A Proposal for Multi-Constellation Advanced RAIM for Vertical Guidance

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BIOGRAPHIES

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Per Enge is a Professor of Aeronautics and Astronautics at Stanford University, where he is the Kleiner-Perkins, Mayfield, Sequoia Capital Professor in the School of Engineering. He directs the GPS Research Laboratory, which develops satellite navigation systems based on the Global Positioning System (GPS). He has been involved in the development of WAAS and LAAS for the FAA. Per has received the Kepler, Thurlow and Burka Awards from the ION for his work. He is also a Fellow of the ION and the Institute of Electrical and Electronics Engineers (IEEE). He received his Ph.D. from the University of Illinois in 1983.

Stefan Wallner graduated with a Diploma in techno-mathematics and was research associate at the Institute of Geodesy and Navigation at the Federal Armed Forces Germany in Munich. Since 2010 he works at the European Space Agency in the field of Galileo evolution, future GNSS integrity schemes, and RNSS compatibility.

Francisco Amarillo works for ESA, as member of the Technical Directorate (TEC-ETN), in the design and verification of the European GNSS systems and their evolutions since 1998. He received his Master’s Degree in Telecommunication Engineering and his Master’s Degree in Surveying Engineering from the Polytechnic University of Madrid (UPM) in Spain.

Riccardo Dellago is system engineer in the GNSS evolutions program at the European Space Agency, where he is working since 2008. He has been involved in satellite navigation since 1998, and for 10 years he has worked since its very early phases in the Galileo project at Thales Alenia Space, in the system design, integration, and verification domains. He received his Ph.D. from the University of Rome in 1998.

Rigas Ioannides was awarded a Ph.D. from University of Leeds in 2001, on the ionospheric effects on GNSS satellite signal propagation. In the past he has worked on several projects on Failure Mode Effect Analysis, integrity and RAIM, on the development of new algorithms and architectures in GNSS sensors and on earth observation satellite systems. His interests include time keeping for GNSS systems at the system and algorithmic levels. He is currently a radio navigation systems and signals engineer at the TEC-ETN at ESA in ESTEC.

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Ignacio Fernandez Hernandez is currently responsible for GNSS R&D and receivers within the European Commission DG ENTR GP1 Unit. He has been working in satellite navigation for more than 10 years, some of them as EGNOS system engineer and test manager. He holds a MSc in Electronic Engineering by ICAI, Madrid, and an MBA by London BS.

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Alexandru Spletter (né Ene) received his Ph.D. in Aeronautics and Astronautics at Stanford University in 2009, based on a doctoral dissertation with the title "Utilization of Modernized GNSS for Aircraft-Based Navigation Integrity". He conducted his graduate research in the GPS Laboratory at Stanford, developing novel multi-constellation 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.

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.

ABSTRACT

The GNSS environment will experience major changes in the coming years. GPS and GLONASS are undergoing modernization phases, while Galileo and Compass are currently in their deployment phase. When all these constellations are in their Full Operational Capability (FOC) state, there will be at least three times as many ranging sources than today. In addition, all of these GNSS core constellations will broadcast signals in the two frequency bands, L1/E1 and L5/E5. These signals will be available for civil aviation, allowing users to cancel the pseudorange errors due to the ionosphere. Many studies suggest that it could be possible to achieve global coverage of vertical guidance using multi-constellation, dual frequency Advanced Receiver Autonomous Integrity Monitoring (ARAIM). The benefits of ARAIM would include a reduced ground infrastructure (which would reduce the maintenance costs compared to current augmentation systems), a reduced dependency on any one GNSS core constellation, and, in general, lessen exposure to single points of failure. However, to achieve vertical guidance using ARAIM, it will not be sufficient to adapt the RAIM algorithms that are used for horizontal navigation. This is due to the increased level of safety required for vertical guidance compared to horizontal guidance. Therefore, ARAIM will require a careful faults and effects analysis. Because the integrity provision will be shared across service providers, it will be necessary to develop a common understanding in at least three domains: the navigation requirements, starting with LPV-200; the airborne algorithm; and the threat model, comprised of both the nominal performance of the constellations and the fault modes.

In this paper, we present a concept for the provision of integrity using multiple constellations with ARAIM and an Integrity Support Message (ISM). We will first propose an interpretation of the LPV-200 requirements in the ARAIM context. We will then propose a typical threat model for GNSS which includes both the nominal performance of the constellations and all the faults that need to be mitigated. These threats include both single satellite faults, multiple satellite faults, and constellation wide faults, one of them being the use or broadcast of erroneous Earth Orientation Parameters. We will show how the threats can be mitigated through the use of ground monitoring and the ISM in addition to the ARAIM subset position and residual test. Finally, we will give examples of multiple constellation configurations and performance providing worldwide coverage of LPV-200.

1. INTRODUCTION

GPS with Receiver Autonomous Integrity Monitoring (RAIM) has been used for aircraft navigation since the mid-nineties [1], [2]. Today, RAIM can provide horizontal error bounds of one nautical mile worldwide with high availability, and some availability down to 0.3 nautical miles, without additional ground infrastructure [3], [4], [5]. With the deployment of new GNSS constellations and new signals in Aeronautical Radio Navigation Service (ARNS) bands, there is a strong interest to expand the role of RAIM in aircraft navigation [6].

It is expected that at the end of this decade there will be at least three GNSS constellations with signals in the L1/E1 and L5/E5a frequency bands: GPS, Galileo, and COMPASS [7]. The increased number of satellites in view will improve the user geometry, and the new signals in L5/E5a will allow receivers to cancel the first order ionospheric delay which is the largest pseudorange error source. In addition, in the case of GPS, there have been significant gains in clock and ephemeris accuracy as well as satellite reliability in the last decade.

This has naturally led us to consider the use of RAIM for more demanding phases of flight, in particular precision approach, which requires Vertical Protection Levels (VPL) less than 50 m for LPV and less than 35 m for LPV-200. These VPLs are more stringent for two reasons. First, because they are one to two orders of magnitude smaller than the HPLs for non precision approach; second, because the level of safety associated with these VPLs is higher than the one required for the HPLs used in en route and non-precision approach. A violation of an error bound for the latter would constitute a Major event, whereas it would be Hazardous for the former [8]. In practice, this means that the generation of the VPL must go through much more scrutiny. It is therefore not sufficient to use the current RAIM algorithms and constellation assumptions for vertical guidance. The new algorithms and assumptions that could provide vertical guidance have been labeled Advanced RAIM (ARAIM) to distinguish them from the current RAIM. In this paper, ARAIM will refer to the architecture providing integrity (not only to the avionics.)

In the early nineties, GPS positioning errors using L1 C/A were far too large to be considered for vertical guidance. Satellite-based Augmentation Systems (SBAS) and Ground-based Augmentation Systems (GBAS) were developed to enable GNSS based navigation for precision approach. These systems add two elements that are missing in stand alone GPS for vertical guidance: accuracy and integrity. Currently, there are two SBAS systems that provide vertical guidance: the Wide Area Augmentation System (WAAS) (providing high availability of LPV-200 over North America since 2003) and the European Geostationary Navigation Overlay Service (EGNOS) (certified for APV-I over Europe since March 2011). As these two SBAS systems are the only GNSS based systems that have been certified for vertical guidance, they constitute the only precedent for the development of any GNSS based system for vertical guidance, and in particular ARAIM.

