H-ARAIM Exclusion: Requirements and Performance

Yawei Zhai, Boris Pervan
Illinois Institute of Technology, Chicago, IL

Mathieu Joerger
The University of Arizona, Tucson, AZ

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Background

- Two key developments in future GNSS:
  - **Dual Frequency Signal**: reduce measurement error
  - **Multi-Constellation**: provide more measurement redundancy

  are expected to bring significant navigation performance improvement in civil aviation using RAIM method [1].

- RAIM employs redundant measurements to achieve self-contained fault detection and exclusion (FDE) [2].

- Advanced RAIM (ARAIM) will serve for applications with more stringent navigation requirements [3].

[1] Phase II of the GNSS Evolutionary Architecture Study, February 2010

[2] Lee, Y., et al., "Summary of RTCA SC-159 GPS Integrity Working Group Activities", *NAVIGATION, Journal of The Institute of Navigation,* Vol. 43, No. 3, Fall 1996, pp. 307-362.

[3] Blanch *et al.*, "ARAIM user Algorithm Description: Integrity Support Message Processing, Fault Detection, Exclusion, and Protection Level Calculation," *ION GNSS 2012*.

Introduction

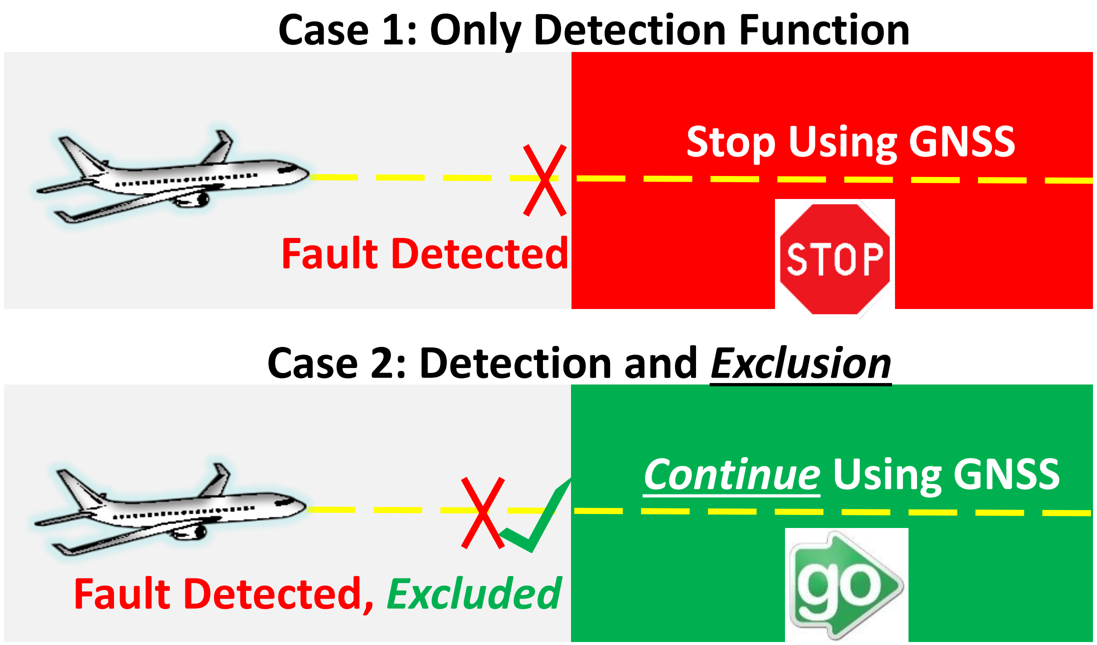
- Horizontal ARAIM (H-ARAIM) is currently of primary interest [4].
  - H-ARAIM aims at providing ***horizontal navigation service*** for the aircraft during en-route flight, terminal, non-precision approach (NPA), etc.

➢ **Detection function:**

- Ensure Integrity

➢ ***Exclusion* function:**

- Maintain Continuity



[4] EU-U.S. Cooperation on Satellite Navigation, Working Group C, "ARAIM Technical Subgroup Milestone 3 Report," February 25, 2016.

Outline

- H-ARAIM Exclusion and Continuity:
  - Interpret H-ARAIM continuity requirements, show that exclusion is required.
  - Assess the impact of different sources on H-ARAIM continuity, and quantify the overall continuity risk.
- Describe H-ARAIM FDE algorithm, quantify predictive FDE integrity risk.
  - Introduce a computationally efficient upper bound on integrity risk, analyze its tightness.
- Evaluate the overall predicted FDE availability.
  - Show the availability performance for H-ARAIM targeted service.
  - Address the impact of unscheduled satellite outages on continuity.

Why

How

Results

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Navigation Requirements

- For H-ARAIM service, both misleading information and **loss of continuity** (LOC) are specified as ***major*** failure conditions [5].

Table 1. Navigation Performance Requirements [6]

	Horizontal Alert Limit **(HAL)**	Integrity Risk I_{REQ}	Continuity Risk C_{REQ}
RNP 0.1	0.1nm (185m)	10^{-7}/hour	10^{-8}/hour to 10^{-4}/hour
RNP 0.3	0.3nm (556m)		

- To declare the service being available, both I_{REQ} and C_{REQ} need to be met.
  - RNP 0.1/0.3 are used as examples to illustrate H-ARAIM performance.

