Continuity and Availability in Dual-Frequency Multi-Constellation ARAIM

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BIOGRAPHY

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ABSTRACT

Future multi-constellation global navigation satellite systems (GNSS) will provide a greatly increased number of redundant ranging signals, which can improve integrity monitoring capability using receiver autonomous integrity monitoring (RAIM). Advanced RAIM (ARAIM) aims at providing localizer precision with vertical guidance down to 200 feet altitude (LPV-200) for worldwide aircraft landing navigation. This paper assesses the need of exclusion for continuity and availability in future dual-frequency, multi-constellation ARAIM. The first part of the paper is a three-part analysis of the need of fault-exclusion at the aircraft for continuity. First, an interpretation of 'average sense' continuity is given, which is specified but not fully defined by the International Civil Aviation Organization (ICAO). Second, a critical satellite analysis is carried out to show that, for future multi-constellation GNSS, the impact of unscheduled satellite outages is small as compared to other sources of loss of continuity. Third, the paper shows that fault-exclusion at the aircraft is not required to meet the LPV-200 continuity risk requirement using dual-constellation GPS/Galileo ARAIM. The second part of the paper addresses the need of airborne exclusion for availability. Without airborne exclusion, ARAIM service outages due to fault detection can potentially last for one hour or longer. Such periods of continuous outage are highly undesirable. In response, fault exclusion methods can help reduce service outage periods at the cost of increased integrity risk due wrong exclusions. In this paper, availability is evaluated using ARAIM detection-only as compared to using ARAIM detection-and-exclusion. Results indicate that outage duration can be significantly reduced without substantial decrease in overall integrity performance.

INTRODUCTION

Global navigation satellite system (GNSS) measurements are vulnerable to faults including satellite and constellation failures, which can potentially lead to major integrity threats for users. To mitigate their impact, fault detection algorithms, such as receiver autonomous integrity monitoring (RAIM), can be implemented [1, 2]. The core principle of RAIM is to exploit redundant measurements to achieve self-contained fault detection at the user receiver [3].

With the modernization of GPS, the full deployment of GLONASS, and the emergence of Galileo and Beidou, an increased number of redundant measurements becomes available, which has recently led to a renewed interest in RAIM. In particular, due to its potential to achieve worldwide coverage of vertical guidance with a reduced investment in ground infrastructure, advanced RAIM (ARAIM) fault detection and exclusion (FDE) has attracted considerable attention in the European Union and the United States [4, 5, 6].

Two conflicting aspects of RAIM FDE arise in future dual-frequency, multi-constellation ARAIM. On the one hand, the integrity risk is reduced due to increased number of redundant measurements. On the other hand, the resulting heightened likelihood of satellite and constellation faults causes more occurrences of mission interruptions, thereby increasing the continuity risk. In response, in prior work [7, 8, 9], we established fault exclusion methods including general integrity and continuity risk equations for ARAIM FDE. These equations express the fact that the reduction in continuity risk, achieved using exclusion, comes at the cost of an increased integrity risk because of the possibility of removing the wrong measurements.

Our prior work on exclusion focused on the derivation of ARAIM FDE methods [7, 8, 9], but it did not identify cases where exclusion was or was not needed. Airborne exclusion can be implemented whenever a fault is detected so that the aircraft can continue using the navigation system. Using exclusion can improve continuity or availability performance, depending on which phase of flight the aircraft is in. In this paper, the need of exclusion for both continuity and availability is assessed for multi-constellation ARAIM.

ARAIM aims at meeting localizer precision requirements for aircraft landing with vertical guidance down to 200 feet altitude (LPV-200) [5]. LPV-200 approach is a relatively new operation and its navigation requirements are not clearly defined [5]. In response, this paper starts with an interpretation of 'average sense' continuity risk requirement that is specified by the International Civil Aviation Organization (ICAO) [10]. To evaluate the 'average' continuity risk for LPV-200, the overall navigation service performance must be considered *over time*, and it must account for loss of continuity (LOC) due to (a) false alarms, (b) fault detections, and (c) unscheduled satellite outages.

The paper analyzes each source of LOC. In particular, the impact of unscheduled satellite outages on continuity risk is evaluated as the average number of critical satellites multiplied by the probability of unscheduled satellite outages. A critical satellite is one which, if removed, causes a loss of continuity [12]. In this work, the average number of critical satellites is determined to be small for dual-constellation ARAIM, and is zero when three or four constellations are considered.

In addition, over its history, the GPS control segment has successfully limited the number of satellite faults to less than three per year [11]. With this fault rate, the average continuity risk requirement for LPV-200 is met by the GPS constellation itself. However, for multi-constellation GNSS, the continuity risk requirement stays the same, but the fault rate increases. The paper identifies cases where airborne exclusion is not needed, and others where it is required for continuity. For example, there is no need for fault-exclusion at the aircraft to meet the LPV-200 continuity requirement using dual-constellation GPS/Galileo ARAIM.