Previous work has shown that with the projected accuracy for GPS and new GNSS systems and assuming fault rates comparable to the ones observed in GPS today, it would be possible to obtain worldwide coverage of LPV-200 using multi-constellation ARAIM [6]. The prospect of achieving vertical guidance without a real time monitoring system like SBAS using ARAIM is attractive to service providers because it could reduce the cost of ground infrastructure, although probably not eliminate it. There are other additional benefits as for example the elimination of single points of failure (like interference at the monitoring station for GBAS), especially in the case of multi-constellation ARAIM.

Before any of this is possible, ARAIM must be proven to have the necessary accuracy and integrity. The accuracy will be a direct function of the constellation geometries and the pseudorange errors. It is important to note that this is not a trivial point: for example, stand alone GPS position accuracy is still not sufficient for LPV-200 – although the projected accuracy of GPS III would be sufficient. However, achieving the necessary accuracy is easy compared to the integrity problem. ARAIM must protect users against satellite and constellation faults that are not flagged by the ground in real time. The performance of ARAIM is extremely dependent on which faults are assumed to occur, how often, and on whether they can be mitigated by the user or the ground, and by a long latency Integrity Support Message.

For these reasons, the EU/US Working Group C [9] has identified the investigation on ARAIM techniques as one of its fundamental activities. In order to advance the technical discussions, a technical sub-group on ARAIM was established at the WGC meeting on 01 July 2010. The objective of this group is to define a reference multi-constellation ARAIM concept allowing vertical guidance (LPV, LPV-200, and beyond) worldwide.

This paper describes a concept for ARAIM as it has been studied and analyzed within this technical subgroup of the EU/US Working Group (it does not represent an official view by any of the represented organizations, but does express the positions of the authors) and reflects the current points of discussion. Section 2 provides an interpretation of the LPV-200 requirements based on the experience of WAAS and EGNOS. Section 3 describes a typical threat model for GNSS which includes both the nominal performance of the constellations and all the faults that need to be mitigated. These threats include both single satellite faults, multiple satellite faults, and constellation wide faults. Section 4 discusses how the threats can be mitigated through the use of ground monitoring and the ISM in addition to the ARAIM user algorithm. Section 5 describes the contents of an Integrity Support Message, a high level view of how it could be generated, and options for the broadcast channel. Section 6 describes the requirements of the avionics algorithm. In the last section, we will show the performance that can be expected from ARAIM using a range of assumptions.

2. LPV-200 REQUIREMENTS

In order to evaluate the possibility of using ARAIM for vertical guidance, it is first necessary to understand which requirements need to be met by the system. In this section, we suggest an interpretation of the LPV-200 requirements, as described in the ICAO SARPS [8] that can be used for ARAIM. Four requirements are discussed:

- 4 m 95% accuracy requirement,
- 10 m fault free 10^{-7} vertical position error requirement,

- 15 m Effective Monitor Threshold (EMT) requirement and,
- 35 m Vertical Protection Level (VPL) requirement.

When interpreting these requirements, it is important to account for the Hazard Category associated with each requirement [10]. The 95% accuracy, 10^{-7} fault free error bound, and the EMT requirements are in the Major risk category: "For errors larger than 15 metres, there can be a significant increase in the flight crew workload and potentially a significant reduction in the safety margin, particularly for errors that shift the point where the aircraft reaches the decision altitude closer to the runway threshold where the flight crew may attempt to land with an unusually high rate of descent. The hazard severity of this event is Major (see ICAO Doc 9859, Safety Management Manual)." As a point of comparison, this is the same risk category as the HPL in non–precision approach. In contrast, the hazard severity of a violation of the VPL is in the Hazardous category. This distinction is taken into account in the interpretation of the requirements proposed here.

2.1. Accuracy and fault free NSE

For these two requirements, the SARPS states that: "The fault-free accuracy is equivalent to ILS. This includes system 95% vertical NSE less than 4 meters, and fault-free system vertical NSE exceeds 10 meters with a probability less than 10^{-7} for each location where the operation is to be approved. This assessment is performed over all environmental and operational conditions under which the service is declared available."

The accuracy requirement is that the 95% bound on the vertical position error must be below 4 m for any given geometry. Most positioning algorithms are locally linear so the formula for the standard deviation of the error for a given geometry is straightforward. As this requirement is meant to reflect the actual expected accuracy, and not the accuracy under anomalous conditions, a pseudorange error model resulting in a correct prediction of the 95% accuracy should be used. For WAAS, it was deemed acceptable to use data only to show that this requirement was met, as the inspection of three years of WAAS data has shown that for a given geometry, a VPL below a VAL of 50 m easily results in an expected 95% error bound below 4 m [11].

The fault free 10^{-7} vertical error does not need to take into account known anomalies (including clock run offs, code carrier divergence, ephemeris errors, un-flagged maneuvers, etc.). It also should be based entirely on measured past performance. However, unlike the accuracy determination, it is not possible to collect sufficient data to fully characterize fault free behavior to 10^{-7} under all conditions. It will be necessary to extrapolate the existing fault free data to a 10^{-7} value. In the WAAS single frequency case, a data driven analysis has shown that out of 1.7 billion position fixes, there were no cases with an error larger than 14 m, and there were less than twenty cases where the VPL was below the VAL and the error was larger than 10 m. Further, this data set did not exclude faults or anomalies. It was found that these larger errors corresponded to anomalous ionospheric conditions [11].

For both requirements, it is acceptable to use data to determine the appropriate pseudorange error model rather than basing it upon threat models.

2.2. Effective monitor threshold

The SARPS states that: "Under system failure conditions, the system design is such that the probability of an error greater than 15 meters is lower than 10^{-5}, so that the likelihood of occurrence is Remote. The fault conditions to be taken into account are the ones affecting either the core constellations or the GNSS augmentation under consideration. This probability is to be understood as the combination of the occurrence probability of a given failure with the probability of detection for applicable monitor(s). Typically, the probability of a single fault is large enough that a monitor is required to satisfy this condition."

This requirement targets fault conditions that have a probability larger than 10^{-5} to occur. The third sentence clarifies that the probability of 10^{-5} is the product of the occurrence probability of a given failure and the probability that the error exceeds 15 m. The requirement can therefore be expressed as:

$$P\left(\text{Vertical Position Error} \geq 15\text{ m} \mid fault\right) P\left(fault\right) \leq 10^{-5}$$

for any fault (if the probability of the fault is smaller than 10^{-5} then it is automatically met).

2.3. Protection Level

The Protection Level is required to bound the position error under any fault condition included in the threat model with very high probability. For LPV-200, the probability that the horizontal position error (HPE) exceeds the HPL or the vertical position error (VPE) exceeds the VPL for longer than the Time-to-Alert (TTA) (Probability of Hazardously Misleading Information), should be less than 2 x 10^{-7} per approach [8]. The VPL and HPL should be computed such that, for a given geometry, the Probability of Hazardously Misleading Information (PHMI) is below the allowable integrity budget. Specifically, we must have:

$$PHMI = \sum_{threats} p_{threat_i} P\left(VPE > VPL \text{ or } HPE > HPL \mid threat_i\right) \leq 2*10^{-7}$$

As opposed to the previous requirements, the PL requirement is in the Hazardous category, so it must account for all threats that cannot be ruled out, whether or not they have been observed historically. For this reason, the error bounds for the PL are based on a more conservative error model, which means that measurement data alone is not sufficient to establish the standard deviations used to compute the PL.