[5] FAA AC 20-138B, Airworthiness Approval of Positioning and Navigation Systems, September 27, 2010.
[6] ICAO, Annex 10, Aeronautical Telecommunications, Volume 1 (Radio Navigation Aids), Amendment 84

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Need of H-ARAIM Exclusion

- The range of the continuity risk accounts for the number of aircraft using the same service.
  - "**Intermediate values of continuity (e.g. 1 – 1 x 10^{-6} per hour) are considered to be appropriate** for areas of high traffic density and complexity where there is a high degree of reliance on the navigation system but in which mitigation for navigation system failures is possible." [ICAO Annex 10]

- In this work, we use: **$C_{REQ} = 10^{-6}$ / hour** [7].
  - Consider a typical example case for H-ARAIM: two constellations, 16 satellites in view, $R_{sat} = 10^{-5}$/hour and $R_{const} = 10^{-4}$/hour [8].
  - Without exclusion, the probability of LOC due to detection is:

$$10^{-5} \text{ / hour / SV} \cdot 16 \text{ SVs} + 10^{-4} \text{ / hour} = \mathbf{2.6 \cdot 10^{-4} \text{ / hour} \gg C_{REQ}}$$

  - **Therefore, H-ARAIM exclusion is required for navigation continuity.**

[7] FAA-E-2892d, System Specification for the Wide Area Augmentation System, March 28, 2012
[8] T. Walter et al., "Determination of Fault Probabilities for ARAIM," *Proceedings of IEEE/ION PLANS 2016*

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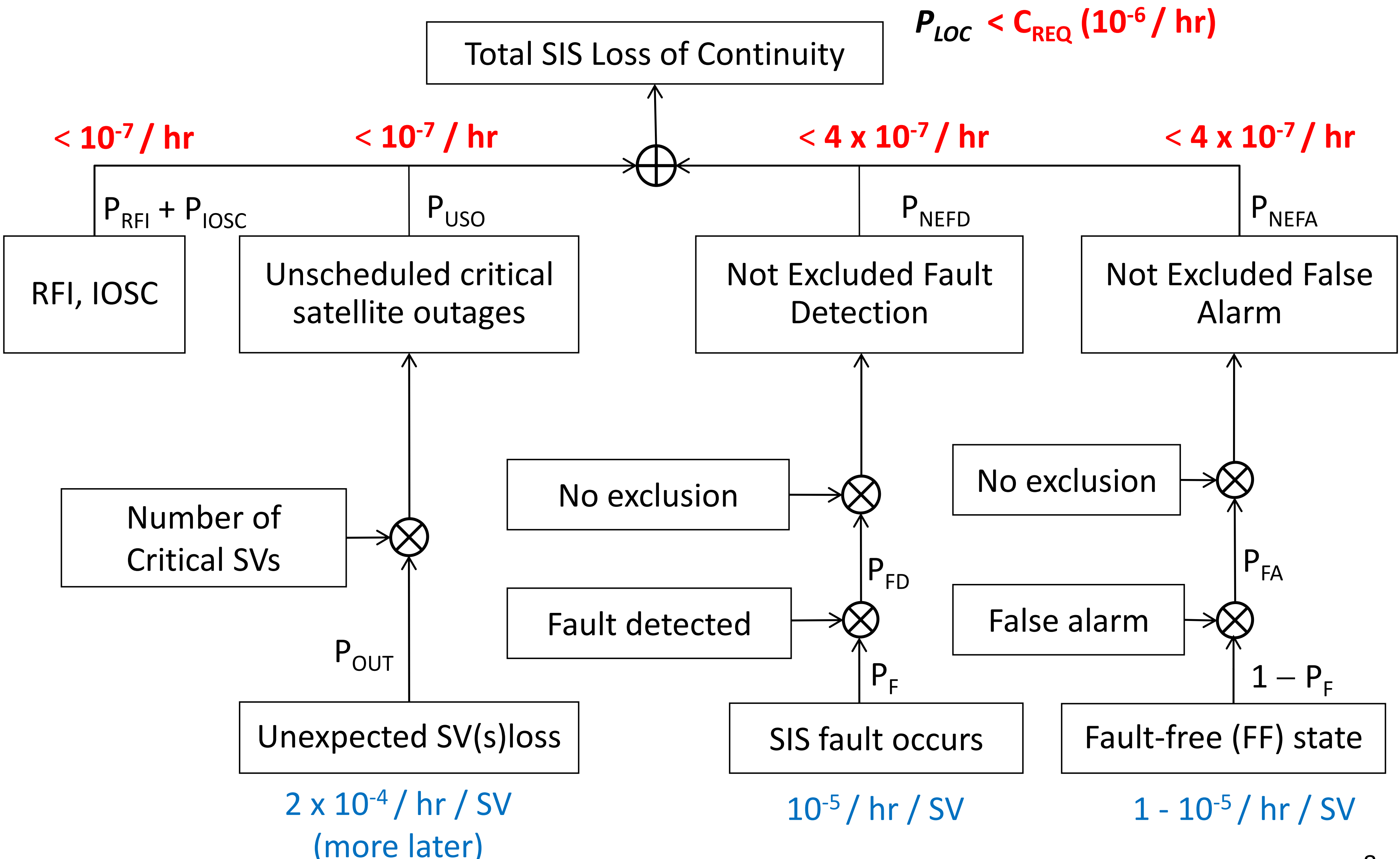
H-ARAIM LOC

