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ORIGINAL ARTICLE

Sensitivity of advanced RAIM performance to mischaracterizations in integrity support message values

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Abstract

With the increasing number of navigation satellite constellations from multiple service providers, an emerging concept for receiver avionics is being developed which will significantly improve the current, widely available operations based on the classical Receiver Autonomous Integrity Monitoring (RAIM). This emerging concept, called Advanced RAIM (ARAIM), is envisioned to eventually provide a worldwide approach capability for Localizer Performance with Vertical Guidance (LPV). One major architectural change of ARAIM from RAIM is introduction of the Integrity Support Message (ISM), which is a set of parameters representing the statistical characterization of the core navigation constellation performance. The ISM values will be periodically updated and used as a priori information in the ARAIM user algorithm. Therefore, it is critical to broadcast ISM values that would provide optimal ARAIM performance balanced between the margins of integrity, continuity, and availability. In this paper, we analyze the sensitivity of ARAIM performance to potential ISM mischaracterization.

KEYWORDS

Advanced RAIM (ARAIM), Horizontal ARAIM (H-ARAIM), Integrity Support Message (ISM), Vertical ARAIM (V-ARAIM)

1 | INTRODUCTION

This introduction includes some background on how Advanced RAIM (ARAIM) evolved from classical RAIM, the roles ISM plays, and the critical issues of ISM, which is followed by the purpose and a brief outline of the paper.

1.1 | Classical RAIM

The concept of classical RAIM was first proposed in 1986 (Lee, 1986) when the initial operational capability of the US Global Positioning System (GPS) was still being developed. The basic idea of RAIM was to provide integrity for a GPS receiver position solution by exploiting GPS receiver-to-satellite range measurement redundancy. One fundamental assumption with the classical RAIM is that only up to one satellite can become faulty at a time, and the probability of two or more satellite faults occurring, either mutually independent or correlated, may be neglected. The concept gradually grew to mature techniques published in many papers since then (Parkinson & Axelrad, 1988; Sturza, 1988-89; Lee, 1993; Brenner, 1996; Lee et al., 1996; Brown & Chin, 1998; Kelly, 1998). In the meantime, the Federal Aviation Administration (FAA) Navigation Satellite Operational Implementation Team (SOIT) wrote the Technical Standards Order (TSO) C-129 (later replaced with TSO C-129A), which described the capabilities of GPS avionics to be used as a supplemental means of navigation for en route through non-precision approach phases of flight. The analyses performed to support the development of the TSO and the further development of an FAA position on the use of GPS as a primary means of navigation in oceanic and remote airspace are described in Fernow and Lee (1994) and Lee and Fernow (1995), respectively. These developments launched the era of satellite-based navigation for civil aviation.

1.2 | Development of Advanced RAIM (ARAIM)

ARAIM, an advanced version of RAIM, has been developed with the long-term vision to support air navigation globally with horizontal and vertical guidance using emerging navigation satellite constellations from multiple GNSS service providers (e.g., GPS, GLONASS, Galileo, and BeiDou). These multiple core constellations provide many more satellites than available with GPS alone and thus would significantly improve range measurement redundancy and create stronger user-to-satellite geometry. In addition, these satellites would provide dual frequency signals yielding significantly better ranging accuracy by removing relatively large ionospheric delay estimation errors.

The ARAIM concept was initially identified and comprehensively documented as a viable future GNSS option in the FAA's GNSS Evolutionary Architecture Study (GEAS) team (GNSS, 2010). Subsequently, the ARAIM Technical Subgroup (ARAIM TSG), created by the leadership of the EU-US Cooperative Working Group (WG)-C, has taken over the GEAS work and has been leading the effort to develop and implement ARAIM (*Milestone 2 Report*, 2015; *Milestone 3 Report*, 2016).

The initial focus of the ARAIM TSG was on ARAIM that could support Localizer Performance with Vertical Guidance (LPV), LPV-200 in particular, operations in anticipation of more significant operational benefits worldwide than with Required Navigation Performance (RNP) operations. This, called Vertical ARAIM (V-ARAIM), provides both vertical and horizontal navigation. However, LPV operations with V-ARAIM may take a decade or longer to implement, and therefore there are many critical issues to resolve.

On the other hand, RNP implementation supported by Horizontal ARAIM (H-ARAIM) carries less risk, is less demanding than LPV implementation, and can be completed much earlier. Although operational benefits attained with the RNP could be rather modest compared with the LPV operations with V-ARAIM, H-ARAIM would provide enhanced RNP 0.3 operations with higher availability than is possible with classical RAIM. Implementing H-ARAIM first would allow civil aviation users' transition to V-ARAIM at a later date to go more smoothly. For this reason, the joint effort between the US (RTCA SC-159) and Europe (EUROCAE WG-62) currently underway to develop the Minimum Operational Performance Standards (MOPS) for aviation user equipment calls for the inclusion of H-ARAIM.

While the algorithms for V-ARAIM and H-ARAIM share a common baseline ARAIM algorithmic definition [WG-C Advanced RAIM Technical Subgroup (ARAIM TSG) Reference Airborne Algorithm Description Document (ADD), 2019], the performance requirements for H-ARAIM and V-ARAIM differ significantly. In particular, continuity requirements for H-ARAIM supporting RNP operations are much more stringent than those for V-ARAIM supporting LPV, primarily because the exposure time for RNP is much longer. This necessitates invoking fault exclusion upon fault detection in the H-ARAIM algorithm, while the exposure time for LPV operations supported by V-ARAIM is much shorter and its continuity requirement can be met without the exclusion function [WG-C Advanced RAIM Technical Subgroup (ARAIM TSG) Reference Airborne Algorithm Description Document (ADD), 2019]. For smooth flow of presentation, V-ARAIM will be discussed before H-RAIM in this paper.

Many additional features were incorporated into ARAIM to improve its integrity performance and the availability of its service. One distinct feature of ARAIM that improves its capability from that of RAIM is the introduction of an Integrity Support Message (ISM). The ISM is a periodically updated set of parameters that represents the statistical characterization of the core navigation constellation performance. This ISM is used in the avionics as a priori information in the ARAIM user algorithm. ARAIM performance depends on how well the ISM parameter values bound the core constellation GNSS signal performance.

Highlights of ARAIM features enhanced from classical RAIM are as follows:

- Use of Dual-Frequency Multiple Constellations (DFMC) improving the integrity and availability/coverage of ARAIM service
- Optimization of Protection Level (PL) formulas in solving for PL by iterative means while allowing variable probability of missed detection (P_{md}) for individual satellites, but still meeting the total probability of Hazardously Misleading Information (Pr{HMI}). These methods reduce PLs and thus increase availability of ARAIM service
- Capability to handle multiple satellite faults, if necessary, to accommodate increased overall probability of satellite faults when multiple constellations, some of which may not be as reliable as GPS, are included. Note that classical RAIM assumes that only up to a single satellite may be faulty at a time. ARAIM is designed to handle fault characteristics that may be different among the satellites or constellations

- Introduction of ISM for the timely update of the core navigation constellation performance

1.3 | Critical role of ISM for ARAIM

Classical RAIM was based on a set of fixed assertions regarding the nominal error characteristics and fault rates of GPS. In contrast, ARAIM uses an ARAIM-dedicated ground monitoring network to provide updates regarding the nominal performance and fault rates of the contributing constellations. This integrity data, which is ISM, is to be developed on the ground and provided to the airborne fleet.

Successful implementation of ARAIM services require the resolution of multiple challenging issues. One major challenge is how to carry out global coordination of ISM generation and provisions to achieve seamless worldwide coverage using multiple constellations. ISM parameters are intended to reflect the core constellation performance, and the more truthfully the broadcast parameter values reflect actual constellation performance, the more effectively ARAIM can perform to meet its requirements.

For a judicious selection of the ISM parameter values to broadcast, one needs to consider a trade-off between integrity performance (i.e., Pr{HMI}) and ARAIM availability, which varies in PL. In general, if the broadcast ISM parameter values are not conservative enough, ARAIM would fail to assure the required level of safety of service; however, if they are too conservative, the availability would decrease, reducing the operational benefits of ARAIM. This paper analyzes the sensitivities of ARAIM performance to the selection of ISM parameters. ISM values representing actual core constellation performance are to be termed as *actual* ISM values in contrast to the ISM values broadcast to and used by the user avionics. The difference between these two values is the ISM deviation reflecting the mischaracterization of the ISM to the actual.

In general, ISM parameter values would be initially chosen based on documented commitments by Constellation Service Providers (CSP) and core constellation performance observed for a limited time period. This would be followed by the careful evaluation of the constellation performance data collected over a long period of time against those CSP commitments. In the statistical characterization of the constellation performance, subjective judgements could be introduced.

In addition, different organizations in different countries could have different ideas on the selection of ISM parameter values. For example, some core CSPs may want to assert high confidence in their system and want to broadcast ISM values even before they are fully validated and supported by service history, whereas Air Navigation Service Providers (ANSP) in individual countries may not feel comfortable accepting such values in their airspace. In order to avoid such potentially conflicting situations and achieve successful global implementation of ARAIM, analyses need to be performed and standardized procedures need to be developed that would be acceptable to all parties.

This paper analyzes how ISM deviations affect ARAIM performance (specifically in integrity and availability) and evaluates its sensitivity to ISM deviations. This work has been performed to support the ARAIM TSG of European Union-United States (EU-US) Cooperative Working Group (WG)-C.

1.4 | ARAIM architecture

Figure 1 illustrates an architecture of a multi-constellation ARAIM as envisioned by the ARAIM TSG (*Milestone 2 Report*, 2015; *Milestone 3 Report*, 2016) comparing it with that of classical RAIM.

