High Integrity Augmentation Systems for Train Control Systems

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THE RAILWAY SCENARIO
Technology shift: Network-centric railroading

**Train Control systems** are integrated C3I systems for controlling train movements with safety, security, precision, and efficiency.

1. **Central Office (RBC & IXL)**
2. **Wayside**
3. **Locomotive**
4. **Maintenance crew**
5. **DMI in-cab display**
6. **Track forces terminals**

**Digital data link communications networks** for moving command and control instructions

**Augmented GNSS** for positioning accuracy & integrity to on-board localization system

**DMI in-cab display** for status information and command & control instructions to train crews

**Track forces terminals** provide information and instructions to and from permanent way workers and maintenance-of-way vehicles.
ERTMS Standard Configurations

Fixed block

Moving block

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GNSS Integrity Concept for ERTMS-ETCS

Hazard Misleading Position is processed at system level. No driver decision required but only execution of movement authority.
GNSS Target Performance: ETCS Level 2

Approaching Dangerous point

Start of Mission

ETCS «linking»

Normal operation

THR: 3e-8/1 h CI ~ 14 m

THR: 1.4e-10/1 h CI ~ 3 m (pt)

THR: 3e-8/1 h CI: 20 – 100 m

Ref. 3InSat project Safety case (Ales Filip, AZD); verified by Italcertifer (Independent Notify Body)
**ETCS L3: Train Integrity**

- **Train integrity**
- **Protection Level**
- **Virtual Track Circuit**

~ 40-60% + capacity

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**AnsaldoSTS**
A Finmeccanica Company

**Sogei Radiolabs**

**ION 2014, Tampa**

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Satellite-based projects roadmap

Development & Test
satellite technologies for rail
signalling applications:
- Sat-com
- Geo-localization
http://artes-apps.esa.int/projects/3insat

Integrated Test-Bed
- EGNOS + Local Au-Networks
- Multi-bearer TLC
- Signalling

Joint Undertaking for innovation in rail sector
- IP-2: Innovative train control systems
http://www.shift2rail.org

ERSAT - EAV
ERSAT - EAV
Satellite-based projects roadmap

2012 2013 2014 2015 2016 2017 2018

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The core of the innovative ERSAT-EAV application

Enhanced Railway Signalling Application

Multi-bearer TLC solution

Satellite-based enhanced localisation

ERTMS

Multi constellation

Local Area Trusted Augmentation service

Localisation in GNSS-denied areas

EGNSS-based localisation

EGNOS

Galileo Early Services

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ERSAT CONSORTIUM: the partners in the value chain

Italy: Ansaldo STS, ANSF, Bocconi, RadioLabs, RFI, SOGEI, Trenitalia
France: ESSP
Germany: DB Netz, DLR
Spain: CEIT

Ansaldo STS: Consortium leader
Region Sardinia Transport Department: sponsoring partner
ERSAT: Test Bed for Integrated Tests on field

[Diagram of ERSAT test bed with labels: Mobile Access Router, Train On-board System, CAUSE Localizer, Track area station, Rail TLC, IP-based TLC, Virtual balise, LDS, Radio, RBC, Points.]

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Challenge

- **Technology:**
  - Adoption of technology developed for other applications
  - Requirements of safety, availability, reliability, maintainability
  - QoS

- **Procedures:**
  - Acceptance and adaptation of certifications released by other sectors
  - Updating of existing reference norms

- **Contractual:**
  - Role & responsibility: maintenance, service provider
GNSS High Integrity for mobiles: Closing the circle?

- Self-driving cars: i.e. Google-car
- Autonomous cargo vessels could set sail without a crew
- Drones already fly civilian missions

"Dependability" is the capability of a system to deliver the correct service with an acceptable trust, specially in presence of faults, either due to internal or external causes.
High Integrity Augmentation for Rail

- ERTMS and SIL4 requirements met from the integration of the evolved EGNOS and Local Augmentation networks

- **Two tiers System:**
  - 1st tier: Wide Area Differential Corrections and EGNOS RIMS data through EDAS
  - 2nd tier: Track Areas Augmentation Network (TAAN), Local Augmentation Systems Reference Stations (RIM)

- Need for a single entity in charge of the overall safety case of the system (EGNOS + Local Augmentation)

- Health status of the 2nd tier as well as the integrity of the GNSS SIS will be computed by joint processing of 1rst tier Wide Area Differential Corrections and 2nd tier RIM station data

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Train Control System Architectural Components

TAAN (Track Areas Augmentation Network):
  - RIM Stations along the railways,
  - a Control Centre (TAAN-CC),
  - a Communication Network connecting the TAAN-CC with the RIM Stations

