. At isolated locations the 99.9% VPL exceeds the VAL, and the global VPL coverage has slightly deteriorated from 100.00% to 99.99%. The same probability assumptions used in a triple constellation scenario result in VPLs always below 25m, and the few availability holes have successfully been mitigated (Figure 5).

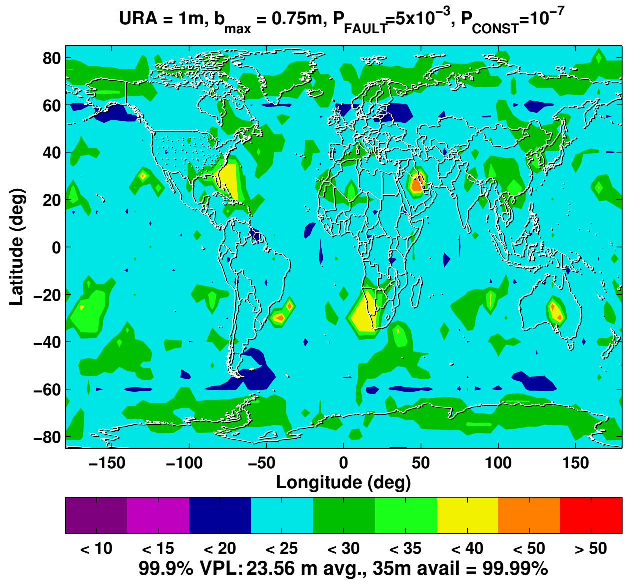

Fig. 4. Dual GPS+Galileo constellation VPL at $P_{\text{sat}} = 5 \cdot 10^{-3}$/approach. Most locations fulfill the VPL requirement, and most locations have more than 10m headroom before exceeding the VAL.

V. Dependence on SV fault probability

The following analysis results from direct comparison of otherwise identical scenarios where the probability of satellite fault, P_{sat}, varied ranging from a minimum of 10^{-6}/approach to a maximum of $5 \cdot 10^{-3}$/approach. Previous work on ARAIM has assumed a per approach fault probability of 10^{-5}/satellite, this value stemming from past data that has been collected from observations on the operating GPS constellation [8]. The fault probability is determined by converting an average annual fault rate of the GNSS into the hypothetic probability of a single satellite fault within one approach of 150s duration. While this approach is valid if an underlying continuous transmission of the ISM data is assumed, extension of the time intervals that elapse between ISM transmissions lead to a higher effective probability of satellite fault that has to be used for navigation integrity. Instead of the approach duration, the significantly longer time interval of external updates is then used as a basis for converting the annual fault rate into a corresponding SV fault probability, ultimately increasing the latter.

A second rationale for analysis of high fault probabilities follows from the inclusion of GNSS space segments that will only be fully operating in a few years from now. Until

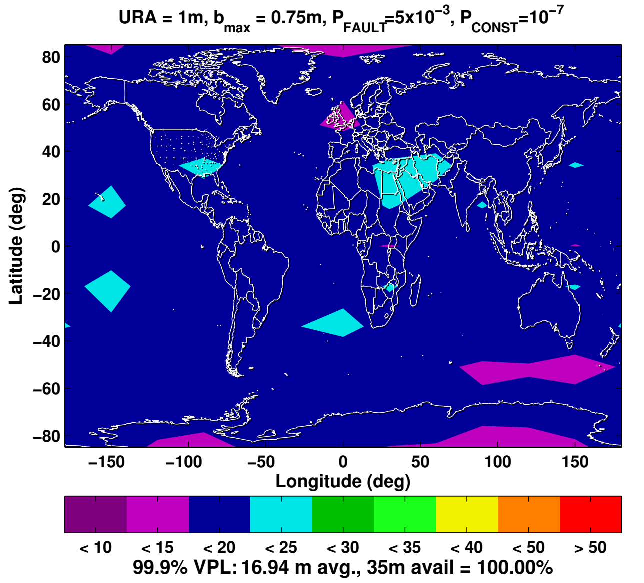

Fig. 5. Triple GPS+Galileo+GLONASS constellation VPL at $P_{\text{sat}} = 5 \cdot 10^{-3}$/approach. All locations are within the requirement, and the average VPL performance is significantly increased.

enough data is collected on actual fault performance of the operating system, only assumptions and deductions from other existing GNSS (i.e. GPS) can be used to assess the reliability of the signals and its monitoring. High confidence in this assessment necessarily depends on long-term observation data, thus additional time will have to pass until Galileo or modernized GLONASS can trustingly be used for ARAIM if a low probability of satellite fault needs to be assumed. The following analysis shows the deterioration in performance if the systems are assumed only to guarantee a higher fault probability.