- *With exclusion implemented*, H-ARAIM LOC can result from any of the following:
  - Not excluded false alarm (NEFA), not excluded fault detection (NEFD), unscheduled satellite outage (USO), radio frequency interference (RFI), and ionospheric scintillation (IOSC).
- The probability of H-ARAIM LOC is:

(per hour)

$$P_{LOC} = \underbrace{P_{NEFA}}_{\text{controllable by choice of detection threshold.}} + \overbrace{P_{NEFD}}^{\text{controllable by choice of exclusion threshold.}} + \underbrace{P_{USO}}_{\text{can be evaluated using critical satellite analysis}} + \overbrace{P_{RFI} + P_{IOSC}}^{\text{a margin is left to account for these events}} \quad (1)$$

H-ARAIM LOC Tree



C_{REQ} Allocation

- Not excluded false alarm (NEFA):

$$P_{NEFA} < P\,(\,D \mid FF\,)\,P_{FF} \quad \mathbf{< 4 \times 10^{-7} / hr} \qquad (2)$$

  - The probability of fault free (FF) detection could be limited by setting the **detection threshold**.

- Not excluded fault detection (NEFD):

$$P_{NEFD} < P\,(\,NE \mid F\,)\,P_{F} \quad \mathbf{< 4 \times 10^{-7} / hr} \qquad (3)$$

  - The probability of no exclusion (NE) when faults occur could be limited by setting the **exclusion threshold**.

- RFI + IOSC:
  - These two impacts are not quantified, and we assume $P_{RFI} + P_{IOSC} < 10^{-7}$ / hr is always true in this work.

C_{REQ} Allocation

- The impact of USO on H-ARAIM continuity is [9]:

$$P_{USO} = n_c \cdot P_{OUT} < 10^{-7} / hr \quad (4)$$

  - P_{OUT} is the occurrence rate of USO: **2 x 10^{-4}/hr/SV** [10].
  - n_c is the number of critical satellites. A critical satellite is the one whose loss leads to LOC during flight.
  - Eqn. (4) is equivalent to: $n_c < 5 \times 10^{-4}$ SV, which indicates *no critical satellite is allowed to exist for H-ARAIM applications*.

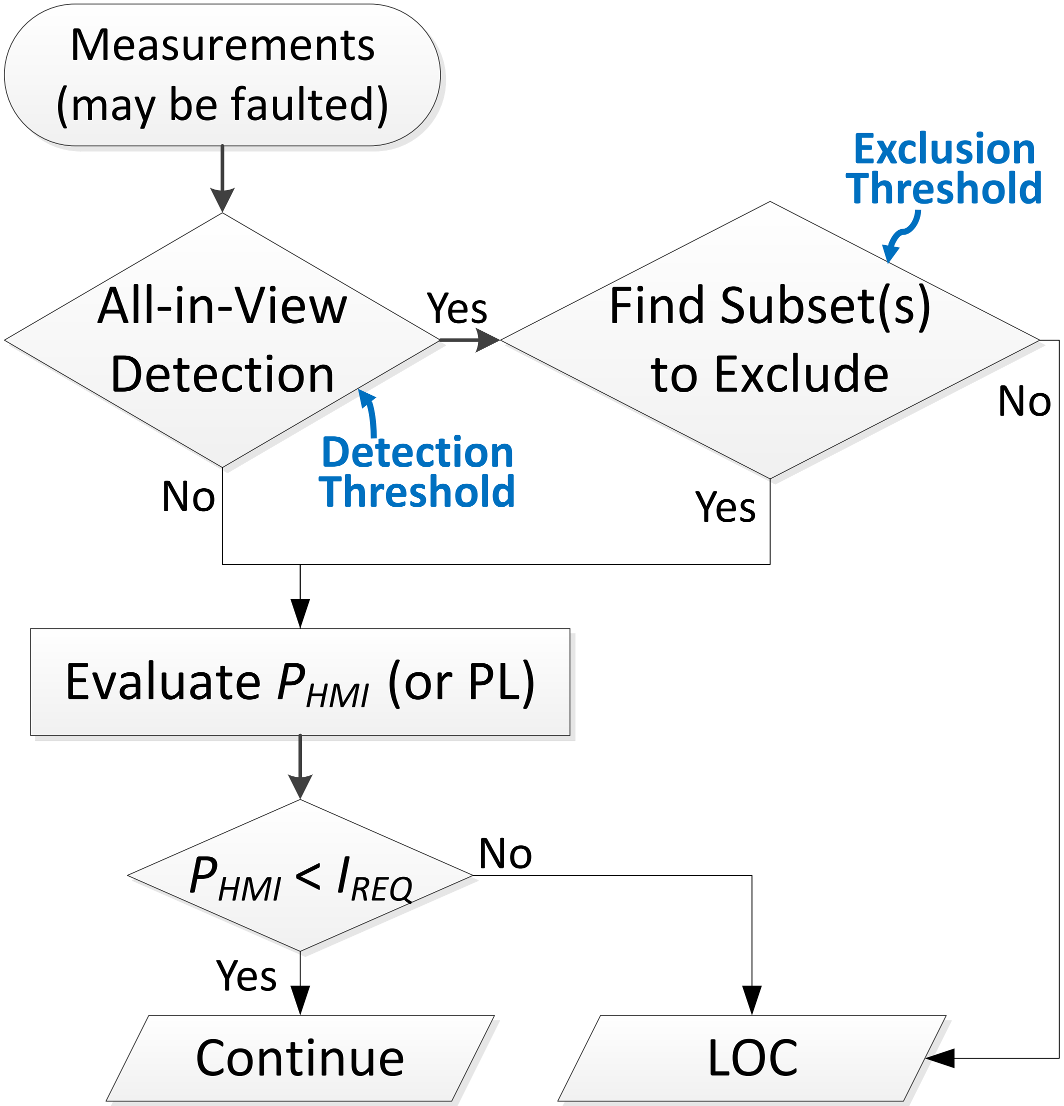
- Determine a critical satellite:
  - For a geometry where $P_{HMI} < I_{REQ}$, if removing a satellite results in $P_{HMI} > I_{REQ}$, then the removed satellite is regarded as a critical satellite.
  - Therefore, n_c depends on the method of evaluating P_{HMI} (or *PL*).

