Towards a Unified Standard for Adopting GNSS in Train Control Systems

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Introduction

• RHINOS WP 11 examines adoption of GNSS for train control in light of lessons learned from aviation:
  
  – Description of comparable efforts in aviation (standardization and validation of GNSS augmentation and user systems)
  
  – Proposed approach for railway requirements development and standardization based on aviation experience
  
  – Proposed approach for wayside and onboard equipment validation and certification based on aviation experience
In addition to R&D on GNSS design and augmentation, the Stanford GNSS laboratory has been deeply involved in standardization and certification:

- RAIM and now ARAIM (Receiver Autonomous Integrity Monitoring)
- Satellite-based Augmentation Systems (SBAS)
- Ground-based Augmentation Systems (GBAS)

All of these systems contribute to the proposed RHINOS architecture and to other uses of GNSS for train control.
Unified Standard for GNSS in Train Control
GNSS Integrity Elements (1)

SBAS:
• Confirm ionospheric health
• Confirm satellite health w.r.t. possible faults:
  – clock dynamics
  – ephemeris anomalies
  – signal deformation
  – code carrier divergence

LDGNSS:
• Provide accurate local corrections to:
  – reduce SV errors (clock and ephemeris)
  – reduce ionospheric error
  – Reduce tropospheric error
• help identify RFI & spoofing
GNSS Integrity Elements (2)

Advanced Receiver Autonomous Integrity Monitoring (ARAIM)

- “end around check” of user measurements in position domain
- detects single or multiple anomalies in satellite measurements (including from local causes, such as multipath)
- detects GNSS constellation faults (if needed)
- best used at the end of the monitoring chain (after other monitors have acted to remove any individual faults)
GNSS Integrity Elements (3)

GNSS code correlation peak monitoring
- helps identify LoS & nLoS signals
- can exclude nLoS signals
- helps determine appropriate measurement variance for LoS signals
- aids spoof detection (DLR)

Multi-frequency measurement combining
- helps identify LoS & nLoS signals
- can exclude nLoS signals
- helps determine appropriate measurement variance for LoS signals
- frequency diversity supports multipath mitigation

\[ H_{DF}[s] = \frac{1}{s LP + 1} \]
\[ H_{CMC}[s] = \frac{s \sqrt{BPa BPb}}{(s BPa + 1)(s BPb + 1)} \]
Multipath masking (UNOTT & DLR)
- based on camera surveys every 3 to 12 months
- used to identify & discard nLoS signals
- determine measurement variance depending on arrival angle

C/N₀ monitoring
- identify & discard nLoS signals
- identify mixed LoS + nLoS
- discard signals with weak C/N₀
- front-line detection of RFI and spoofing
Advantages of Standardization

• In aviation, standardization maximizes interoperability between system segments designed and controlled by different parties, e.g.:
  – Ground navigation aids maintained by Air Navigation Service Providers (ANSPs) and avionics aboard aircraft
  – Air Traffic Control (ATC) voice and data communications with aircraft equipment.

• Global standards provide operators with confidence that their investments in modernized equipment can be used worldwide.

• When ANSPs mandate local variations, standardized equipment adapt without major HW/SW changes.
## GNSS Standards for Train Control

### What Needs to Be Standardized (for each GNSS signal provider)?

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Example Parameters</th>
<th>Aviation Status</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal Structure</strong></td>
<td>Characteristics of received signals</td>
<td>Code spectrum, min. power, coherency, req’d. user processing</td>
<td>Detailed in existing standards</td>
</tr>
<tr>
<td><strong>Nominal Performance</strong></td>
<td>Typical user performance</td>
<td>Range error model, basic measurement monitoring</td>
<td>Detailed in standards for aviation applications</td>
</tr>
<tr>
<td><strong>Fault Probabilities</strong></td>
<td>Probs. of faults leading to off-nominal behavior</td>
<td>$P_{sat}$, $P_{const}$, maximum fault duration</td>
<td>Some info., but hard to determine for newer GNSS sats.</td>
</tr>
<tr>
<td><strong>Threat Models</strong></td>
<td>Behavior under faulted conditions</td>
<td>Bounded descriptions for each possible fault</td>
<td>Detailed info. for several fault types (e.g., signal deform.)</td>
</tr>
</tbody>
</table>
Handling Integrity Parameter Changes

• Many integrity-related parameters are defined in aviation standards, but not all can be assigned fixed values, which cannot easily be changed.

