A Proposed Concept of Operations for Advanced Receiver Autonomous Integrity Monitoring

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ABSTRACT

Advanced Receiver Autonomous Integrity Monitoring (ARAIM) is a concept that extends today's RAIM by incorporating dual frequency and multiple constellations. ARAIM will dramatically improve the availability of horizontal guidance, and has the possibility to evolve to provide worldwide vertical guidance. A key feature of ARAIM is the Integrity Support Message (ISM). The ISM includes information about the constellations and satellites that the receiver requires in order to provide integrity to the user. Since it was first proposed, the concept of ARAIM and the ISM has evolved to take into account institutional and technical constraints, but there are still many open questions.

In this paper we describe our vision for the ARAIM concept of operations for Horizontal ARAIM, which would be the first step in the deployment of ARAIM. We describe high level requirements for the different stakeholders (GNSS providers, the air navigation service providers, and the receiver manufacturers) by addressing the following topics: ISM origin, ISM latency, ISM broadcast, receiver requirements, and ICAO SARPs requirements.

INTRODUCTION

Advanced Receiver Autonomous Integrity Monitoring (ARAIM) is a proposed extension of today's RAIM that incorporates dual frequency and multiple constellations [1]. As reported in [1], ARAIM protection levels would be significantly lower than in today's RAIM. This improved performance would dramatically improve the availability of horizontal guidance, and could evolve to provide worldwide vertical guidance [2]. In addition to the use of new signals and new constellations, one of the distinguishing features of ARAIM is the Integrity Support Message (ISM). The ISM includes information about the constellations and satellites that the receiver requires in order to provide integrity to the user. In RAIM, this information is hardcoded into aviation receivers. In contrast, in ARAIM, the ISM will be broadcast to the user, and its contents may change with time. The basic architecture of ARAIM was proposed in [1], but that description left many open questions that are key for the implementation. These questions are:

- How many ISMs per constellation?
- Who determines the ISM?
- How is it determined? According to what rules?
- How is it broadcast?
- How often is it updated?

By answering these questions, we describe our vision for the ARAIM concept of operations for Horizontal ARAIM, which would be the first step in the deployment of ARAIM.

We start with an overview of the potential benefits of Advanced RAIM, both for horizontal guidance and vertical guidance. We continue by reviewing the ARAIM architecture as it was described in [1]. Finally, we go through each one of the above questions.

Although the information in this paper does not represent any official position or policy of the participating organizations it closely follows a draft ARAIM Concept of Operations document that is being circulated within aviation standards forums.

ADVANCED RAIM BENEFITS

The potential benefits of ARAIM have been well established in [1] and [2]. In Figure 1, we show the 99.5% percentile Horizontal Protection Level obtained using the simulation tool MAAST [3]. For this availability simulation Figure 1 a) reflects current RAIM performance (single frequency, a current GPS almanac, and a URA of 2.5 m). Figure 1 b) assumes two full dual frequency L1-L5 constellations (GPS 27- Galileo 27) with the ISM values as indicated in Table 1, and a URA of 2.5 m. Both plots account for the possible exclusion of one satellite, that is, they illustrate Fault Detection and Exclusion performance (following the terminology of [4]).

