Development of Advanced RAIM Minimum Operational Performance Standards

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ABSTRACT

Advanced Receiver Autonomous Integrity Monitoring (ARAIM) is a concept that extends today's RAIM by incorporating dual frequency signals and multiple constellations [1], [2]. The potential benefits of Horizontal ARAIM have been well established, both through simulation ([1],[2],[3]), and using flight data [4]. Looking further into the future, we expect that implementing horizontal guidance will pave the way for vertical guidance.

As the concept of operations converges ([5], [6]), and the Dual Frequency Multi-Constellation SBAS Minimum Operational Performance Standards (MOPS) are being developed [7], it is time to start drafting the ARAIM receiver requirements. The goal of this paper is to describe a basis for the ARAIM MOPS as it has been discussed within aviation standards fora and the bilateral EU - US Working Group ([1],[2]) that developed the concept.

INTRODUCTION

To achieve its full potential, Advanced RAIM (ARAIM) will require significant changes in the receiver requirements compared to current single frequency GPS RAIM [8]. These changes ensue from several factors. Among them, the most important are:

1. *the need to process signals from multiple constellations at multiple frequencies*. This topic deals with issues that are mostly common to the current draft Dual Frequency Multi-constellation MOPS (to which the H-ARAIM MOPS will be integrated)
2. *the need to receive and process the Integrity Support Message (ISM).* Now that the distribution channel for the ISM has been decided (GNSS navigation message), and that there are already

concrete proposals for the message format [5], the new MOPS must describe the conditions and rules under which it can be used, including aspects that are specific to each constellation [11].

3. *the variability of the fault probabilities and introduction of a constellation wide fault probability*. This is one of the most significant changes with respect to RAIM, where only single faults with a fixed probability are assumed.
4. *the variability of the missed detection probabilities*. This variability is key for the availability performance of ARAIM. The probability of missed detection requirement for RAIM as specified in [8] is replaced by a more general integrity requirement that is a function of the fault probabilities. This change will in turn have an impact on the fault detection receiver tests, which we outline as well.

In addition, the development of this new MOPS allows us to clarify some points with respect to the RAIM sections in the current WAAS MOPS [8]. These clarifications will increase their traceability and ensure that their effect on integrity and continuity are properly accounted for. These include:

1. *the effect of temporal decorrelation.* RAIM algorithms are designed to make an instantaneous assessment on integrity. However, the integrity requirements are typically specified over a period of time, and the relationship between the instantaneous integrity and the integrity over a period of time is not obvious ([9],[10]).

2. *the exclusion function relationship to integrity and continuity.* Adding an exclusion function to the RAIM algorithm does two things: it reduces the risk of continuity loss and it increases the integrity risk. These two effects must be taken into account.

Status of ARAIM development

The main elements of the ARAIM concept have been described in the bilateral U.S. E.U Working Group C ARAIM reports [1], [2]. These reports presented several possible ground monitoring architectures, broadcasting options, and an example airborne algorithm. ARAIM was further defined in the concept of operations (ARAIM CONOPS) [5], [15]. Work is ongoing to develop the Standards and Recommended Practices (SARPS) to be included in [14], which will specify the responsibilities of the service providers [16] and high-level offline monitoring requirements. Prototypes of the offline monitoring tools have been described in [17-22], and are currently being tested. In parallel, and as part of the concept validation, several prototypes of the airborne algorithm are being evaluated [23-25]. Finally, a preliminary safety case based on previous analyses [19, 21, 26, 27, 28] is being developed.

Framework of Advanced RAIM development

The Horizontal ARAIM (H-ARAIM) standards will be specified within the MOPS for Galileo, GPS, and SBAS (ED 259) [8]. This follows the example of RAIM, whose standards where specified in the SBAS MOPS 229E [7]. However, unlike RAIM, there is no current plan to develop a standalone set of standards for ARAIM. This new MOPS section will cover H-ARAIM, FD and FDE. The plan is that the H-ARAIM MOPS will be the basis of Vertical ARAIM, and that as few changes as possible will be required to enable it.