The WAAS safety case focuses on the VPL requirement, and takes into account all credible threats. The proof of safety is based on a fault tree, where each threat has a probability of occurring assigned *a priori* (which can be one in certain cases). Even a summary of the approach that has been taken would exceed the scope of this document, so we refer the reader to [12].

2.4. Continuity

In addition to the four requirements above, the interpretation of continuity in this context needs some clarification. The ICAO false alert requirement for Cat I is 8×10^{-6} per 15-second interval, which applies to losses of service from all causes, including those external to the receiver processing [8]. In [6], it was assumed that the required probability for the airborne algorithm was half of that of the ICAO requirement, that is, 4×10^{-6} per 15-sec interval. The allowable false alert probability per sample was taken to be the same as the probability per 15-second interval at 4×10^{-6}. This is the interpretation that will be adopted here. This false alarm rate is used to set the detection threshold of the integrity monitors. For LPV-200, an interruption of service due to a false alarm is a Minor event in the hazard category, so it is acceptable to use data to characterize the error model.

3. LIST OF THREATS

A complete threat model should include the nature of the threat, its magnitude, duration, and likelihood. Since ARAIM would be using GNSS constellations that are not fully deployed yet it is not possible to define a final threat model. We will start by presenting a list of threats that need to be mitigated by both the ground and the avionics. One of the threats that is the most troublesome for ARAIM is the case where a large number of satellites (for example, all satellites, or a whole constellation) is affected with a probability that cannot be neglected. An overview of these common mode faults and their effects is provided.

Finally, we will describe a framework for the threat model parameterization after the effect of the ground monitor, i.e., the list of threats that need to be mitigated by the avionics. One of the most challenging parts of defining the threat model is determining the prior probabilities of fault that should be assumed when designing the mitigation algorithms. At this point, we can only provide a likely range of values for each parameter.

3.1. Potential faults

A starting point for the threat model is given by a partial list of the GPS threats that are mitigated by WAAS [12]. The errors due to the ionosphere are mostly not mentioned because ARAIM assumes the use of a dual frequency combination to cancel the first order ionospheric delay (second term effects have been shown to be well below a meter in the worst case [13]). In this paper, the threats have been classified into three groups described in the following paragraphs.

- Nominal errors correspond to the errors when the all operational capabilities are nominal (ground segment, satellites and user)
- Narrow failure errors correspond to errors induced by ground segment or satellite failures which affect the navigation signals or/and the navigation message of just one satellite
- Wide failure errors correspond to errors induced by ground segment or satellite failures which affect simultaneously the navigation signals or/and the navigation messages of several satellites

3.2. Nominal errors

3.2.1. Nominal clock and ephemeris errors

These errors are caused by the accuracy limits of the ground segment's orbit and clock determination process, by the modeling limits of the navigation message format (e.g. selected set of orbit and clock parameters), and mainly by the accuracy limits of the on-board clock prediction model, given that the navigation message may not be refreshed by the ground segment for a few hours. Information regarding nominal GPS ephemeris and clock nominal errors can be found in [14], [15], [16], and [17]. Information regarding Galileo ephemeris and clock foreseen nominal errors can be found in [30].

3.2.2. Nominal signal deformation errors

These errors are caused by the temporal variability of the small imperfections of the equivalent transfer function (defined in terms of amplitude and phase response versus frequency) of the end-to-end on-board signal generation chain, which encompasses the navigation signal generation in baseband, its up-conversion from baseband to L-band, its amplification, its filtering (e.g., to limit out-band emissions), and its feeding to the L-band antenna excluding its subsequent radiation. The induced tracking errors are user receiver dependent (e.g., on the pre-correlation bandwidth and on the code-loop discriminator).

3.2.3. Antenna biases

Look-angle dependent biases in the code phase on both L1/E1 and L5/E5a are present on GNSS satellite L-band antennas [25] [26]. These biases, depending on the GNSS L-band antenna, may be up to several tens of centimeters. Given that the spacecraft's positions and attitude relative to a fixed user repeat every sidereal day for GPS spacecrafts (excluding long-term drifts) and approximately every 10 days for the Galileo spacecrafts, the effect of the antenna biases could be considered as a periodic systematic error for a fixed user. Therefore, there might be some points in the service volume where the biases tend to add together coherently consistently. Although calibration may be applied, the possibility of temporal changes hampers its practicality. Moreover, any correction scheme based on calibration data would require the GNSS spacecraft attitude relative to the user to be determined at the user receiver level.

3.2.4. Tropospheric errors

Tropospheric errors are typically small compared to satellite faults. For SBAS, historical observations were used to formulate a model and analyze deviations from that model [27]. A conservative bound was applied to the distribution of those deviations. The user protects against the direct effect using the specified formulas [8], [28].

3.2.5. Code noise and multipath

The airborne code noise and multipath can be characterized by a Gaussian distribution. GPS L1 C/A follows the formula provided in [29] for the Airborne Accuracy Designator – Model A (AAD-A). For Galileo, the error model is expected to be slightly different, due to the different signal modulation.

3.3. Narrow failure errors

3.3.1. Clock and ephemeris estimation errors

A system fault, either on the ground or in the satellites, may create jumps, ramps, or higher order errors in the satellite clock, ephemeris, or both [18], [19], [20], [21], [22]. Such faults may be created by changes in state of the satellite orbit or clock, or simply due to the broadcasting of erroneous information. All faults arising from a satellite malfunction (clock failure or component failure) can likely be considered independent across different satellites.

3.3.2. Signal deformations

Signal distortions may occur in the L1/E1 or L5/E5a signals. For the GPS L1 C/A code, the International Civil Aviation Organization (ICAO) adopted a threat model in 2000 to describe the possible signal distortions [8]. These distortions will lead to biases that depend upon the correlator spacing and bandwidth of the observing receivers.

3.3.3. Code-carrier incoherency

A satellite may fail to maintain the coherency between the broadcast code and carrier. This has never been observed on the GPS L1 signals, but has been observed on WAAS geostationary signals and on the GPS L5 signal [23], [24]. This fault mode occurs on the satellite and is unrelated to incoherence caused by the ionosphere. This threat causes either a step or a rate of change between the code and carrier broadcast from the satellite. In addition to these events occurring at satellite level, code-carrier incoherencies can also be caused by scintillation.

