Progress Update on Multi-constellation Safety-of-Life Activities

Supplemental Technical Charts

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Acknowledgement and Disclaimer

Acknowledgement: Technical content of this presentation is the result of participants in the Advanced Receiver Autonomous Integrity Monitoring (ARAIM) Subgroup of U.S./EU Working Group C on Design of Next Generation GNSS

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Foundational Studies

- Published two reports in 2009 on combined GPS/Galileo and EGNOS/WAAS performance
- Multi-constellation performance was significantly improved as compared to single system performance
- Dual-frequency receivers provide additional improvement over single-frequency in most environs
- Most significant improvement is for partially obscured environments, where obstacles or terrain obscure sky
- Study illustrated benefits expected from future broadband signals
- Performance obtained with SBAS UE was "always" better than obtained by GPS/RAIM performance
- Results confirmed improved availability for a wide range of aviation services in both hemispheres and significantly improved robustness to satellite outages

Advanced RAIM User Algorithm

Special recognition to: Juan Blanch, Todd Walter, Per Enge, Stanford University; Young Lee, MITRE; Boris Pervan, Illinois Institute of Technology; Markus Rippl, Alex Spletter, German Aerospace Center for their contributions based on ARAIM Subgroup work as recorded in ION GNSS 2012 Paper, *Advanced RAIM User Algorithm: Fault Detection, Exclusion, and Protection Level Calculation*, 21 September 2012

Navigation Requirements for Vertical Guidance

- Vertical guidance for Space-based Augmentation Systems:
  - Prob (Vertical Position Error > 4 m) < 0.05
  - Detection threshold must not exceed 15 m
  - Prob (Vertical Position Error > 35 m) < 10^{-7}

$$\sum_{k=0}^{N_{all\ faults}} \mathrm{P}\left(\text{Vertical Position Error} > 35\ \text{m} \mid \text{fault k}\right)\ P_{fault,k} \leq 10^{-7}$$

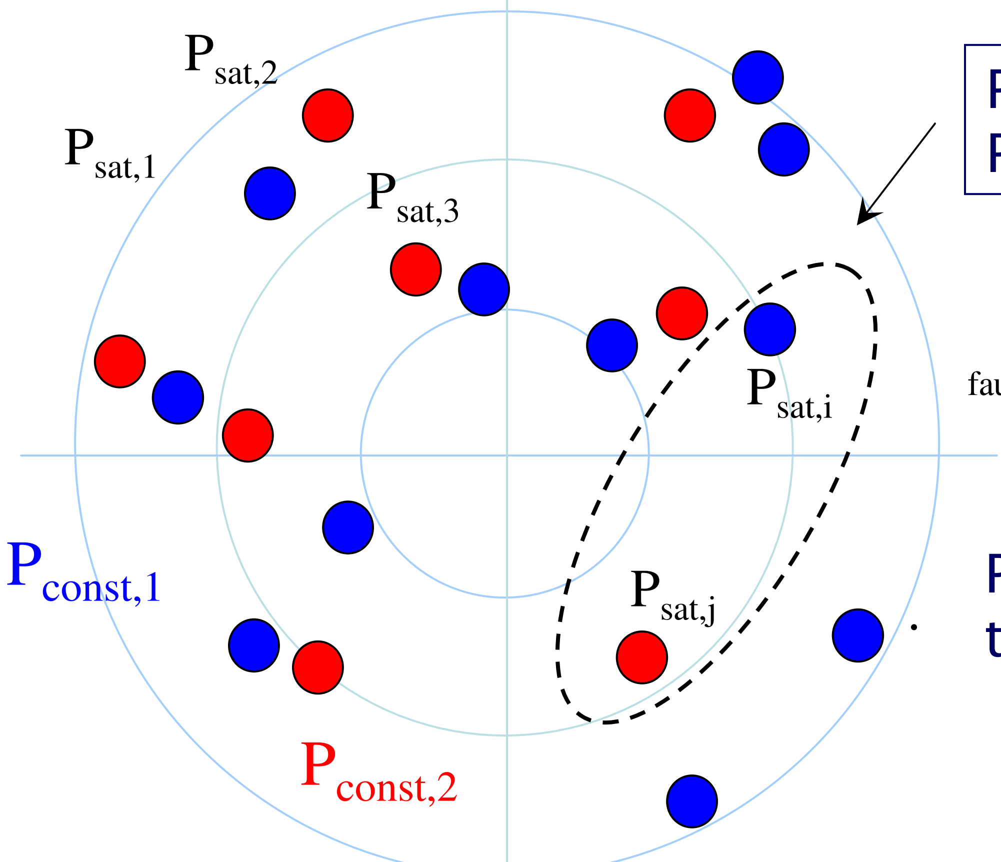
Probability of exceeding 35 m error given that a fault is present

Vertical Alert Limit

Prior probability of fault k

Fault List

- Algorithm ensures that the accumulated risk of not-monitored subset faults is below a fraction of the integrity budget



Prob (Sat. *i* and *j* faulted) = $P_{sat,i}\ P_{sat,j}$

$$\sum_{\text{faults k not monitored}} P_{fault,k} \leq \text{fraction of } 10^{-7}$$