Table 1. Main differences between RAIM and ARAIM resulting in a different treatment in the standards.

	RAIM	Advanced RAIM
Signals	GPS L1 CA only	GPS L1-L5 + Galileo E1-E5a (at least)
Integrity parameters	Fixed	Broadcast in Integrity Support Message (ISM)
Fault probabilities	Fixed	Variable
Integrity assessment	Fixed probability of missed detection (10^{-3})	Variable probability of missed detection
Effect of temporal decorrelation	Only discussed for false alert rate	Taken into account explicitly (integrity and continuity)
Exclusion function effect on integrity	Probability of missed detection is not modified to account for the exclusion function	Integrity risk explicitly includes the effect of exclusion

The main differences between RAIM FDE as described in [8] and ARAIM are highlighted in Table 1. In the rest of the paper we develop these points and describe how these differences will be reflected in the ARAIM MOPS.

SIGNAL PROCESSING REQUIREMENTS

The use of new signals and new constellations (GPS L5 with CNAV, Galileo E1/E5a with F/NAV) is perhaps the change that has the most impact on the airborne algorithm. Signal processing requirements have already been specified in [7] (section 3.1.1.5) for Dual Frequency Multi-constellation SBAS, and the current plan is to use the same requirements for Horizontal ARAIM. In particular, the equipment will be required to apply the design constraints on receiver bandwidth and correlator spacing described in section 3.1.1.5.4. Among other reasons, these constraints are used to limit the worst case bias caused by nominal signal deformation.

A new section (3.1.1.6.4) will describe the GNSS satellite pseudorange determination and use for ARAIM. This section will in particular specify all the conditions that have to be met by a measurement to be used in the ARAIM position solution (as for example, conditions on the health bit in Message Type 10, on the

Alert flag, on the parity checks, etc), and the limitations on the use of the broadcast ephemeris. These conditions will mostly follow what was done in [8].

INTEGRITY SUPPORT MESSAGE PROCESSING

A new set of requirements in section 3.1.1.8.3 in [7] will ensure that receivers will decode and use the integrity information broadcast in the ISM. As an example we cite three of these requirements:

- The equipment shall be able to process the data from the Integrity Support Message broadcast by GPS and Galileo as detailed in Appendix L.
- The equipment shall be able to identify the GPS PRN and Galileo SVID for use in ARAIM through the satellite mask information broadcast in any GPS ISM messages and any Galileo ISM messages.
- The equipment shall be able to compute the time of applicability of the ISM data received from any GPS ISM messages and any Galileo ISM messages.

It is important to note that the new Appendix L mentioned in these requirements will not necessarily describe the GPS and Galileo ISM at the bit level. The ISM will be instead described in the corresponding Interface Specifications of each constellation. Appendix L function will be to ensure that the information included in each ISM is interpreted correctly (since each Constellation Service Provider (CSP) might send the integrity information in different formats). The processing of the GPS ISM (Message Type 38 in CNAV) and Galileo ISM will be specified in Appendix L.3 and Appendix L.2 respectively.

We examine the content derived from the ISM in the next section.

INPUTS TO RECEIVER ARAIM ALGORITHM

The receiver must be able to decode the message or set of messages containing the ISM for each constellation included in the ARAIM position solution. Sufficient information will be provided in the interface specification, the performance standards, or through the ISM such that in conjunction with the navigation message (CNAV for GPS and F/NAV for Galileo), the receiver will be able to determine:

a. The satellite mask

b. The satellite fault rate $R_{sat,i}$ or the probability of satellite fault $P_{sat,i}$ and the CSP mean time to notify $MTTN_{sat,i}$

c. The constellation fault rate $R_{const,j}$ or the probability of constellation fault $P_{const,j}$ and the CSP mean time to notify $MTTN_{const,i}$

d. The signal-in-space error variance used for integrity $\sigma_{URA,ISM,i}^2$

e. The signal-in-space error variance used for continuity and accuracy $\sigma_{URE,ISM,i}^2$

f. The nominal bias $b_{nom,i}$

g. The time of applicability of the parameters listed above

Satellites used in the ARAIM position solution will be subject to the criteria defined in 3.1.1.6.4.4 for Galileo and in 3.1.1.6.4.2 for GPS.

