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

Supplemental Technical Charts

International Committee on GNSS – ICG–7 Meeting
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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) < $10^{-7}$

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

- Probability of exceeding 35 m error given that a fault is present
- Prior probability of fault $k$
- Vertical Alert Limit
Fault List

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

\[
\text{Prob (Sat. } i \text{ and } j \text{ faulted)} = P_{\text{sat}, i} P_{\text{sat}, j}
\]

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

\(P_{\text{sat}}\) and \(P_{\text{const}}\) are included in the Integrity Support Message.
Test Statistic

• Fault $k$:

\[
\begin{bmatrix}
  y_1 \\
  \vdots \\
  y_i \\
  y_j \\
  \vdots \\
  y_n
\end{bmatrix}
= \text{true range} + \text{nominal noise} +
\begin{bmatrix}
  0 \\
  \vdots \\
  b_i \\
  b_j \\
  \vdots \\
  0
\end{bmatrix}
\]

• Optimal test:

\[|\hat{x} - \hat{x}_k| \leq T_k\]

All-in-view position solution
Position solution excluding $i$ and $j$

Test threshold based on continuity requirements
Protection Level Equation

\[
\sum_{k=0}^{N_{\text{all faults}}} \left( P\left( \text{Vertical Position Error} > VPL | \text{fault } k \right) \right) P_{\text{fault},k} \leq 10^{-7}
\]

\[
\sum_{\text{faults } k \text{ not monitored}} P_{\text{fault},k} \leq \theta \times 10^{-7}
\]

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

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

\[ |\hat{x}_i - \hat{x}_{ij}| \leq T_{i,ij} \]

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

\[ |\hat{x}_j - \hat{x}_{ij}| \geq T_{j,ij,ex} \]

Ensure exclusion is confirmed by each subset.
Exclusion: Example

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

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

\[ \sum_j Q \left( \frac{VPL_{\text{ex}} - T_{ij}}{\sigma_{ij}} \right) \delta_j p_{\text{fault}, j} = \text{Integrity risk} \]
Rank one update formulas for subset computation

- Subset solutions use rank one update formulas:

\[ \text{Cov}_i = \text{Cov} + \frac{h_i h_i^T}{1 - g_i^T w_i h_i} \]

- Covariance of the subset
- All-in-view covariance
- i\textsuperscript{th} row of observation matrix
- i\textsuperscript{th} column of coefficient matrix
An Analysis of Architectures Supporting ARAIM

Special recognition to: Todd Walter, Juan Blanch, and Per Enge, Stanford University for their contributions 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

<table>
<thead>
<tr>
<th>None.</th>
<th>Offline Determination – Quasi-static ISM</th>
<th>Real-time Determination – Dynamic ISM</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAIM</td>
<td></td>
<td>SBAS</td>
</tr>
</tbody>
</table>
• Time for ISM Alert (TIA)
  - Time for Integrity Support Message (ISM) alert to reach user
  - Includes latency of delivery channel

<table>
<thead>
<tr>
<th>Years</th>
<th>Months</th>
<th>Days</th>
<th>Hours</th>
<th>Minutes</th>
<th>6 seconds</th>
</tr>
</thead>
</table>

RAIM

SBAS
Broadcast Methodology

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

<table>
<thead>
<tr>
<th>None</th>
<th>At Dispatch</th>
<th>At Arrival</th>
<th>Continuous</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAIM</td>
<td></td>
<td></td>
<td>SBAS</td>
</tr>
</tbody>
</table>
**Constellation Faults**

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

<table>
<thead>
<tr>
<th>None</th>
<th>Slow / Uncorrelated / and/or &lt; 3D</th>
<th>Fast and Uncorrelated and 3D</th>
<th>Correlated</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAIM</td>
<td></td>
<td></td>
<td>SBAS</td>
</tr>
</tbody>
</table>
Reference Network

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

<table>
<thead>
<tr>
<th>None</th>
<th>Single</th>
<th>Sparse Regional</th>
<th>Dense Regional</th>
<th>Sparse Global</th>
<th>Dense Global</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- RAIM
- SBAS
## Architecture Matrix

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Network</th>
<th>TIA</th>
<th>Bounding</th>
<th>Conellation Faults</th>
<th>Broadcast</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAIM</td>
<td>None</td>
<td>Infinite</td>
<td>Off-line, service history</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>L1 SBAS</td>
<td>Dedicated, trusted, dense, regional</td>
<td>6 seconds</td>
<td>Real-time, trusted</td>
<td>Mitigated by Ground</td>
<td>Continuous, GEO</td>
</tr>
</tbody>
</table>
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
• 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

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The required average $P_{md}$ can be derived from the average PHMI limit

- Mean time between failures is $\sim 1/P_{onset}$
- 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

Integrity Risk with Satellite Fault

\( = P_{md} \)

10\(^{-7}\) Limit

Integrity Risk with No Satellite Faults

\( \sim 0 \)

Duration of Fault (TIA)

\[
PHMI = N_{\text{faults}} \times P_{md} \times \text{TIA} \\
\text{Total time}
\]
Example Values

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

<table>
<thead>
<tr>
<th>TIA</th>
<th>Maximum Mean $P_{\text{md}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 hour</td>
<td>$8.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>6 hours</td>
<td>$1.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>10 hours</td>
<td>$8.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>100 hours</td>
<td>$8.3 \times 10^{-6}$</td>
</tr>
</tbody>
</table>
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