RHINOS Proof of Concept Design, Analysis, and Preliminary Results

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21 June 2017
RHINOS WP 9 Objectives

• Define a proof-of-concept railway system design for integrity analysis
  – Based upon RHINOS reference architecture (earlier work)

• Develop GNSS error models for performance under nominal conditions (wayside and onboard)

• Develop GNSS threat models for performance under anomalous conditions (wayside and onboard)

• Simulate and/or take actual data to assess RHINOS performance based on these models
RHINOS Reference Architecture

Onboard

- GNSS Antenna
- OBU
- DMI
- Radio I/F

Trackside

- GNSS Antenna
- SBAS Receiver
- GBAS/LADGNSS Augmentation
- TALS/Trackside Verification
- LDS Mng
- Augmentation & Integrity
- Core RBC Functions
- Radio I/F

External

- High QoS/security Communication Network
- Interlocking
- SBAS Ground Services
- External Network RSs
- GPS and Galileo Ground Service
# Reference Architecture Components and Anomaly Mitigations

<table>
<thead>
<tr>
<th>Purpose</th>
<th>SBAS</th>
<th>LDGNSS</th>
<th>Multipath Masking</th>
<th>Measurement Tests</th>
<th>Residuals Tests</th>
<th>Destination Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purpose</strong></td>
<td>Detect errors visible over large areas</td>
<td>Provide corrections, detect local errors, PL equations</td>
<td>Camera derived multipath mask for eliminating NLOS, inflated prior probability of multipath</td>
<td>Correlator measurement tests, L1-L5 measurement comparisons</td>
<td>ARAIM residuals tests, comp. of DD code (narrow) carrier (wide), Doppler</td>
<td>Independent integrity checks (accelerometer, others)</td>
</tr>
<tr>
<td><strong>Hazard / Threat Mitigated</strong></td>
<td>SV faults, ionospheric gradients</td>
<td>SV faults, iono. gradients, erroneous corrections</td>
<td></td>
<td>Anomalous Multipath, other local errors</td>
<td></td>
<td>RF interference, spoofing</td>
</tr>
</tbody>
</table>
Simplified Architecture and Protection Levels

SBAS, LDGNSS Corrections, Detection, Fault Exclusion

ARAIM fault excluded subset

ARAIM PL

PL = MAX

LDGNSS PL

MAX (H₀, H₁, H_{eph})

3 LDGNSS PL:
- Nominal (H₀)
- Ref. Rx fault (H₁)
- Ephemeris fault (H_{eph})

Augmentation Systems

Onboard Unit (OBU)
Response to Faulted Conditions

Fault Scenarios

Detected by monitors (with required $P_{MD}$)

- Remove satellite(s) from user geometry
  - Compute PLs without removed satellite(s)

Not Detected by monitors (with required $P_{MD}$)

- Determine largest possible undetected error $\rightarrow$ MDE
  - Compute PLs with MDE added to affected satellite(s)

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RHINOS PoC Design and Results
## Faults and Anomalies Considered

<table>
<thead>
<tr>
<th>Fault</th>
<th>Mitigation</th>
<th>Action</th>
<th>Modeling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anomalous Ionosphere Gradient</td>
<td>Inside SBAS coverage: SBAS detects</td>
<td>Identify satellite(s) for user</td>
<td>Exclude affected satellite(s), other satellites use nominal gradient model</td>
</tr>
<tr>
<td></td>
<td>Outside SBAS coverage: LDGNSS detects</td>
<td>Exclude satellite(s) or increase gradient bound for affected satellite(s)</td>
<td>Worst-case gradient model applied to <em>worst satellite</em> to determine impact. Compare with calc. PLs</td>
</tr>
<tr>
<td>Ephemeris/Clock failure</td>
<td>Detection by SBAS and LDGNSS</td>
<td>Satellite excluded, MDE included in ephem. PL</td>
<td>Exclude <em>worst satellite(s)</em> and evaluate impact on PLs</td>
</tr>
<tr>
<td>Extreme Multipath (1)</td>
<td>Satellite masking (by elevation angle, etc.)</td>
<td>Simulate range errors, implement ARAIM simulation and exclude detected satellite</td>
<td>Exclude <em>worst satellite(s)</em> and evaluate impact on PLs. Include impact in ARAIM P$_{sat}$ parameter.</td>
</tr>
<tr>
<td></td>
<td>Residuals check by ARAIM, detect and exclude satellite</td>
<td>Same</td>
<td>Same, except use mixed Gaussian distribution</td>
</tr>
</tbody>
</table>