3.4. Wide failure errors

In this paragraph, potential physical causes of a wide failure for a generic GNSS System are listed. In general we can make a distinction between wide failures originating from inadequate manned operations and failures inherent to the ground segment or induced externally. Failures originated at the satellite level will not likely lead to wide failures. Inadequate manned operations may appear during an update of the operational ground segment or during the commanding of the spacecraft. Wide failures caused by the ground segment may be traced back to failures within the navigation message generation or from the spacecraft and constellation control. In addition, Earth Orientation Parameter (EOP) errors or EOP Prediction (EOPP) errors may have their origin either fully outside the system or within the ground segment and therefore they are listed separately. The following list addresses a large number of potential physical causes for wide failures that have been identified up to now,; however, it may not be exhaustive and may need to be expanded. Possible design mitigation strategies to counteract wide failures at the ground segment can be found in the Appendix.

a. Induced by inadequate manned operations during the updates of the operational ground segment:
   1. Occasional update of the information related to the Solar Radiation Pressure modeling for one or more spacecrafts.
   2. Occasional upgrade of the tracking station network (e.g., technical description of a new tracking station which is being integrated in the tracking network).
   3. Occasional upgrade of the constellation (e.g., technical description of a new spacecraft which is being integrated in the constellation).
   4. Occasional update of the software configuration and/or upgrade of the software replaceable units, of the ground segment facilities in charge of the navigation message generation and uplink.
   5. Occasional update of the software configuration and/or upgrade of the software replaceable units of the ground segment in charge of the spacecraft(s) and constellation control.

b. Induced by inadequate manned operations during the commanding of the spacecraft(s):
   1. Occasional uplink of commands for spacecraft housekeeping and maintenance.
   2. Occasional uplink of commands for spacecraft orbit-keeping.
   3. Occasional uplink of information required by the attitude and orbit control sub-system.

c. Induced by failure in the ground segment facilities in charge of the navigation message generation and uplink (including propagation up to spacecraft):
   1. Common tracking station network failures (e.g., false locks), including failures induced by atmospheric perturbations (e.g., tracking loop instability), erroneous phase center location estimates of one or more station antenna, and communication failures with the Ground Control Center (e.g., reception of contaminated tracking data).
   2. Internal failures of the ground segment facilities in charge of the navigation message generation and uplink. This includes design failures (i.e. latent

coding errors of failure to recognize and address a change in operation/performance).

3. Reference GNSS system time not behaving nominally, without implying a facility failure. (e.g., sudden shift of frequency, sudden shift of frequency drift, or transitory frequency instability).

d. Induced by failure in the ground segment facilities in charge of the spacecrafts and constellation control
    1. Internal failures of the ground segment facilities in charge of the spacecrafts and constellation control (e.g., provision of erroneous satellite information).
    2. Induced by the contamination of the commands (uplink) or contamination of the telemetry (downlink).

e. Induced by erroneous EOP and EOP Prediction (EOPP): In principle, if such erroneous EOP and EOPP faults are not detected by the GNSS ground system, the satellite ephemerides could be corrupted in a consistent way, rendering existing ARAIM algorithms ineffective. The initial credibility of the EOP/EOPP threat is established by the fact that it is, for instance, explicitly listed as a potential integrity failure mode in the current GPS Standard Positioning Service Performance Standard (GPS SPS-PS) [35]. It is distinguished from other postulated consistent faults because it is the only consistent fault specifically identified in GPS SPS-PS. It is possible to separate potential EOP threats into two basic types (analogous to GBAS ephemeris fault types):

    1. Type A: EOPPs used in Orbit Determination process were good, but Earth motion has changed since upload – e.g., earthquakes.
    2. Type B: EOPPs used in Orbit Determination process were bad, and situation was not detected by MCS prior to upload.

    These two types of EOP threats can have the same general impact on ephemeris parameters and user positioning errors, but can differ in magnitude and also in methods of detection. Type A faults can only be detected using real-time ground station data, e.g., civil monitoring network, GPS Master Station monitoring, or Galileo GMS. (Even ARAIM using satellites from independent core constellations would not be effective for this type of fault.) However, given that daily, or even weekly, EOP updates are used, any abrupt changes in earth angular rate would need to be extremely large to accumulate significant orientation errors between EOP update periods. Although the situation seems unlikely, more investigation on the subject is needed to rule out Type A threats.

    Independence of Type B faults across constellations

    Type B events, like Type A, can be detected with real-time ground station data. But these may also be detectable at user level via comparison of current broadcast ephemerides with previously validated broadcast ephemerides, or civil-generated ephemerides provided in an Integrity Support Message (ISM). Significantly, Type B events are also potentially detectable with ARAIM by using multiple, independent core constellations. There is evidence that independence of EOP faults between GPS and other core GNSS constellations, such as Galileo, would be a reasonable assumption. Observations used to generate EOPs are collected and used internationally. For different core constellations, some of the same raw data may be processed, but by different organizations applying independent processing schemes. This independence in monitoring schemes between core constellations may be sufficient to ensure the effectiveness of ARAIM for EOP fault detection. However, the availability ARAIM for this purpose will ultimately depend on the prior probability of the fault itself.

Note: The grouping in nominal errors, narrow failure errors, and wide failure errors does not convey all the complexity of the problem. For instance, ionospheric regional distortions affecting code-carrier coherency, such as scintillation, may likely affect simultaneously the signals from several spacecrafts received in a relatively large region (e.g., a few degrees in latitude x a few degrees in longitude).

3.5. Nominal Error Model and Continuity Model for User Integrity Processing

In this section we describe a model of the threats that need to be mitigated by the avionics. That is, some of the threats mentioned in the previous two sections might not need to be mitigated, because they are already mitigated at ground. The previous list of threats needs to be modeled so that it can be understood by the user receiver. This can be done by dividing, somewhat arbitrarily, the threat model between nominal and faulted.

The nominal model includes conditions that are always present: nominal clock and ephemeris, nominal signal deformation, tropospheric error, code noise and multipath. It could also include conditions that cannot be detected by the receiver and whose probability of occurring is high. As discussed in the first section, the nominal error model used for the Protection Level calculation needs to go through a fault analysis. This error model would include nominal biases to account for signal deformation and for deviations from a normal distribution. For each pseudorange, the error is characterized by a Gaussian distribution and a maximum bias.

For the requirements that are not Hazardous, it might be sufficient to use an error model that is based solely on data. In this paper, we will label this error model the continuity error model. This was the approach taken in [6]. Although it is conceivable that there could be a different error model per requirement, in this work we will consider one single data based model for the accuracy, the fault free NSE, the EMT, and the continuity requirement.

As can be seen from the above list of faults, it might be necessary to expand the list of threats that need to be mitigated by the user beyond the current single fault assumption used in horizontal RAIM. This can be simply done by considering more subsets that might be faulted and assigning a probability of fault to each subset [31], [32], and [33]. The threat model is then a collection of satellite subsets with a given probability of fault. These probabilities should reflect the effect of the ground segment in mitigating some of the threats [see Appendix]. In particular, they should take into account the latency of the Integrity Support Message (which will be introduced below). Two types of subsets have been considered: First, subset failures resulting from independent faults, for which the probability can be approximated by the product of the probability that each satellite is faulted; second, subset failures resulting from a common mode failure, for example, an EOP fault which could affect all satellites in a constellation. It is also possible to limit the effect of a subset failure by constraining its effect. For example, an EOP fault will affect the horizontal position, but might not affect the vertical position.

4. THREAT MITIGATION CONSIDERATIONS

Once the list of threats has been defined, it is necessary to decide how they will be mitigated. For ARAIM, the threat mitigation can be divided into three distinct levels: the ground and space segments of each constellation, an independent ground segment, and the user receiver. The combination of these three elements needs to eliminate the integrity threats to an extent compliant with the required integrity risk. It is important to consider that each element might only mitigate a certain class of threats, and only up to a certain probability. In this section, we attempt to describe the role of each of these levels.

The most important characteristic of ARAIM is the fact that the ground segment is not intended to identify threats requiring a TTA of 6 s, as this role is taken over by the user ARAIM algorithms. It is therefore useful to distinguish between threats which require a TTA of 6 s (labeled as "High Dynamics Threats" (HDT)), from those threats which do not (labeled as "Low Dynamics Threats" (LDT)). This last type of threats refer to anomalies which only need to be identified after a period of time longer than the TTA (this could include increases in the nominal error model).