P_{sat} and P_{const} are included in the Integrity Support Message

Test Statistic

- Fault k: $$\begin{bmatrix} y_1 \\ \vdots \\ y_i \\ \vdots \\ y_j \\ \vdots \\ y_n \end{bmatrix} = \text{true range} + \text{nominal noise} + \begin{bmatrix} 0 \\ \vdots \\ b_i \\ \vdots \\ b_j \\ \vdots \\ 0 \end{bmatrix}$$

Arbitrary

- Optimal test: $$\left| \hat{x} - \hat{x}_k \right| \leq T_k$$

Test threshold based on continuity requirements

All-in-view position solution

Position solution excluding *i* and *j*

Protection Level Equation

$$\sum_{k=0}^{N_{all\ faults}} \mathrm{P}\left(\text{Vertical Position Error} > VPL \mid \text{fault k}\right) \; P_{fault,k} \le 10^{-7}$$

$$\sum_{\text{faults } k \text{ not monitored}} P_{fault,k} \le \theta \times 10^{-7}$$

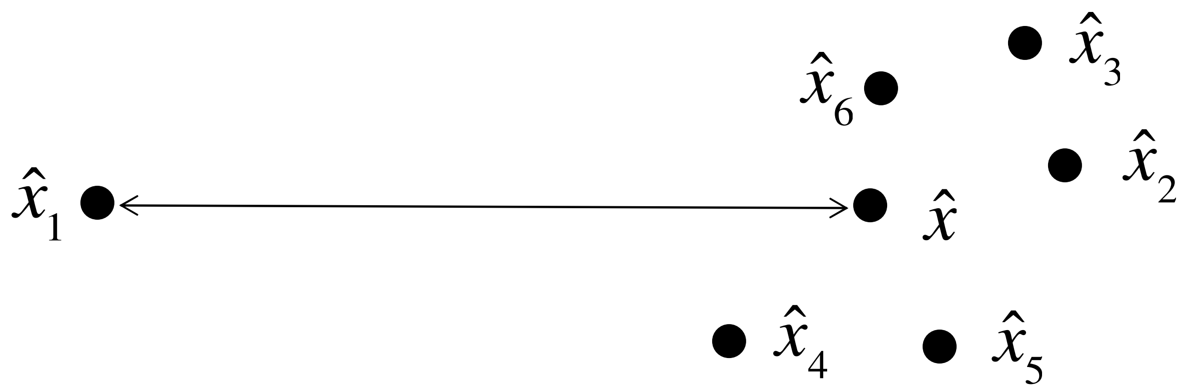
$$\sum_{k=0}^{N_{faults,mon}} \mathrm{P}\left(\left|x - \hat{x}\right| > VPL,\ \left|\hat{x} - \hat{x}_k\right| \le T_k \mid \text{fault k}\right) \; P_{fault,k} \le \left(1-\theta\right) \times 10^{-7}$$

$$\sum_{k=0}^{N_{faults,mon}} \mathrm{Q}\left(\frac{VPL - T_k}{\sigma_k}\right) \cdot P_{fault,k} = \left(1-\theta\right) \times 10^{-7}$$

Exclusion Function: Identifying Faulty Satellites

- Exclusion function makes use of the solution separation test statistics:

$$k_{ex} = \arg\max_{k} \left| \frac{\hat{x} - \hat{x}_k}{\sigma_{ss,k}} \right|$$



- Only one candidate for exclusion (per size of subset to be excluded)

Exclusion Function: Confirming exclusion

- After exclusion, the algorithm checks the consistency of the remaining set of satellites:

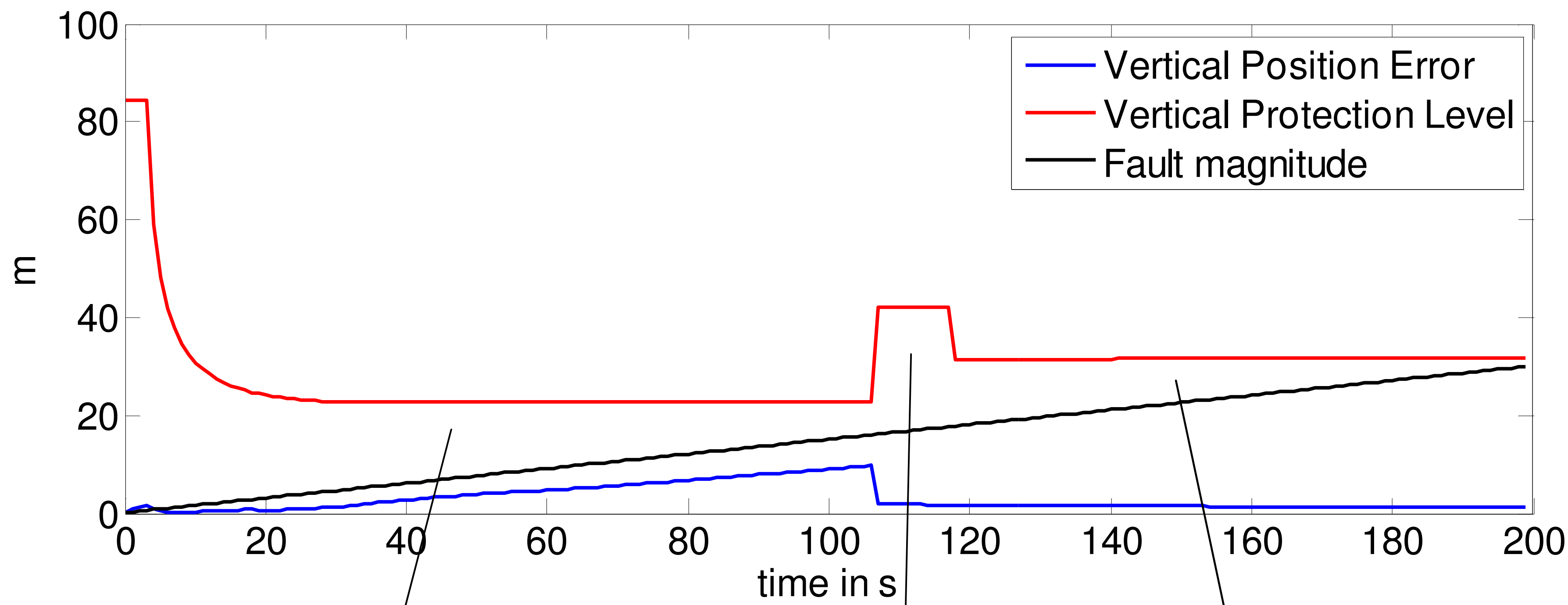
$$\left|\hat{x}_i - \hat{x}_{ij}\right| \leq T_{i,ij}$$

- To guarantee position requirements given that exclusion is attempted, additional exclusion tests are performed

$$\left|\hat{x}_j - \hat{x}_{ij}\right| \geq T_{j,ij,ex}$$

Ensure exclusion is confirmed by each subset

Exclusion: Example



$$\sum_j Q\left(\frac{VPL-T_j}{\sigma_j}\right) P_{fault,j} = \text{Integrity risk}$$

$$\sum_j Q\left(\frac{VPL_{ex}-T_{ij}}{\sigma_{ij}}\right) P_{fault,j} = \text{Integrity risk}$$

$$\sum_j Q\left(\frac{VPL_{ex}-T_{ij}}{\sigma_{ij}}\right) \delta_j P_{fault,j} = \text{Integrity risk}$$

Rank one update formulas for subset computation

- Subset solutions use rank one update formulas:

$$Cov_{\hat{i}} = Cov + \frac{h_i h_i^T}{1 - g_i^T w_i h_i}$$

i^{th} column of coefficient matrix

Covariance of the subset

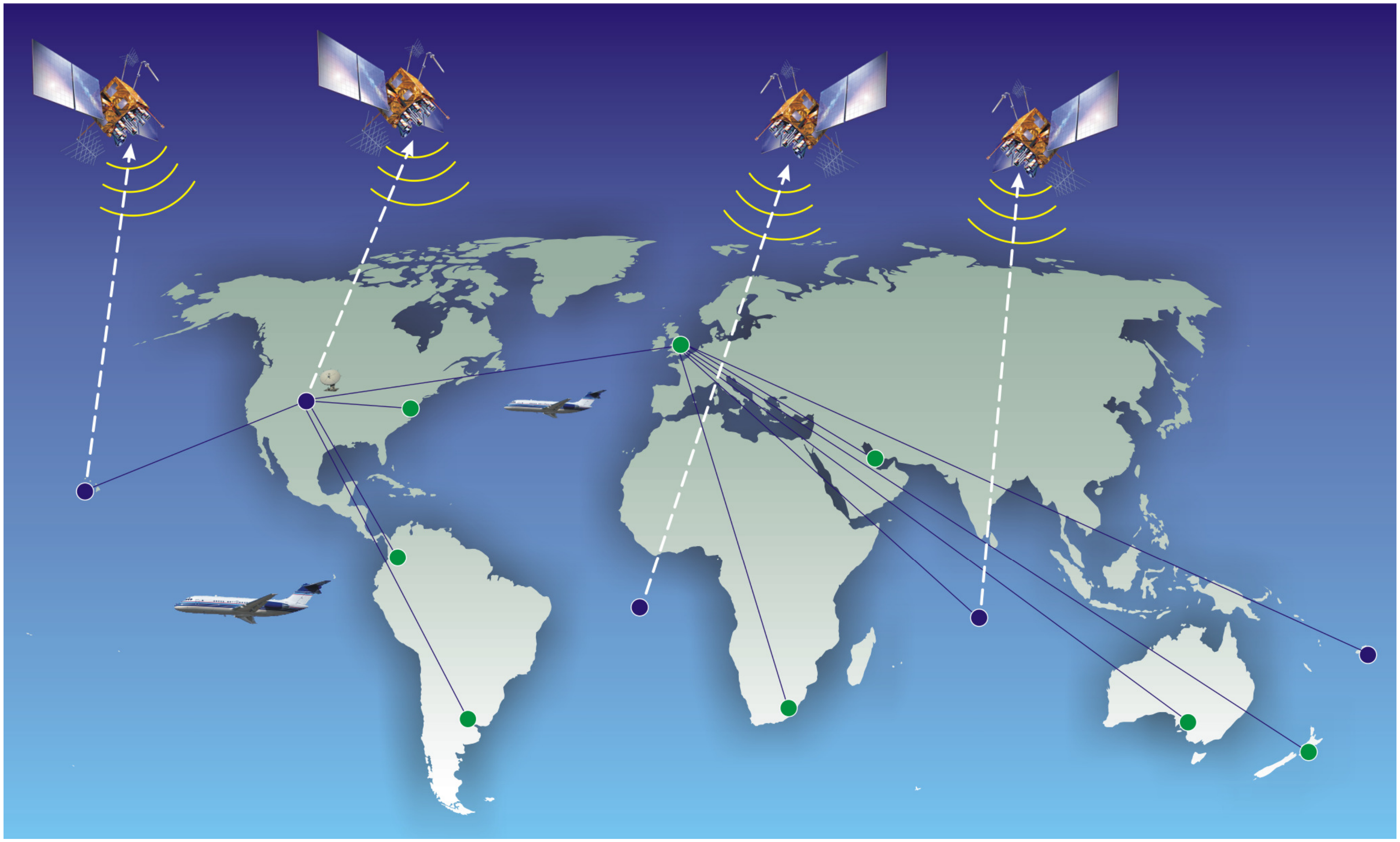
All-in-view covariance

ith row of observation matrix

An Analysis of Architectures Supporting ARAIM

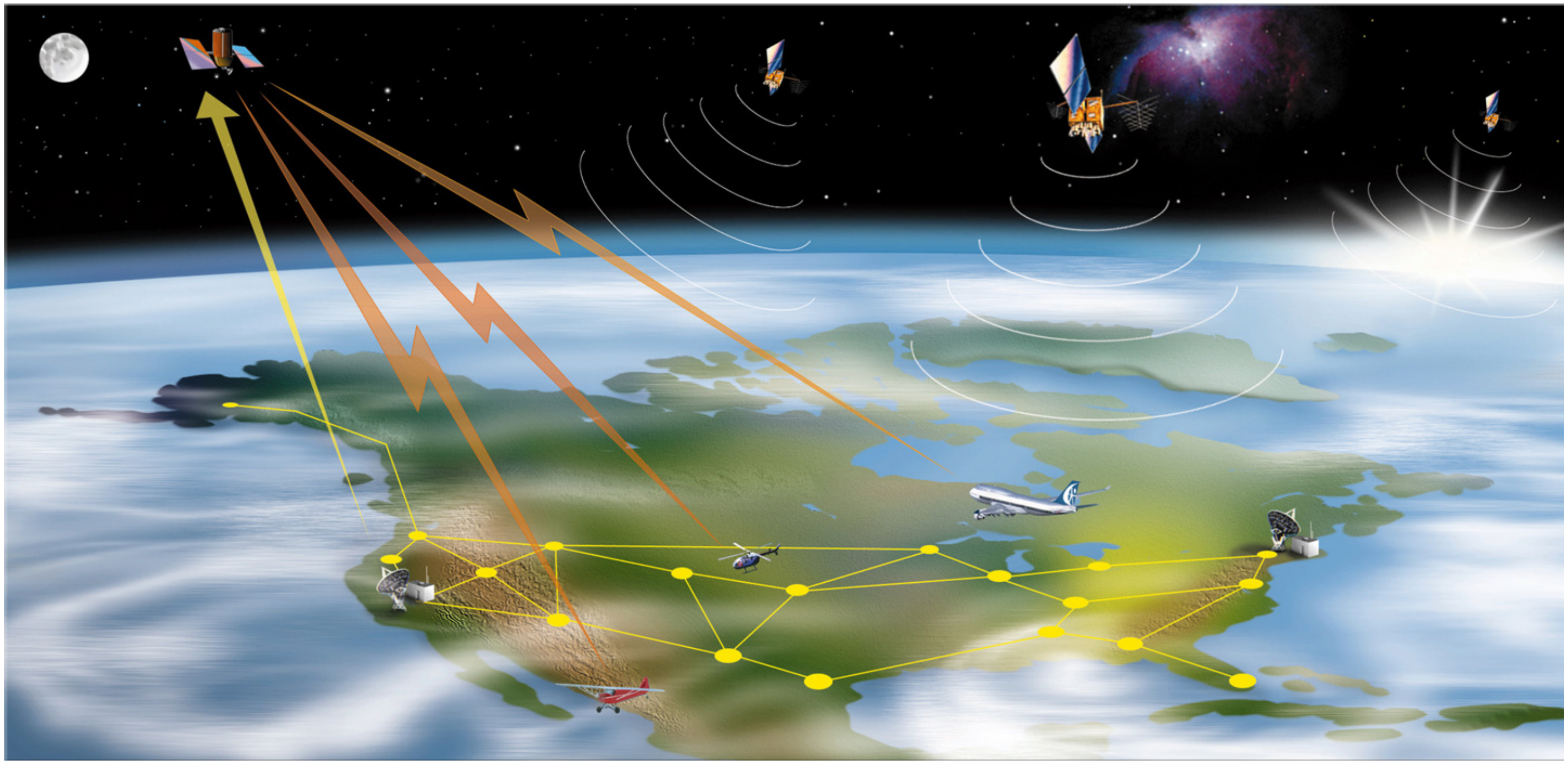
Special recognition to: Todd Walter, Juan Blanch, and Per Enge, Stanford University for their contributions based on based on ARAIM Subgroup work as recorded in ION GNSS 2012 Paper, *An Analysis of Architectures Supporting ARAIM,* 21 September 2012

