Recent Progress on Aviation Integrity

for the Institute of Navigation
on September 17, 2008

by Per Enge, Stanford University

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Disclaimer: The opinions may be mine alone, and the mistakes certainly are.
Outline

• Integrity & continuity
• Space based augmentation systems
• Ground based augmentation systems
• Impact of new constellations & frequencies
Exceptions Drive Aviation Architectures
(GPS as Seen by a Aerospace Engineer)

October 1993 modulation fault

Clock “runoffs”
7/28/01, 5/26/03
6/11/03 & more

40 notable iono events
during the last solar peak

RFI events:
• San Diego
• St Louis
• Santa Cruz

April 10, 2007 ephemeris fault & 24 smaller faults
over the last 5 years
Performance of an Integrity Augmentation from WAAS
Space Based Augmentation Systems (SBAS)

- 33,000 equipped GA aircraft in the U.S.
- 700 equipped regional & business aircraft
- 1161 LPV procedures
- No integrity faults since commissioning in July 2003
- Interoperability between SBASs
Ground Based Augmentation Systems (GBAS)
HMI Collaboration of FAA, Honeywell, Mitre, Zeta, Sequoia, Rannoch, OU, IIT & SU

1. Code carrier divergence
2. Signal deformation monitoring
3. Tropospheric anomalies
4. Nominal ionosphere
5. Anomalous ionosphere
6. Low-power
7. Ephemeris faults (Types B, A1 & A2)
8. Excessive acceleration
9. Radio frequency interference
10. Sigma monitoring
Signal Deformation Threat Analysis is Ten Dimensional
SDM Threat Embellished

- Nominal signal deformation must be treated.
- Fault analysis depends on ten parameters.
- Fault onset cases must also be considered.
  - SV failed when GBAS installed
  - Readmission after SDM detection
  - SV failed when launched
  - SV failed when set “unhealthy”
Ionospheric Analysis is also Ten Dimensional

Ionospheric Gradients

\[ I_{\text{Air}}(t) \rightarrow \text{Aircraft CSC} \]

\[ I_{\text{Gnd}}(t) \rightarrow \text{LGF CSC} \]

\[ \text{LGF CCD Monitor} \rightarrow \text{CCD Threshold} \]

Range Error

+ inflation!

Graph showing time (s) on the x-axis and CSC at Craft & Port in on the y-axis.
Frequency & Spatial Diversity
(from Günter Hein, FAF Munich)
Aviation Benefits from Frequency & Spatial Diversity

- Worldwide approach capability with vertical guidance, but no airport equipment.
- Worldwide landing capability (Cat. II/III)
- Robust against
  - Ionosphere
  - Scheduled RFI
  - Unscheduled RFI
# GEAS Panel

<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
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<tbody>
<tr>
<td>Deane Bunce (Co-Chair)</td>
<td>FAA ATO-W</td>
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<tr>
<td>Leo Eldredge</td>
<td>FAA ATO-W</td>
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<td>Deborah Lawrence</td>
<td>FAA ATO-W</td>
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<td>Calvin Miles</td>
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<td>Kevin Bridges</td>
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<td>Hamza Abduselam</td>
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<td>Bill Wanner</td>
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<td>David Schoonenberg</td>
<td>NSSO</td>
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<td>Mike David</td>
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<tr>
<td>Karen Van Dyke</td>
<td>RITA/Volpe</td>
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<tr>
<td>Ed Sigler</td>
<td>GPS TAC</td>
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<td>Joe Palermo</td>
<td>JPDO/BAH</td>
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<td>Jiyun Lee</td>
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<td>Tim Murphy</td>
<td>Boeing CAG</td>
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<td>Victor Lin</td>
<td>G-Wing/Aerospace</td>
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<td>Karl Shallberg</td>
<td>GREI</td>
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<td>Boris Pervan</td>
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<td>John Dobyne</td>
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<td>Chris Hegarty</td>
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<td>Young Lee</td>
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<td>JP Fernow</td>
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<td>Frank Van Grass</td>
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<td>Pat Reddan</td>
<td>Zeta</td>
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<td>AJ van Dierendonck</td>
<td>AJ Systems</td>
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<td>Juan Blanch</td>
<td>Stanford University</td>
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<td>Todd Walter</td>
<td>Stanford University</td>
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<tr>
<td>Per Enge (Co-Chair)</td>
<td>Stanford University</td>
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</table>
Integrity Architectures for Vertical Approach Guidance

number of satellites

24

Compare measurements to ground truth

27

Avionics compare SV range rate residuals “Relative RAIM”

30

Avionics compare SV range residuals “Absolute RAIM”

seconds

minutes

hours

update time
Integrity Architectures for Vertical Approach Guidance

Each GNSS is independent

- Ground monitors
  - 24 seconds
- Relative RAIM
  - 27 minutes
- Absolute RAIM
  - 30 hours

- Terrestrial radio (GBAS)
- Regional GEOs (SBAS)
- Global SBAS seems difficult
- Within a GNSS
  - could add SV-based monitors
  - update rate may be difficult
  - complicated
Integrity Architectures for Vertical Approach Guidance

Each GNSS is independent

- Terrestrial radio (GBAS)
- Regional GEOs (SBAS)
- Global SBAS seems difficult
- Within a GNSS
  - could add SV-based monitors
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Ground monitors: 24 seconds
Relative RAIM: 27 minutes
Absolute RAIM: 30 hours
Integrity Architectures for Vertical Approach Guidance

Each GNSS is independent

- Big GNSS
- 30+6 for GPS!
- Rely on more than one GNSS

Monitors & pipe still needed
Way Forward with Multiple Constellations & Frequencies

• Dual-frequency, multiple-constellation GBAS
  • VDB needed to support advanced operations
  • Capacity of VDB

• Dual-frequency SBAS
  • Semi-codeless sunset
  • Support L5 users
  • Smooth transition for an operational system
  • Coverage extensions (e.g. WAAS to South America)

• Longer term: Anticipate ARAIM
  • 30+6 for GPS
  • Strong multi-constellation protocol & policy
Way Forward with Multiple Constellations & Frequencies

- Galvanize MOPS activity
  - Coast through RFI outages
  - Backwards compatibility
  - Single frequency reversion
  - Enable integration of other aircraft sensors
# Coverage/Availability Results

<table>
<thead>
<tr>
<th>Constellation</th>
<th>Architecture</th>
<th>24 minus 1</th>
<th>24</th>
<th>27 minus 1</th>
<th>27</th>
<th>30 minus 1</th>
<th>30</th>
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</thead>
<tbody>
<tr>
<td>GIC</td>
<td>86.6%</td>
<td>100%</td>
<td>97.8%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
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<tr>
<td>RRAIM 30 s coasting</td>
<td>81.2%</td>
<td>99.4%</td>
<td>96.8%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
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<tr>
<td>RRAIM 60 s coasting</td>
<td>74.4%</td>
<td>98.5%</td>
<td>92.8%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
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<tr>
<td>RRAIM 300 s coasting</td>
<td>28.0%</td>
<td>76.1%</td>
<td>52.3%</td>
<td>99.6%</td>
<td>93.9%</td>
<td>100%</td>
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<tr>
<td>ARAIM</td>
<td>7.80%</td>
<td>44.7%</td>
<td>30.6%</td>
<td>94.1%</td>
<td>90.5%</td>
<td>100%</td>
<td></td>
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<table>
<thead>
<tr>
<th>Ground to air latency</th>
<th>GIC</th>
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<tr>
<td></td>
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<tr>
<td></td>
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