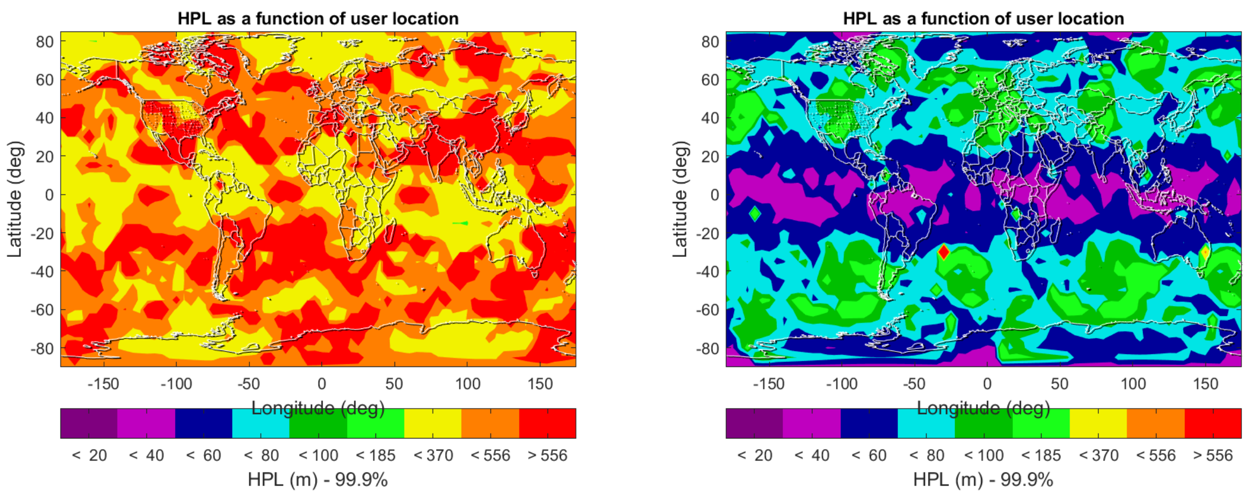

Figure 1. a) and b) FDE HPL maps as predicted by the simulation tool MAAST [3] for RAIM (a) and Horizontal ARAIM (b)

Whereas in RAIM HPLs often exceed 556 m, in ARAIM they would almost always be below 185 m. Based on these types of predictions, it is likely that ARAIM could initially provide: 1) high availability of RNP0.3, 2) the suppression of the dispatch RAIM availability pre-flight check (which is currently necessary, and cumbersome, for many aircraft), and 3 a means to meet ADS-B surveillance requirements. Although initially we are only targeting RNP0.3, ARAIM capability to sustain low HPLs may allow lower RNP levels (including Authorization Required operations). Looking further into the future, we expect that horizontal guidance will pave the way for vertical guidance.

INTEGRITY SUPPORT MESSAGE

ARAIM, like RAIM, is not autonomous. The performance is critically dependent on the parameters describing each constellation [1]. These parameters, which constitute the core of the Integrity Support Message, are the probability of satellite fault ($P_{sat,j}$), the probability of constellation fault ($P_{const,i}$), the standard deviation of the signal-in-space pseudorange error , and a nominal bias [1]. In Table 1 we show a possible ISM parameter set for horizontal guidance. (Note that for pseudorange error, the ISM would only include two multiplying factors $\alpha_{URA,j}$ and $\alpha_{URE,j}$ that would modify the already broadcast URA/SISA. The first, $\alpha_{URA,j}$, would be used for integrity critical error models.) The values for GPS are consistent with what is implicitly assumed in RAIM now. Most of the simulation results shown in [1] were generated using this ISM.

Table 1. Example parameter values for horizontal guidance

	GPS	Galileo
$Mask_i$	All 1	All 1
$P_{const,i}$	**10^{-8}**	**10^{-4}**
$P_{sat,j}$	**10^{-5}**	**10^{-4}**
$\alpha_{URA,j}$	**1**	**1**
$\alpha_{URE,j}$	**1**	**1**
$b_{nom,j}$	**0**	**0**

ARCHITECTURE FROM ARAIM MILESTONE REPORTS

The main questions are who determines the ISM and how to determine it. The ARAIM Milestone 3 Report [1] proposed a preliminary answer to these questions under what was labeled the "offline ARAIM architecture". Figure 2 provides the main elements in this architecture. The Constellation Service Providers (CSP) would publish a set of performance commitments (like the ones published in the GPS Performance Standards [5]), which, together with the results of an offline monitoring process, would produce the ISM. This ISM would then be broadcast to the user.