ARAIM concept feasibility requires:

- that the user receiver mitigates all HDT failures that could lead to an HMI event, that are not completely mitigated by the ground segment of each constellation; and,
- that the ground segment and the user receiver mitigates all real LDT failure errors (a more precise description follows)

4.1. GNSS ground and space segments

The GNSS ground and space segments may not have been designed considering the civil aviation safety requirements for precision approach. Therefore, it is not possible to assume that all failure modes relevant to precision approach, which are in practice GNSS system design specific, have been identified, characterized, and mitigated. Moreover, the real failure modes and detailed mitigation mechanisms in these GNSS ground segments may not be publicly known. It is however reasonable to assume that mitigation mechanisms exist to some extent. Assigning a level of trust to these mitigations is one of the most delicate and critical questions in ARAIM.

This level of trust will depend partly on what is known of the ground segments and on service history. If the integrity service provider has full control and confidence in the ground segment, it may be willing to assign a high level of trust. Historical performance of the constellations is very valuable and should be used, but it is not sufficient as both spacecraft and ground segment design are regularly upgraded (e.g., GPS blocks II, IIA, IIR, IIF, Galileo IOV, Galileo FOC), or the conditions that could trigger a fault may have not been realized. For new constellations, the use of historical data will be even more problematic simply due to the lack of data.

For the feasibility of ARAIM it would be necessary that some level of trust could be put in the ground segments of all constellations included in the solution. This rationale will be elaborated upon later in this paper.

4.2. Independent ground monitoring network

In case this is needed, the level of trust in the ground segments can be increased with the introduction of an independent ground monitoring network fully open to certification for civil aviation use. The role of the monitoring network is to check that the assumptions made by the user receiver are met. This independent ground monitoring network would not be required to flag faults to users within the TTA. Instead, it would guarantee any necessary user assumption and supply users with a statistical characterization of the pseudorange errors and failure rates. It would also prevent the accumulation of fault conditions that are not addressed by the constellation ground segment.

At this point, the exact role of the ground monitoring network is not fully determined and ranges between an offline monitoring capability and an almost real time ground monitoring network akin to SBAS or the Safety of Life concept proposed for Galileo.

4.3. Receiver Algorithm

The receiver algorithm uses redundancy to mitigate all the threats that might not yet have been flagged by the ground. It does so by trusting the threat model characterization and nominal error model generated and broadcast by the monitoring network. Some threats may have to be treated as part of the nominal effects and therefore be included in the nominal error model. This may be the case of threats whose characterization, for instance in terms, of probability of occurrence, is not reliable.

If the integrity service provider has control over one of the constellation ground segments, it could have the capability to completely mitigate faults that would otherwise have to be eliminated by the user receiver. However, these mitigations can be extremely costly and very complex. Note that an increase in the complexity of a system may sometimes degrade (instead of improve) its safety.

4.4. Design Assurance Level

To be certified by the Civil Aviation Authorities for the targeted aviation missions with vertical guidance, the overall ARAIM system needs to comply with the corresponding Design Assurance Level (DAL). For LPV-200 approaches the failure condition for an integrity fault is classified as Hazardous requiring in consequence a DAL Level B implementation.

The question that arises then is which elements need to be Level B. As with SBAS, the avionics will need to be Level B. For the ground segment and the independent monitoring system, this is a more difficult question, as it is not clear what it means for a partial mitigation to be Level B. Both WAAS and LAAS use data that is collected by receivers that are Level D. Yet the information processed from these receivers is checked by an element implemented in Level B. This result is achieved by the assumption that the more than 100 receivers will not fail in a way that is invisible to the WAAS Master Station (or the EGNOS Master Control Center). For EGNOS the receivers (RIMS-B) are Level C, and the element processing their information is implemented in Level B.

Similarly, in ARAIM, there might be a prior probability above which it is acceptable that the ground segment is not Level B. For example, let us suppose that the assumed constellation wide failure prior probability is below 10^{-3} per sample. Further let us assume that there are three available constellations. Given that the total integrity budget is 10^{-7}, the simultaneous failure of two of the constellations needs to be mitigated at the receiver level (which may be possible with full constellations). However, the simultaneous failure of the three constellations does not need to be mitigated because the probability of such an event is below 10^{-9}.

5. INDEPENDENT GROUND MONITORING AND INTEGRITY SUPPORT MESSAGE

As outlined above, ground monitoring may be divided into two elements: the ground monitoring performed by the GNSS constellation provider and, when deemed necessary, the ground monitoring performed by an independent ground monitoring network. This second monitoring network should be considered because the ground segments of the core GNSS constellations are currently not designed according to the stringent safety requirements necessary for certification.

In addition – and even if the GNSS constellation ground segment were compliant with the required DAL level – aspects of independence and sovereignty might still be a strong driver for some nations/regions of the world to request an independent ground monitoring network in order for ARAIM to be certified in their airspace. In the following paragraphs, we will first review the role of ground monitoring, then we will introduce the Integrity Support Message contents and its latency. Finally, we will propose some options for dissemination.

5.1. Faults to be addressed by the ground

The ground monitoring network is considered to be a critical element to:

- Identify consistent and common mode faults among satellites where more than one satellite, a full constellation, or even more than one constellation may be affected simultaneously. An overview of sources leading to common mode faults has been presented in section 3.4.
- Identify single and multiple independent satellite faults at any growth rate and eventually mitigate some of them.
- Characterize the behavior of the individual satellites, determine the ARAIM algorithm input parameters (SISA/URA, SISE/URE, P_{sat}, P_{const}, biases) for further dissemination within the Integrity Support Message (ISM) and verify their validity. A possible approach to characterize these values has been outlined in [33].

This information will be disseminated to the users, though not in real time as with today's SBAS. It is important to keep in mind that even with an independent monitoring network, ARAIM would still rely on each constellation ground segment for some threats, because of the latency of the ISM.

5.2. Integrity Support Message Content

As discussed, the ARAIM ground monitoring network can be identified as the most promising element to determine the additional support data required by the ARAIM user algorithm. This support data shall be provided to the user within the Integrity Support Message (ISM). The ISM data content as envisaged as of today is listed next:

- Signal in Space Accuracy (SISA)/User Range Accuracy (URA)
- Signal in Space Error (SISE)/User Range Error (URE)

- Nominal biases to be applied for continuity/accuracy determination
- Maximal biases to be applied for integrity determination
- Probability of a single satellite fault (P_{sat})
- Probability of a constellation wide fault (P_{const})

A methodology to determine these parameters is proposed in [34].

5.3. Integrity Support Message Latency

The time to alert requirement of 6 seconds applicable to APV-II, LPV-200, and CAT-I approaches is a main driver for today's SBAS network architecture and dimensioning. While for SBAS the full integrity processing load is within the ground segment, ARAIM distributes this load between the user and the ground monitoring. This leads thus to significantly relaxed latency times for the update rate of the necessary ARAIM algorithm input data to be provided by the ground monitoring network. Preliminary analyses indicate that latency times for the ISM data update should be located in the order of several minutes or even longer. As the ISM requirements are highly interrelated with the ARAIM algorithm performance and the theoretical analyses and assessments are still ongoing, only indicative figures can be given at this stage.