[9] RTCA Special Committee 159, "LAAS MASPS," *RTCA/DO-245*, 2004, Appendix D.
[10] GPS Standard Positioning Service Performance Standard, 4th Ed., Sep 2008, Table 3.6-1, p. 28.

FDE Flow Diagram

- This algorithm is based on solution separation (SS) method.
  - Motivated from improving H-ARAIM continuity, this algorithm could be extended to other applications.

- The flow diagram described the FDE procedure in real time.



Real Time FDE Algorithm

- Summary of implementing this algorithm in real time:
  - **Step 1:** Using all in view satellites, if there is no fault detection ($\overline{D_0}$), go to step 4; if a fault detection (D_0) occurs, go to step 2.
  - **Step 2:** Array the normalized detection statistics in a magnitude descending order. This order is called "exclusion option order".
    - Example:

Descending Magnitudes →

$$\text{Statistics: } |q_3|,\ |q_7|,\ |q_1|,\ |q_5|,\ \ldots\ |q_h|,\ |q_2| \qquad (5)$$

Order: *1st, 2nd, 3rd, 4th, … …*

  - **Step 3:** Follow the order made in step 2, employ a ***second layer detection test*** for each option. The first option that passes this test is E_j.
  - **Step 4:** Evaluate the integrity risk (or PL) using the present satellites.

Predictive FDE P_{HMI}

- To predict the FDE integrity risk, all exclusion options must be accounted for:

No Fault Detection ($\overline{D_0}$), and user is in hazardous state (HI_0)

Fault is detected (D_0) and j is excluded (E_j), and user is still in hazardous state (Hi_j)

$$P_{HMI} = P(HI_0, \overline{D}_0) + \sum_{j=1}^{h} P(HI_j, E_j, D_0) \qquad (6)$$

- According to the algorithm, two conditions will result in j being excluded:

E_j ⟷
- No second layer detection after excluding j : $\overline{\boldsymbol{D_j}}$
- j corresponds to the maximum statistic among the subsets that pass the second layer detection test: $\boldsymbol{MAX_j}$

Multiple Fault Hypothesis

- Account for all fault hypothesis, Eqn. (6) becomes:

$$P_{HMI} \le \sum_{i=0}^{h} \max_{f_i} \left(P(HI_0, \overline{D}_0 \mid H_i, f_i) + \sum_{j=1}^{h} P(HI_j, \overbrace{\overline{D}_j, MAX_j}^{E_j}, D_0 \mid H_i, f_i) \right) P_{Hi} + P_{NM} \quad (7)$$

  – P_{NM} : probability of rarely fault occurring (Not Monitored).

  – *Hi*: fault mode from *i* = 0 … h.