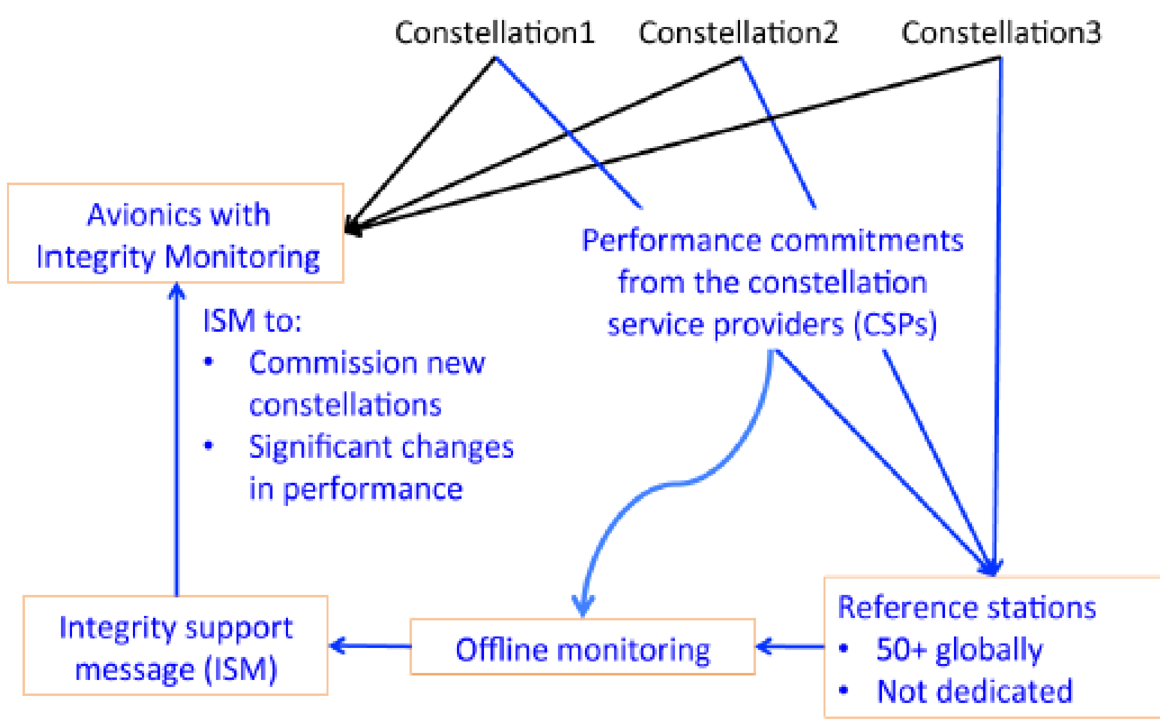

Figure 2. ARAIM architecture as described in [1]

This description still left many open questions, such as: How many ISMs? Who determines the ISM? How is it determined? According to what rules? How is it broadcast? How often is it updated?

LIST OF STAKEHOLDERS

Since one of the main questions to answer is who does what, we introduce a list of the main stakeholders in Table 2. The CSP is the group or company that manages each of the constellations. For GPS it would be the GPS Directorate. For Galileo the CSP will be the Galileo Service Operator and the System Architect (ESA) overseen by the European GNSS Agency. For the US, the ANSP and the CAA are within the FAA. In other cases, these two organizations are not the same. ICAO is an agency of the United Nations that has the role, among others, of codifying the principles and techniques of international air navigation to ensure safety.

Table 2. List of stakeholders for ARAIM

Acronym	Description
CSP	Constellation Service Provider
ANSP	Air Navigation Service Provider
CAA	Civil Aviation Authority
ICAO	International Civil Aviation Organization
ISMG	ISM generator
	Receiver Manufacturers
	Air frame Manufacturers

ISM ORIGIN

ISM Unicity: In the concept of operations we propose, each GNSS constellation included in the ARAIM solution would have one set of ISM parameters and one only per criticality level. (Note that this is a change with respect to what was suggested in [1], where each ANSP would have published a set of ISMs for all constellations.) The reason there needs to be a different ISM depending on the criticality level is the different interpretation of the probabilities that is applied by the avionics depending on the criticality level of the operation. (For example, even though RAIM computes the integrity at the 10^{-7} level, it only has a severity level of "major", which means that the integrity is only trusted down to 10^{-5}.)