5.4. Integrity Support Message Dissemination

In order to keep the modifications at the avionics level required to support ARAIM in the future to the minimum extent possible, the utilization of already available data links for ISM provision shall be preferred and investigated on a primary basis. A number of different potential links can be identified:

- **L-Band RNSS allocation:**
  Minimum impact at avionics side can be envisaged in case the ISM data would be disseminated by links required by ARAIM per-se. In particular L1/E1 and L5/E5a RNSS signals need to be considered here.
  - **GNSS:** As the ARAIM concept is based on dual frequency L1/E1 and L5/E5a measurements, an obvious choice for the ISM data dissemination could be the re-use of the GNSS signal's data message link. Without any additional element for the avionics, the ISM data could be provided to the user. However, the interface specification for the GNSS signals are already defined and published, limiting thus the amount of data that could potentially be used for ISM data dissemination. In addition, the transmission of ISM data via the core GNSS constellation could imply significant modifications within the ground segments of each system, depending on the provisions made by the constellation provider. Another aspect that needs to be considered as well is the fact that this dissemination means may not be fully under civil control, as is the case for GPS. Applying a two-layer strategy for the ISM data, where part of the data with longer latency is directly injected to the avionics at gate dispatch and part of the data with shorter latency is provided via the GNSS message, could perhaps overcome the bandwidth limitations in the GNSS message channels.
  - **SBAS:** At present the definition of the future SBAS L5 standard and its message structure is ongoing. As the signal structure for SBAS L5 signal will show high analogy to the GPS L5 and Galileo E5a signal, it could also be made use of for the dissemination of ISM data if just enough spare data capacity could be reserved during the currently ongoing definition phase. The interconnection between ARAIM and SBAS that comes along with this approach, however, needs further careful assessment. ISM dissemination via SBAS or GNSS would not imply any additional, and in consequence costly, extension of the avionics, as already existing channels would be used.
- **VHF Aeronautical Mobile Route Services (AMRS) allocation:**
  VHF data links could be an interesting alternative for the dissemination of the ARAIM ISM data. For instance, the VHF Data Link (VDL) is an already existing means to send information between an aircraft and ground stations in the band 117.975 – 137 MHz. Further studies will be necessary to assess the potential of the VDL links to carry ARAIM ISM data.
- **ISM dissemination at gate dispatch:**
  In case an ARAIM concept materializes that allows a validity of the ISM data on the order of several hours, it could be feasible to update the ISM parameters directly at the dispatch of the aircraft at the gate. The ISM parameters are then to be used throughout the entire duration of the flight. The implementation of this concept in a stand alone mode seems to be highly challenging, however, a combination with the GNSS message link could make it work. Further investigations will be carried out in the near future.

6. AIRBORNE ALGORITHM REQUIREMENTS

The goal of this section is to provide guidance on how to meet the requirements outlined in the first section taking into account the user threat model described in Sections 3.3 and 3.4. An example ARAIM algorithm for single faults is given in [6]. A generalization to multiple failures is described in [31] and [32].

6.1. VPL and HPL

The user ARAIM algorithm must be such that the following relationship holds for a given user geometry and a given set of ISM parameters:

$$PHMI = \sum_{threats} p_{threat_i} P\left(VPE > VPL \text{ or } HPE > HPL \mid threat_i\right) \le 2*10^{-7}$$

Since the nominal error model for integrity includes biases, the user algorithm must be able to account for them rigorously.

As defined in the equation above, the allocation of the integrity budget across the faults cannot by definition be dependent on the specific measurements. Instead it is based on the observed geometry and prior description of the error distributions. The threat model is defined such that an analytical proof of the above equation is possible. One example of an ARAIM algorithm and VPL formula that fulfill this condition can be found in [6] for single failures , and in [31], [32], and [33] for multiple failures.

6.2. Continuity Requirement

The receiver must be able to predict an upper bound of the VPL and the HPL with a probability matching the ICAO false alert requirement of 8x10^{-6}. That is, the receiver must be able to compute VPL$_{\mathrm{pred}}$ and HPL$_{\mathrm{pred}}$ such that:

$$P\left(VPL > VPL_{pred} \text{ or } HPL > HPL_{pred}\right) \le P_{fa}$$

In most algorithms, this requirement is met by adjusting the monitor thresholds adequately. In [6], a fault free error model was assumed when computing VPL$_{\mathrm{pred}}$. Whether one should account for the possibility of satellite fault when predicting the VPL is an open question.

6.3. Exclusion Algorithm

A satellite should be excluded form the position solution under at least three sets of conditions:

- it is flagged as unusable by the ground segment of the constellation;
- it is flagged as unusable by the ISM; or,
- the consistency check has failed and the satellite in question has been flagged by the receiver FDE to be faulted

To be re-accepted in the solution a satellite would have to:

- be cleared by the ground segment (although it might not have ever been flagged);
- be cleared by the ISM (although it might not have ever been flagged); and,
- pass the consistency check for a period of time $T_{recovery}$, possibly more stringent than the regular consistency check.

At this point, it has not being specified what the consistency check should be. It could be a chi-square test on the residuals or a test on the solution separations. The advantage of the chi-square test is that it would be more likely to detect anomalies than the solution separations. The solution separation statistics only target the fault modes that are explicitly listed in the threat model.

6.4. Other Requirements

In addition to the VPL and the HPL, the receiver should ensure that the accuracy, fault free NSE, and EMT requirements are met. Although this could be done using offline monitoring, as was done for WAAS, here it is recommended that the user receiver computes the accuracy, the fault-free NSE, and the EMT in real time. As indicated above, it would be acceptable to use data driven models to compute these figures of merit.

6.4.1. Accuracy and fault free NSE

The accuracy requirement is that the 95% bound on the vertical position error must be below 4 m for any given geometry. Most positioning algorithms are locally linear so the formula for the standard deviation of the error for a given geometry is straightforward:

$$\sigma_{v,acc} = \sqrt{\sum_{k=1}^{n} s_{3,k}^2 \sigma_{acc,k}^2}$$

Assuming that the errors behave as Gaussian distributions, the requirement is given by:

$$1.96\sigma_{v,acc} \le 4 \text{ m}$$

$s_{3,k}$ is the coefficient that projects the k^{th} pseudorange error on the vertical position error. The term $\sigma_{acc,k}$ is the standard deviation of the k^{th} pseudorange under nominal conditions. An acceptable formula for the standard deviation of the pseudorange is given by:

$$\sigma_{acc,k} = \sqrt{\sigma_{URE,acc,k}^2 + \sigma_{user,acc,k}^2 + \sigma_{tropo,acc,k}^2}$$

Similarly, we propose that 10^{-7} fault free NSE take the same form as the accuracy:

$$10^{-7} \text{ Fault free NSE} = 5.33\sigma_{v,ff}$$

$$\sigma_{v,ff} = \sqrt{\sum_{k=1}^{n} s_{3,k}^2 \sigma_{ff,k}^2}$$

As with the accuracy, a possible formula for $\sigma_{ff,k}$ is:

$$\sigma_{ff,k} = \sqrt{\sigma_{URE,ff,k}^2 + \sigma_{user,ff,k}^2 + \sigma_{tropo,ff,k}^2}$$

For each requirement, the index *-acc* , *-ff* , or *–EMT*, leaves open the possibility of using different error models for the different requirements (because they target different probabilities and the actual distributions are not necessarily normal). In particular, $\sigma_{ff,k}^2$ may need to be larger than $\sigma_{acc,k}^2$ since it must bound the actual distribution including 95% and as well as out to 99.99999%.