The second part of the paper addresses the use of airborne exclusion to reduce periods of continuous unavailability occurring when the aircraft is detects a fault. Without airborne exclusion, if a fault is detected during an approach, it causes LOC. But, if it is detected prior to the start of the approach, it causes service unavailability until the ground segment removes the faulty satellite. Assuming that the GNSS ground segment's mean time to alarm is one hour [12], the average ARAIM outage duration using detection-only is one hour. Outage times of one hour are unacceptable. In response, fault exclusion can be implemented at the aircraft receiver, at the cost of an increase in integrity risk due to potential wrong exclusions. In this paper, worldwide availability of ARAIM FDE is evaluated for aircraft approach navigation. Availability maps are established for a baseline GPS / Galileo navigation system described in detail in [13]. The results show that the airborne exclusion function efficiently reduces the outage time without substantially decreasing the overall integrity performance.

INTEGRITY AND CONTINUITY RISK

Integrity is a measure of the trust that can be placed in the correctness of the information supplied by the total system [10]. Integrity risk is defined as the probability that an undetected navigation system error results in hazardous misleading information:

$$P_{HMI} \equiv P(|\varepsilon_0| > \ell \cap |q| < T) \quad (1)$$

where

- ε_0 is the estimation error on the parameter of interest, referred to as 'state' of interest (e.g., the vertical position coordinate is of primary interest in aircraft landing applications).
- ℓ is a specified alert limit that defines hazardous situations (e.g., specified in [12] for aircraft approach navigation).
- q is the detection test statistic.
- T is the detection threshold.

In ARAIM, a multi-hypothesis fault detection algorithm can be employed [4], which accounts for all faulty space vehicle (SV) combinations. In this case, the integrity risk can be bounded by [3]:

$$P_{HMI} \le \sum_{i=0}^{h} P(|\varepsilon_0| > \ell \cap |q| < T \mid H_i) P_{Hi} + P_{NM} \quad (2)$$

where

- H_i is a set of mutually exclusive, jointly exhaustive hypotheses for i = 0, … , h. H_0 is the fault-free hypothesis. The remaining h hypotheses include single-satellite fault, multi-satellite faults and constellation fault.
- P_{Hi} is the prior probability of H_i occurrence.
- P_{NM} is the prior probability of very rarely occurring faults that need not to be monitored against [5].

Continuity of a service is the capability of the system to perform its function without unscheduled interruptions during the intended operation [10]. Continuity risk, or probability of loss of continuity (LOC), is the probability of a detected but unscheduled navigation function interruption after an operation has been initiated:

$$P_{LOC} = P_{FA} + P_{D,F} + P_{Other} \quad (3)$$

where

- P_{FA} is the probability of false alarm, which is set by the ARAIM detection threshold T.
- $P_{D,F}$ is the probability of fault detection when a fault occurs.
- P_{Other} includes all other causes of continuity loss, including satellite outages. This term is further discussed in the next sections.

Equation (3) expresses three causes for continuity loss. The first term, P_{FA}, can be made as small as desired. In fact, the ARAIM fault-detection threshold T in equation (2) is typically set based on an allocated continuity risk requirement $C_{REQ,0}$ to limit P_{FA} [3]:

$$P_{FA} = P(|q| > T \mid H_0) P_{H_0} \le C_{REQ,0} \quad (4)$$

If the detector is efficient, the second right hand term in equation (3) can be bounded by the overall probability of fault occurrence P_F, where P_F is the sum of all the fault probabilities:

$$P_{D,F} \le P_F = \sum_{i=1}^{h} P_{Fi} \quad (5)$$

where P_{Fi} is the probability of fault occurrence for i = 1, …, h. It is worth noting that P_{Fi} is used for continuity and P_{Hi} is used for integrity. The two notations capture the difference between average-sense continuity versus approach-specific integrity, which is discussed in the next section.

If P_F is larger than the overall continuity risk requirement C_{REQ}, which is likely to occur in multi-constellation GNSS, then P_{LOC} exceeds C_{REQ}. This is true regardless of the detection threshold T, i.e., even if P_{FA} is made much lower than C_{REQ}. In this case, fault exclusion is required to continue using the system. This is why ARAIM fault exclusion algorithms were designed in [7, 8, 9].

To identify cases where exclusion is needed, the continuity risk requirement must first be clarified and all causes of continuity loss must then be accounted for. For LPV-200 requirements, prior work does not provide a clear interpretation of the continuity risk requirement and does not quantify the impact of satellite outage on continuity. In response, this paper starts with an interpretation of continuity risk requirement.