  – f_i : fault vector corresponds to fault mode *i.*

- Employ an example to illustrate in parity space:

  – Measurement Model: $\mathbf{z} = \mathbf{H}x + \mathbf{v} + \mathbf{f}$ (8)

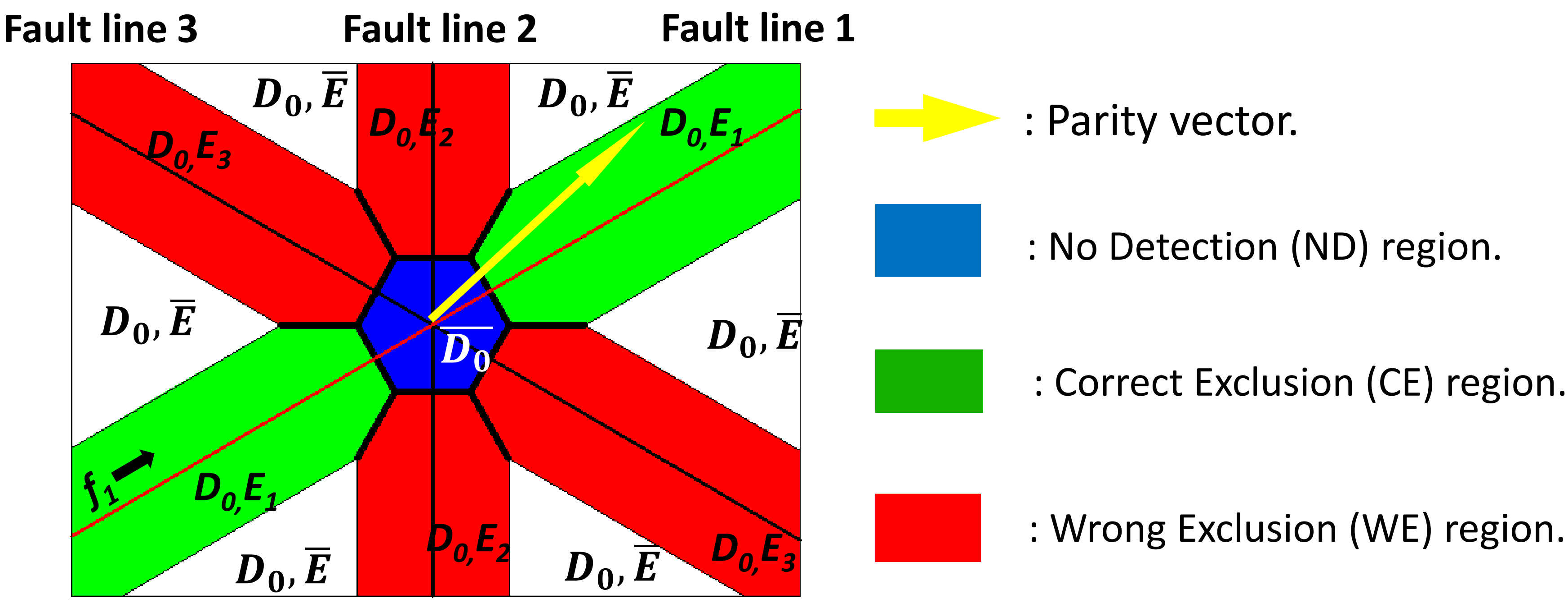
    ➢ where, $\mathbf{H} = [1 \quad 1 \quad 1]^T$ and $v \sim N(\mathbf{0}_{3\times1}, \mathbf{I}_3)$

  – Only consider single fault mode. Assuming the fault is on ***i* = 1**.

Parity Space Representation

- The conditional FDE integrity risk for H_1 is:

$$P_{HMI,H_1} = \max_{f_1}\left(\begin{aligned} & P(HI_0, \overline{D}_0 \mid H_i, f_1) + P(HI_1, \overline{D}_1, MAX_1, D_0 \mid H_1, f_1) \\ & + \sum_{j=2}^{3} P(HI_j, \overline{D}_j, MAX_j, D_0 \mid H_1, f_1) \end{aligned} \right) P_{H_1} \quad (9)$$



Practical Approach

- An upper bound of the FDE integrity risk is used [11].

$$P_{HMI} \le \sum_{i=0}^{h} \max_{f_i} \left(P(HI_0, \overline{D}_0 \mid H_i, f_i) + \sum_{j=1}^{h} P(HI_j, \overline{D}_j, MAX_j, D_0 \mid H_i, f_i) \right) P_{Hi} + P_{NM} \quad (7)$$

$$\le \sum_{i=0}^{h} \max_{f_{i,0}} P(HI_0, \overline{D}_0 \mid H_i, f_{i,0}) P_{Hi} + \sum_{i=0}^{h} \sum_{j=1}^{h} \max_{f_{i,j}} P(HI_j, \overline{D}_j \mid H_i, f_{i,j}) P_{Hi} + P_{NM} \quad (10)$$

Details in Paper

- Two conservative steps from Eqn. (7) to (10):
  - The knowledge of MAX_j and D_0 are not used.
  - The risks in Eqn. (10) are maximized individually for same hypothesis.