RAIM Architecture



- *Global Reference Stations*
- *Airborne Consistency Check*
- *GPS Broadcast Data*
- *Master Control Segment*

SBAS Architecture



- *Network of Reference Stations*
- *Master Stations*
- *Corrections & Integrity*
- *Geostationary Satellites*
- *Geo Uplink Stations*
- *6 Second Time-To-Alert*

Architecture Properties

- Bounding methodology
- Broadcast methodology
  - Content
  - Time-to-Integrity Support Message (ISM)-Alert (TIA)
    - Latency
  - Bandwidth
- Handling of constellation faults
- Reference network

Bounding Methodology

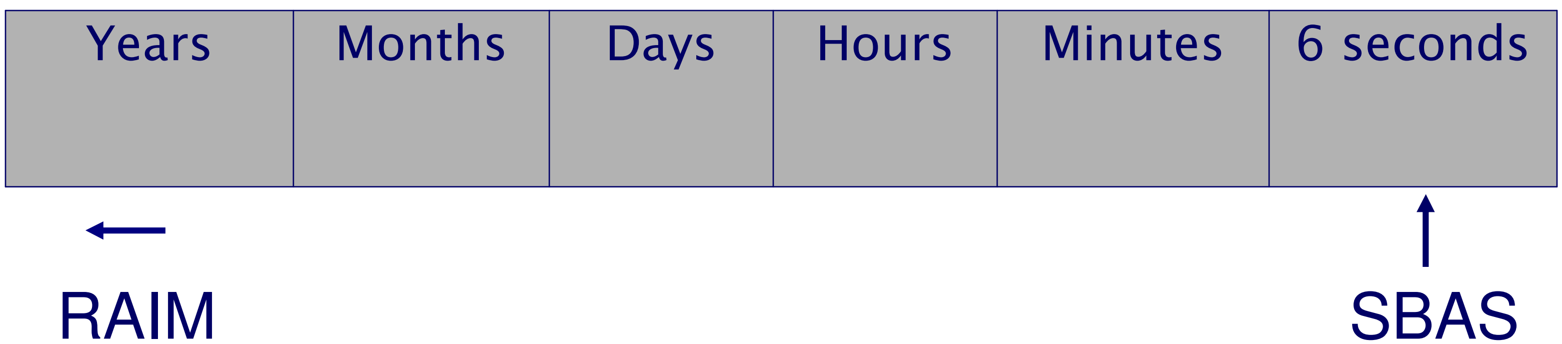
- Threats mitigated by ground
  - Versus threats mitigated by satellites and/or airborne algorithm
- Determination of ISM parameters
  - Required design assurance level
  - Update rate of ISM parameters

None.	Offline Determination – Quasi-static ISM	Real-time Determination – Dynamic ISM

↑ RAIM ↑ SBAS

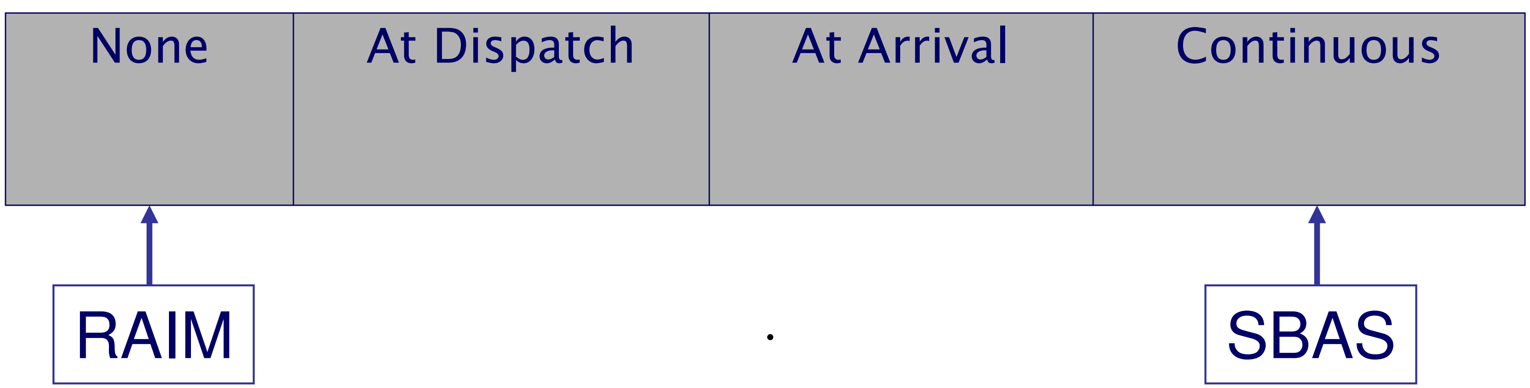
TIA/Latency

- Time for ISM Alert (TIA)
  - Time for Integrity Support Message (ISM) alert to to reach user
  - Includes latency of delivery channel