• Parameters which might change are thus required to be monitored by the ground system, updated as needed, and transmitted to users.

• Example from Advanced RAIM (ARAIM): Integrity Support Message (ISM)
  – Fault probabilities and error bounds for each GNSS constellation are continually monitored.
  – These parameters are broadcast to users infrequently, as significant changes are expected to be rare.
• ICAO Standards and Recommended Practices (SARPs)
  – Worldwide requirements and guidance for service providers
  – Include top-level requirements for both ground system and airborne subsystems
  – Goal is to “harmonize” global operations
  – *Allocation between ground and airborne subsystem requirements occurs here.*

• Ground System Specifications
  – Detailed requirements and specifications on ground systems provided by each ANSP
  – Generally consistent with SARPs, but deviations may exist to allow for regional differences (e.g., ionospheric behavior)
• Minimum Operational Performance Standards (MOPS)
  – Developed by non-governmental standards bodies: RTCA in U.S., EUROCAE in EUROPE
  – Define “minimum” requirements and validation tests for equipment aboard aircraft
  – Resulting standards represent the consensus of private companies, service providers, researchers, etc.

• Interface Control Documents (ICD)
  – Define the protocols for transmitting information between ground systems and aircraft
  – Include details of transmitter design (RF signal strength, modulation), message formats, content of each message, etc.
  – Developed in parallel with MOPS and ICAO SARPs
Validation and Certification

- Airborne validation is governed by MOPS test procedures, which are referenced (and possibly added to) by approval authority (FAA in U.S. → TSO)

- Ground system validation
  - Service provider rigorously oversees manufacturer development of system built to SARPs/specification standards.
  - Manufacturer must demonstrate that integrity requirements are met through development and external review of “ADD” and “HMI” documents (next slide).
  - Approval of documentation and passing of required tests leads to “System Design Approval,” or “SDA,” which represents “certification”
Ground System Integrity
Documentation

• Algorithm Description Documents (ADD)
  – One ADD is written for each integrity function.
  – Each ADD describes the algorithms implemented in sufficient
detial for both software coding and external expert review.
  – Allows “line-by-line” review of algorithm specifics.

• Hazardously Misleading Information (HMI) documents
  – Each HMI document demonstrates how the corresponding ADD
satisfies the allocated integrity requirements for its function in
the context of other requirements (e.g., continuity, availability).
  – Demonstration includes analysis, simulation results, results from
data collection, and test results.
  – Documents are reviewed by service provider and external
experts.
Mapping Aviation Approach to Train Control Systems: Standards

<table>
<thead>
<tr>
<th>RHINOS Function</th>
<th>Aviation Precedent</th>
<th>Aviation Standards Document</th>
<th>Train Standards Document</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trackside/Wayside</td>
<td>Ground System</td>
<td>ICAO SARPs, Service Provider Specification</td>
<td>Global or Regional Standard, Manufacturer Specification</td>
</tr>
<tr>
<td>Communications Network</td>
<td>Similar (Terrestrial or Satellite)</td>
<td>ICAO SARPs, RTCA / EUROCAE ICD</td>
<td>Unclear, but preferably at least Regional Standard ICD</td>
</tr>
<tr>
<td>Onboard Unit</td>
<td>Aircraft / Avionics</td>
<td>ICAO SARPs, RTCA / EUROCAE MOPS</td>
<td>Global or Regional MOPS</td>
</tr>
</tbody>
</table>

The current objective is to standardize the GNSS implementation only
• Aviation standards allow ground and airborne validation to proceed separately but to work together to meet the needs of the overall system.

• The same approach is advantageous for train systems:
  – Allows different trackside, communication network, and onboard unit subsystem providers
  – Allows flexibility for regions or tracks with different requirements or operating environments

• Aviation documentation approach, using ADDs and HMI documents for integrity validation, can also be transferred to train control domain.
Summary

• The proposed architecture for RHINOS utilizes multiple GNSS elements and provides a model for standardizing the use of GNSS in train control systems.

• Aviation standards for GNSS use in aviation are well-advanced and provide both templates and extensive source material for future train control standards.

• A detailed and comprehensive approach to integrity validation has also been developed for aviation.
  – Analysis, simulation, and test procedures
  – Documentation via ADDs and HMI reports
  – External expert review