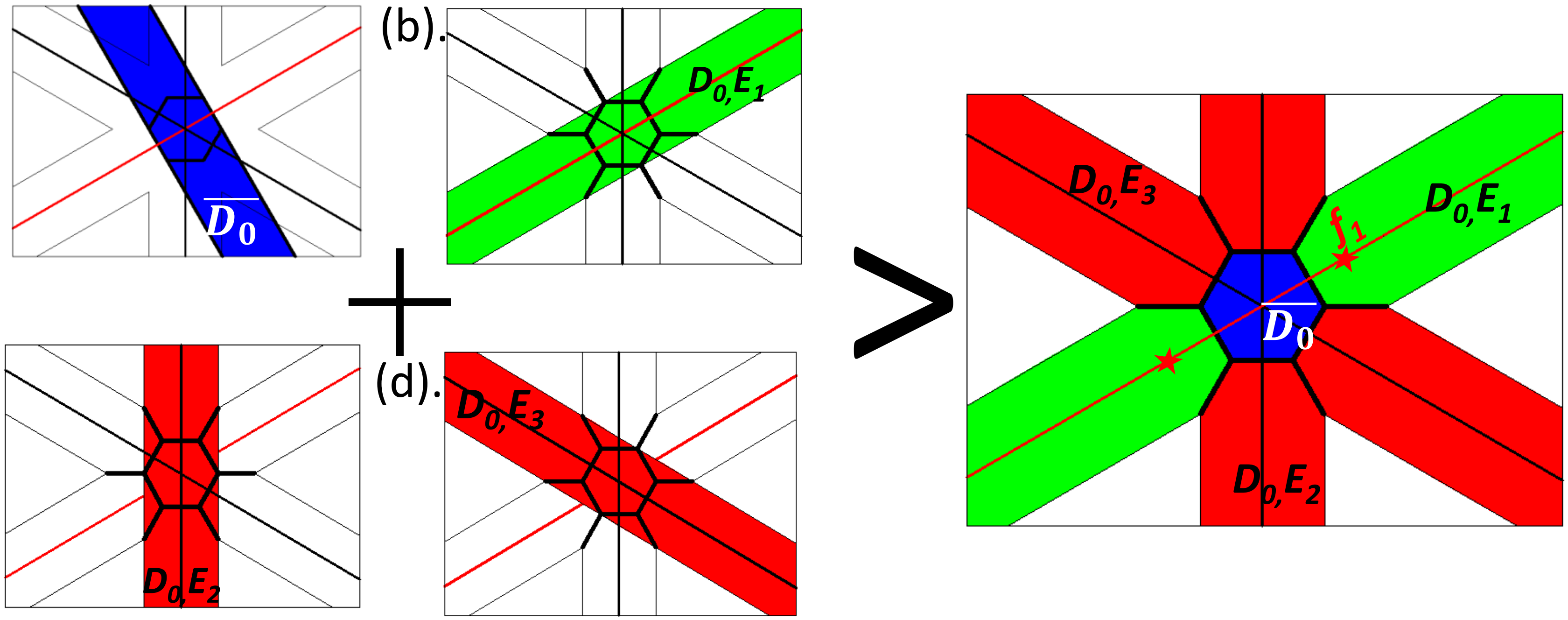
- However, using Eqn. (10) could potentially cause a loose bound. (next slides).

[11] Joerger, M., Pervan, B., "Fault Detection and Exclusion Using Solution Separation and Chi-Squared RAIM," *Transactions on Aerospace and Electronic Systems*, vol. 52, April 2016, pp. 726-742.

Express Bound in Parity Space

- The expression of the bound in parity space is:

(a). (b). (c). (d).



  - (c) and (d) may cause loose bound since the red region overlaps with the actual fault mode line.
  - The tightness of this bound could be investigated by comparing the bound with numerical results.

Tightness of the Bound

- To investigate the tightness of the bound, Monte-Carlo simulation is employed for this example.
  - Run 10^7 trials, standard deviation σ = 1m, prior probability 10^{-3} and false alarm requirement is set to be 10^{-6}.
  - The numbers in the table are predictive FDE integrity risk corresponding their requirements. *The exclusion requirement in case 2 is more stringent than case 1.* (more results in paper)

Table 2. Comparison of the Numerical Results and Bound

	AL = 4m		AL = 5m	
	Numerical	**Bound**	**Numerical**	**Bound**
Case 1	2.43×10^{-6}	7.37×10^{-5}	2.92×10^{-8}	1.91×10^{-6}
Case 2	4.03×10^{-6}	7.62×10^{-4}	7.45×10^{-7}	6.67×10^{-5}

  - Tighten the FDE integrity bound is not the focus of this work, and it will be considered in future work.

H-ARAIM Simulation

- In this work, integrity risk bound is used to analyze H-ARAIM FDE performance:
  - Computationally efficient.
  - Guarantee safety.
- Baseline simulation conditions:
  - Nominal error model
  - Dual-frequency, baseline GPS/Galileo constellation