*Worst satellite(s), or most-useful satellite(s): satellite(s) determined by simulation to cause the largest loss of performance (e.g., largest increase in PL) when impacted by fault or excluded due to detected fault.*
Horizontal Protection Level Equations

**LDGNSS**
(3 equations + implicit ionospheric gradient equation)

**ARAIM**
(1 numerical equation for each linear position axis)

\[
HPL_{H0} = K_{ff\text{md},2D} \sum_{i=1}^{N} (S_{1,i}^2 \sigma_{i}^T + S_{2,i}^2 \sigma_{i}^T)
\]

\[
HPL_{H1} = K_{fd,2D} \sum_{i=1}^{N} (S_{1,i}^2 \sigma_{B,i}^2 + S_{2,i}^2 \sigma_{B,i}^2) + K_{md,2D} \sum_{i=1}^{N} (S_{1,i}^2 \sigma_{M-1,i}^2 + S_{2,i}^2 \sigma_{M-1,i}^2)
\]

\[
HPL_{eph} = \max \left( \sqrt{S(1,:)^2 + S(2,:)^2} \right) \times P_{\text{value}} \times 1000 \times x_{\text{train}} + K_{\text{md},2D} \sum_{i=1}^{N} (S_{1,i}^2 \sigma_{i}^2 + S_{2,i}^2 \sigma_{i}^2)
\]

\[
2Q \left( \frac{HPL_q - b_q^{(k)}}{\sigma_q^{(k)}} \right) \sum_{k=1}^{N_{\text{faults,mon}}} P_{\text{fault},k} Q \left( \frac{HPL_q - T_{k,q} - b_q^{(k)}}{\sigma_q^{(k)}} \right) = \frac{1}{2} \text{PHMI} \left( \frac{1 - P_{\text{sat,not mon}} - P_{\text{const,not mon}}}{\text{PHMI}} \right)
\]
Simulation Conditions

- 24 GPS + 24 Galileo satellites
- L1 C/A and E1 OS signals only
  - L5 and E5a optionally used for multipath mitigation
- 13 European user locations shown below
  - Singapore (on equator) added for comparison
- Calculate RHINOS HPLs for satellite geometries at 5-min updates over 1 or 10 days
- Assume 10° minimum satellite elevation mask angle

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HPL Under Nominal Conditions (1) (SBAS/LDGNSS and ARAIM)

HPL at 14 Locations Over 24 Hours

Almost all HPLs under 10 m

Reykjavik

Cagliari

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HPL Under Nominal Conditions (2) (SBAS/LDGNSS and ARAIM)

East and North PL (EPL and NPL) at 14 Locations Over 24 Hours

East PL

North PL

East PL from Ref Architecture

North PL from Ref Architecture

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Complementary CDF of HPL at 14 Locations Over 10 Days

CCDF of HPL

- Sevilla
- Cagliari
- Ankara
- Zurich
- Vienna
- Paris
- Kiev
- Warsaw
- Berlin
- Moscow
- Oslo
- Helsinki
- Reykjavik
- Singapore

Increasing Latitude

CDF Percentiles

99.99 % 99.9 % 99 % 90 % 0 %

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RHINOS PoC Design and Results
Number of GPS and Galileo Satellites in view at Reykjavik

Only 4 GPS satellites usable when ARAIM HPL spikes
HPL Under Nominal Conditions (SBAS/LDGNSS only)

HPL at Berlin
(within EGNOS coverage)

HPL at Moscow
(outside EGNOS coverage)

SBAS monitoring reduces ephemeris HPL to insignificance, but other LDGNSS HPLs dominate.

ARAIM HPL from previous slides almost always exceeds these values and thus drives the achievable integrity bounds.
Worst-case Satellite Exclusion Under Anomalous Scenarios

Complementary CDF of HPL at 14 Locations Over 10 Days after Most-Useful Satellite is Excluded from Each Satellite Geometry
Minimum Detectable Error (MDE) of Monitoring Within ARAIM (1)

MDE of Anomaly Affecting a Single SV at 14 Locations Over 24 Hours

MD Range Error Bias (m)

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Minimum Detectable Error (MDE) of Monitoring Within ARAIM (2)

MDE of Anomaly Affecting a Single SV at 14 Locations Over 10 Days after Most-Useful Satellite is Excluded

MD Range Error Bias (m)

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Worst-Case MDE for LDGNSS under Anomalous Ionospheric Gradient

Ionospheric Gradient Threat Model based upon GBAS at mid-latitudes

LDGNSS detection via:
• CCD at Ref. 0
• “B-value” comparison between Refs. 0 and 1

ARAIM detection via:
• Differential error difference between affected and un-affected SVs