- Constellations: Typically, ARAIM will use two or more constellations
- ARAIM-dedicated ground monitoring network: Hundreds of reference stations at widely separated locations globally monitor the core constellation performance and provide data to determine the ISM parameter values to be used by the airborne ARAIM algorithms. While hundreds of reference stations are envisioned, a smaller number may be enough
- ISM dissemination: ISM parameters representing core constellation performance are updated periodically. How often they are updated depends on its application. For ground monitoring of ARAIM performance for LPV operations, the update rate for ISMs would be very modest compared with the update rate for SBAS message data. For example, monthly updates could be sufficient. For RNP operations, the update rate may be much less frequent than for LPV (once a year or longer). While different candidate ISM dissemination mechanisms were discussed by the ARAIM TSG (*Milestone 2 Report*, 2015), the mechanism of disseminating ISMs for each core constellation performance parameter by the respective constellations using their navigation message spare bits is a leading candidate (Kovach, 2018; Kovach, 2019)
- User receiver process: ARAIM is executed for measured data from satellites to detect and exclude (if exclusion function is implemented) faults in satellites or in a constellation, assuming the broadcast ISM parameter values overbound the distribution of actual values representing the core constellation performance

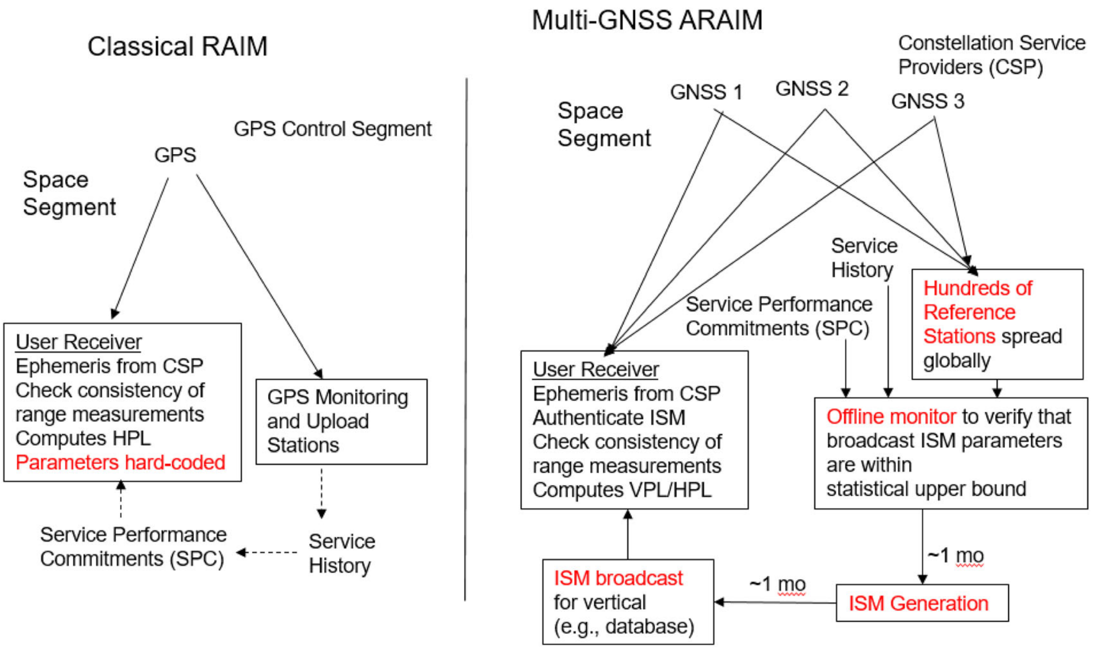

FIGURE 1 Architectures for Classical RAIM vs. MDFC-Based Multi-Constellation ARAIM (Milestone 2 Report, 2015; Milestone 3 Report, 2016) [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

While Figure 1 represents V-ARAIM architecture supporting LPV-200, the architecture for H-ARAIM supporting an RNP operation is similar except for the generation and update rate of the ISM parameters.

1.5 | Outline of the paper

In the following text, we will address topics that apply to both V-ARAIM and H-ARAIM: baseline ARAIM algorithms and our approach for ISM sensitivity analysis methods. We will then investigate the sensitivity of navigation performance to ISM parameter mischaracterizations individually for V-ARAIM followed by H-ARAIM. Finally, we have a summary/conclusion.

2 | KEY ARAIM TERMINOLOGIES FOR ISM SENSITIVITY ANALYSIS

The analysis in this paper is based on the ARAIM reference algorithms in the ARAIM Algorithms Description Document (ADD) developed by the ARAIM TSG (2019). Many of the equations supporting the algorithms are derived in Blanch et al. (2012) and Juan et al. (2015). This section introduces key ARAIM terminologies to understand our ISM sensitivity analysis.

2.1 | ISM parameters for satellite range measurement error model and fault probabilities

Five parameters that are defined in the current ARAIM reference algorithm are as follows [WG-C Advanced RAIM Technical Subgroup (ARAIM TSG) Reference Airborne Algorithm Description Document (ADD), 2019]: σ_{URA}, σ_{URE}, b_{nom}, P_{sat}, and P_{const}

- The user-to-satellite range measurement error is modeled as a Gaussian overbounding:
  - $\sigma_{URA,i}$ and $\sigma_{URE,i}$ denote the standard deviations of the clock and ephemeris error of satellite i used to assure integrity and accuracy, respectively.
  - $b_{nom,i}$ denotes the nominal bias error bound for satellite i used to assure integrity. For accuracy and continuity, the bias term is set at zero.
- ARAIM defines two different types of faults whose probabilities are typically specified per approach or per hour:
  - $P_{sat,i}$ denotes the prior probability of a fault in satellite i that occurs independently from other satellites
  - $P_{const,j}$ denotes a correlated fault affecting more than one satellite in the j^{th} constellation simultaneously.

2.2 | Fault modes

In ARAIM, each fault mode is defined as a specific set of satellite- and/or constellation-wide faults that occur, and every fault mode is associated with a corresponding subset of satellites that are free from those faults. For the k^{th} fault mode, for example, the corresponding subset is one containing all satellites in the full set except for the satellites that belong to the k^{th} fault mode. Therefore, the k^{th} subset is a subset free from the k^{th} fault mode.

For each fault mode k ($k = 1, \ldots$ N), where N is the number of fault modes, the following terms are defined:

$P_{fault,k}$: Probability of occurrence of the k^{th} fault mode, calculated from $P_{sat,i}$ and $P_{const,j}$ for all i's and j's where the i^{th} satellite and the j^{th} constellation faults are in the k^{th} fault mode

${\sigma_q}^{(k)}$: Standard deviation of the position along the q axis, derived from $\sigma_{URA,i}$ for all i's

${b_q}^{(k)}$: The worst-case impact on the k^{th} fault mode subset position solution along the q axis, derived from $b_{nom,i}$ for all i

${\sigma_q}^{(0)}$, ${b_q}^{(0)}$: Similar to ${\sigma_q}^{(k)}$ and ${b_q}^{(k)}$, respectively, except that they are for the full set of satellites in view

Not all fault modes are monitored (that is, the fault detection test is applied to the subset) as long as the total Pr{HMI} requirement can be met considering the probabilities of all the monitored and unmonitored fault modes. ARAIM identifies all the fault modes that need to be actively monitored.

2.3 | Fault detection test statistic and the threshold

The current baseline ARAIM algorithm developed thus far and described in the ARAIM TSG is similar to one of the classical RAIM methods called the *solution separation* method (Brenner, 1996) in the fault-detection mechanism. The absence or presence of fault(s) is decided by evaluating the consistency (or lack of consistency) among the position solutions estimated using different sets of range measurements. However, ARAIM has many features that significantly improve its capabilities.

The test statistic for each fault mode and for each axis (e.g., East, North, or Up) of interest is the separation along that axis between two position estimates: one obtained using the full-set solution (i.e., navigation solution) and the other obtained using the subset solution that excludes those satellites that would be faulty for the given fault mode. Each fault-detection test raises a detection flag if and only if the test statistic exceeds its detection threshold. A detection test is performed for each coordinate axis and for each fault mode. A detection flag is raised when any test statistics exceed their respective thresholds.

A detection threshold $T_{k,q}$ for fault mode k and axis q is defined as follows:

$$T_{k,q} = K_{fa,q} \times \sigma_{ss,q}^{(k)} \tag{1}$$

$K_{fa,q}$ is the scalar multiplier determined to meet the allocated false-detection probability requirement along the q axis derived from the continuity requirement [WG-C Advanced RAIM Technical Subgroup (ARAIM TSG) Reference Airborne Algorithm Description Document (ADD), 2019]. The ${\sigma_{ss,q}}^{(k)}$ is the standard deviation of the separation of the two position solutions, one derived from the full-set and the other, from the k^{th} subset. ${\sigma_{ss,q}}^{(k)}$ is derived from σ_{URE}.

2.4 | Initial settings of ISM parameter values

Numerical analyses for Pr{HMI} sensitivity are performed in this paper based on a set of ISM parameter values used in the ARAIM ADD [WG-C Advanced RAIM Technical Subgroup (ARAIM TSG) Reference Airborne Algorithm Description Document (ADD), 2019] and shown in Table 1. Parameters for the numerical analysis are shown in Table 2. Out of these parameters, small values for P_{sat} and P_{const} require years of observation and thus are probably the most difficult to estimate. Also, as our analysis will show, P_{const} is also the dominant factor in the sensitivity analysis. For this reason, the rationale behind our

TABLE 1 Default broadcast GPS and Galileo ISM parameters

Constellations		**Two (2) constellations: GPS and Galileo.**
[Pre-deviation (baseline broadcast) GPS and Galileo ISM parameters (same as those assumed in the availability/coverage analysis in MS-3 report (2016)]		
Parameter	**Assumed Pre-deviation Values**	**Constellation**
σ_{URE}	0.5 m	Both GPS and Galileo
σ_{URA}*	0.75 m	Both GPS and Galileo
b_{nom}	0.75 m	Both GPS and Galileo
P_{sat}	10^{-5}	Both GPS and Galileo
P_{const}	10^{-8}	GPS
	10^{-4}	Galileo

*σ_{URA} is the product of the broadcast URA in the navigation message and a scale factor, which is one of the ISM parameters.

TABLE 2 Parameters for numerical analysis

Constellation configurations	Baseline (24 GPS + 24 Gal)Depleted (23 GPS + 23 Gal)
Presentation	Over 24 hours sampled every 5 minDifferent locations in CONUS
Input variables	Broadcast ISM parameter values ISM deviation (in terms of percentage (%) change) Number of satellites affected by deviation
Output variables	Pr{HMI} VPL/HPL

selection of the widely different values of P_{const} between GPS and Galileo is described.

Regarding P_{const} of 10^{-8} for GPS, such values cannot be validated with observed operational data alone, even with a long history of GPS, but they are consistent with the experience of no single GPS constellation-wide fault in its history. Also, the fifth edition of the *GPS Standard Positioning Service Performance Standard* (GPS SPS PS) released in April 2020 commits to a P_{const} value no larger than 10^{-8}. Regarding P_{const} of 10^{-4} for Galileo, this value is chosen since Galileo does not have a long performance history.