ISM Determination: The set of ISM parameters would be entirely based on the Constellation Service Provider (CSP) commitments, as documented in the performance standards. An off-line monitoring process would be used to establish trust in the CSP and ensure a common understanding of the commitments, but it would not set parameter values. High level requirements on the generation of the ISM would be agreed upon at ICAO, and codified in the ICAO SARPS Annex 10. The actual analysis would be performed by the *ISM generator*. The ISM generator does not need to be the ANSP or the CAA (it could be a private company), but the national or regional regulator in the country of origin of the ISMG would be required to approve the ISMG in accordance to the ISM standards in ICAO SARPs Annex 10. The key in this model is the close coordination between the CSP provider, the ISM generator, the associated ANSP provider, and the associated CAA.

Performance commitments

This proposed approach will be dependent on the CSP's understanding of the ISM aviation integrity requirements. This is already happening on the GPS side. For example, the next GPS SPS Performance Standards are expected to include a commitment on the probability of constellation fault, and will be, in general, more closely aligned with the ISM parameters. Similarly, the Galileo program has put in place a work plan to derive justified commitments for Horizontal ARAIM that can be provided to the relevant organizations, in particular to ICAO. The goal of the work plan is to provide commitments in line with the service targets as defined in [1].

It is important to stress that the Galileo Initial Service stage (which began December 2016) was not intended to deliver specific commitments for ARAIM, and that the current level of faults (although not high) is not the one that is expected for Final Operation Capability. Ground segment releases and tuning of the system configuration will make it feasible to ensure commitments at the time of the Full Operational Capability declaration, because many observed failure modes will be mitigated in new system releases. Galileo commitments will then be justified and supported by real data analyses, and will take into account the final state of the system implementation.

Service history and offline monitoring

The data validation methodology should be internationally coordinated at ICAO such that, given the same data sets and ISM parameters, all interested parties should agree on whether or not they are consistent. There also needs to be agreement on how much margin should be required relative to the final ISM parameters (and this may further be a function of constellation maturity). Assuming that the processes for interpreting commitments, analyzing historical data, and assessing required levels of margin can be internationally coordinated, it then becomes possible to agree on acceptable values of the ISM parameters for each constellation. Examples of data validation methodologies that could be used are described in [1], [6], [7], [8].

ISM BROADCAST

Initially ([1], [2]), several broadcast means were considered including: dissemination through the aviation database update cycle, SBAS GEOs, hardcoded ISM, and through the GNSS navigation message. The aviation database option was ruled out because it requires a communication channel between the user GNSS receiver and the Flight Management System that does not currently exist, and because it could restrict ARAIM to aviation users (and not all of them). The SBAS GEO option was appealing, but it would make the ISM transmission dependent on SBAS, which would both restrict the user space to the GEO footprint, and limit the potential of ARAIM as an eventual replacement for SBAS.

In this concept of operations, the ISM is sent in the GNSS navigation message. Although the details still need to be defined, there has been considerable progress since the publication of [1]. The GPS Directorate has proposed a draft message (Message Type 38), which would include the main ISM parameters and would be broadcast in L5 CNAV (Table 3). . At the moment, this message still lacks two key features: a criticality flag (see above) and a time of applicability. Also, the message includes the option of sending the ISM parameters of constellations other than GPS, which we do not consider necessary for civilian applications.

Table 3. Proposed Message Type 38 with ISM content from GPS Directorate
(courtesy of Karl Kovach at Aerospace Corporation)

Table 20-XII. ISM Parameters

Parameter		No. of Bits**	Scale Factor (LSB)	Effective Range***	Units
GNSS ID	GNSS Constellation ID	4	1	8	see text
P_{const}	Probability of constellation integrity fault	3			see text
P_{sat}	Probability of satellite integrity fault	3			see text
t_{correl}	Correlation time constant	3			see text
$M_{integrity}$	URA multiplier for integrity	3			see text
$M_{accuracy}$	URA multiplier for accuracy	3			see text
$b_{nominal}$	Nominal pseudorange bias	4			see text
Flags	Valid for ARAIM flags	63 x (2)			see text

* Parameters so indicated are two's complement, with the sign bit (+ or -) occupying the MSB.
** See Figure 20-15 for complete bit allocation in Message Type 38.
*** Unless otherwise indicated in this column, effective range is the maximum range attainable with indicated bit allocation and scale factor.