6.4.2. Effective Monitor Threshold

As pointed out earlier, the requirement can be expressed as:

$$P\left(\text{Vertical Position Error} \ge 15 \text{ m} \mid fault\right) P\left(fault\right) \le 10^{-5}$$

for any fault. As an example, for the solution separation algorithm used in the GEAS ARAIM studies [6], this requirement can be enforced by making sure that for any fault with a probability $P_{fault,i}$ larger than 10^{-5} we have:

$$D_i + K_{md,EMT,i}\sigma_{v,EMT}^{(i)} \le 15\text{ m}$$

$$K_{md,EMT,i} = Q^{-1}\left(\frac{10^{-5}}{2P_{fault,i}}\right)$$

$$\sigma_{v,EMT}^{(i)} = \sqrt{\sum_{k=1}^{n} s_{3,k}^2 \sigma_{EMT,k}^2}$$

$$\sigma_{EMT,k}^2 = \sigma_{URE,EMT,k}^2 + \sigma_{user,EMT,k}^2 + \sigma_{tropo,EMT,k}^2$$

In this equation, D_i is the solution separation threshold associated with the fault and $\sigma_{v,EMT}^{(i)}$ is the standard deviation of the position error associated with the subset solution [6].

7. PROJECTED PERFORMANCE

A set of service volume simulations is presented in order to allow an estimation of possible performance using ARAIM and the introduced assumptions and error models. All simulations use a grid of simulated users on Earth and an orbit propagator to generate user specific geometries in bulk, using Stanford University's simulation toolset MAAST [34].

7.1. Scenario, Applied Threat Model and Parameters

7.1.1. GNSS parameters

Three different constellation setups were simulated: Galileo in a nominal state of 27 SVs, a combination of 27 Galileo SVs and 27 GPS SVs on 27 slots, and a triple constellation scenario including GPS, Galileo, and a third GNSS. For the latter case, the third GNSS signal characteristics have been assumed identical to those of GPS, the orbital characteristics of the constellation resemble those of the nominal GLONASS constellation (three planes).

While for GPS and the third constellation, a 5 degrees user elevation mask has been applied, the masking angle for Galileo was set to 10 degrees.

7.1.2. Signal Characteristics / Error model

The GNSS signal error model was assumed according to the description in Sections 3.5 and 5.1. The URA for GPS and the third constellation was assumed at 0.75 m, while the maximum bias for these SVs was simulated at 0.75 m. For Galileo, the SISA (corresponding to URA) was assumed at 0.957 m and the maximum bias at 1.0 m.

The continuity error model (see Section 3.6) for the two types of signals was assumed as: URE=0.5 m and nominal bias=0.1m for GPS, and SISA=0.67 m with nominal bias=0 m for Galileo.

7.1.3. Satellite Fault and Constellation Fault Probabilities

Generally, single faults and constellation faults are considered by the proposed algorithm. The simulations with multi-constellation scenarios assume a single satellite fault probability of zero while the constellation fault prior is altered. The single constellation scenarios assume no constellation fault.

7.1.4. Requirements

The applied LPV-200 requirements follow the description in Section 2. A continuity risk of 4x10^{-6} is allocated to the avionics algorithm, and an allowed probability of HMI of 2x10^{-7} is assumed. In the simulation, only the vertical component of user integrity is implemented and the integrity budget is completely allocated into the vertical domain. [6] suggests that that horizontal integrity for LPV-200 can already be assumed using only 2% of the complete budget, while 98% remains in the vertical allocation sub-tree.

7.2. Simulated Algorithm

The user algorithm follows [6] and [31] and accounts for multiple simultaneous satellite faults depending on their likelihood. The VPL used in the result analysis corresponds to a prediction based on the threat model. No optimization according to [31] is performed. EMT and the vertical accuracy requirement are taken into account for computation of the service availability. The fault-free NSE requirement and the HPL have not been considered in this study.

7.3. Simulation results

Table 1 gives an overview on the availability of LPV-200 for all parametric simulations. The tabular overview is structured into three sections: single constellation (Galileo), dual constellation (GPS and Galileo), and triple constellation results. In each scenario, one parameter has been altered. For single constellation, the prior probability of a single satellite fault was changed between 10^{-5} and 10^{-3}. In this case, no constellation faults have been considered. For the multiple constellation scenarios, the satellite fault probability has been neglected and the constellation fault probability was modulated.

Galileo27				
P_sat	**Combined**	**VPL**	**EMT**	**Acc$_V$**
1,00E-05	64,61%	65,82%	100,00%	74,76%
1.00E-04	0.76%	30.21%	0.76%	74.76%
1.00E-03	0.00%	0.00%	0.00%	74.76%
GPS27 + Galileo27				
P_const	**Combined**	**VPL**	**EMT**	**Acc$_V$**
1,00E-05	99,25%	99,66%	99,25%	100,00%
1,00E-04	99,25%	99,58%	99,25%	100,00%
GPS27 + Galileo27 + GNSS3_27				
P_const	**Combined**	**VPL**	**EMT**	**Acc$_V$**
1,00E-06	100,00%	100,00%	100,00%	100,00%
1,00E-04	100,00%	100,00%	100,00%	100,00%
1,00E-03	100,00%	100,00%	100,00%	100,00%

Table 1. Global coverage of availability coverage figures for ARAIM simulations

For the single constellation Galileo simulations, it is observed that no LPV-200 requirements except that of

EMT are met. A detailed view of the VPL (Figure 1) and EMT (Figure 2) percentile plots for the smallest assumed fault prior, $P_{sat} = 10^{-5}$, shows that the geometric deficits lie in bands at high latitudes, and around 20 degrees.

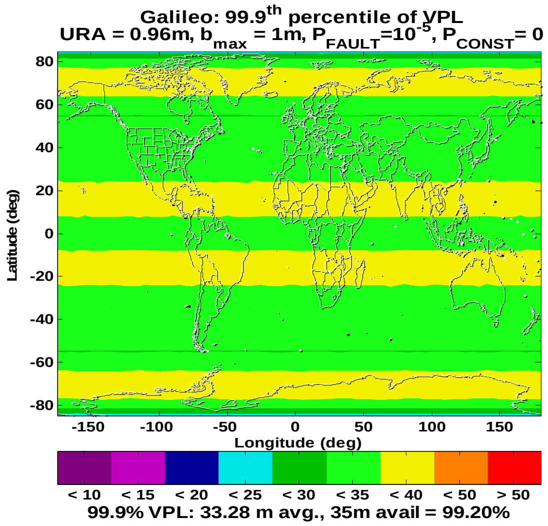

Figure 1. 99.9th VPL percentile for ARAIM using the 27SV Galileo constellation

Dual constellation results demonstrate the result sensitivity with respect to the availability criterion. While for a 99.5% availability limit, all requirements can be met for any simulated user, some locations suffer from service unavailability that are not compatible with a more demanding availability requirement of 99.9%. Figure 3 shows the combined availability for the one dual constellation scenario. A few regions at high latitudes only obtain <99.9% availability. These are, however, in locations of minor interest for civil aviation.