AVERAGE SENSE CONTINUITY

The continuity risk requirement for LPV-200 approach is 8×10^{-6} per 15s. The International Civil Aviation Organization (ICAO) specifies that this requirement should be understood in an average sense:

"Missed approach is considered a normal operation, since it occurs whenever the aircraft descends to the decision altitude for the approach and the pilot is unable to continue with visual reference. The continuity requirement for these operations applies to the average risk (over time) of loss of service, normalized to a 15-second exposure time. Therefore, the specific risk of loss

of continuity for a given approach could exceed the average requirement without necessarily affecting the safety of the service provided or the approach."[10]

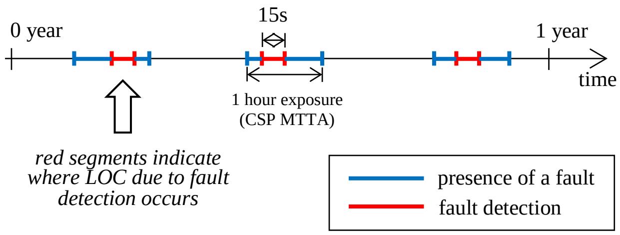

Fig. 1 One year time line (not to scale), used to interpret the LPV200 average sense continuity risk requirement

To illustrate the average sense continuity risk requirement, a one year time line is showed in Fig. 1. Based on the GPS constellation service provider (CSP) performance commitment [11], we use the following two assumptions. First, there can be no more than three SV faults per year [11]. Second, the CSP's mean time to alarm (MTTA) is one hour [12]; the MTTA is the average time needed by the ground segment to detect a fault and alert users. Thus, users could be exposed to a fault lasting for a period as long as MTTA before this fault is removed by the ground. In Fig. 1, the blue segments indicate the presence of faults. Therefore, on average, GPS users may be exposed to three faults per year.

In this interpretation, the following three assumptions are made, which are conservative with respect to continuity: (a) all three faults are detected, (b) detection always occurs during approach and (c) all three faulted SVs are visible to this aircraft receiver (while only about a third of the constellation is visible at a given time at locations near the surface of the earth). We will later discuss the fact that once a fault is detected, it may or may not impact the aircraft again. But, for clarity of exposition, Fig. 1 first assumes single-exposures to the three faults.

The red segments in Fig. 1 indicate loss of continuity due to fault detection. Under the above assumptions, there can only be one 15 seconds segment of continuity loss during the one-hour fault occurrence period, regardless of when the fault is detected. Therefore, the probability of LOC due to fault detection for one satellite is:

$$P_{F_i} = 3 \times 15\text{s} / 1\text{year} / 24\text{SV} = 6 \times 10^{-8} / \text{SV} \qquad (6)$$

It is worth noting that the above number is computed based on the commitment of GPS performance [11]. In future multi-constellation ARAIM, other values may be used for different constellations.

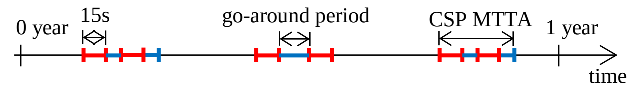

Fig. 2 Multiple exposures to same fault

Figure 2 illustrates the fact that a same fault could affect continuity more than once. For example, if an aircraft is impacted by a fault once, it could be exposed to the same fault again after it goes around to start a new approach. In Fig. 2, the second red segment within each blue segment represents faults affecting the second approach.

To quantify the impact of multiple exposures to same fault, we introduce a multiplier γ for the probability of LOC due to fault detection. On the one hand, since fault detection could occur multiple times during the one-hour exposure period, γ should be larger than 1. On the other hand, if a fault is detected during a first attempted approach, it will most likely be detected again by the airborne algorithm *prior* to next approach (because the magnitude of GNSS ranging faults typically increases monotonically). Detection prior to an approach impacts availability, not continuity. Therefore, γ should be a small value which only accounts for the less likely, not monotonically increasing faults. $\gamma = 1.1$ is used in this paper, which means that we assume one tenth of aircraft being exposed to the same fault again during their second approach.

The continuity risk equation (3) can then be bounded by:

$$P_{LOC} \le m_A \cdot P_{FA} + m_A \cdot \gamma \cdot \sum_{i=1}^{h} P_{H_i} + m_A \cdot P_{Other} \qquad (7)$$

A multiplier m_A is included in equation (7) to account for the average number of aircraft simultaneously losing continuity. In aircraft approach applications, navigation service can be used simultaneously by many aircraft. Continuity loss for an aircraft causes a missed approach, which can result in increased stress for the air traffic controllers (ATC) at the airport. However, a missed approach of an aircraft at one airport does not impact ATC at other airports. Therefore, m_A only accounts for LOC simultaneously impacting aircraft at the same airport. This approach is consistent with current GPS RAIM for en-route horizontal navigation [14], where a multiplier is applied to account for aircraft using the same navigation service during en-route flight. $m_A = 3$ is assumed in this paper.

The multiplier m_A is also applied to the first term in equation (7) for the following reason. False alarms are driven by nominal signal in space errors, which are larger than other error sources (including multipath and receiver noise) and are common to all receivers at an airport.

The third term of equation (7) expresses other reasons for LOC, including radio-frequency interference and SV outages. In this work, we focus on the impact of SV outages on continuity risk and are not accounting for radio-frequency interference. There are two types of SV outages: scheduled SV outages and unscheduled SV outages. Assuming that the aircraft will be notified in advance by the ground, e.g., via the ARAIM Integrity Support Message (ISM), scheduled SV outages only impact availability, not continuity. Thus, the third term of equation (7) accounts for LOC due to unscheduled SV outages. Since such outages could impact all aircraft at an airport, the multiplier m_A is also applied for this term.