A. Availability Limitations due to VPL/EMT

Figures 6 and 7 show the global availability coverage of a dual-constellation scenario for different P_{sat}. The underlying constellation fault probability has been assumed at $P_{\text{const}} = 10^{-7}$/approach here. In Figure 6, the global coverage was computed based on the availability criterion for meeting the VPL requirement only. The plot shows the percentage of area in the simulated region ($\pm 85°$ latitude) where the VPL is below VAL $= 35$m at 99.9 percent of the time or more. The four sets of data depict the nominal dual-constellation scenario, the critical-out scenario with the satellite most vital to vertical positioning accuracy being excluded, the fixed-out scenario where one pre-defined PRN was excluded to reproduce the effect of a SV maintenance, and a combined outage scenario where a fixed SV (not necessarily in view for all users), and in addition the critical SV (always in view) were excluded.

Note that the availability coverage of worst-case scenarios such as the critical-out and the combined outage case is clearly not a requirement for proving the performance of the analyzed scenario. It is helpful though to assess the degradation of

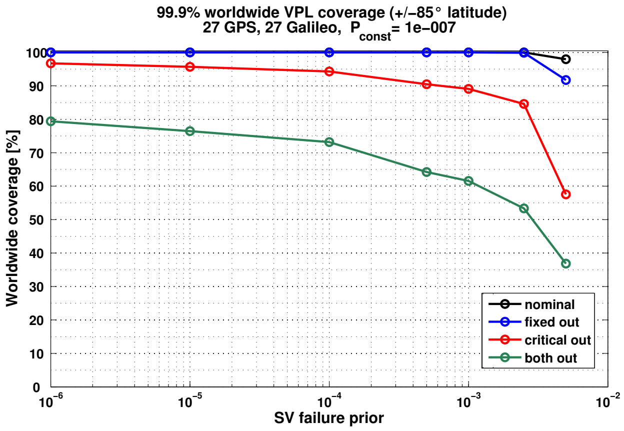

Fig. 6. GPS+Galileo constellation availability coverages, based only on the VPL requirement. For nominal and "maintenance" scenarios, all assumed satellite fault probabilities up to $2.5 \cdot 10^{-3}$/approach result in 100% coverage.

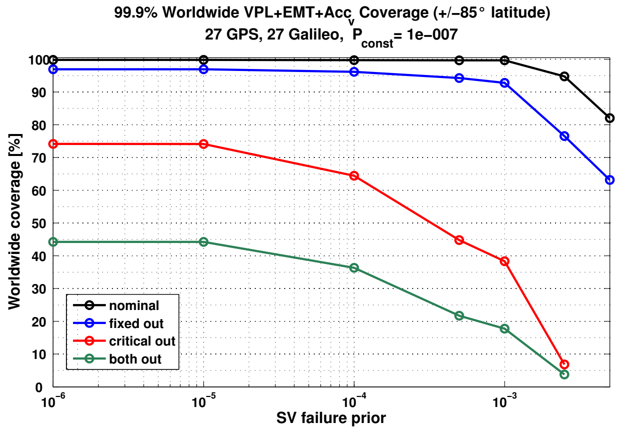

Fig. 7. GPS+Galileo constellation availability coverages, now based on VPL+EMT+Acc$_\text{v}$ requirement. The nominal scenario provides only 100% coverage for $P_\text{sat} \leq 10^{-3}$/approach. A single satellite exclusion leads to constant degradation of the EMT performance for all SV fault probabilities.

performance in a worst case in order to estimate the maximum susceptibility of the system to unexpected geometry loss.