While the paper has performed an analysis based on this set of initial parameter settings selected for a good reason, one of the results of this study is that when actual changes occur, we will need to revisit the analysis for a different set of initial parameter values and re-perform the analysis illustrated in this paper.

3 | V-ARAIM Pr{HMI} SENSITIVITY TO ISM MISCHARACTERIZATIONS

It is noted that the Pr{HMI} sensitivity to ISM mischaracterization in this paper is based on the PL algorithms described in the current ARAIM ADD (2019) and that the PL values and the Pr{HMI} sensitivity to ISM may vary if the PL algorithms evolve.

3.1 | PL equation for V-ARAIM

V-ARAIM computes PL for each axis of q by solving the following equation iteratively based on broadcast ISM parameter values:

$$2Q\left(\frac{PL_q - b_q^{(0)}}{\sigma_q^{(0)}}\right) + \sum_{k=1}^{N_{fault\ modes}} p_{fault,\,k}\, Q\left(\frac{PL_q - T_{k,q} - b_q^{(k)}}{\sigma_q^{(k)}}\right) = PHMI_{REQ\_allocated\_to\_q}\left(1 - \frac{P_{fault,not\ monitored}}{PHMI_{total\_req}}\right) \tag{2}$$

where $Q(u)$ is the tail probability of a zero-mean unit normal distribution defined as:

$$Q(u) = \frac{1}{\sqrt{2\pi}} \int_u^{+\infty} e^{-\frac{t^2}{2}} dt \quad \text{for } u > 0;$$

$$\text{For } u < 0, Q(u) = 1 (Q \text{ function modified to avoid under-bounding of the integrity risk}) \tag{3}$$

3.2 | V-ARAIM Pr{HMI} degradation due to ISM mischaracterization

When actual core constellation performance deviates from the performance represented by the broadcast ISM values (i.e., mischaracterized by ISM), then integrity performance may degrade from the Pr{HMI} requirement. Pr{HMI} degradation that results in this case can be estimated as shown in Figure 2 derived from the PL equation in (2).

The upper half of Figure 2 shows how the protection level PL_q is calculated for each axis q under consideration. First, the maximum allowable contribution to the probability of HMI for the axis $Pr\{HMI\}_{ARAIM,q}$ for all monitored fault modes is determined from $Pr\{HMI_{REQ}\}$ and allocated to the axis ($Pr\{HMI\}_{REQ\_q}$). Then the values of $\sigma_q^{(0)}$, $\sigma_q^{(k)}$, $b_q^{(k)}$, and $b_q^{(0)}$ that are computed from the broadcast ISM, together with $T_{fa,q}$ and $Pr\{HMI\}_{ARAIM,q}$, which are also computed from the broadcast ISM, are used to iteratively solve for the value of the protection level for axis q (PL_q). The lower half of Figure 2 shows that the values of $\sigma_q^{(0)}$, $\sigma_q^{(k)}$, $b_q^{(k)}$, and $b_q^{(0)}$ that are computed from true ISM parameter values deviated from the broadcast are used along with the $T_{fa,q}$ and PL_q values to compute $Pr\{HMI\}_{ARAIM,q}$.

By following the flowchart in Figure 2, our analysis evaluates how much ARAIM performance (e.g., Pr{HMI}) degrades when actual ISM values deviate from the broadcast by a different amount (in percentage). This is a straightforward, brute-force method used in most of our analysis of the impact of ISM deviation on Pr{HMI}. However, a similar analysis can also be performed by expanding the VPL equation in Equation (2) in a Taylor series and retaining only the first-order terms. The equations for the first-order Taylor polynomial approximation are derived for Pr{HMI} as a function of ISM in Lee and Bian (2018).

Since the Taylor series is truncated after the first-order terms, it has a limited region of validity. However, this analytic approach allows the increase in Pr{HMI} to be expressed as a linear function of the ISM deviations and

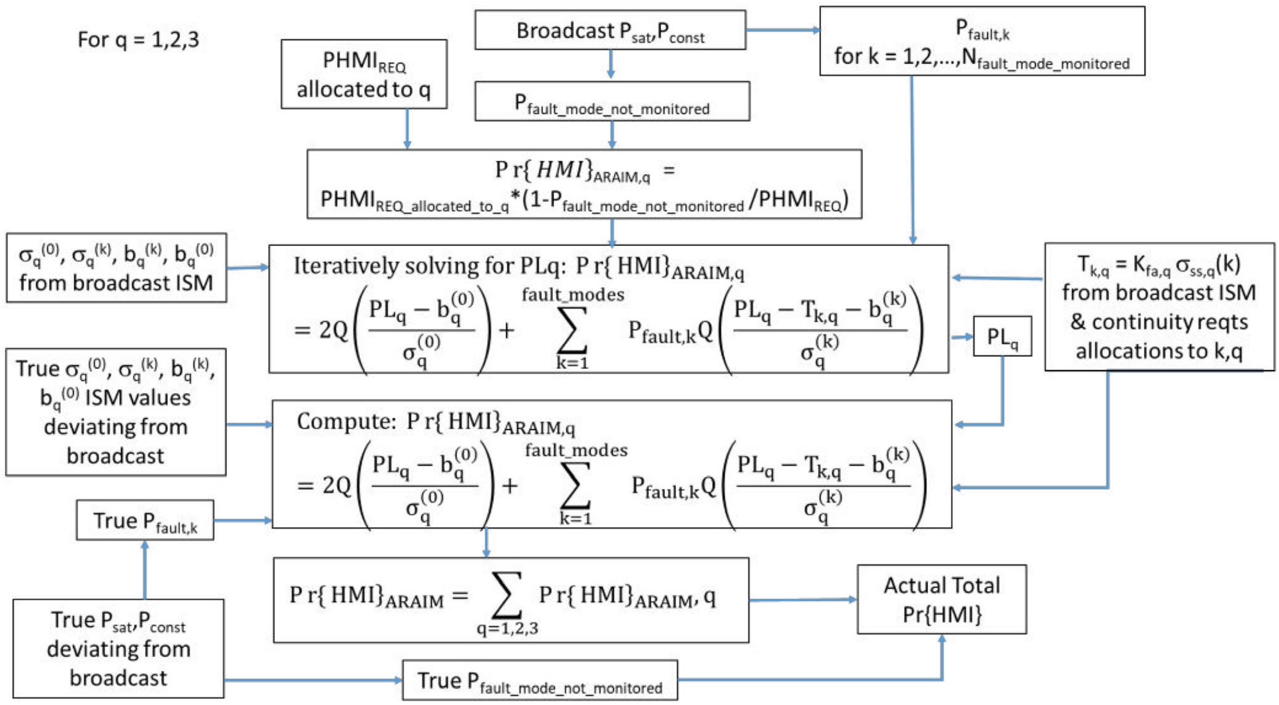

FIGURE 2 Evaluation of Pr{HMI} degradation for V-ARAIM in the presence of ISM deviation (Lee & Bian, 2018) [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

gives additional insight on how the deviation of ISM parameter values that occur on multiple ISMs simultaneously on multiple satellites and/or across multiple constellations can affect Pr{HMI} individually or in combination.

3.3 | Numerical results for V-ARAIM ISM sensitivity

In this section, we evaluate the impact of the mischaracterizations in ISM parameter values on Pr{HMI} for V-ARAIM following the flowchart in Figure 2 by assuming that the actual ISM parameter values deviate individually and in combination by a hypothetical percentage from their broadcast values, which stay unchanged. It is noted that for all plots of Pr{HMI} in this paper, the phrase *URA deviated by X%* should be interpreted as the true characterization of σ_{URA} being larger than the broadcast characterization by X%. We will discuss the Pr{HMI} sensitivity to ISM deviations for different cases.

3.3.1 | V-ARAIM Pr{HMI} degradation due to ISM deviation on all satellites in a constellation

Pr{HMI} degradation due to deviation from the value for each of the ISM parameters has been analyzed assuming ISM deviation affects all satellites in a given constellation. The analysis reveals that Pr{HMI} degradation depends significantly on the ISM parameter that deviates and the affected constellation.

Figure 3 compares Pr{HMI} degradation between the deviations of $\sigma_{URA,GPS}$ and $\sigma_{URA,Gal}$ as an example. It is interesting to observe that Pr{HMI} is widely different between the two cases, one with GPS and the other with Galileo. This wide difference is caused by the dramatic difference in the value of P_{const} between GPS and Galileo. As shown earlier in Table 1, the difference is four orders of magnitude with $P_{const,Gal}$ of 10^{-4} and $P_{const,GPS}$ of 10^{-8}. Pr{HMI} sensitivity to $b_{nom,GPS}$ and $b_{nom,Gal}$ exhibits similar behavior as shown in Figure 4. That is, Pr{HMI} sensitivity to $b_{nom,GPS}$ is significant whereas the sensitivity to $b_{nom,Gal}$ is negligible.

V-ARAIM Pr{HMI} sensitivity to the deviations of all the other ISM parameter values has been analyzed as well and summarized in Table 3. It is revealed that the sensitivity is significant only for the deviations of σ_{URA} and b_{nom}.