Finally, the probability P_{Other} can be expressed as:

$$P_{Other} = n_{c,a} \cdot P_{out} \quad (8)$$

where

$n_{c,a}$ is the average number of critical satellites, further discussed in the next section.

P_{out} is the probability of unscheduled SV outages: 4.3×10^{-7} / SV over 15s [12].

To quantify the impact of unscheduled SV outages on continuity risk, we need to determine the average number of critical satellites $n_{c,a}$. A critical satellite analysis is carried out in the next section.

CRITICAL SATELLITE ANALYSIS

A critical satellite is one whose removal is expected to lead to LOC during an approach [12]. In other words, the loss of a critical satellite results in integrity risk (P_{HMI}) exceeding its requirement (I_{REQ}) because the remaining satellites provide poor geometry. In this section, a critical satellite analysis for multi-constellation ARAIM detection is carried out following the following three steps:

- Evaluate the P_{HMI} at one location, at one point in time.
- If the $P_{HMI} < I_{REQ}$, then take out one visible satellite and evaluate the P_{HMI} again using the remaining satellites. Otherwise, evaluate P_{HMI} for the next point.
- Then, if the P_{HMI} evaluated using the remaining satellites exceeds I_{REQ}, then the satellite that was taken out is regarded as a critical satellite.

Table 1. Critical Satellite Analysis Using Dual-Constellation ARAIM

n_c	P
0	0.8406
1	0.1383
2	0.0159
3	0.0039
4	0.0010
5	3.03×10^{-4}
6	7.01×10^{-5}

In order to determine the average number of critical satellites, we consider all locations in the world over the constellation's repeatability period (e.g., over 10 days for GPS/Galileo). Table 1 presents the results of the critical satellite analysis using dual-constellation ARAIM detection. The left column of the table lists the values that we considered for the number n_c of critical satellites. The right column gives the probability of having n_c critical satellites. For example, the second row of the table shows that there are 84.06% of occurrences where the critical satellite number is 0. The average number of critical satellites using dual-constellation ARAIM is computed as the sum of the products of n_c in the first column of Table 1, with the corresponding occurrence probability in the second column. This number is:

$$n_{c,a} = 0.19 \quad (9)$$

With this value, along with P_{out}, the impact of unscheduled SV outages on continuity can be quantified following equation (8).

It is worth noting that the average number of critical satellites is $n_{c,a}$ = 0 for ARAIM using three or four constellations. As the number of available satellites increases, the impact of an unscheduled outage for a specific satellite decreases because the geometry of the remaining satellites is strong enough to meet the navigation requirements.

NEED OF EXCLUSION FOR CONTINUITY

With the above interpretation of continuity risk and the analysis on unscheduled SV outages, we can assess the need of exclusion for continuity. As mentioned in previous sections, fault exclusion is required when the probability of fault occurrence exceeds the continuity risk requirement. Therefore, whether fault exclusion is required for continuity depends on the probability of fault occurrence.

To incorporate information from multiple constellations at different stages of their development, ARAIM relies on an Integrity Support Message (ISM) generated at the ground and broadcast to airborne receivers [4]. The probability of satellite fault P_{sat} and constellation fault P_{const} are provided in the ISM. For GPS, the specified P_{sat} value is $P_{sat} = 10^{-5}$ [4, 13]. Also, $P_{const} = 10^{-4}$ is used in ARAIM to account for constellation faults [13].

It is worth clarifying that P_{sat} and P_{const} are provided for integrity. The integrity requirement is given in an approach-specific sense, as described in Appendix A. The following conversion should be considered for the probability of satellite fault occurrence used in the continuity risk equation (3):

$$P_{F_i} = P_{sat} \cdot \frac{15\text{s}}{1\text{hour}} \tag{10}$$

For constellation fault:

$$P_{F_i} = P_{const} \cdot \frac{15\text{s}}{1\text{hour}} \tag{11}$$

In this section, an analysis is carried out to assess the necessity of exclusion in ARAIM for representative cases using two, three, and four constellations.

Dual-Constellation ARAIM

For dual-constellation ARAIM, the following assumptions are made to give a preliminary assessment of the necessity of fault exclusion:

- ARAIM is implemented using fault detection-only (no exclusion);
- the two constellations have the same P_{sat} and P_{const} values as GPS, i.e. $P_{sat} = 10^{-5}$ and $P_{const} = 10^{-4}$;
- 8 satellites are in view for each constellation; and
- $n_A = 3$ and $\gamma = 1.1$ for equation (7).

Under these assumptions, equation (7) can be written as:

$$P_{LOC} \le 3 \times P_{FA} + 4.9 \times 10^{-6} + 2.5 \times 10^{-7} \tag{12}$$

Numerical values for the second and third right-hand-side terms are determined based on the discussion on LOC in the previous two sections. In equation (12), the sum of the last two terms is 5.15×10^{-6}, which is lower than the continuity risk requirement of 8×10^{-6}. Since P_{FA} can be made as small as desired, the navigation system using airborne detection-only can meet the continuity requirement. In this case, there is no need to implement exclusion for continuity.