The VPL-based availability of combined GPS-Galileo ARAIM achieves full coverage for almost any of the simulated fault priors. Only when the simulated satellite fault probability is above $5 \cdot 10^{-4}$/approach, some user locations do not fully meet the availability requirement. This is not only true for the nominal combination of the constellations, but also if one of the satellites is unavailable due to maintenance. In the scenarios where every set of measurements has been degraded by the VDOP-critical satellite, availability coverage is observed to drop significantly.

Figure 7 shows the same scenario with the combined availability requirement being assessed instead of the VPL-based availability. This means only the area where all of the VPL, EMT and vertical accuracy requirements have been met at the same time at least in 99.9% of the time steps count for this availability figure. The resulting overall performance has a more significant drop at high priors. More interestingly, the worldwide coverage is slightly degraded for the nominal constellations already at the $P_\text{sat} = 5 \cdot 10^{-4}$/approach prior, and in the maintenance situation the coverage is only slightly above 95% for most simulated priors. In contrast to the case shown in Figure 6, this result again suggests that EMT, interpreted in the current manner, is a more limiting factor to ARAIM usability than VPL, and this requirement needs to be more accurately investigated on.

B. Constellation Prior Effect on Availability

The following figures illustrate the effect of different constellation fault assumptions on the performance of ARAIM. First depicted is the dual constellation scenario in Figure 8, with the most critical satellite removed in every geometry, and using a high constellation prior assumption of $P_\text{const} = 10^{-7}$/approach.

All individual availability requirements are shown here, along with the combined requirement which coincides closely

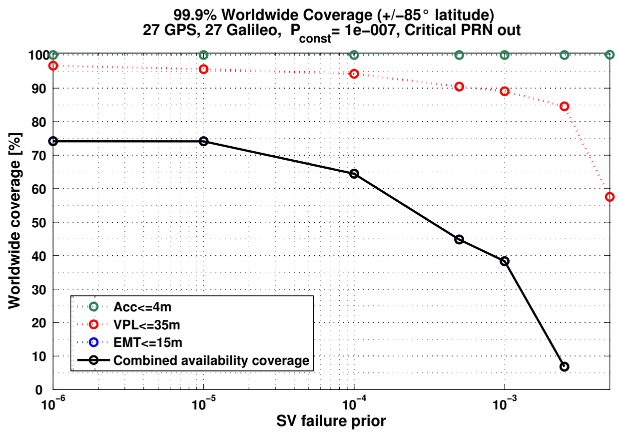

Fig. 8. Critical GPS+Galileo constellation, availability coverages, at a high constellation fault probability of $P_\text{const} = 10^{-7}$/approach. The individual requirements show different susceptibility to satellite fault probability.

with the EMT requirement. Note that technically, the combined coverage is bounded by the individual requirements and thus can be smaller than the minimum of {VPL, EMT, Acc$_v$}; however the EMT requirement is dominant here. Apart from the more significant EMT results, small deficiencies already exist also in the VPL coverage at low priors. Since the worst-case situation that has been remodeled here is strictly speaking not applicable for availability analysis, these holes in coverage are not necessarily a threat to meeting the integrity requirement. However, they may represent situations of non-availability due to loss of signal during approach, where the resulting drop in performance would make missed approach procedure necessary. The implications are therefore significant in what concerns continuity, and will become important once ARAIM is used as primary means of navigation in critical situations, where unscheduled aircraft maneuvers create additional workload and thus more operational risk at the air traffic control (ATC) level.

The second figure for this comparison, Figure 9, shows how a lower assumption on the constellation fault probability results in more robust performance especially for the EMT. The effect previously introduced in Figure 7, which revealed a significant deficiency in meeting the EMT requirement even for only one satellite in maintenance is mitigated by a smaller constellation fault prior.