Galileo is working on the definition of a similar ISM message for Horizontal ARAIM. In addition to the ISM parameters, it would include an identifier for the ISM Generator, a mask to indicate to which satellites the ISM would apply, and the parameters for a second constellation (e.g. GPS). However, as pointed out above, to avoid ambiguity and to simplify the management of the ISM in the receiver, we would prefer that each constellation sends its own ISM parameters and no other (at least for civilian applications).

As an interim option, there could be the possibility for receivers to use a hardcoded ISM. There are however two possible risks if the hardcoded ISM is superseded by a new one: it could result in lost performance for the receiver if the new ISM is better (in the sense of lower probabilities of fault), or could result in the receiver being decertified if the new ISM is worse.

ISM LATENCY

RAIM depends on the notion that GPS performance is quasi-static. This would be similar for Horizontal ARAIM. Under this model the ISM should only change if the CSP commitment changes, that is, an ISM will be considered valid until a formal change in the CSP's commitments. The ISM changes should be announced years in advance, and the ISM content should be approved by the corresponding CAA and coordinated at ICAO level. Therefore, ISM values should be valid for years after confirmation of the CSP and its commitments. We stress the fact that, for this to happen, ICAO must agree on a process and requirements to set ISM values to overbound the CSP's commitments. Figure 3 shows an example of notional latency requirements

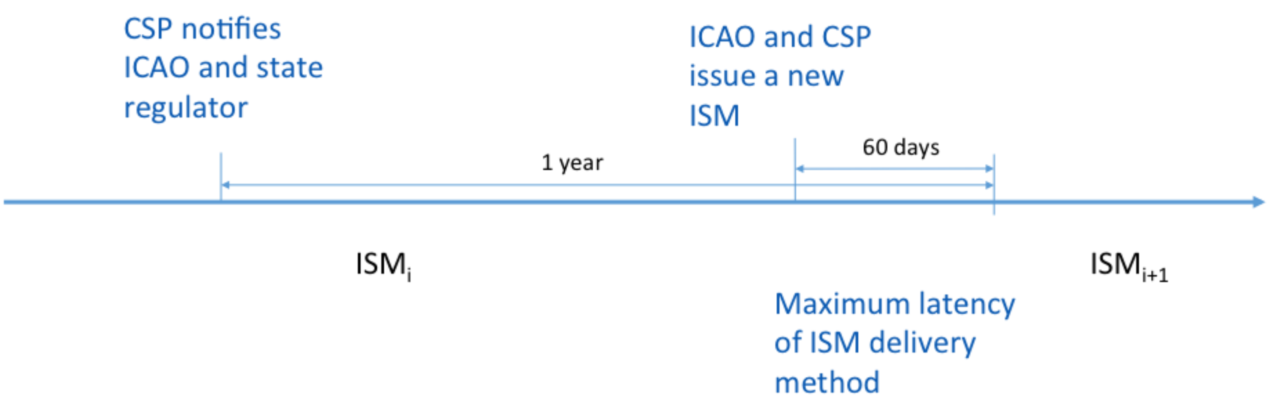

Figure 3. Notional latency requirements for Horizontal ARAIM ISM

RECEIVER REQUIREMENTS

Advanced RAIM will require significant updates in the receiver requirements. These changes derive from the possibility of having to monitor multiple faults depending on the ISM parameters and the possible variability of the prior probability of those faults. As is the case for RAIM today, the receiver standards will not mandate a particular algorithm. Instead, they will describe minimum requirements on the fault monitoring as a function of the ISM. A draft of these requirements and an example algorithm can be found in [9].

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