However, equation (12) assumes the same P_{sat} and P_{const} values for both constellations. Whether exclusion is required using dual-constellation ARAIM depends on the values of P_{sat} and P_{const} for each constellation.

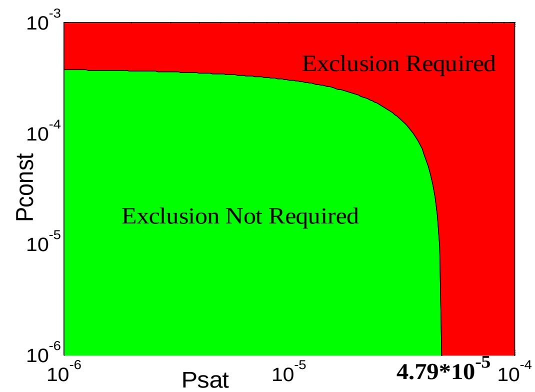

Fig. 3 Need of Exclusion with Varying P_{sat}, P_{const} for GNSS2 given $P_{sat} = 10^{-5}, P_{const} = 10^{-4}$ for GNSS1

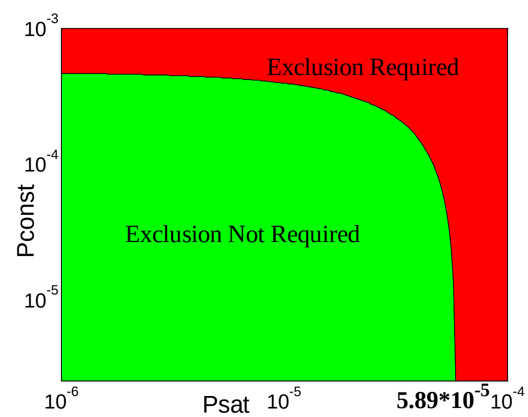

Fig. 4 Need of Exclusion with Varying P_{sat}, P_{const} for GNSS2 given $P_{sat} = 10^{-5}, P_{const} = 10^{-5}$ for GNSS1

Fig. 3 shows cases where exclusion is required for dual constellation ARAIM with varying values of P_{sat} and P_{const} for the first constellation labeled GNSS2, given that the second constellation (GNSS1) assumes $P_{sat} = 10^{-5}$ and $P_{const} = 10^{-4}$. Fig. 4 displays similar results assuming $P_{sat} = 10^{-5}$ and $P_{const} = 10^{-5}$ for GNSS1. In both cases, if the satellite fault probability P_{sat} is larger than 6×10^{-5} for one of the two constellations, exclusion is required.

ARAIM Using Three or Four Constellations

When using more than two GNSS, the higher number of satellites and constellations increases the probability of fault occurrence. It follows that the need of exclusion for continuity also increases. Similar to dual-constellation ARAIM, the following assumptions are made to assess the need of exclusion:

- ARAIM is implemented using detection-only (no exclusion);
- 8 satellites are in view for each constellation; and
- $n_A = 3$ and $\gamma = 1.1$ in equation (7).

Table 2. Need of Exclusion for ARAIM Using 3 Constellations

GNSS3 \ GNSS1-2	$P_{sat} / P_{const} : 10^{-5} / 10^{-4}$
10^{-5} / 10^{-4}	Exclusion not required
10^{-4} / 10^{-4}	Exclusion required

Table 3. Need of Exclusion for ARAIM Using 4 Constellations

GNSS4 \ GNSS1-3	$P_{sat} / P_{const} : 10^{-5} / 10^{-4}$
10^{-5} / 10^{-4}	Exclusion required
10^{-4} / 10^{-4}	Exclusion required

Tables 2 and 3 illustrate the cases where exclusion is required when using three and four constellations, respectively. Table 2 assumes that and $P_{sat} = 10^{-5}$ and $P_{const} = 10^{-4}$ for GNSS1 and GNSS2, and that $P_{const} = 10^{-4}$ and P_{sat} = 10^{-5} or P_{sat} = 10^{-4} for GNSS3. Similar assumptions are made in Table 3, with $P_{sat} = 10^{-5}$ or P_{sat} = 10^{-4} for GNSS4. In both tables, red cells indicate cases where exclusion is required. In contrast, green cells show cases where exclusion is not needed for continuity. Table 3 suggests that, under the simplifying assumptions made at the beginning of this section (including for example that 8 SV are in view for each constellation), exclusion is always required if four constellations are used in ARAIM.

EXCLUSION FOR AVAILABILITY

Mission interruptions due to false alarms, satellite outages, fault detections, or poor satellite geometries causing $P_{HMI} > I_{REQ}$ impact continuity if they occur during an approach. But, if they occur prior to the start of the approach, they affect availability. This section focuses on the impact of exclusion on availability.

First, without airborne exclusion, we must consider the availability outage duration occurring when a fault is detected prior to the approach. Once a fault is detected, the aircraft can either (a) wait for the ground segment to remove the fault, or (b) avoid imposing a delay and instead, continuously perform fault-detection and thus detect the fault again and again until it is removed by the ground. In both cases, the average unavailability duration is the ground segment's mean time to alarm (MTTA).