Max. Diff. Error:
• Max. error not detected with required $P_{MD}$

For worst-case gradient:
• CCD unlikely to detect
• B-value detection with minimum of 2 RR’s gives $MDE \approx 3.3$ meters
• ARAIM MDE is much larger (from previous slides)
Sensitivity Studies

• First set of sensitivity studies:
  – Increased ARAIM $P_{\text{sat}}$ due to influence of local multipath
  – Apply multipath mitigation to lower $P_{\text{sat}}$ (by 99%)

<table>
<thead>
<tr>
<th>Elevation Angle</th>
<th>Without Multipath Mitigation</th>
<th>With Multipath Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_{\text{sat,1}}$</td>
<td>$P_{\text{sat,2}}$</td>
</tr>
<tr>
<td>Below 15°</td>
<td>$10^{-9}$</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>15 – 45°</td>
<td>$10^{-9}$</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Above 45°</td>
<td>$10^{-9}$</td>
<td>$10^{-3}$</td>
</tr>
</tbody>
</table>

• Second set of sensitivity studies:
  – Apply two-term Gaussian mixture model to represent different types of nominal multipath behavior (and reduce $P_{\text{sat,2}}$ by 90%)

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Prior Probability</th>
<th>Standard Deviation Multiplier in User CNMP model ($r_{\text{rail}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical</td>
<td>0.97</td>
<td>3.0</td>
</tr>
<tr>
<td>Rare-Typical</td>
<td>0.03</td>
<td>8.0</td>
</tr>
</tbody>
</table>
ARAIM HPLs are uncomfortably large under these assumptions for multipath, given that no faults or satellite exclusions are modeled.
HPLs for Berlin and Paris Over 24 Hours with Multipath Mitigation (no satellites excluded)

Dramatic reduction in ARAIM HPLs with multipath mitigation shows that such mitigation is greatly beneficial.

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As before, removing the most important satellite is painful, but multipath mitigation provides significant robustness to satellite geometry.
Results of 2nd Sensitivity Study (1)

HPLs for Berlin Over 24 Hours from Separate Gauss Mixture Terms without Multipath Mitigation (no satellites excluded)

1st Gaussian Term (3 × User CNMP)

2nd Gaussian Term (8 × User CNMP)

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Results of 2nd Sensitivity Study (2)

HPLs for Berlin Over 24 Hours from Separate Gauss Mixture Terms with Multipath Mitigation (no satellites excluded)

1st Gaussian Term (3 × User CNMP)

2nd Gaussian Term (8 × User CNMP)

As before, multipath mitigation lowers ARAIM HPLs. The 2nd Gaussian term increases both LDGNSS and ARAIM HPLs.
Results of 2nd Sensitivity Study (3)

CCDF of HPLs for 14 Locations Over 10 Days from Combined Gauss Mixture Terms without Multipath Mitigation (no satellites excluded)

Increasing Latitude

Note “kink” in curve at 97th percentile
Results of 2nd Sensitivity Study (4)

CCDF of HPLs for 14 Locations Over 10 Days from Combined Gauss Mixture Terms with Multipath Mitigation (no satellites excluded)

Note “kink” in curve at 97th percentile

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Summary

- RHINOS proof-of-concept architecture has been developed from earlier baseline and evaluated for integrity performance.

- Proof-of-Concept architecture combines SBAS/LDGNSS and local monitoring via ARAIM along with (optional) additional monitoring to mitigate multipath.

- Initial simulation results show the following:
  - HPLs are mostly driven by ARAIM, which is constrained by both satellite geometry and anomalous multipath.
  - SBAS and LDGNSS mitigate satellite and atmospheric anomalies before ARAIM is applied by users.
  - Detection and Exclusion of a faulted satellite that happens to be most useful (geometrically) significantly increases HPL.
  - OBU multipath mitigation is key to making ARAIM monitoring practical.
Backup Slides

• Backup Slides follow…
Aviation Hazard Definition
(Error Exceeding Computed Protection Level)

All errors outside protection level boundaries are deemed to be hazards (severity of these hazards depends on operation being conducted).
## Nominal Error Models