Our evaluation reveals that Pr{HMI} is most sensitive to the deviations of $\sigma_{URA,GPS}$ and $b_{nom,GPS}$ and negligible for most other ISM parameters, as summarized in Table 3. However, it should be noted that this observation applies only to the selected set of ISM parameters and may well change. As will be shown later in Figure 5, when the P_{const}

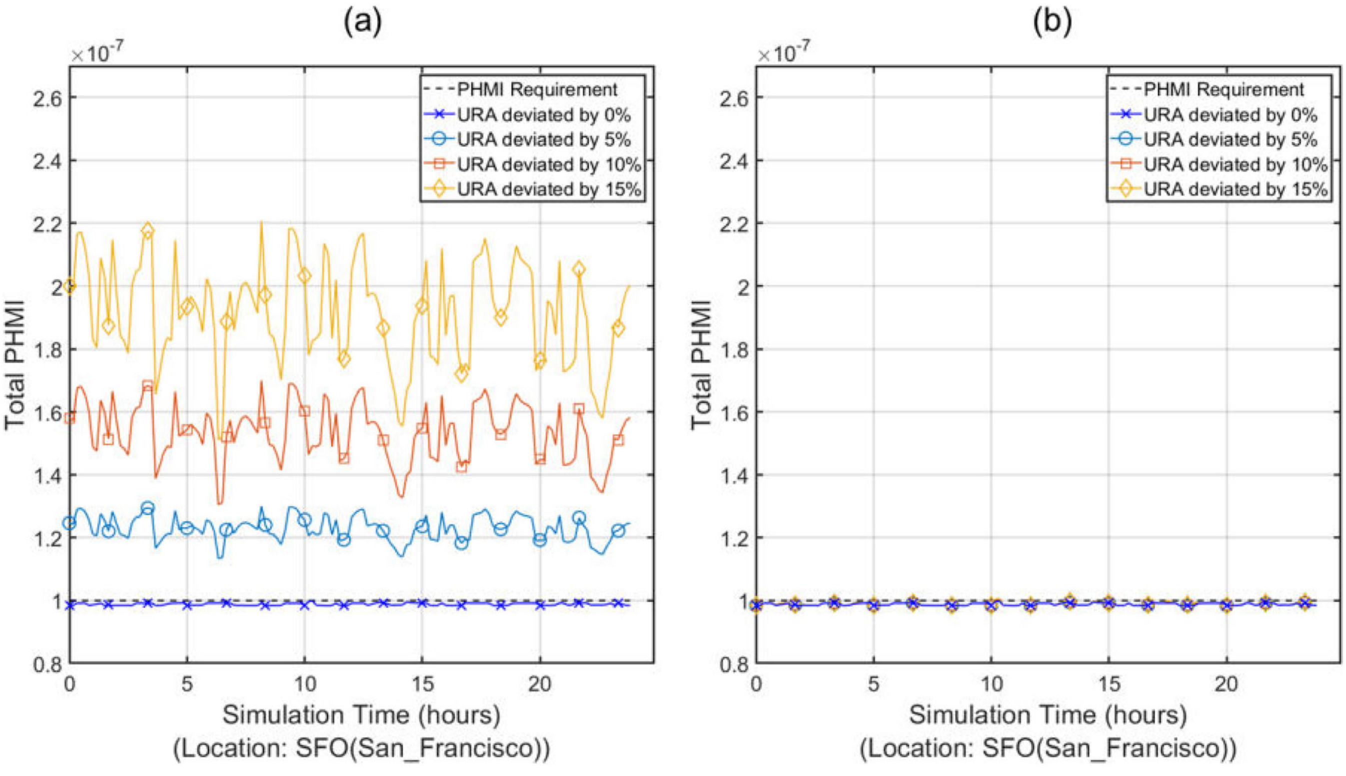

FIGURE 3 Pr{HMI} degradation due to (a) deviations of $\sigma_{\mathrm{URA,GPS}}$ and (b) deviations of $\sigma_{\mathrm{URA,Gal}}$ [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

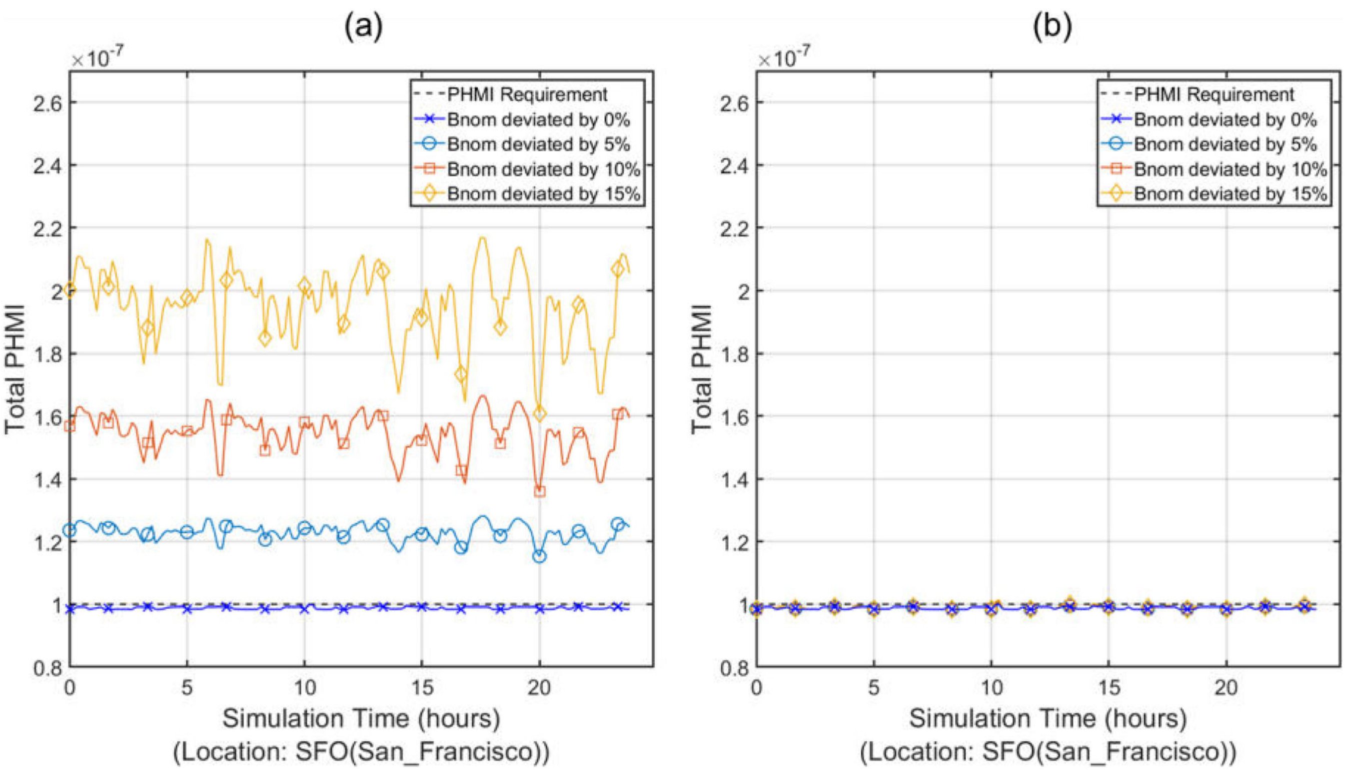

FIGURE 4 Pr{HMI} degradation due to (a) deviations of bnom,$_{\mathrm{GPS}}$ and (b) deviations of bnom,$_{\mathrm{Gal}}$ [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

TABLE 3 V-ARAIM Pr{HMI} sensitivity to ISM deviation for the baseline broadcast ISM parameter values (for 15% deviation)

ISM	Constellation	Pr{HMI} sensitivity to ISM deviation		
		Significant (RD* ≥ 20%)	Fairly small (RD* > 10%, <20%)	Negligible (RD* ≤ 10%)
σ_{URA}	GPS	X		
	Galileo			X
b_{nom}	GPS	X		
	Galileo			X
P_{sat}	GPS			X
	Galileo			X
P_{const}	GPS			X
	Galileo		X	

*Relative Difference (RD) is defined as:

$$RD(\Delta ISM) = \frac{\max_{i=1...N_t}(PHMI(t_i, \Delta ISM) - 10^{-7})}{10^{-7}}$$

where

$\Delta ISM = ISM_{Actual} - ISM_{Broadcast}$

N_t : the number of time sampling points

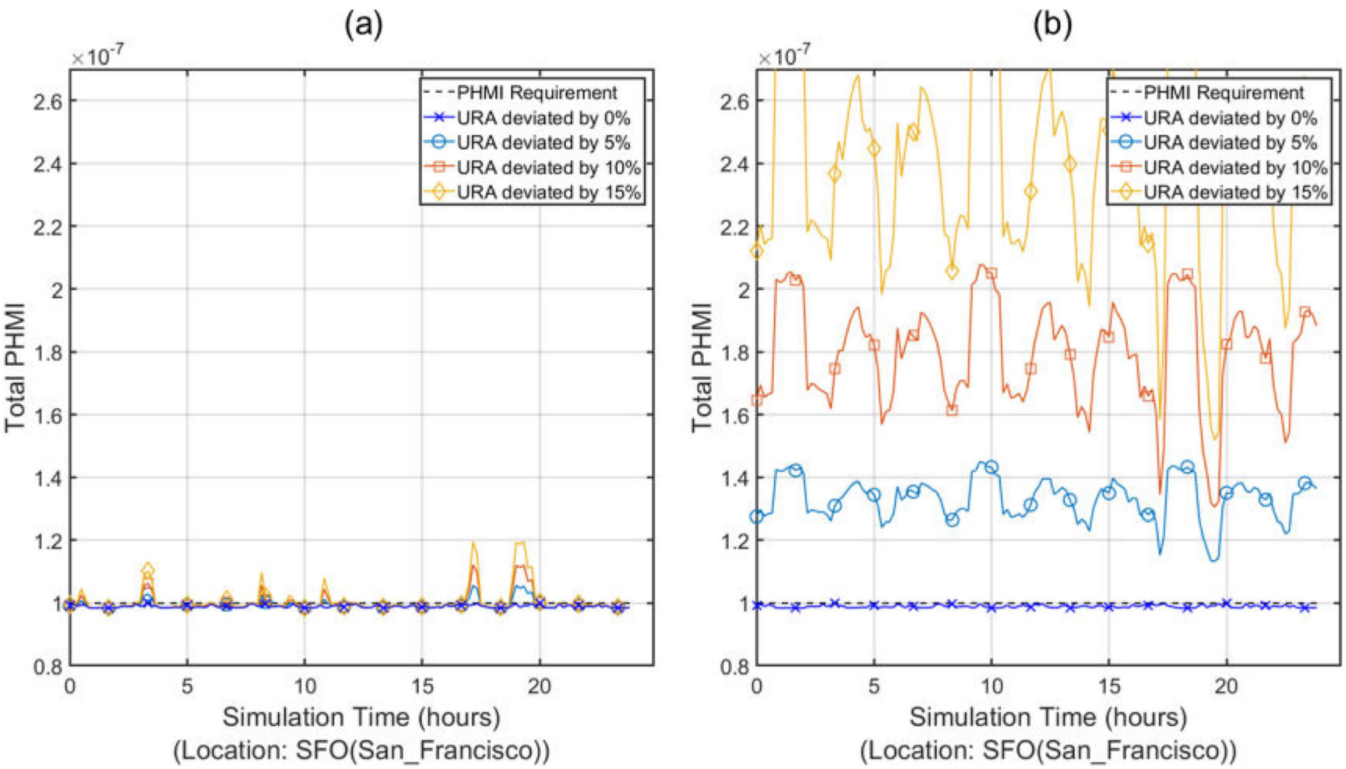

FIGURE 5 Pr{HMI} degradation due to (a) deviations of $\sigma_{URA,GPS}$ and (b) deviations of $\sigma_{URA,Gal}$ when P_{const} values are switched between GPS and Galileo from the case shown in Figure 3 (i.e., $P_{const,\,GPS} = 10^{-4}$ and $P_{const,\,Gal} = 10^{-8}$) [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

values are switched between GPS and Galileo, the result becomes almost the opposite.