Assuming that the MTTA is one hour, and that the fault rate per constellation is three faults per year, dual-constellation ARAIM using detection-only (no airborne exclusion) can be affected by six continuous one-hour-long outage periods per year. This number becomes even larger if three or four GNSS are used.

Continuous one-hour unavailability durations are highly undesirable for aircraft operations. In response, airborne exclusion can be implemented to quickly remove the faulty satellite after it is detected. This section describes a solution separation (SS) ARAIM FDE method, which is designed to not only meet continuity requirements as in [7, 8, 9], but also to meet an availability requirement.

First, using the same notations as in equation (2) and in references [7, 8, 9], the solution separations for fault detection are defined as[1, 3]:

$$\Delta_i \equiv \hat{x}_0 - \hat{x}_i = \varepsilon_0 - \varepsilon_i, \text{ for } i = 1, ..., h. \qquad (13)$$

where

$\hat{x}_0$ is the full-set solution.

$\hat{x}_i$ is the subset solution derived using only the fault-free measurements under H_i.

ε_i is the estimation error derived using only the fault-free measurements under H_i.

Δ_i follows a normal distribution with standard deviation σ_{Δ_i} [3, 9]. For SS ARAIM, the detection threshold under H_i can be determined using the following expression:

$$T_i = Q^{-1}\left\{\frac{C_{REQ,0}}{2P_{H0}\cdot h}\right\}\sigma_{\Delta_i} \qquad (14)$$

The integrity risk using detection-only (no exclusion) can be bounded by [3]:

$$P_{HMI} \le P(|\varepsilon_0| > \ell \mid H_0)P_{H0} + \sum_{i=1}^{h} P(|\varepsilon_i| + T_i > \ell \mid H_i)P_{Hi} + P_{NM} \quad (15)$$

Then, we can design an exclusion method to reduce the average unavailability duration, for example by setting a desired mean time to exclude (MTTE) at the aircraft receiver. The resulting requirement on loss of availability (LOA) can be given by:

$$P_{LOA,REQ} = \sum_{i=1}^{h} MTTE \cdot \frac{P_{Hi}}{MTTA} \quad (16)$$

where MTTA is the ground segment's mean time to alarm. Equation (16) expresses $P_{LOA,REQ}$ as the sum of products of the fault rate $\frac{P_{Hi}}{MTTA}$ and the required MTTE.

The exclusion procedure can then be described as follows [7, 8, 9]. A fault is detected if:

$$|\Delta_k| \equiv |\hat{x}_0 - \hat{x}_k| \ge T_k \quad \text{for any } k,\ k = 1, ..., h. \quad (17)$$

In case of detection, an attempt is made at exclusion. All exclusion candidate subsets '*j*', noted S_j, for *j* =1, …, *h* are considered. In order to find the remaining subset $\hat{x}_j$ that can be assumed fault-free, a second layer of detection is carried out using all subset solutions $\hat{x}_{j,l}$ within $\hat{x}_j$. Thus, S_j is excluded if [7, 8, 9]:

$$|\Delta_{j,l}| \equiv |\hat{x}_j - \hat{x}_{j,l}| < T_{j,l} \quad \forall l,\ \begin{cases} l = 1,\ ...,\ h \\ \forall\ S_l \not\subset S_j \end{cases} \quad (18)$$

If the exclusion test fails for all the candidates $\hat{x}_j$ being tested prior to the approach, then this no-exclusion '*NE*' event causes loss of availability. The probability of loss of availability caused by '*NE*' can be written as:

$$P_{LOA} = \sum_{i=1}^{h} P(D, NE \mid H_i)P_{Hi} \quad (19)$$

Appendix B of [9] provides an upper bound on P_{LOA}, which can be expressed as:

$$P_{LOA} \le \sum_{j=1}^{h} \sum_{\substack{i=1 \\ S_i \not\subset S_j}}^{h} P(|\Delta_{j,i}| \ge T_{j,i} \mid H_0)P_{H_i} \quad (20)$$

Therefore, the exclusion threshold can be set by:

$$T_{j,i} = Q^{-1}\left\{\frac{P_{LOA,REQ}}{2P_{Hi} \cdot h \cdot \tau_i}\right\}\sigma_{\Delta_{j,i}} \quad (21)$$

where τ_i is the number of exclusion tests needed under H_i [9]. Equation (21) expresses the fact that the exclusion threshold is set based on an availability requirement.

Given T_i and $T_{j,i}$ in equations (14) and (21), respectively, the SS ARAIM FDE integrity risk bound can be expressed as [9]:

$$P_{HMI} \le P(|\varepsilon_0| > \ell \mid H_0)P_{H0} + \sum_{i=1}^{h} P(|\varepsilon_i| + T_i > \ell \mid H_i)P_{Hi} + \sum_{j=1}^{h}\left(\sum_{\substack{i=0 \\ S_i \subset S_j}}^{h} P(|\varepsilon_i| > \ell \mid H_i)P_{H_i} + \sum_{\substack{i=1 \\ S_i \not\subset S_j}}^{h} P(|\varepsilon_{j,i}| + T_{j,i} > \ell \mid H_i)P_{H_i}\right) + P_{NM} \quad (22)$$

where the first two right-hand-side terms are the same as in equation (15) for detection-only, and the third term captures the additional integrity risk caused by potential wrong exclusions.