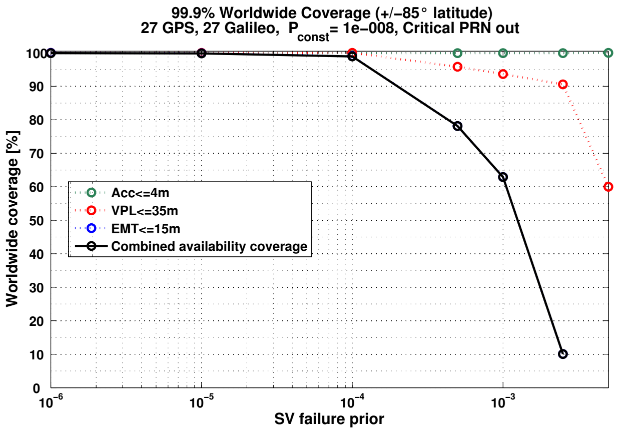

Fig. 9. Critical GPS+Galileo constellation, availability coverages, at a lower constellation fault probability of only $P_{\text{const}} = 10^{-8}$/approach. For low satellite fault probabilities, the relaxed constellation fault assumption leads to full performance even for the EMT requirement in this worst case scenario.

Next, the impact of engaging a third constellation into the navigation solution is discussed. Following from the results above, the gain in availability may be small, since dual constellation GPS+Galileo can already achieve good performance. Figures 10 and 11 show the VPL percentiles of different degradation scenarios for dual- and triple constellation simulations. While the baseline VPL for the less degraded 'Nominal' and 'Fixed PRN out' scenarios only changes insignificantly when additional 24 satellites are introduced, a performance gain can be seen for the worst cases. Therefore, only minor benefit results from using three constellations, while the trade-off between a marginal gain for worst case scenarios and additional computational complexity has to be considered.

Combined (VPL, EMT, Accuracy) availability is presented in Figure 12. Unsurprisingly, the EMT limitation has also disappeared when three constellations are used at the same time. A scaled detail of the availability is depicted here, showing that only the worst-case degraded scenarios miss full coverage at higher magnitudes of P_{sat}. Because of the computational complexity, the triple constellation scenarios with relatively high Psat have only been simulated for the nominal case, and no data points are available for degraded scenarios. However it can be seen that triple constellation ARAIM provides very robust performance, even under the more pessimistic assumptions.

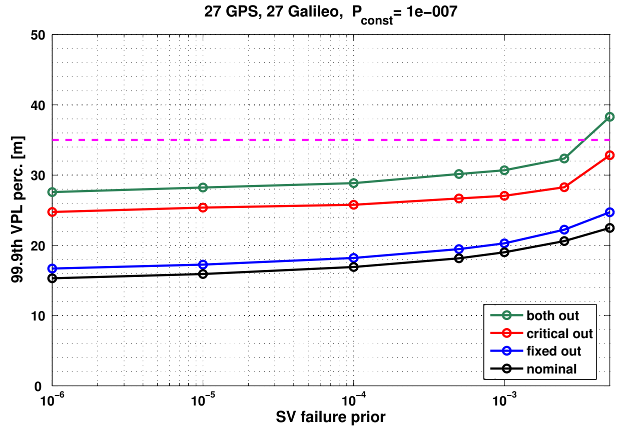

Fig. 10. GPS+Galileo constellation VPL results. For high SV fault probabilities, worst case scenarios have high 99.9th percentiles of the VPL.

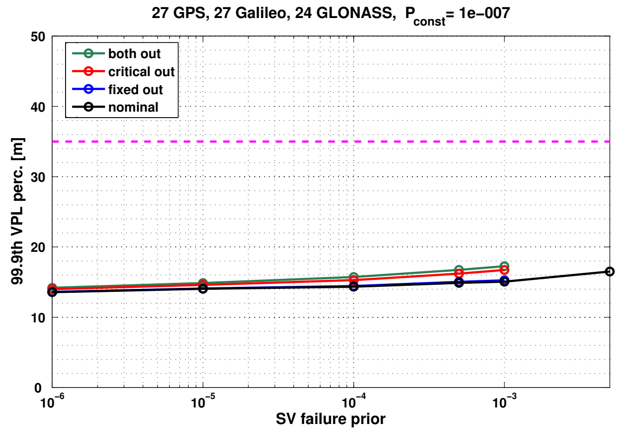

Fig. 11. GPS+Galileo+GLONASS triple constellation VPL results. All geometries are now apparently more robust against loss of signal scenarios.