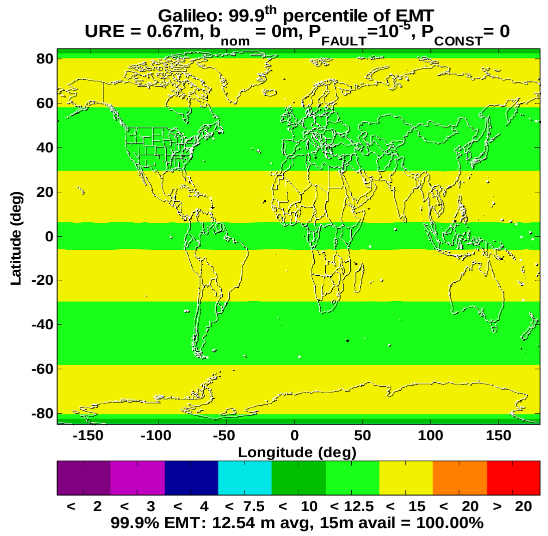

Figure 2. 99.9th EMT percentile for ARAIM using 27 Galileo satellites

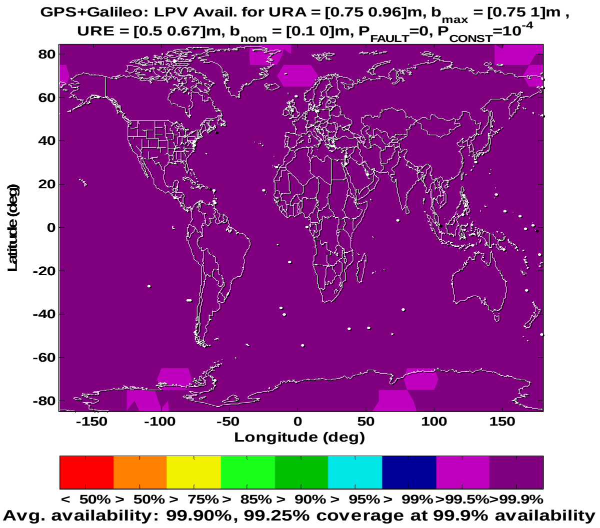

Figure 3. Combined Availability for GPS+Galileo

Galileo27			
P_sat	VPL	EMT	Acc_V
1.00E-05	33.28 m	12.54 m	3.77 m
1.00E-04	36.01 m	21.78 m	3,77 m
1.00E-03	-	960,21 m	3,77 m
GPS27 + Galileo27			
P_const	VPL	EMT	Acc_V
1.00E-05	24.39 m	10.34 m	2.80 m
1.00E-04	26.30 m	10.34 m	2.80 m
GPS27 + Galileo27 + GNSS3_27			
P_const	VPL	EMT	Acc_V
1.00E-06	17.09 m	7.06 m	2.47 m
1.00E-04	20.26 m	7.06 m	2.47 m
1.00E-03	21.46 m	7.06 m	2.47 m

Table 2. VPL/EMT/Acc_v Percentiles averaged over all users

The triple constellation simulations all meet the LPV-200 requirements completely. Even for very high constellation fault probabilities (which might be necessary to assume for new constellations when confidence must still be gained), a triple constellation baseline is robust enough to enable full vertical guidance for aviation users.

8. SUMMARY AND CONCLUSIONS

ARAIM has been identified as a promising concept enabling aviation safety of life operations, in particular approaches with vertical guidance. The benefits of ARAIM would include a reduced ground infrastructure, a reduced dependency on any one GNSS core constellation, and, in general, a lesser exposure to single points of failure. This paper presents the current status of the work on ARAIM ongoing at the international level within the EU/US WG-C ARAIM Subgroup.

The paper identifies a list of threats and categorizes them into nominal errors, narrow failure errors and wide failure errors. These failures can be either of low or high dynamic type depending on whether they need to be detected within the time to alert. At this point, this list is not yet complete, so future work on ARAIM must develop complete models for the individual threats, assigning magnitude, duration and likelihood to them.

Each threat will need to be mitigated by a combination of three elements: the ground segments of the constellations, an independent ground monitoring network, and the user. This mitigation must fulfill the needs of the Civil Aviation Authorities requirements.

Current GNSS ground segments deployed or under deployment may not fulfill the civil aviation safety requirements for precision approach. Therefore, it should not be assumed that all relevant failure modes have been identified, characterized, and mitigated within the GNSS ground segment. In this case, an independent ground monitoring network may provide the level of trust required. Anyhow, the ARAIM ground segment is not required to protect the user from threats within a TTA of 6 seconds, as this role is taken over by the avionics.

The future certification process by the civil aviation authorities needs to be considered within the design of the ARAIM concept and architecture, in particular its compliance to the appropriate design assurance level (DAL) - Level B for LPV-200 approaches.

Potential ISM dissemination means for the Integrity Support Message (ISM) have been identified within the paper, namely L-band (SBAS or GNSS), VHF and gate dispatch. Channels that keep avionics modifications to a minimum shall be preferred in the future ARAIM consolidation process.

Finally, the paper has presented ARAIM performances through a set of simulations further underlining the potential of the ARAIM concept.

APPENDIX

Mitigation strategies for constellation wide failures in the ground segment

The underlying assumption that most likely failures can be modeled as independent failures affecting a single spacecraft at a time is only reasonable if adequate mechanisms are put in place in the GNSS system design. These mechanisms should prevent a general contamination of the navigation message generation and uplink process, named Wide Failure (WF) in this paper, induced by potential system-external or system-internal feared events. In general, these failures may induce dependent failures affecting simultaneously every spacecraft. While in general error propagation mitigation strategies can be found and are necessary in a GNSS system design, the best protection is to ensure that the likelihood of the root cause of the problem is extremely low. Software failures can always be neglected, from safety standards perspective, by adopting the adequate assurance level in their development.

WF causes [a.1] through [a.5] in Section 3.4 could be mitigated by a system design, and by a system operations strategy in which all modifications to the operational ground segment are tested, before being adopted, in a parallel on-line chain identical to the operational chain, which is disconnected from the uplink, and which can take over the role of being the operational chain (the entire process being transparent to the end user). [a.1] could be mitigated, in addition, by an operational chain able to perform a constrained re-estimation of the EOP and SRP parameters.

WF causes [b.1] through [b.3] could be mitigated by a similar conceptual strategy to the one described for [a.1] up to [a.5], but would require of a spacecraft emulator. In addition, operations as [b.2] should require the spacecraft to be flagged as transitorily non-operational.

WF cause [c.1] could be mitigated by a tracking station design able to confirm the non-presence of a shifted main correlation peak; and, in addition, by various algorithmic barriers within the operational processing evaluating the consistency of the tracking data against other unprocessed tracking data, and/or evaluating the stability of the tracking data against processed tracking data, gathered in the past. WF cause [c.3] could be mitigated by a system design able to detect by an on-line and unmanned process the GNSS system time reference abnormal behavior before it affects visibly to the end user, able to exclude the system physical constituent(s) responsible for the anomaly, and able, immediately after, to restore the GNSS system time reference nominal behavior. WF causes [c.2], [d.1], and [d.2] could be mitigated by a system design which adopts for each SW constituent the adequate SW assurance level, as well as by implementing adequate coding and redundancy mechanisms.

Please note that the real failure modes and real failure mitigation design strategies are in practice system specific and may not be publicly accessible.

In general there are failures which may stay undetected for long time periods, as far as the associated perturbation is persistent and remains below certain limits, which are typically established keeping in mind stringent availability and continuity specifications. This may require, from a safety perspective, visibly adapting the performance assumptions on the GNSS operational systems.

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