A Global Safety of Life Service from Multiple GNSS Constellations (e.g. GPS + Compass)

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This briefing is NOT intended to convey a US Government position; rather, it is provided to facilitate a working-level discussion and exchange of ideas.
GPS Essential Ingredients & Normal Performance

1. Time of Transmission
2. Correct Satellite Location
3. Speed of Radio Wave
4. Time of Arrival
Our Canoe
But Every Once in a While
GPS Faults Occur Three Times a Year

*Rare Normals* Due to Space Weather

1. Time of Transmission
2. Correct Satellite Location
3. Speed of Radio Wave
4. Time of Arrival

[Diagram of GPS satellite signal propagation and satellite location over Earth.]
Today’s Single Frequency Technology for Detection of GPS Faults

<table>
<thead>
<tr>
<th>Positioning &amp; Fault Detection</th>
<th>Navigation</th>
<th>Surveillance</th>
</tr>
</thead>
<tbody>
<tr>
<td>GBAS detect 10 (28) m in 2 sec. vertical &amp; horizontal (23 sats)</td>
<td>En Route</td>
<td>5 nm</td>
</tr>
<tr>
<td>SBAS detect 35 m in 6 seconds vertical &amp; horizontal (22 sats)</td>
<td>Terminal &amp; LNAV</td>
<td>3 nm</td>
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<tr>
<td>RAIM detect 200 m in 2 seconds (28 sats)</td>
<td>RNP</td>
<td>Dependent parallel approaches</td>
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<td>LPV LPV-200</td>
<td>Independent parallel approaches</td>
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<td></td>
<td>Cat I &amp; Cat II/III</td>
<td>Independent parallel approaches</td>
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Compared to RAIM, SBAS Provides More Performance With Fewer MEO Satellites

- Each GEO is roughly equivalent to 2 or 3 satellites.
- SBAS compares satellites to ground truth
- RAIM compares satellites to satellites

Receiver autonomous integrity monitoring (RAIM) requires 28 satellites
WAAS only requires 22 to 23 SVs
Coverage of Space Based Augmentation Systems (WAAS, EGNOS & MSAS, from Dr. T. Walter)
Utility of Dual Frequencies & Multiple Constellations

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<td>Dual freq GBAS detect 10 m in 2 sec. (23 sat)</td>
<td>Dual freq SBAS Research &amp; Development on Multi-constellation ARAIM</td>
<td>En Route 5 nm</td>
</tr>
<tr>
<td>Hardened against RFI</td>
<td></td>
<td>Terminal &amp; LNAV 3 nm</td>
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<td></td>
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<td>RNP Dependent parallel approaches</td>
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Dual Frequency Coverage
(WAAS, EGNOS, MSAS, from Dr. T. Walter)
Dual Frequency, Dual GNSS, Expanded Networks (from Dr. T. Walter)

But it will cost $200M to add the 2nd string of reference receivers to WAAS. (and what if we add the wrong string?)

Data capacity could also be an issue.
Dual Frequency Advanced RAIM
With 27 GPS + 27 Other GNSS (from Dr. J. Blanch)

Allow other constellations.

Robust to weak constellations?

URA = 1m

$P_{sat} = 10^{-3}$

$P_{const} = 10^{-6}$

Availability with VAL = 35, HAL = 40, Coverage(99.5%) = 99.78%
Receiver Autonomous Integrity Monitoring (RAIM) + Integrity Support Message (ISM)

Dual frequency open service
Fast single faults & most multiple faults on the aircraft

Nation-state approves ARAIM on dispatch

GNSS #1 Ground Control
ISM for GNSS #1

GNSS #2 Ground Control
ISM for GNSS #2
Common cause for SV theo-range faults have been posited:
- Earth orientation parameters
- Bad clock rotates ephemeris
- Widespread URA optimism
Seeking Something Sublime

• Aviation wants to use the new GNSS
• Availability & continuity
• Aviation does not want the downside
  – if a GNSS constellation becomes weaker
  – if a GNSS constellation has a spate of faults
• Aviation does want the upside
  – if integrity performance improves
  – e.g. clocks are added or URA reduced
  – e.g. GPS performance has improved dramatically in the last ten years
  – LPV-100 from space
## ARAIM + SBAS Mixtures

<table>
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<tr>
<th>Air &amp; ground responsibilities</th>
<th>Update rate</th>
<th># SVs (?)</th>
<th>Risk (of proof)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>I</strong> ARAIM&lt;br&gt;Ground: priors &amp; URAs</td>
<td>hourly</td>
<td>27 + 27</td>
<td>High ! EOP + Level D</td>
</tr>
<tr>
<td><strong>II</strong> ARAIM + constellation cross check&lt;br&gt;Ground: priors &amp; URAs</td>
<td>hourly</td>
<td>30 + ?</td>
<td>Medium EOP common cause</td>
</tr>
<tr>
<td><strong>III</strong> ARAIM&lt;br&gt;Ground: priors &amp; URAs&lt;br&gt;Ground: level B GNSS nav. messages</td>
<td>hourly</td>
<td>27 + 27</td>
<td>Low&lt;br&gt;Must build a global network with level B</td>
</tr>
<tr>
<td><strong>IV</strong> Regional SBAS for primary GNSS&lt;br&gt;ARAIM for secondary GNSS</td>
<td>real time</td>
<td>18 + 18?</td>
<td>Low, availability penalty for high URAs for secondary GNSS</td>
</tr>
<tr>
<td><strong>V</strong> Regional SBAS for primary&lt;br&gt;Global civil network: priors &amp; URAs</td>
<td>real time</td>
<td>15 + 15?</td>
<td>Low, availability credit from low URAs</td>
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I. Prove that multi-satellite navigation message faults cannot cause HMI since the last ISM.
II. Believe that multi-SV failures are independent from one constellation to another

Need 27 SVs in each constellation.
III. Use SBAS monitoring network & ISM to replace the navigation message
IV. Use SBAS to monitor one constellation and use ARAIM to accept SVs from other constellations.
V. Need Global Network to Reduce the URAs

### GPS 27 + GNSS 27

<table>
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<tr>
<th>$P_{sat}/URA$</th>
<th>0.5 m</th>
<th>1 m</th>
<th>1.5 m</th>
<th>2 m</th>
<th>3 m</th>
<th>3.5 m</th>
<th>4 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-5}$</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>42.9%</td>
<td>3.4%</td>
</tr>
<tr>
<td>$10^{-4}$</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$10^{-3}$</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>99.6%</td>
<td>6.6%</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Less accuracy (URA)

Less satellite reliability

Less constellation reliability

$P_{const} < 10^{-8}$

$P_{const} = 10^{-6}$

$P_{const} = 10^{-4}$

$P_{sat} = \text{Prob. of satellite fault}$

$P_{const} = \text{Prob. of constellation fault}$

$b = 0.75 \text{ m}$
Summary:
Safety from Frequency & Geometric Diversity

• GPS + SBAS works
  – Over 70,000 aircraft installations
  – No known integrity failures
  – Hundreds of engineer-years to build
• Frequency diversity obviates iono storms & most RFI
• Multi-constellation requires something sublime
  – Geometric diversity from new GNSS
  – With 30 year equipment lifetimes, aviation cannot afford to be brittle.
  – Need elegant integration of SBAS and ARAIM