Model of signal-in-space uncertainty (nominal error model)

The signal-in-space uncertainty is assumed to be bounded by a normal distribution with mean μ and standard deviation σ, where:

a. For integrity purposes $\sigma \le \sigma_{URA,ISM}$ and $|\mu| \le b_{nom}$
b. For continuity and accuracy purposes $\sigma \le \sigma_{URE,ISM}$ and $\mu = 0$

The variance for the total pseudorange error model is obtained by summing the variance as defined in 3.1.1.6.5 with the variance of the signal-in-space error. As described in [1], the continuity and accuracy model can be used to set detection thresholds and to compute the predicted 95% accuracy.

Differences with RAIM: RAIM uses the URA broadcast in the LNAV message, it assumes a zero mean error, and it uses the same error model for each of integrity, continuity, and accuracy.

Primary fault modes

As mentioned above, for each constellation, the interface specification in conjunction with the ISM provides a means to compute:

- The fault rate for each satellite ($R_{sat,i}$)
- The constellation wide fault rate ($R_{const,j}$)
- The mean time to notify for each satellite ($MTTN_{sat,i}$) and for each constellation ($MTTN_{const,j}$)

A constellation fault is such that a single cause may affect two or more satellites simultaneously.

Each of the events defined by the parameters listed above is assumed to be independent. For example, the probability that a fault characterized by $R_{sat,i}$ appears in satellite *i* is independent of whether there is another fault present. As such, they could happen simultaneously with a probability derived from the independence assumption.

It is not necessary to determine all the possible combinations of satellite and constellation faults. Appendix L.4 will define an acceptable means to determine the list of fault modes to be monitored derived from the ISM parameters. This method will be based on the algorithms described in [1].

The probability of the fault modes that are not monitored is removed directly from the integrity budget. This allocation is for those fault modes which cannot be monitored by ARAIM (because they are not observable) or those which are sufficiently rare that they can be kept out of the ARAIM monitor (to improve computation efficiency).

Differences with RAIM: In RAIM, only single faults are explicitly protected against. It is assumed that the probability that a satellite fault is included in the position solution over an hour exposure is equal to 10^{-4}.

INTEGRITY REQUIREMENT

Formulation

In RAIM, the integrity requirement is met through a fixed probability of missed detection (P_{md}) requirement, which is set at 10^{-3}. This approach does not work for Advanced RAIM, because all fault modes must be accounted for, even very unlikely ones. For these rare modes (and possibly corresponding to weak subset geometries), requiring a small P_{md} is not necessary and it is potentially harmful for performance.

As a consequence, in ARAIM the P_{md} requirement is replaced with a more general integrity requirement. This integrity risk (corresponding to a given HPL or HAL) is computed by summing the contribution of each possible fault mode derived from the ISM. For each mode, the integrity risk is the product of the prior probability of the fault mode with the probability of missed alert due to this mode. For Horizontal guidance, the integrity risk over a given hour must be below 10^{-7}.

Exclusion function effect on integrity risk

The effect of the exclusion function on integrity risk is not explicitly described in [8]. For the Advanced RAIM standards we take it into account explicitly. This is done by stating that the integrity risk must take into account the possibility that the algorithm attempts exclusion. In the baseline algorithm described in [1], this is achieved by pre-allocating the integrity risk among a pre-defined set of exclusion options (for example, all single satellite faults).

The integrity risk must also account for the effect of the temporal decorrelation of the errors over the course of the exposure window. Because this decorrelation affects the false alert as well, we discuss it in a separate section.

Time to alert

The time to alert requirement is planned to be identical to the one specified for RAIM FDE, which is 8 s.