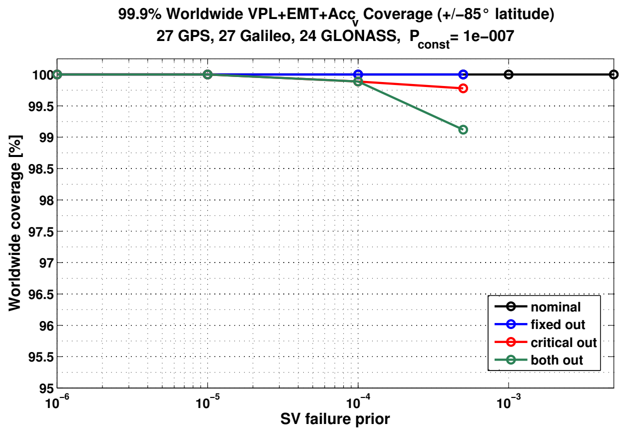

Fig. 12. Zoomed-in view of triple constellation availability coverages. Only at high satellite fault probabilities, the artificial worst-case scenario show any deficiency in availability coverage. This figure depicts a zoomed-in view of the plot to illustrate the small magnitude of degradation. For higher probabilities than $5 \cdot 10^{-4}$/approach, this simulation has not been run for degraded geometries, thus no data is available except for the nominal case.

VI. Conclusions and Future Work

The present work provides a parametric study on the ARAIM algorithm examining the LPV-200 relevant performance criteria when combinations of two or three GNSS are used. Since, at present, estimates on the probability of satellite fault on newly operating constellations are difficult to justify, this analysis made the approach of determining the availability of different sets of probability assumptions for ARAIM users.

Dual-constellation combinations of 27 GPS and 27 Galileo satellites, as well as a triple constellation combination based on 27 GPS, 27 Galileo and 24 GLONASS-K satellites have been simulated worldwide using a range of prior satellite fault probabilities between 10^{-6} and $5 \cdot 10^{-3}$ per approach. Constellation fault probabilities have been simulated at 10^{-8} and 10^{-7} per approach.

As a result, the Galileo-GPS combination can provide worldwide performance suitable for LPV-200 compliant approaches. Unless the actual fault probability measured for satellites of future modernized constellations will be unusually high (i.e. of over 200 faults/year in each constellation with a 6-hr fault latency), the VPL requirement is met even when one satellite is taken offline for maintenance. Surprisingly, the newly discussed EMT requirement poses a more stringent limitation on availability for all scenarios. However, the specific EMT requirements published in the ICAO Annex 10 [16] are still currently subject to interpretation. The authors of this study recommend that the wording of the EMT requirement be further clarified, with hindsight to the significant impact these requirements can have on satellite navigation availability for civil aviation.

If a triple constellation GNSS is employed, simulation results show some headroom towards the requirements that have to be met. Even under worst case situations, LPV-200 precision approaches are possible given the current interpretation of the ICAO requirements, including EMT [8]. Singular worst case geometries that might affect continuity with a dual constellation approach no longer occur, and the dependence of average availability and availability coverage on the constellation and satellite fault priors is further reduced. However, a triple constellation under the paradigm of multiple independent satellite faults leads to high numbers of hypotheses if the fault probabilities are high, and this could pose a limitation on real-time applications due to potentially increased processing times.

In conclusion, the current research results recommend two possible options for achieving the LPV-200 required navigation performance with multiple-constellation GNSS:

1) Setting stricter performance limits for a system comprising of at most two constellations, such that this system will provide the necessary performance in conjunction with ARAIM for certification as a primary navigation means in civil aviation applications.
2) Adapting MHSS ARAIM for use with more than two constellations at a time by limiting the total number of satellites used for processing integrity limits, possibly by employing a selection process applicable to visible satellites from all available constellations.

Under both options, in order to provide the necessary integrity, an ARAIM algorithm would require a ground monitoring network to provide an ISM to GNSS users, which would allow them to periodically update their assumptions around the necessary fault probabilities and GNSS measurement error model. This monitoring system is foreseen to be compatible with existing SBAS infrastructure, while being less technically demanding and less cost-expensive to develop in regions without SBAS coverage at present.

The Navigation Integrity team at DLR is currently in the process of investigating both of the above-mentioned options in order to come up with further recommendations regarding the feasibility of implementing each option. These recommendations would then be provided in combination with a corresponding proposal for an ISM architecture.

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