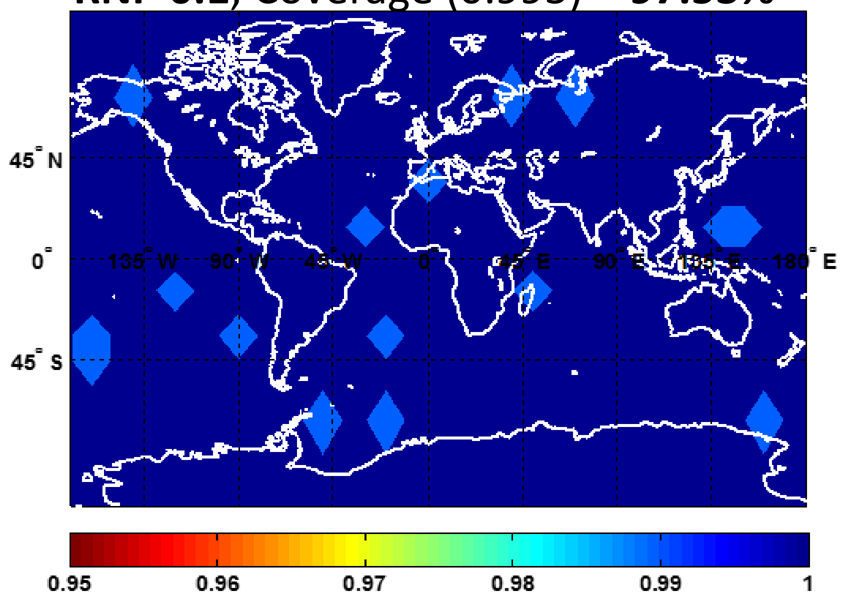
Table 3. Simulation Parameters

Integrity Risk I_{REQ}	10^{-7}/hour
$P_{NEFA, REQ}$	4 x 10^{-7}/hour
$P_{NEFD, REQ}$	4 x 10^{-7}/hour
HAL	185m / 556m
P_{sat}	10^{-5}
P_{const}	GPS: 10^{-8} / GAL: 10^{-4}
σ_{URA}	2.5m
b_{nom}	0.75m
Mask Angle	5 degrees
Coverage Range	Worldwide

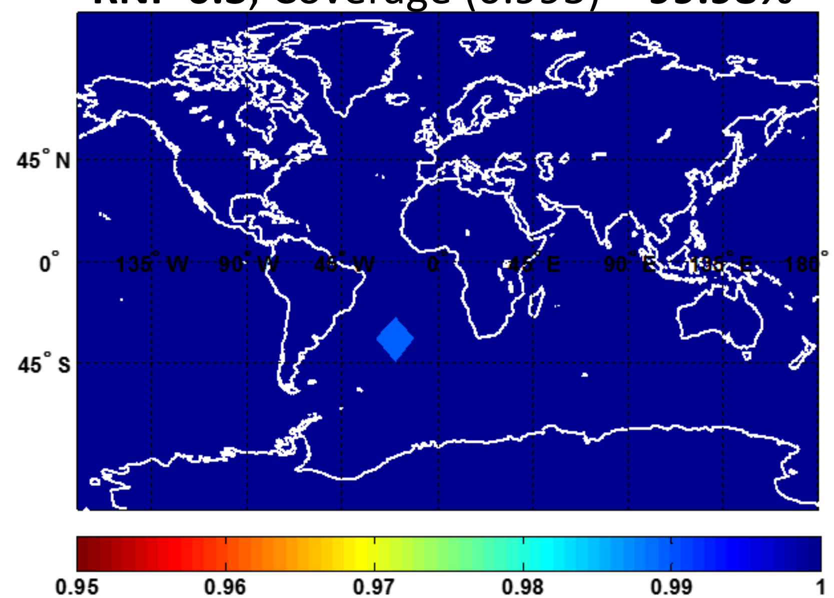
H-ARAIM FDE Performance

- The results show the predicted H-ARAIM FDE availability performance of $\boldsymbol{P_{HMI} < I_{REQ}}$.
- In comparison with detection only, continuity is improved by implementing exclusion.