AVAILABILITY ANALYSIS AND AVERAGE UNAVAILABILITY PERIOD EVALUATION

In this section, worldwide availability performance is evaluated for baseline GPS and Galileo constellations described in [13], and for simulation parameters given in Table 4. Table 4 describes LPV-200 navigation requirements, including vertical alert limit (VAL), and horizontal alert limit (HAL) [4]. Table 4 also lists values of the ISM parameters: these include P_{const} and P_{sat}, the standard deviations σ_{URA} and σ_{URE} of SV clock and ephemeris error for integrity and continuity, respectively , and the maximum nominal bias b_{nom} for integrity [4]. In this simulation, the probability of constellation-wide fault P_{const} is assumed to be zero. Constellation faults are discussed in the next section.

Global availability maps are displayed in Fig. 5 to 8 for a 5 deg × 5 deg grid of locations. At each location, availability is computed at regular 5 minute intervals as the fraction of time over 24 hours where P_{HMI} meets the integrity risk requirement I_{REQ}.

Table 4. Simulation Parameters

VAL	35m
HAL	40m
I_{REQ}	10^{-7}
C_{REQ}	2×10^{-6}
Location Grid	5 deg × 5 deg
P_{sat}	10^{-5}
P_{const}	0
σ_{URA}	1m
σ_{URE}	0.67m
b_{nom}	0.75m
MTTE	5min

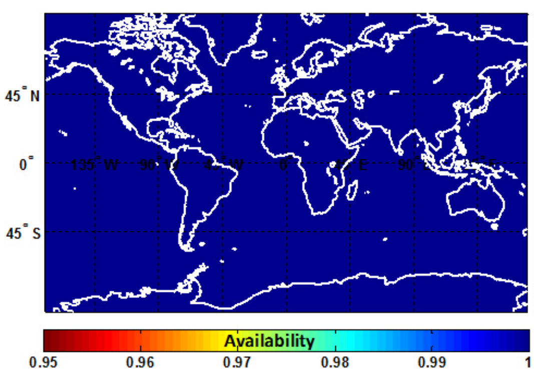

Fig. 5 Availability of $P_{HMI} < I_{REQ}$ without Airborne Exclusion, Coverage of 99.5% Availability is 100%

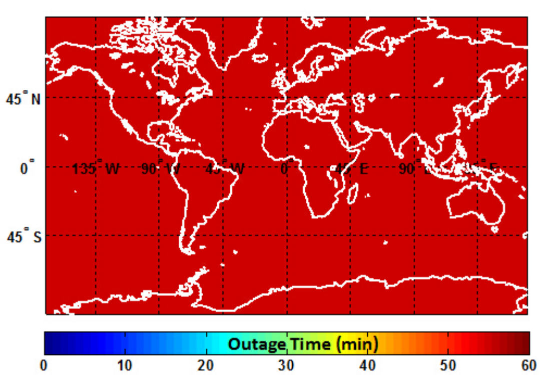

Fig. 6 Average Continuous Unavailability Duration for Fault Detection without Airborne Exclusion

Fig.5 and Fig. 6 show the availability performance of dual-constellation ARAIM using detection-only (without airborne exclusion), considering the P_{HMI} -bound in equation (15). Fig. 5 indicates that we can achieve high availability of $P_{HMI} < I_{REQ}$. The worldwide availability metric given in the figure caption is the weighted coverage of 99.5% availability: coverage is defined as the percentage of grid point locations exceeding 99.5% availability. The coverage computation is weighted at each location by the cosine of the location's latitude, because grid point locations near the equator represent larger areas than near the poles. Fig. 5 shows that the coverage of 99.5% availability is 100%.

In contrast, Fig. 6 focuses on the average period of continuous unavailability as a performance metric. Fig. 6 assumes the same configuration as in Fig. 5, i.e., dual-constellation ARAIM using detection only. Without airborne exclusion, once a fault occurs, the average continuous unavailability duration is the ground segment's MTTA of one hour, as represented in Fig. 6.

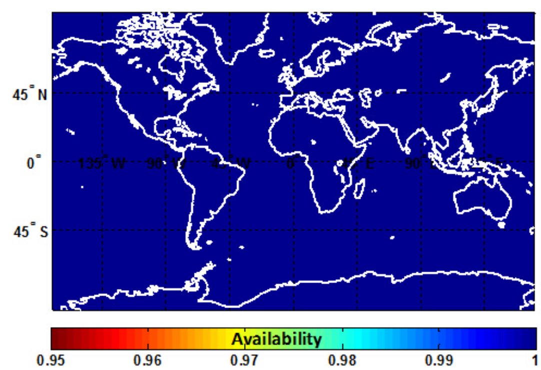

Fig. 7 Availability of $P_{HMI} < I_{REQ}$ Using Airborne Exclusion, Coverage of 99.5% Availability is 100%

