Multi-constellation Navigation for Air & Sea: Advanced Receiver Autonomous Integrity Monitoring for the Space-Based Position, Navigation & Time Advisory Board by Per Enge, Stanford University* on October 30, 2015

based on work of the ARAIM Technical Subgroup Within Working Group C of the EU/US Bilateral Activity on GNSS

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The opinions expressed in this presentation may only belong to the speakers.

These thoughts do not necessarily correspond to any present or future view of the
• U.S. government, or
• Federal Aviation Administration, or
• Working Group C, or the
• European Commission

The mistakes are certainly mine alone.
Receiver Autonomous Integrity Monitoring (RAIM) Supports Lateral Navigation for 100,000’s of Aircraft

GPS only
L1 only

\[(p^{(k)} - G^{(k)}x)\]

GPS Ground Control Segment
- GPS reference stations
- GPS commitments & history on \(P_{\text{sat}}\)
- GPS history on \(P_{\text{const}}\)

RAIM Dispatch Check
Wide Area Augmentation System (WAAS)
Operational Since July 2003
Ground Based Augmentation System

GPS Satellite Signals

VHF Data Broadcast from the Ground to the Aircraft
Advanced RAIM (aka Almost RAIM) to Support Lateral + Vertical Navigation Worldwide

Multi-constellation
Two frequencies

Reference Stations
- global network
- e.g. SBAS reuse or
- e.g. NASA’s GDGPS

Offline monitors check GNSS commitments on \( P_{\text{sat}} \) & \( P_{\text{const}} \)

Integrity support message (ISM)
- new constellations
- \{URA, \( P_{\text{sat}} \) & \( P_{\text{const}} \)\}
- broadcast using databases or GNSS

\[ (p^{(k)} - G^{(k)}x) \]
# ARAIM Benefits

**Horizontal ARAIM in the Near Term Based on One Frequency**
- Before dual frequency GPS + dual frequency Galileo
- e.g. single frequency GPS + single frequency GLONASS
- Two constellations with very different $P_{\text{sat}}$ & $P_{\text{const}}$

**ARAIM to Support Artic Navigation with High Integrity**
- Energy exploration, eco-tourism & shipping
- Ship speed is doubled in ice cracks
- SBAS GEOs do not cover the poles

**Vertical ARAIM Worldwide Without GEOs**

**ARAIM to Harden GNSS Receivers**
- Does not need GEOs
- Does not need low SVs
Benefit From Following a Crack in the Ice
Polar Coverage of Dual Frequency SBAS & ARAIM

24 GPS + 24 Galileo

24 GPS + 24 Galileo
Offline ARAIM Uses the Ephemeris & Clock Data Broadcast by the Core Constellations

Multi-constellation
Two frequencies

Reference Stations
- 100 to 300 globally
- SBAS reuse or
- Not dedicated
- e.g. NASA’s GDGPS

Offline monitor of
URA, $P_{\text{const}}$, $P_{\text{sat}}$ & $B_{\text{nom}}$

ISM updated monthly:
- using databases or
- GNSS with 1 bps (15 min. TTFF)

$\left( p^{(k)} - G^{(k)}x \right)$
Online ARAIM Replaces the Ephemeris & Clock Data (ECD) Generated by the Core Constellations

Reference Stations
- 15-20 globally
- SBAS reuse
- 3 rcvrs/station

Orbit & clock estimator

Online monitor

Offline monitor

Ephemeris overlay to ensure lower URA, $P_{\text{const}}$, $P_{\text{sat}}$ & $B_{\text{nom}}$

ISM update 12 minutes
- ECD, URA, $P_{\text{sat}}$ & $P_{\text{const}}$
- GNSS data rate < 6 bps
Multi-constellation for Toughening Air Navigation example is based on RNP 0.3

<table>
<thead>
<tr>
<th>Constellation</th>
<th>GPS only Mask=5°</th>
<th>GPS only Mask=15°</th>
<th>GPS+Galileo Mask=5°</th>
<th>GPS+Galileo Mask=15°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depleted with 23 satellites</td>
<td>99.1%</td>
<td>0%</td>
<td>100%</td>
<td>69.3%</td>
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<tr>
<td>Baseline with 24 satellites</td>
<td>100.0%</td>
<td>2.3%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>“Optimistic” with 27 satellites</td>
<td>100.0%</td>
<td>19.0%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
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Small part of aviation portfolio for intentional interference and spoofing
Please see Ken Alexander briefing to RTCA in October, 2015.
Seeking orderly adoption of new constellations for aviation
Vertical guidance worldwide
Tough against RFI (still requires quiet background)
Tough against frailties of new constellation