- It provides the OBU with RTK corrections, the subset of satellites to be used for PVT and integrity data relevant for meeting rail reqs
- It performs TAAN Heath Status monitoring using 1st and 2nd layer raw data
- Open standard and use of the GRDNet Network
- Network densification with any existing National/Regional Reference Station along the railway
Train Control System Architectural Components

**TALS (Track Area LDS Server):**
located in Radio Control Block, it relays the augmentation data received by the TAAN-CC to train OBUs, including EGNOS-GALILEO Application data for Railway

**LDS (Location Determination System) OBUs:**
including two GNSS receivers, they calculate PVT and performs Integrity checks and self check for achieving SIL4 requirements, through Augmentation data provided by the TAAN-CC
GNSS-based services for Train Control

- The High Integrity Augmentation System has to support
  - Train Location Determination
  - Track Determination
  - Train Integrity

- Functionalities

<table>
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<th>Monitoring</th>
<th>Augmentation DGNSS (code)</th>
<th>Augmentation RTK (phase)</th>
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<tr>
<td>Train Integrity</td>
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Virtual Balise

- In ERTMS Level 2 the train position and speed are computed on board by the odometer, which relies on the balises deployed along the track, as reference points, to periodically reset the accumulated errors.
  
  1. The balises determine the train absolute position
  2. the odometer estimate the relative distance from the Last Relevant

- In GNSS based Train Control the GNSS Location Determination System detect the passage of the train over a Virtual Balise Group by comparing the current train location with the location of the Virtual Balises.
Location Determination

- Train location is given by the intersection of the spheres centered on visible satellites and the railway track.
- **Major Unknowns:**
  - Train mileage from Head End
  - Train clock offset

DGNSS Pseudorange EQ.

\[
\Delta \rho = H D z + \nu
\]

\[
H = \begin{bmatrix} P & 1_{N_{Sat}} \end{bmatrix}
\]

\[
P_{ij} = - \frac{\hat{x}_{i,j}^{Sat} - x_{j}^{Train}(\hat{s})}{\left\| X_{i}^{Sat} - X_{j}^{Train}(\hat{s}) \right\|}
\]

\[
D = \begin{bmatrix}
\frac{\partial x_{1}^{Train}}{\partial s} & 0 \\
\frac{\partial x_{2}^{Train}}{\partial s} & 0 \\
\frac{\partial x_{3}^{Train}}{\partial s} & 0 \\
0 & 1
\end{bmatrix}
\]
The Track Area Augmentation Network Control Center (TAAN-CC) for each satellite, monitors
- the Differential Pseudorange Residuals (DPR)
- the Double Difference Residuals (DDR)
of the pseudoranges observed by the reference stations, located in known position, see [1].

- DPR monitoring allows detecting ephemeris error components parallel to the satellite line of sights,
- DDR monitoring allows detecting those components orthogonal to the line of sights.

**DDR Monitoring**

- When the SIS of each satellite is healthy, the DDR is a zero mean Gaussian random variable

\[
dd_{R_n,R_m}^{S_i,S_j} \sim N\left(0, \sigma_{dd_{n,m}^{ij}}^2\right)
\]

\[
\sigma_{dd_{n,m}^{ij}}^2 = \sigma_{\Delta \rho_n}^2 + \sigma_{\Delta \rho_m}^2 + \sigma_{\Delta \rho_m}^2 + \sigma_{\Delta \rho_m}^2
\]

- When the \(i\)-th SIS is affected by a satellite position error, the DDR is a Gaussian random variable with expectation

\[
E\{dd_{R_n,R_m}^{S_i,S_j}\} = -\left(e_{RI_M n}^i - e_{RI_M m}^i, \beta^i\right)
\]

i.e.

\[
dd_{R_n,R_m}^{S_i,S_j} \sim N\left(-\left(e_{RI_M n}^i - e_{RI_M m}^i, \beta^i\right), \sigma_{dd_{n,m}^{ij}}^2\right)
\]
**DDR Monitoring**

- Compute the average DDR of the $i$-th satellite and its variance:

$$
\overline{dd}^{S_i}_{R_n, R_m} = \frac{1}{N_{\text{sat}} - 1} \sum_{j \neq i} dd^{S_i, S_j}_{R_n, R_m} \quad \sigma^2_{dd}^{S_i}_{R_n, R_m} = \sigma^2_{\Delta \rho_n} + \sigma^2_{\Delta \rho_m} + \frac{1}{N_{\text{sat}} - 1} \sum_{j \neq i} \left( \sigma^2_{\Delta \rho_n} + \sigma^2_{\Delta \rho_m} \right).
$$