RNP 0.1, Coverage (0.995) = **97.53%**

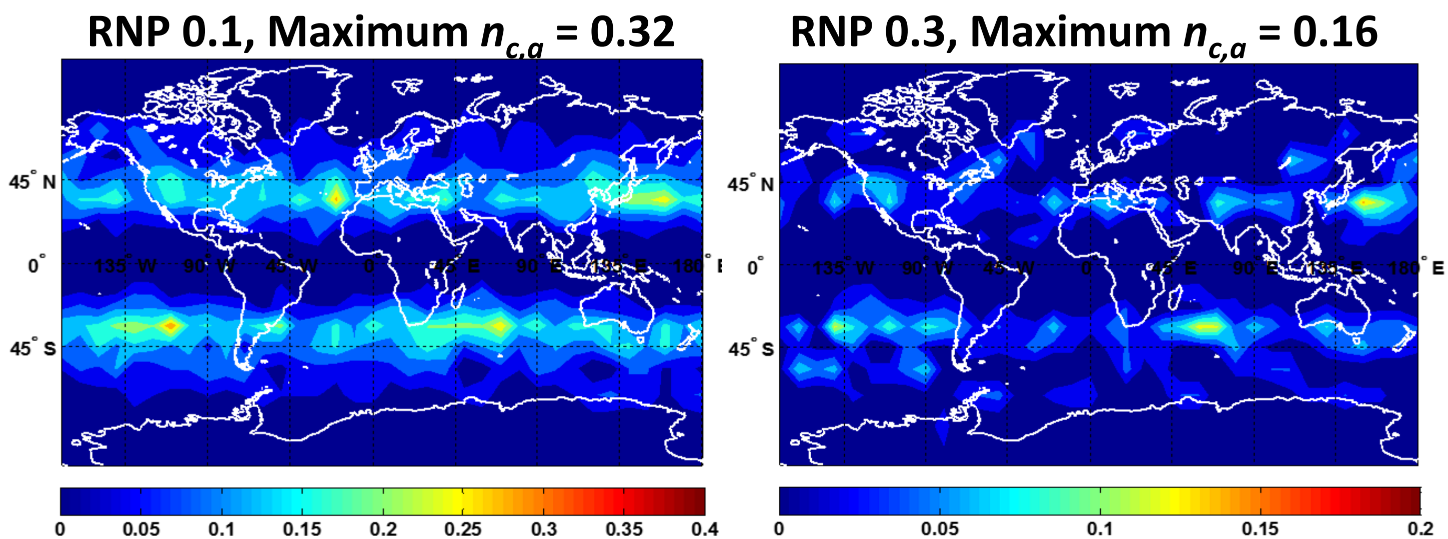


RNP 0.3, Coverage (0.995) = **99.98%**



Impact of USO on Continuity

- Recall: ***C_{req} could be met only if n_c = 0.***



Average Critical Satellite Number over Time

- At many locations, n_c = 0. At locations where $n_c \neq 0$, the occurrence of USO on critical satellites could impact H-ARAIM continuity.
- However, an upper bound is used to achieve this analysis. This bound may reduce the robustness to satellite geometry, declare a satellite to be 'critical' when it actually is not.

Conclusion

- Due to the stringent continuity requirement, fault exclusion is needed for H-ARAIM applications.

- By implementing the FDE algorithm described in this presentation:
  - H-ARAIM continuity could be significantly improved.
  - *High availability performance could be achieved for H-ARAIM*.

- From the critical satellite analysis:
  - The occurrence of USO have a noticeable impact on H-ARAIM continuity.
  - This impact may be mitigated by tighten the FDE integrity bound, and we are investigating it.

Acknowledgement

We would like to thank
the **Federal Aviation Administration**
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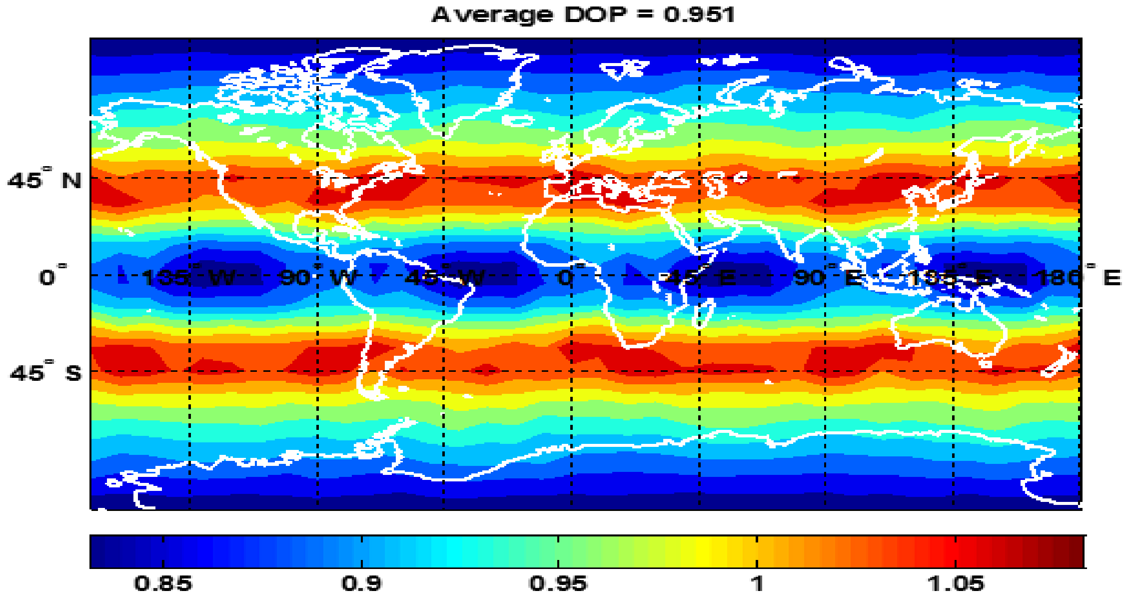
BS 1 : HDOP

- Results show that there are more critical satellites in the mid-latitude region.
- Since the average critical satellite number is a reflection of the satellite geometry, horizontal dilution of precision (HDOP) could be used to illustrate this trend.



Worldwide Mean HDOP Over Time

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BS 2 : Determine n_c

- To evaluate the critical satellite number n_c:

(1) At a location and a time epoch, evaluate P_{HMI} (or PL). If $P_{HMI} < I_{REQ}$, then go to step 2, otherwise, $n_c = 0$.

(2) Remove one satellite and reevaluate P_{HMI} . If $P_{HMI} > I_{REQ}$, then the removed satellite is regarded as a critical satellite. Otherwise, it is not a critical satellite.

(3) Repeat step 2 for all the in view satellites, record all the critical satellites.

(4) Sum up the number of critical satellites in step 3, the number is n_c for that location and time epoch.