EFFECT OF THE TEMPORAL DECORRELATION OF THE ERRORS

The integrity requirement for horizontal guidance is stated as a per hour requirement, not per sample. The decision on whether a geometry and set of measurements meet the integrity requirement is however an instantaneous decision that is made at discrete points in time at a certain rate. The algorithm therefore needs a relationship between the per hour requirement and the per sample requirement. Since this relationship is dependent on the FDE algorithm design and other receiver parameters, there will not necessarily be a specific requirement. Instead, the offline tests for integrity and continuity will ensure that this effect is correctly taken into account by the manufacturer's implementation.

Appendix L will include a method to account for the effect of the temporal decorrelation based on the worst-case effect. The basis of this method is to use a number of effectively independent samples (N_{ES}) for the nominal error. Initial analyses show that this parameter will be between 1 and 360 depending on, the integrity bounding method, the FD and FDE rates, how we exploit the margin in the overbounding of the range errors and the action of the receiver following a detected failure (e.g. wait times before reinclusion). The upper bound of 360 is a consequence of the 10 s time to alert requirement and the 1 hour exposure window [9], [10] (the equipment requirement is 2 s shorter in case the output of the receiver is used by other equipment).

CONTINUITY

There are two requirements related to continuity: the probability of false alarm and the probability of false exclusion. In RAIM FDE, these were set to 3.33×10^{-7} per sample and 10^{-3} per sample respectively (sections 2.X.2.2.2.2.3 and 2.X.2.2.2.2.4 of [8]). For Horizontal ARAIM, these requirements are updated to 5×10^{-7} per hour for the false alert and 5×10^{-4} per hour for the failed exclusion. If a number of effectively independent samples is used, this translates to $5 \times 10^{-7}/N_{ES}$ per sample for the false alert and $5 \times 10^{-4}/N_{ES}$ per sample the false exclusion. This change is motivated by analyses included in [12,13], which derive from the continuity requirements described in [14].

TEST PROCEDURES

In [8], the integrity of the RAIM FDE receiver algorithm is demonstrated through a set of numerical offline tests. These tests are run on a set of representative user geometries. For each geometry, nominal errors are simulated, and a fault is injected in one of the satellites (either the most difficult to detect or the most difficult to exclude, depending on the test). These tests are run enough times to allow the computation of a reliable probability of missed detection. If this probability of missed detection is below 10^{-3}, the algorithm passes the test.

For the ARAIM MOPS, we plan to adopt the same approach. However, the tests will be updated to account for the variable fault rates and the fact that the probability of missed detection is replaced by an integrity risk requirement. To address the variable fault rates, we will create sets of representative ISM values that will range from the lowest to the highest fault rates that a receiver will be required to process. The set of different ISM values that need to be simulated remains to be determined. This choice will depend on which sets are considered equivalent from a simulation point of view.

To address the variable probability of misdetection without requiring an excessive number of numerical samples, there are at least two options. One of the them is to define a generalized probability of missed detection, as suggested in [29]. The other one would consist in having each manufacturer determine the P_{md} in a parallel software implementation, and verify that P_{md} through the tests.

SUMMARY

Table 2 recapitulates the new material that will be developed as a consequence of the differences between RAIM and H-ARAIM.

	RAIM	Advanced RAIM	Advanced RAIM MOPS
Signals	GPS L1 CA only	GPS L1-L5 + Galileo E1-E5a (at least)	• Already being developed in SBAS DFMC MOPS
Integrity parameters	Fixed	Broadcast in Integrity Support Message	• Appendix describing the content provided by the ISM for each constellation
Fault probabilities	Fixed	Variable	• Section describing the primary fault modes • Appendix on the determination of the fault modes • Appendix on acceptable approach to determine fault modes
Integrity assessment	Fixed probability of missed detection (10^{-3})	Variable probability of missed detection: requirement is replaced with overall integrity risk	• Section describing new integrity requirement • Section describing test procedure to demonstrate integrity requirement • Appendix with example user algorithm
Effect of temporal decorrelation	Only discussed for false alert rate	Taken into account explicitly (integrity and continuity)	• In test procedure section, description of the temporal decorrelation for each of the error sources • Section in Appendix describing N_{es} parameter

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