<table>
<thead>
<tr>
<th>Model (Error/PL)</th>
<th>Residual Error Model ((\sigma^2)) or Protection Level</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionosphere / Troposphere (iono)</td>
<td>[ oblique_{factor}\sigma_{vig,\text{nom}} \left( x_{\text{train}} + \frac{2 \times \varepsilon_{\text{smooth,tau}} \times v_{\text{train}}}{1000} \right)^2 ]</td>
<td>Modified from RTCA LAAS MOPS</td>
</tr>
<tr>
<td>Code Noise and Multipath – User (cmnp, user)</td>
<td>[ r_{\text{if}}^2 \left[ (0.13 + 0.53 \times e^{-el/10})^2 + (0.15 + 0.43 \times e^{-el/6.9})^2 \right] ]</td>
<td>RTCA WAAS/LAAS model modified by ( r_{\text{if}} = 3 )</td>
</tr>
<tr>
<td>Code Noise and Multipath – Wayside with M ref. receivers (CMNP, RS, M)</td>
<td>[ \frac{1}{M} \left( 0.16 + 1.07 \times e^{-el/15.5} \right)^2 + (0.08)^2 ]</td>
<td>RTCA LAAS GAD-B curve with tropo. zeroed out (included above)</td>
</tr>
<tr>
<td>Overall</td>
<td>[ \sigma_{\text{nom}}^2 = \sigma_{\text{cmnp,rs}}^2 + \sigma_{\text{cmnp,user}}^2 + \sigma_{\text{iono}}^2 ] [ \sigma_{M-1}^2 = \sigma_{\text{cmnp,rs,M-1}}^2 + \sigma_{\text{cmnp,user}}^2 + \sigma_{\text{iono}}^2 ] [ \sigma_{\text{acc}}^2 = \sigma_{\text{nom}}^2 ]</td>
<td>RSS of independent error terms</td>
</tr>
</tbody>
</table>
# Fault Probabilities and K-values

## For LDGNSS

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Integrity Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{ffmd,1D}$</td>
<td>6.47</td>
<td>$10^{-10}$</td>
<td>Fault-free missed detection multiplier (1-D)</td>
</tr>
<tr>
<td>$K_{ffmd,2D}$</td>
<td>6.79</td>
<td>$10^{-10}$</td>
<td>Fault-free missed detection multiplier (2-D)</td>
</tr>
<tr>
<td>$K_{fdd,1D}$</td>
<td>4.89</td>
<td>$10^{-6}$</td>
<td>Fault-free detection multiplier (1-D)</td>
</tr>
<tr>
<td>$K_{fdd,2D}$</td>
<td>5.26</td>
<td>$10^{-6}$</td>
<td>Fault-free detection multiplier (2-D)</td>
</tr>
<tr>
<td>$K_{md,1D}$</td>
<td>3.72</td>
<td>$2 \times 10^{-4}$</td>
<td>H1 (B-value) monitor missed detection multiplier (1-D)</td>
</tr>
<tr>
<td>$K_{md,2D}$</td>
<td>4.29</td>
<td>$2 \times 10^{-4}$</td>
<td>H1 (B-value) monitor missed detection multiplier (2-D)</td>
</tr>
<tr>
<td>$K_{mde,1D}$</td>
<td>4.27</td>
<td>$2 \times 10^{-5}$</td>
<td>Ephemeris monitor missed detection multiplier (1-D)</td>
</tr>
<tr>
<td>$K_{mde,2D}$</td>
<td>4.80</td>
<td>$2 \times 10^{-5}$</td>
<td>Ephemeris monitor missed detection multiplier (2-D)</td>
</tr>
</tbody>
</table>

## For ARAIM

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{sat,base}$</td>
<td>$10^{-5}$</td>
<td>[Baseline] Probability of independent faults on individual satellite range measurements</td>
</tr>
<tr>
<td>$P_{const,base}$</td>
<td>$10^{-5}$</td>
<td>[Baseline] Probability of correlated faults on satellite range measurements within a single constellation</td>
</tr>
<tr>
<td>$P_{sat,sens,1}$</td>
<td>$10^{-9}$</td>
<td>[Sensitivity] Probability of independent faults on individual satellite range measurements due to SV faults, with credit given to SBAS and LDGNSS detection</td>
</tr>
<tr>
<td>$P_{sat,sens,2}$</td>
<td>[$10^{-1}$, $10^{-5}$]</td>
<td>[Sensitivity] Probability of independent faults on individual satellite range measurements due to multipath/local effects, depending on elevation angle and application of external multipath mitigation</td>
</tr>
<tr>
<td>$P_{const,sens}$</td>
<td>$10^{-11}$</td>
<td>[Sensitivity] Probability of correlated faults on satellite range measurements within a single constellation, with credit given to SBAS and LDGNSS detection</td>
</tr>
</tbody>
</table>
HPL Under Nominal Conditions (SBAS/LDGNSS only)

HPL at Berlin
(within EGNOS coverage)

HPL at Berlin
(if it were outside EGNOS coverage)

SBAS monitoring reduces ephemeris HPL to insignificance, but other LDGNSS HPLs dominate.

ARAIM HPL from previous slides almost always exceeds these values and thus drives the achievable integrity bounds.