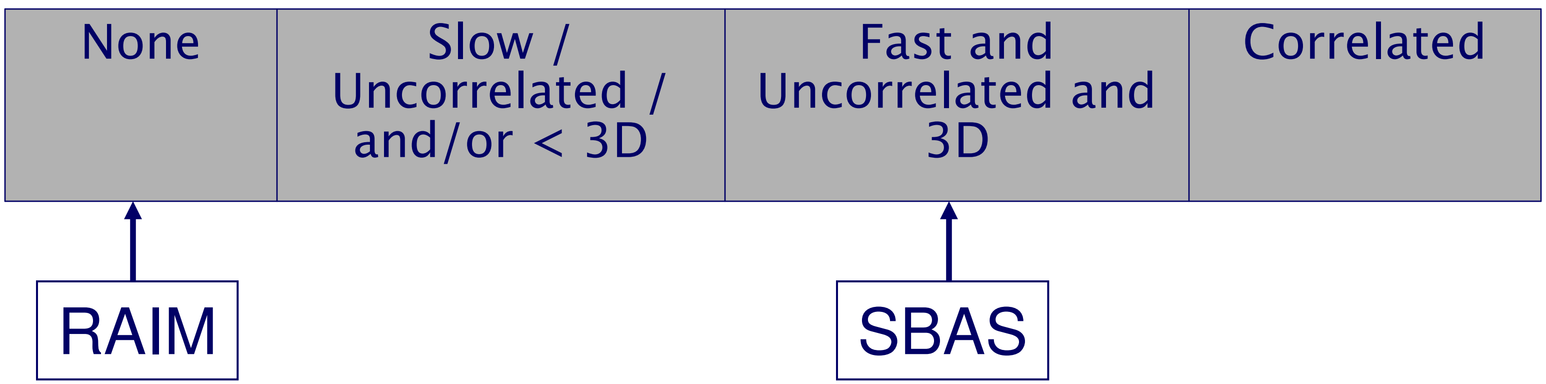
Broadcast Methodology

- ISM Content
- Rate of change of ISM content
- Desired TIA
- Coverage area
- Multiple solutions are desirable



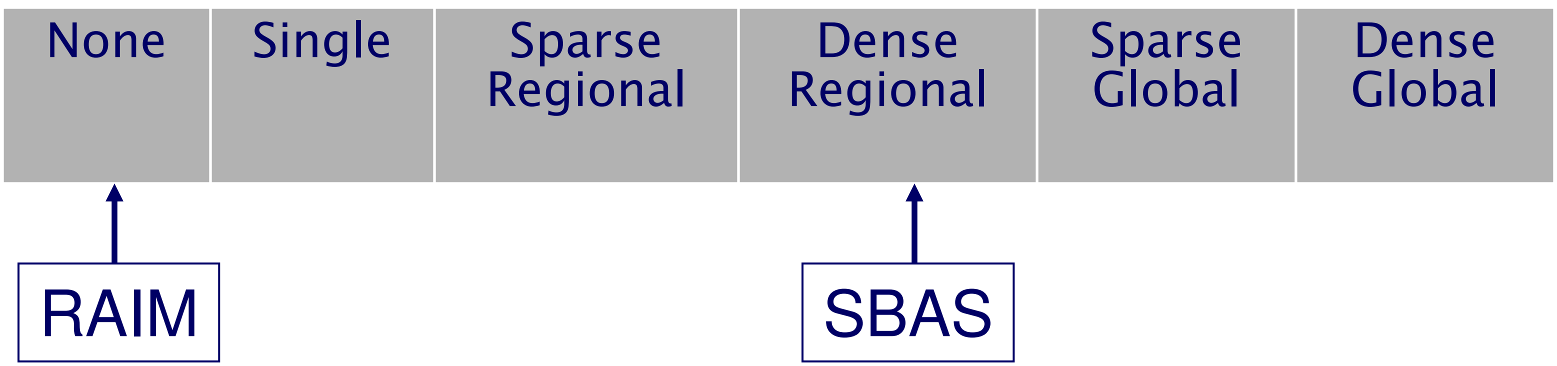
Constellation Faults

- Multiple satellite threat
  - Fault effect
  - Common across constellations
  - Rate of growth
  - Where mitigated



Reference Network

- Network density
- Dedicated vs. Open
- Trusted vs. Untrusted



Architecture Matrix

Architec-ture	Network	TIA	Bounding	Consel-lation Faults	Broadcast
RAIM	None	Infinite	Off-line, service history	None	None
L1 SBAS	Dedicated, trusted, dense, regional	6 seconds	Real-time, trusted	Mitigated by Ground	Continuous, GEO

Key Architectural Decision

- Bounding methodology/TIA
  - All ARAIM architectures place high degree of trust in core constellations
    - Must conform to expectations as defined by ISM and airborne algorithm
      - Nominal conditions properly defined
      - Faults cannot occur more often than expected
      - No unexpected fault modes
- How much effort is required to validate constellation performance?
  - How quickly do we need to respond to problems?