When globally harmonized procedures are developed to select ISM parameter values to broadcast in the overall ISM generation and verification process, this kind of sensitivity analysis results may allow us to focus on a few, more sensitive ISM parameters in the trade-off between integrity margin and availability of ARAIM. It is noted that which ISM parameters the Pr{HMI} are more sensitive to depends on the default set of ISM parameter values.

3.3.2 | Validation of the Pr{HMI} sensitivity using first-order Taylor approach

It was shown earlier in Equation (2) how Protection Level (PL) can be determined to satisfy the Pr{HMI} requirement for a given set of ISM parameter values. This Pr{HMI} equation can be approximated as a first-order Taylor polynomial function of ISM parameters within a small region of convergence.

The expression for differential Pr{HMI} (dPr{HMI}) was derived as a function of the ISM deviations initially in (Lee & Bian, 2018). This derivation is quite lengthy, but when the analytically derived equation in (Lee & Bian, 2018) is simplified with approximations, one can see some of the characteristics of Pr{HMI} degradation due to the deviations of ISM parameters. In the following, we show why P{HMI} degradation due to σ_{URA} or b_{nom}, respectively, widely varies depending on whether the ISM is associated with GPS or Galileo, as shown in Figure 3 and Figure 4. The original equation for the differential Pr{HMI} along each axis of q (Lee & Bian, 2018) can be expressed in a simplified form as follows:

$$d\,\mathrm{Pr}\{HMI\}_q = a_0 + \sum_{k=1}^{fault\ modes} P_{fault,\,k}\, a_k \times \left(\frac{\partial\left(\sigma_q^{(k)}\right)}{\partial \sigma_{URA,GPS}} d\sigma_{URA,GPS} + \frac{\partial\left(\sigma_q^{(k)}\right)}{\partial \sigma_{URA,Gal}} d\sigma_{URA,Gal} \right) + \sum_{k=1}^{fault\ modes} P_{fault,\,k}\, b_k \times \left(\frac{\partial\left(b_q^{(k)}\right)}{\partial b_{nom,GPS}} db_{nom,GPS} + \frac{\partial\left(b_q^{(k)}\right)}{\partial b_{nom,Gal}} db_{nom,Gal} \right) \quad (4)$$

Since it is suspected that the peculiar behavior is caused by such wide difference in P_{const} between GPS and Galileo, we neglect all fault modes but two: GPS and Galileo constellation faults (denoted as fault mode #1 and fault mode #2, respectively). Neglecting the other terms and the notation of q axis, the above equation can be simplified further as shown below.

First, note the following for the derivation:

- We evaluate the sensitivity only with respect to the $d\sigma_{\mathrm{URA,GPS}}$, $d\sigma_{\mathrm{URA,Gal}}$, $db_{nom,GPS}$, and $db_{nom,Gal}$, one at a time
- $\sigma_q^{(\mathrm{k})}$ is the standard deviation of the position estimate obtained from all the range measurements except for those contained in the fault mode k. Therefore, $\sigma_q^{(\mathrm{k})}$ for k =1 is a function of the range measurements from Galileo, but none from GPS. In this case, $\frac{\partial(\sigma_q^{(1)})}{\partial \sigma_{URA,GPS}} = 0$. Likewise, $\frac{\partial(\sigma_q^{(2)})}{\partial \sigma_{URA,Gal}} = 0$
- a_1 and a_2 in the above equation are neglected
- P_{const} values selected in this paper: $P_{\mathrm{const,GPS}} = 10^{-8}$, $P_{\mathrm{fault,2}} = P_{\mathrm{const,Gal}} = 10^{-4}$

Under these conditions, Pr{HMI} sensitivity can be approximated as follows:

$$dPr\{HMI\} \cong (A1 + A2)\, d\sigma_{URA,\,GPS} + (A3 + A4)\, d\sigma_{URA,\,Gal} \quad (5)$$

$$A1 = P_{\mathrm{const,\,GPS}} \frac{\partial\left(\sigma^{(1)}\right)}{\partial \sigma_{URA,\,GPS}} = 10^{-8} \times 0 = 0$$

$$A2 = \mathrm{P}_{\mathrm{const,\,Gal}} \frac{\partial\left(\sigma^{(2)}\right)}{\partial \sigma_{\mathrm{URA,\,GPS}}} = O(10^{-4}) \quad (6)$$

Therefore:

$$dPr\{HMI\}\ \text{due to}\ \sigma_{\mathrm{URA,\,GPS}}\ \text{deviation} = (A1 + A2)\, d\sigma_{URA,\,GPS} = O(10^{-4}) \times d\sigma_{URA,\,GPS} \quad (7)$$

On the other hand:

$$A3 = \mathrm{P}_{\mathrm{const,\,Gal}} \frac{\partial\left(\sigma^{(1)}\right)}{\partial \sigma_{\mathrm{URA,\,Gal}}} = O(10^{-8})$$

$$A4 = \mathrm{P}_{\mathrm{const,\,Gal}} \frac{\partial\left(\sigma^{(2)}\right)}{\partial \sigma_{\mathrm{URA,\,Gal}}} = 10^{-4} \times 0 = 0 \quad (8)$$

Therefore:

$$dPr\{HMI\}\ \text{due to}\ \sigma_{URA,\,Gal}\ \text{deviation} = (A3 + A4)\, d\sigma_{URA,\,Gal} = O(10^{-8})\, d\sigma_{URA,\,Gal} \quad (9)$$

Equation (7) and Equation (9) show that the first-order Taylor polynomial equation gives results consistent with those numerically obtained and plotted in Figure 3. An analysis of Pr{HMI} sensitivity to b_{nom} can be done in a similar manner to show that it is consistent with the result obtained numerically and plotted in Figure 4.

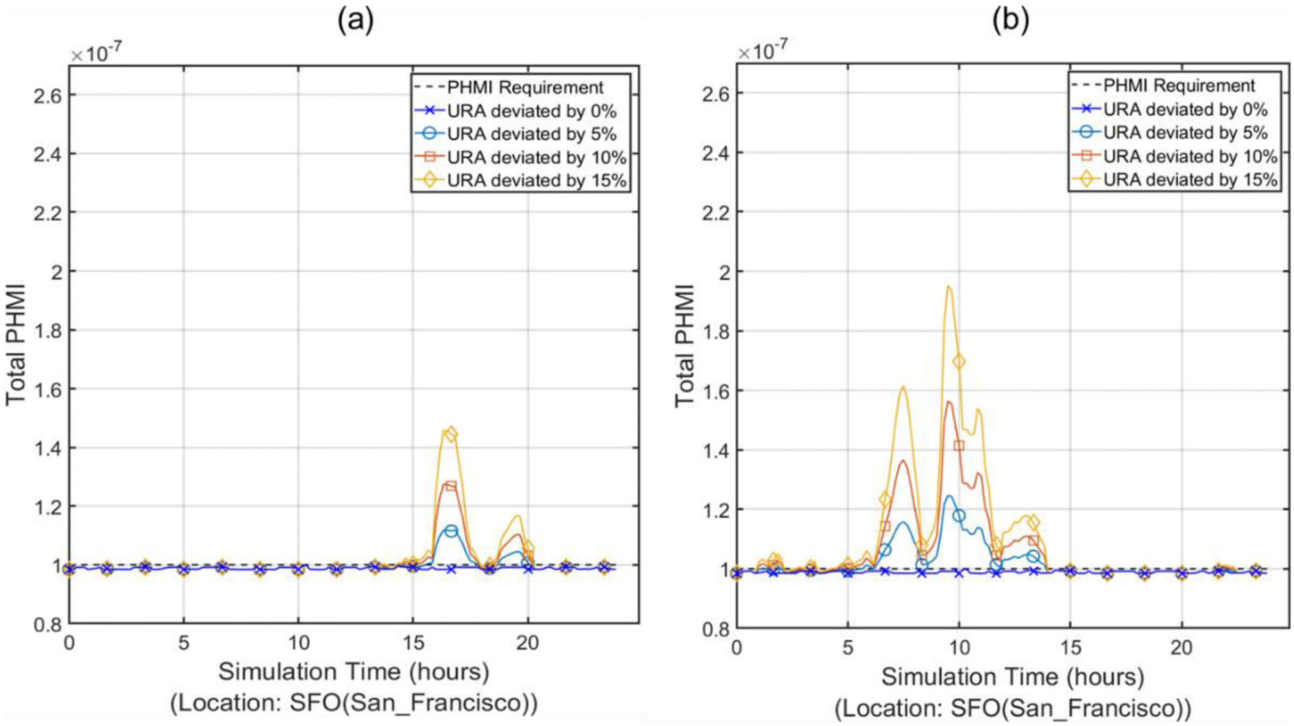

FIGURE 6 Total Pr{HMI} when $\sigma_{URA,GPS}$ deviates (a) for one GPS satellite and (b) for three GPS satellites, each randomly selected [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

3.3.3 | Pr{HMI} degradation due to ISM deviation when P_{const} is switched between GPS and Galileo

It is interesting to observe in Figures 3 and 4 that Pr{HMI} is widely different depending on whether σ_{URA} deviation is with GPS or Galileo. As we will show later, this is because the broadcast P_{const} (baseline) values are widely different between GPS and Galileo by orders of magnitude. Figure 5 shows that when P_{const} values are switched between GPS and Galileo, the Pr{HMI} sensitivity to σ_{URA} is also switched between the two. While not shown, sensitivity to b_{nom} exhibits similar behavior.