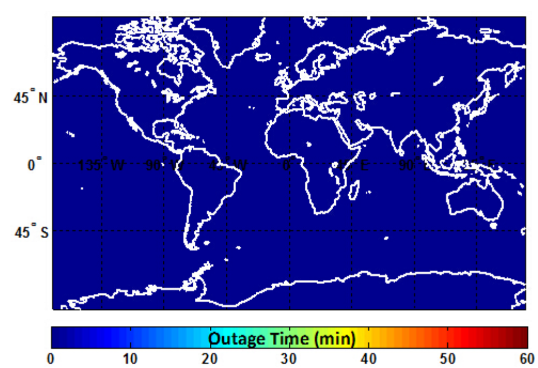

Fig. 8 Average Continuous Unavailability Duration Using Airborne Detection *and Exclusion*

Fig. 7 and Fig. 8 show the availability performance for dual-constellation ARAIM using airborne fault-detection *and exclusion*, i.e., considering the P_{HMI} -bound in equation (22). The extra terms in equation (22) as compared to equation (15) cause the integrity risk to be larger using FDE than using detection-only. Fig. 7 shows that in this case, the increase in integrity risk does not impact global availability, and coverage of 99.5% availability is still 100%. In parallel, the exclusion threshold was set in equation (21) to ensure that the mean time to exclude (MTTE) would not exceed 5 minutes. It follows that the average continuous unavailability period is five minutes (as represented in Fig. 8), which is a significant improvement as compared to the one hour outage period occurring using detection-only.

CONSTELLATION FAULT EXCLUSION USING DUAL-CONSTELLATION ARAIM

When using dual-constellation ARAIM, faults simultaneously affecting all SVs in a constellation can be detected, but cannot be excluded due to lack of redundancy. If airborne exclusion is required for any of the reasons mentioned above in this paper, then alternative solutions must be found.

One option is refining the definition of constellation-wide faults to account for operational constraints that prevent erroneous ephemeris information to simultaneously reach all SVs in a constellation at once. Constellation-wide faults are defined when a single, common cause leads to concurrent faults on more than one satellite in the constellation [4]. Erroneous navigation data broadcast by the constellation service provider (CSP) is the main source of constellation-wide faults [13]. The GPS navigation data is currently uploaded one satellite at a time, with an average interval of 45 minutes between uploads. It takes approximately one day to upload a new ephemeris to the whole constellation. Assuming that the ground segment's MTTA is one hour, it is highly likely that an erroneous ephemeris would be detected before it impacts all satellites in the constellation. Therefore, from a user's perspective, a constellation fault may only affect a few satellites. Airborne exclusion can then be implemented for the potentially faulted satellite subsets using dual-constellation ARAIM. This idea will be further investigated for GPS and for other GNSS, and the resulting performance will be evaluated in the future work.

CONCLUSION

This paper analyzes the need for fault exclusion to ensure continuity and availability in future dual-frequency, multi-constellation ARAIM. The first part of the paper provides a new interpretation of 'average sense' continuity, which is specified but not fully defined in LPV-200 aircraft approach navigation requirements. In parallel, a critical satellite analysis is carried out to demonstrate that the impact of unscheduled satellite outages on the continuity of future multi-constellation ARAIM is small. These results are then applied to show that airborne exclusion is not required to meet LPV-200 continuity risk requirements using dual-constellation ARAIM.

The second part of this paper explores the potential of airborne exclusion to reduce the average continuous unavailability duration. Without airborne exclusion, the mean time for the ground segment to remove a faulty satellite is approximately one hour, which is not a desirable service outage period in aviation applications. But using exclusion increases the integrity risk due to the possibility of removing the wrong satellites. The paper shows that airborne exclusion efficiently reduces the outage durations, while maintaining high availability of integrity and continuity.

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APPENDIX A: APPROACH SPECIFIC INTEGRITY RISK REQUIREMENT

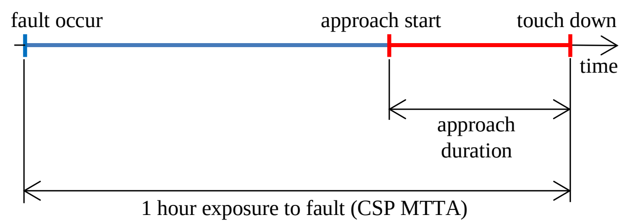

Fig. A.1 One hour time line for LPV-200 integrity risk requirement interpretation (not to scale)

For LPV-200, the integrity risk requirement is specified in an approach-specific sense. To interpret approach-specific integrity, Fig. A.1 displays a timeline for a single approach. In an approach-specific interpretation, we must assume that a latent fault can exist at the start of the approach, and might have been present over a time-period that can be as long as the ground's MTTA. This assumption expresses the worst case exposure time to a fault for one specific approach. It follows that the prior probability of fault is the product of the fault rate with the ground's MTTA. Assuming MTTA = 1hour, the prior probability of single satellite fault occurrence for integrity is [4, 13]:

$$P_{H_i} = P_{sat} \tag{A.1}$$

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