Off-line Bounding

- ISM content changed infrequently
  - New satellites launched
  - Old satellites retired
  - Extended changes in behavior
    - (e.g. over multiple days)
    - May not try to respond to faults that the MCS is likely to flag
- May include human-in-the-loop assessment of performance
- Analysis comparable to PAN reports

Real-time Bounding

- Dedicated and automated network for generating ISM content
- Responds to confirmed faults as quickly as possible
  - No human-in-the-loop decision making
  - But may still take some time to confirm fault and get information to aircraft
- Comparable to GBAS or SBAS but with longer TIA

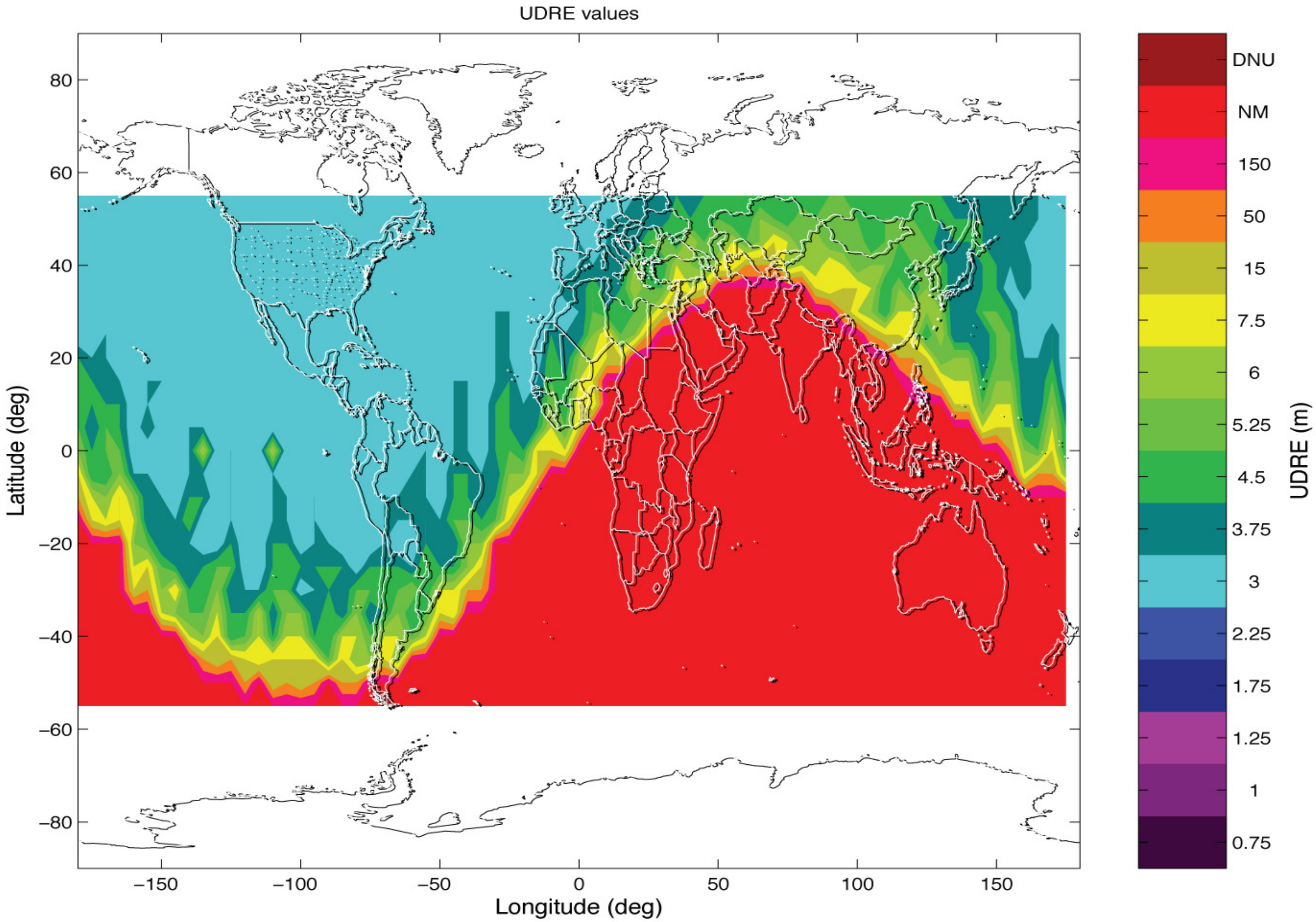
Conclusion

- ARAIM requires significantly increased trust in core constellations
- Overall architecture must support this additional trust through increased assurances and/or monitoring
- Identified key parameters of the architecture and which need to be resolved first
  - Bounding methodology
  - TIA

TIA

- If the TIA cannot be longer than 6 seconds, ARAIM has no future
- A TIA longer than 6 seconds puts trust in the performance of the core constellations
  - How long are we willing to trust them?
  - Assuming we do trust them, how long is it acceptable to expose user to a fault?
    - Given the airborne detection and exclusion algorithms including constellation wide fault mode