3.3.4 | Pr{HMI} degradation due to ISM deviation only on a few randomly selected satellites

We now evaluate Pr{HMI} degradation in case ISM deviations occur only on a few satellites. Figures 6(a) and 6(b) show Pr{HMI} degradations when σ_{URA} deviates for randomly selected one and three GPS satellites, respectively. It is noted that the satellite in Figure 6(a) is one of the three in Figure 6(b). Only GPS satellites are selected. Even if ISM deviates also for Galileo satellites along with GPS satellites, these plots would not be appreciably different because the Pr{HMI} degradation is negligible with Galileo satellites as shown in Figure 3(b). Compared with Figure 3(a) in which σ_{URA} deviates for all GPS satellites, Figure 6 shows the following:

- When deviation occurs only for a few satellites, the Pr{HMI} degradation occurs only for the periods during which these satellites are in view of the user from its location. If a satellite is not in view, it is not included in the position estimate and thus has no impact on Pr{HMI}
- As the number of satellites whose ISMs deviate increases (two or larger), Pr{HMI} tends to be larger and its time duration gets somewhat longer. This is because the Pr{HMI} magnitude accumulates when ISMs deviate for more satellites:

3.4 | Impact of increased broadcast ISM values on VPL

In general, how much Pr{HMI} degrades from the mischaracterization of different ISM parameters depends on the baseline ISM parameter values. For the baseline ISM parameter values in Table 1, our earlier analysis showed that the Pr{HMI} degradation is quite sensitive to the deviation of actual $\sigma_{URA,GPS}$ and $b_{nom,GPS}$ ISM parameters from their broadcast values.

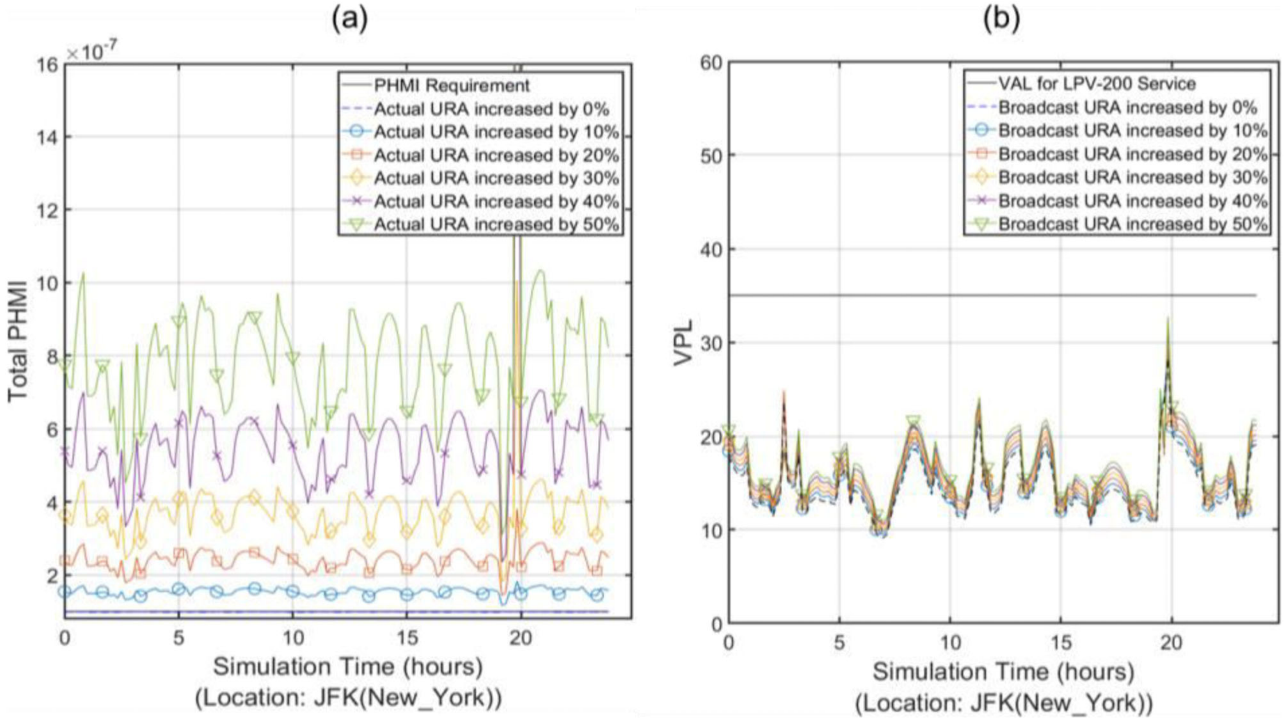

FIGURE 7 (a) Pr{HMI} increase when (actual $\sigma_{\text{URA,GPS}}$) > (broadcast $\sigma_{\text{URA,GPS}}$); (b) VPL increase when (broadcast $\sigma_{\text{URA,GPS}}$) > (actual $\sigma_{\text{URA,GPS}}$) [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

We now want to evaluate how sensitively PL increases, which, in turn, may reduce availability when we increase broadcast values. This can be evaluated by using Equation (2). Since the Pr{HMI} degradation is most sensitive to deviations of $\sigma_{\text{URA,GPS}}$ and $\text{b}_{\text{nom,GPS}}$ and is minimal for other parameters, we will focus on the impact of these two on VPL. Figure 7(a) plots Pr{HMI} degradation when $\sigma_{\text{URA,GPS}}$ deviates, (i.e., actual $\sigma_{\text{URA,GPS}}$ increases), and Figure 7(b) plots VPL increase when the broadcast ISM values are increased.

Figure 7(a) is the same as Figure 3(a) except that Figure 7(a) is for larger increments of deviation to make the message clearer that while the increase in actual $\sigma_{\text{URA,GPS}}$ would cause Pr{HMI} to significantly exceed its requirement, the change in VPL due to the increase of the broadcast value is minimal. Also, the plots in Figure 7(a) and 7(b) are for a depleted (23 GPS + 23 Galileo) constellation configuration. For the case of $\text{b}_{\text{nom,GPS}}$, the sensitivities are similar to the case of $\sigma_{\text{URA,GPS}}$ with respect to Pr{HMI} and VPL respectively.

4 | H-ARAIM Pr{HMI} SENSITIVITY TO ISM MISCHARACTERIZATIONS

4.1 | PL equations for H-ARAIM

The key difference between the V-ARAIM and H-ARAIM algorithms comes from whether the fault exclusion capability is required or not. Compared with V-ARAIM, which is used for LPV operation, H-ARAIM, used for RNP operation, requires tighter continuity. The continuity is improved by the fault exclusion capability by allowing continued navigation after removing the possible source of the fault-detection alarm [WG-C Advanced RAIM Technical Subgroup (ARAIM TSG) Reference Airborne Algorithm Description Document (ADD), 2019].

However, the trade-off in implementing the fault exclusion algorithm is that it can increase the integrity risk, since an erroneous exclusion can compromise position solution integrity. There are two factors negatively affecting integrity associated with the exclusion function. One factor is that the fault exclusion algorithm divides the total Pr{HMI} requirement among multiple exclusion subsets, making the requirement for each subset tighter. The other factor is that each post-exclusion subset always has a reduced number of satellites, thus its user-to-satellite geometry is generally weaker.

Once the detection algorithm alarms, the exclusion process is executed to identify and exclude the source believed to be most likely faulty. In this process, each exclusion option j is apportioned ρ_j, a share of the total requirement Pr{HMI}. For the j^{th} exclusion option and q axis (q = 1, 2), ${}^{(j)}HPL_q$ is obtained by iteratively calculating the following equation using broadcast ISM parameter values [WG-C Advanced RAIM Technical Subgroup (ARAIM TSG) Reference Airborne Algorithm Description Document (ADD), 2019]:

$$2\bar{Q}\left(\frac{{}^{(j)}HPL_q - {}^{(j)}b_q^{(0)}}{{}^{(j)}\sigma_q^{(0)}}\right) + \sum_{k=1}^{N_{\text{fault modes j}}} {}^{(j)}p_{fault,\,k}\bar{Q} \times \left(\frac{{}^{(j)}HPL_q - {}^{(j)}T_{k,q} - {}^{(j)}b_q^{(k)}}{{}^{(j)}\sigma_q^{(k)}}\right) = \rho_j \frac{\Pr\{HMI\}_{HOR}}{2}\left(1 - \frac{{}^{(j)}P_{\text{fault, not monitored}}}{\Pr\{HMI\}}\right) \tag{10}$$

where ${}^{(j)}b_q^{(k)}, {}^{(j)}\sigma_q^{(k)}, {}^{(j)}T_{k,q}$ are computed using the new post-exclusion subset.

The set of parameters ρ_j's allocating the integrity must be selected to satisfy the following condition:

$$\sum_{j=0}^{N_{fault\ modes}} \rho_j = 1 \tag{11}$$

Since this allocation has to be done without the knowledge of the measurements, it is suggested in [WG-C Advanced RAIM Technical Subgroup (ARAIM TSG) Reference Airborne Algorithm Description Document (ADD), 2019] to set ρ_j as:

$$\rho_j = \frac{1}{N_{exc} + 1} \tag{12}$$

where N_{exc} is the number of pre-selected exclusion options.

4.2 | H-ARAIM Pr{HMI} degradation due to ISM mischaracterization

The formula to calculate degraded Pr{HMI} for deviation of ISM parameter values is as follows. First, define the left-hand side of Equation (10) as ${}^{(j)}\Pr\{HMI\}_{HOR,q}$:

$${}^{(j)}\Pr\{HMI\}_{HOR,q} \doteq 2\bar{Q}\left(\frac{{}^{(j)}HPL_q - {}^{(j)}b_q^{(0)}}{{}^{(j)}\sigma_q^{(0)}}\right) + \sum_{k=1}^{N_{\text{fault modes j}}} {}^{(j)}p_{fault,\,k}\bar{Q}\left(\frac{{}^{(j)}HPL_q - {}^{(j)}T_{k,q} - {}^{(j)}b_q^{(k)}}{{}^{(j)}\sigma_q^{(k)}}\right) \tag{13}$$

Then, Equation (10) can be rewritten as:

$${}^{(j)}\Pr\{HMI\}_{HOR,q} = \rho_j \frac{\Pr\{HMI\}_{HOR}}{2} \times \left(1 - \frac{{}^{(j)}P_{\text{fault, not monitored}}}{\Pr\{HMI\}}\right) \tag{14}$$

By summing each side of Equation (14) for $q = 1$ and 2 and assuming Pr{HMI} is all allocated to $\Pr\{HMI\}_{HOR}$, then we get:

$${}^{(j)}\Pr\{HMI\}_{HOR} = \sum_{q=1}^{2} {}^{(j)}\Pr\{HMI\}_{HOR,q}^{ARAIM} + \rho_j {}^{(j)}P_{\text{fault, not monitored}} \tag{15}$$

where:

$${}^{(j)}\Pr\{HMI\}_{HOR,q}^{ARAIM} = \rho_j \frac{\Pr\{HMI\}_{HOR}}{2} \tag{16}$$

In evaluation of ${}^{(j)}\Pr\{HMI\}_{HOR}$ degradation due to ISM deviation, HPL and T_k are calculated with broadcast ISM values while the other terms are calculated with actual ISM values which deviated from the broadcast values. That is:

$${}^{(j)}\Pr\{HMI\}_{HOR,q}^{ARAIM,\ degraded} = 2\bar{Q}\left(\frac{{}^{(j)}HPL_q - {}^{(j)}b_q^{(0)}}{{}^{(j)}\sigma_q^{(0)}}\right) + \sum_{k=1}^{N_{\text{fault modes j}}} {}^{(j)}p_{fault,k}\bar{Q}\left(\frac{{}^{(j)}HPL_q - {}^{(j)}T_{k,q} - {}^{(j)}b_q^{(k)}}{{}^{(j)}\sigma_q^{(k)}}\right), q = 1,2 \tag{17}$$

So:

$${}^{(j)}\Pr\{HMI\}_{HOR}^{degraded} = \sum_{q=1}^{2} {}^{(j)}\Pr\{HMI\}_{HOR,q}^{ARAIM,\ degraded} + \rho_j {}^{(j)}P_{\text{fault, not monitored}}^{deviated} \tag{18}$$

- The three variables $N_{fault\ mode\ j}$, ${}^{(j)}HPL_q$, ${}^{(j)}T_{k,q}$ are calculated based on the broadcast ISM
- The six variables ${}^{(j)}b_q^{(0)}$, ${}^{(j)}b_q^{(k)}$, ${}^{(j)}\sigma_q^{(0)}$, ${}^{(j)}\sigma_q^{(k)}$, ${}^{(j)}p_{fault,k}$, and $P_{\text{fault,not monitored}}^{deviated}$ are calculated based on the actual ISM

4.3 | Numerical results for H-ARAIM ISM sensitivity

${}^{(j)}\Pr\{HMI\}_{HOR}^{degraded}$ above is the Pr{HMI} associated with the j^{th} exclusion option. In actual operation, upon encountering a fault detection, H-ARAIM would identify the fault mode to exclude based on the real satellite range measurements, and navigation would continue with the remaining satellites/constellation. Pr{HMI} at this time would be ${}^{(j)}\Pr\{HMI\}_{HOR}^{degraded}$ for the identified j. In our numerical simulation in which the actual range measurements are

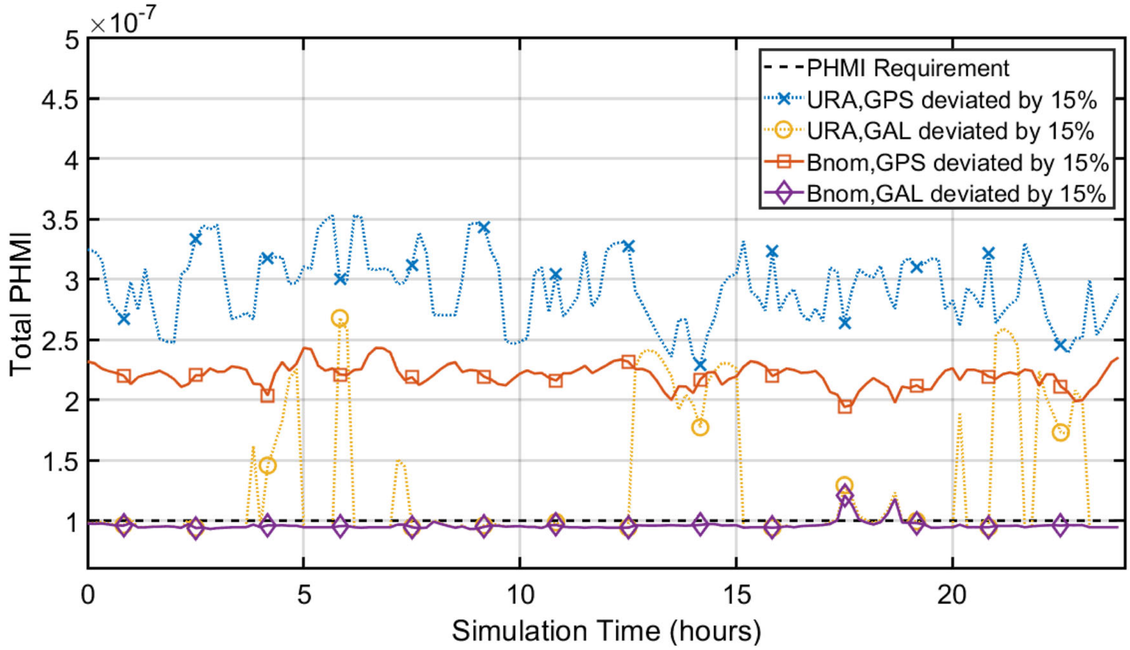

FIGURE 8 Pr{HMI} degradation for H-ARAIM when ISM parameters deviate at San Francisco International Airport [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

unknown, the total Pr{HMI} is calculated from:

$$\Pr\{HMI\}_{HOR}^{degraded} = \sum_{j=1}^{N_{exc}} {}^{(j)}\Pr\{HMI\}_{HOR}^{degraded}$$

4.3.1 | H-ARAIM Pr{HMI} degradation due to ISM deviation on all satellites in a constellation

We evaluate how much the deviations of individual ISM parameters affect H-ARAIM Pr{HMI} when the exclusion function is considered. For the numerical evaluation, similar assumptions are made regarding simulation configurations and baseline broadcast ISM values shown in Tables 1 and 2, which was assumed for V-RAIM analysis earlier as well. Pr{HMI} sensitivity for H-ARAIM due to deviations of σ_{URA} and b_{nom} is plotted in Figure 8 showing that these sensitivities are significantly different, respectively, depending on the constellation that each parameter is associated with. This is similar to what was observed earlier for V-ARAIM in Figures 3 and 4. However, it should be noted that while the sensitivities to $\sigma_{URA,Gal}$ and $b_{nom,Gal}$ deviations for V-ARAIM are negligible all the time, they are not always negligible for H-ARAIM.

For H-ARAIM, the sensitivities of Pr{HMI} show more significant degradations and more volatilities than V-ARAIM for all relevant ISM parameters. This observation can be explained by the nature of the fault exclusion process, in which one or more fault modes are removed from the all-in-view satellite set. It is noted, in particular, that for a fault mode with constellation fault, all satellites in the faulty constellation are removed, and the resulting satellite geometry may be significantly weakened. This, in turn, would sharply increase volatilities in Pr{HMI} sensitivity to ISM deviations.

In Table 4, we see that the ISM parameters σ_{URA} and b_{nom} show significant Pr{HMI} sensitivity to ISM deviation while the remaining parameters' influence on the Pr{HMI} is negligible. Although not included in this paper, our evaluation of the Pr{HMI} sensitivity in the presence of multiple ISM deviations has shown that when multiple ISMs deviate simultaneously in one constellation or across two constellations, the total effect on Pr{HMI} is approximately the sum of the effects of each of those ISM deviations on Pr{HMI}.

4.3.2 | H-ARAIM Pr{HMI} degradation due to ISM deviation only on a few randomly selected satellites

It is assumed ISM deviations occur only for a few satellites in a given constellation. Figure 9 shows Pr{HMI} degradation when σ_{URA} deviates for three randomly selected GPS satellites. We observe that when deviation occurs only for a few satellites, the Pr{HMI} degradation occurs only for the time period during which the satellites are in view of the user at the selected location. We also observe that during this period, the Pr{HMI} degradation is somewhat smaller when the ISM deviates for a subset of satellites than

TABLE 4 H-ARAIM Pr{HMI} sensitivity to ISM deviation for the baseline broadcast ISM parameter values (for 15% deviation)

ISM	Constellation	Pr{HMI} sensitivity to ISM deviation: Significant (RD* ≥ 20%)	Fairly small (RD* > 10%, <20%)	Negligible (RD* ≤ 10%)
σ_{URA}	GPS	x		
	Galileo	x		
b_{nom}	GPS	x		
	Galileo	x		
P_{sat}	GPS			x
	Galileo			x
P_{const}	GPS			x
	Galileo			x

*Relative Difference (RD) is defined as:

$$RD(\Delta ISM) = \frac{\max_{i=1\ldots N_t}(PHMI(t_i,\Delta ISM)-10^{-7})}{10^{-7}}$$

where

$\Delta ISM = ISM_{Actual} - ISM_{Broadcast}$

N_t : the number of time sampling points

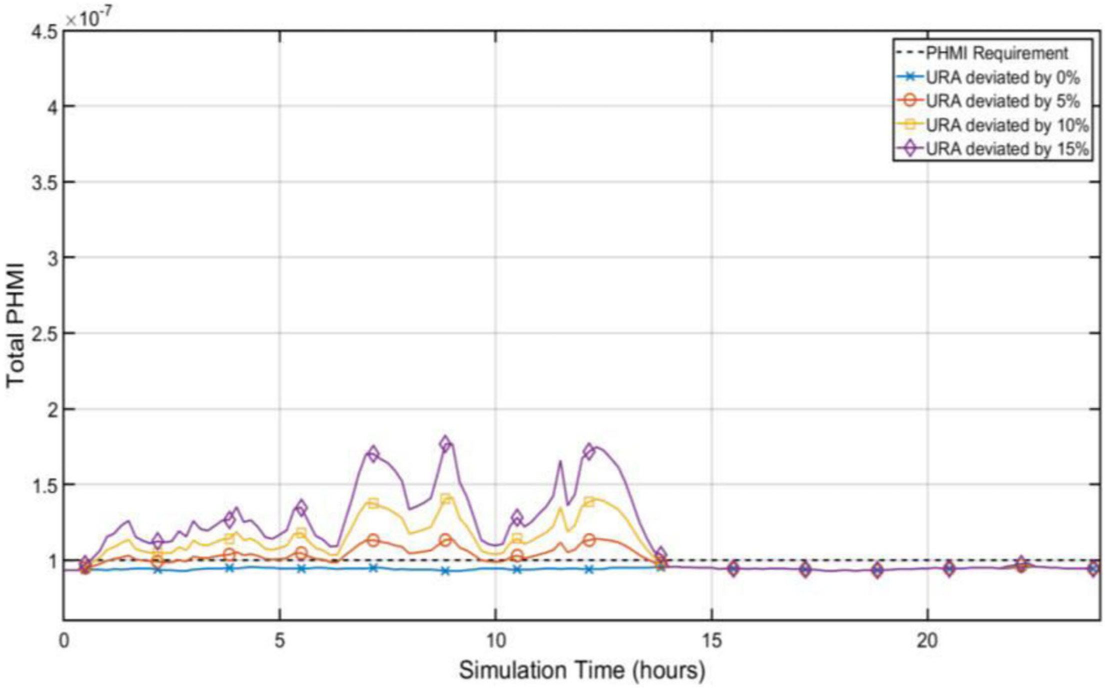

FIGURE 9 Pr{HMI} degradation when σ_{URA} deviates on three randomly selected GPS satellites [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

when the deviation occurs for all satellites, as shown in Figure 8.