UDRE MAP


UDRE values
80
60
40
20
0
−20
−40
−60
−80
Latitude (deg)
−150
−100
−50
0
50
100
150
Longitude (deg)
DNU
NM
150
50
15
7.5
6
5.25
4.5
3.75
3
2.25
1.75
1.25
1
0.75
UDRE (m)

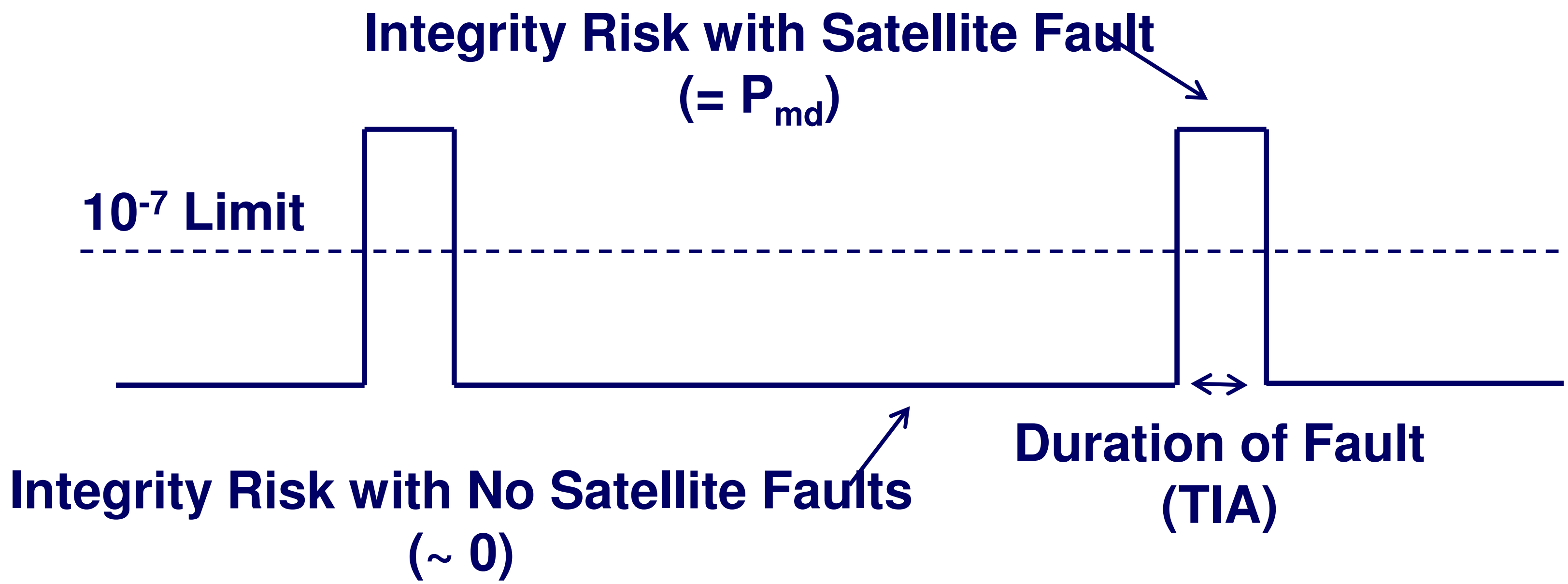
P_{md}

- The required average P_{md} can be derived from the average PHMI limit
  - Mean time between failures is ~1/P_{onset}
  - Expect N_{sat} failures in MTBF
  - Want average PHMI below 10^{-7}

$$P_{md} \leq \frac{MTBF \times 10^{-7}}{N_{sat} \times TIA} = \frac{10^{-7}}{N_{sat} \times P_{onset} \times TIA}$$

  - Real-time algorithm already correctly implements more complex version

Average PHMI



$$PHMI = \frac{N_{faults} \times P_{md} \times TIA}{\text{Total time}}$$

Example Values

- Assuming $P_{onset} = 10^{-5}$/sat/hour, 12 satellites in view, and 1 year average
  - Expect ~1 satellite fault in view
  - TIA provides fault duration

TIA	Maximum Mean P_{md}
1 hour	8.3×10^{-4}
6 hours	1.4×10^{-4}
10 hours	8.3×10^{-5}
100 hours	8.3×10^{-6}

Potential Architecture

- Concern over complexity of having many ISMs during international flight
- Could have two types of ISM
  - One commonly agreed version for horizontal flight (en route)
    - Analogous to today's RAIM
  - One delivered locally for a specific airport that support vertical guidance
    - Only accessed for airports where planning an approach

Key Questions

- When a fault is present, how long is it acceptable to leave it present?
  - Specific risk now increased to P_{md}
  - Ground may observe fault and know that current risk is above specification
  - Affects all users in view of the satellite
- How much can we trust constellations to operate as we expect in the future?
- What do we do if we see an unexpected fault mode?

Interaction of Architectural Elements and Parameters

- Identified elements are not independent of each other
  - Certain choices may only make sense in combination
  - Also may only make sense for narrow range of parameter values

- Parameter space examines availability of architecture