4.4 | Impact of increased broadcast ISM values on HPL

We now investigate how much HPL increases when broadcast ISM parameter values are inflated for H-ARAIM, which utilizes fault exclusion. This evaluation is of significance along with the evaluation of the sensitivity characteristics for Pr{HMI} degradation due to the deviations of ISM because they, together, can provide supporting evidence for ISM parameter selection in the trade-off between system integrity and availability.

Starting with a set of baseline broadcast values and a depleted constellation configuration (23 GPS Satellite Vehicles [SVs] and 23 Galileo SVs), an HPL increase was

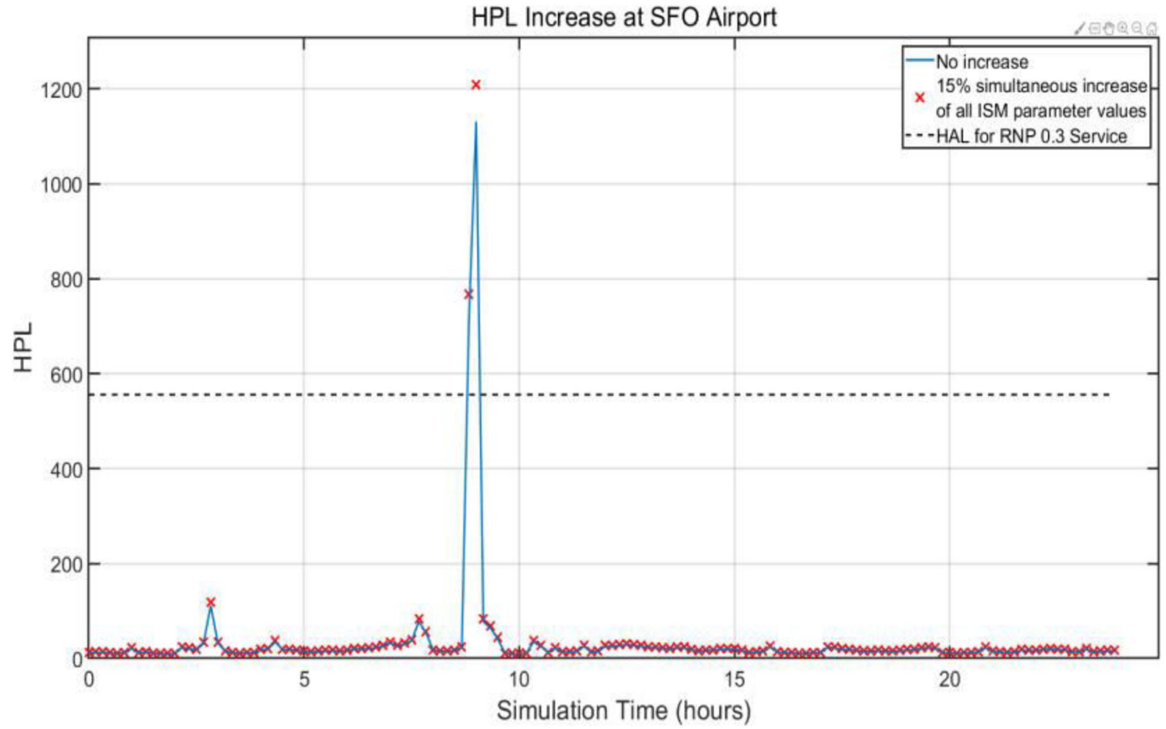

FIGURE 10 HPL variation with and without increase of broadcast ISM values [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

generated by simultaneously increasing all broadcast ISM values by 15%.

As we discussed earlier, the fault exclusion function for H-ARAIM often significantly weakens satellite geometry because it gets into the second-level detection process in which one or more fault modes are removed from the all-in-view satellite set. Therefore, this would sharply increase HPL, as shown in Figure 10. However, the figure also shows that the increased amount of HPL when the broadcast ISM values are inflated is not significant.

This finding is like the case of V-ARAIM. That is, when the broadcast ISM values are increased, the impact on HPL and thus on the availability of flight operations would be minimal, while its impact on Pr{HMI} is significant. This leads to a comparable inference that the selection of conservative broadcast ISM values may be preferred for H-ARAIM as well.

5 | COMPARISONS OF ISM SENSITIVITY BETWEEN H-ARAIM AND V-ARAIM

A key difference for H-ARAIM and V-ARAIM algorithms is that H-ARAIM mandatorily utilizes the fault exclusion algorithm since the more stringent continuity requirements are imposed on flight operations where H-ARAIM is intended to apply. It is interesting to see how the fault exclusion function affects the sensitivity of Pr{HMI} due to the ISM deviations and HPL sensitivity to increased broadcast ISM values.

Even without ISM deviations, H-ARAIM exhibits higher volatilities than V-ARAIM. The reason for this observation can be explained by the nature of the fault exclusion function. While fault exclusion improves system continuity, it necessarily results in dependence on and use of a weaker satellite geometry. This is because the fault exclusion needs to get into the second-level detection process in which more than one ranging source (fault-mode) are removed from the all-in-view satellite set. The weaker geometry results in a larger HPL. While HPL tends to be large without ISM parameter deviations, the amount of its increase with ISM deviations is minimal, as is the case with VPL for V-ARAIM.

6 | SUMMARY AND CONCLUSION

This paper has evaluated the Advanced RAIM (ARAIM) performance when Integrity Support Message (ISM) values that are broadcast to the user mischaracterize the actual core constellation performance. The primary focus of this paper is to characterize the Pr{HMI} sensitivity to the ISM deviations. In addition, the effect of selecting a conservative set of broadcast ISM parameter values on the Protection Level (PL) as a means to minimize the Pr{HMI} degradation is also evaluated to study how much the availability determined by PL can be traded off to ensure adequate integrity performance ARAIM.

Between the two types of ARAIM, namely, H-ARAIM and V-ARAIM, V-ARAIM is presented first for convenience of discussion:

- The paper first develops equations that can be used to determine Pr{HMI} degradation due to ISM deviations. From this equation, the Pr{HMI} sensitivity to ISM deviation for V-ARAIM is numerically evaluated, assuming ISM deviation for all satellites based on similar assumptions to previously published ARAIM documents regarding the system configurations and baseline broadcast ISM values for two constellations, GPS and Galileo. It is noted, in particular, that all ISM values are assumed identical between GPS and Galileo except for P_{const} values: $P_{const,GPS}$ of 10^{-8} and $P_{const,Gal}$ of 10^{-4}. Due to such a dramatic difference, the Pr{HMI} sensitivity exhibits some peculiar behavior when it is assumed that a given ISM deviation affects all the satellites in a given constellation
- The Pr{HMI} sensitivity is significant only for σ_{URA} and b_{nom} deviations for GPS. In contrast, the sensitivity for the same σ_{URA} and b_{nom} deviations for Galileo is negligible. The sensitivity to all the other ISM parameters is also almost negligible. It turns out that this peculiar characteristic is caused by the dramatic difference in P_{const} values between GPS and Galileo. This behavior is explained analytically by using a first-order Taylor polynomial equation developed by the authors and published in an earlier paper
- In case the deviation affects only a few satellites in view, deviation of $\sigma_{URA,GPS}$ and $b_{nom,GPS}$ also degrades Pr{HMI}, though not as much as the case in which all satellites are affected. This is because the total Pr{HMI} magnitude accumulates when the ISM is deviated for more satellites. Also, Pr{HMI} degrades only during the time the satellites with a deviated ISM are in view of the user. Obviously, if a satellite whose ISM has deviated is not in view of the user, the satellite is not included in the position estimation, and thus it does not degrade Pr{HMI}
- For the ISM parameters to which Pr{HMI} is sensitive, it may be advisable to marginally increase ISM parameter values so that Pr{HMI} may remain small enough to meet the integrity requirements. (It should be noted, however, that the true ISM parameter values are not precisely known.) An analysis of VPL increasing as a function of the increase of broadcast ISM parameter values reveals that an increased broadcast ISM value does not cause any appreciable increase of VPL and thus does not cause an appreciable reduction of availability

The key difference in H-ARAIM performance in the presence of ISM deviations from that of V-ARAIM comes from the fault exclusion requirement. While the fault exclusion improves system continuity, it results in dependence on and use of a weaker satellite geometry. This is because the fault exclusion needs to get into the second-level detection process in which more than one ranging source (fault-mode) is removed from the all-in-view satellite set. In particular, for a fault mode with a constellation fault, all satellites in that constellation are excluded from the in-view satellite set in the calculation of the protection level and Pr{HMI}. This would significantly weaken the satellite geometry. Therefore, H-ARAIM sensitivities of both Pr{HMI} and HPL show more significant degradations and more volatilities than V-ARAIM for all relevant ISM parameters. The analysis of H-ARAIM reveals the following:

- Other than the occasional volatility, H-ARAIM exhibits similar behavior to V-ARAIM in both Pr{HMI} sensitivity and PL. Like V-ARAIM, Pr{HMI} sensitivity for both σ_{URA} and b_{nom} deviations is significant for GPS, but relatively small except for occasional spikes in the case of Galileo
- When the broadcast ISM values are increased, HPL increases only slightly, similar to the case with VPL for V-ARAIM

Our results emphasize the importance of understanding and choosing the right ISM parameter values for each constellation. In turn, this will affect whether service providers will be able to successfully deploy H-ARAIM and V-ARAIM in the coming years.

Our results also show that for a given baseline of broadcast ISM parameters, we can determine which ISM parameters and which constellation we should focus on in the selection of ISM parameter values that would give a balanced trade-off between integrity and availability. This analysis should be useful in developing globally harmonized procedures to select ISM parameter values to broadcast in an overall ISM generation and ISM verification process.

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