- Exclude the $i$-th satellite if

$$
\xi_i^2 \geq E L \sum_{n=1 \atop n \neq m}^{N_{\text{RIM}}} \frac{\left| \overline{dd}^{S_i}_{R_n, R_m} \right|^2}{\sigma^2_{dd}^{S_i}_{R_n, R_m}}
$$

\[ \text{False Exclusion Probability} \]

| All SISs Healthy | $\xi_i^2 \not\geq \chi^2_{N_{\text{RIM}}} - 2$ | $P_{fe} = D^{2} \chi^2_{N_{\text{RIM}} - 2} \left( EL \right)$ |
| All SISs Healthy | $\xi_i^2 \not\geq \chi^2_{N_{\text{RIM}}} - 2 \left[ \lambda \left( \beta' \right) \right]$ | $P_{ME}^{SF} = D^{2} \chi^2_{N_{\text{RIM}} - 2} \left[ D^{-1} \chi^2_{N_{\text{RIM}} - 1} \left( 1 - P_{fe} \right), \lambda \left( \beta' \right) \right]$ |

\[ \lambda \left( \beta' \right) = \sum_{n=1 \atop n \neq m}^{N_{\text{RIM}}} \left| \frac{e^{i}_{RIM_n} - e^{i}_{RIM_m}, \beta' \left( \right)}{\sigma^2_{dd, m, n}} \right|^2 \]

\[ \text{Missed Exclusion Probability} \]
LDS Protection Levels

• Healthy Satellites (Nominal operations)

\[ P_{\text{MI/SH}}^{\text{LDS}} \equiv \text{erfc}\left( \frac{PL}{\sqrt{2}\sigma_{s/SH}} \right) \]

\[ PL \equiv \sqrt{2} \text{ erfc}^{-1} \left( P_{\text{MI/SH}}^{\text{LDS}} \right) \sigma_{s/SH} \]

• One Faulty Satellite, No Autonomous RAIM on Board

\[ P_{\text{MI/SF}}^{\text{LDS}} \equiv \text{erfc}\left( \frac{PL}{\sqrt{2}\sigma_{s/SH}} \right) + \]

\[ + \left[ \frac{1}{2} \text{erfc}\left( \frac{PL + \gamma^{(i)} \beta^{(i)}}{\sqrt{2}\sigma_{s/SF}} \right) - \text{erfc}\left( \frac{PL}{\sqrt{2}\sigma_{s/SF}} \right) \right] \cdot D_{\kappa_{\text{NBI}}}^{\text{nc}} \left[ EL, \lambda(\beta^{(i)}) \right] \]
LDS Performance

- TAAN vs. EGNOS performance assessment
LDS Performance: DGNSS vs. EGNOS

Roma Anular Ring Test Campaign
LDS: DGNSS vs. EGNOS

DGNSS

EGNOS

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Reduced PseudoRange Residual Statistics
Trivial solution based on the selection of the track nearest to the unconstrained DGNSS train location do not satisfy SIL-4 requirements.
When the railway consists of multiple tracks, the single track PVT estimate is combined with the track detection.

We assume that the train can be located along one of \( M \) tracks and we denote with \( H_k \) the hypothesis corresponding to the \( k \)-th track.

\[
\rho = \tilde{\rho}_{H_k} + \delta^D_{H_k} + H_{H_k} D_{H_k} z_{H_k} + v
\]

\[
\Lambda_1(\rho) = \frac{P_{P/H_1}(\rho / H_1)}{w(\rho)}
\]

\[
\Lambda_2(\rho) = \frac{P_{P/H_2}(\rho / H_2)}{w(\rho)}
\]

\[
\Lambda_M(\rho) = \frac{P_{P/H_M}(\rho / H_M)}{w(\rho)}
\]

Select the Largest

\( \hat{H}_k \)
Track Determination

- Under Gaussianity assumption
  \[ \ln \Lambda_k (\rho) = -\frac{1}{2} \left\| \zeta_{H_k} \right\|^2 \]

- Therefore, the Bayesian detector will select the track with the smallest residual weighted squared L² norm, that is
  \[ \left\| \zeta_{H_k} \right\|^2 = \hat{v}^T_{H_k} \mathbf{R}_v^{-1} \hat{v}_{H_k}, \]

- In addition, the posterior probability of each hypothesis is approximated as
  \[ \text{Prob}\{H_k\} = \frac{\exp\left(-\frac{1}{2} \left\| \zeta_{H_k} \right\|^2\right)}{\sum_m \exp\left(-\frac{1}{2} \left\| \zeta_{H_m} \right\|^2\right)}. \]
**Track Determination Performance**

**Track Error Probability**

- **DGNSS - Single Epoch, M equispaced Tracks**

\[ P_e = \left(1 - \frac{1}{M}\right) \text{erfc} \left\{ \frac{\| \Gamma_i e \|}{2\sqrt{2}} \Delta b \right\} \]

\[ \Gamma_i = C_v (I - HK) p \]

- **DGNSS - N_0 epochs, M equispaced Tracks (Slow motion)**

\[ P_e^{(N_0, I)} = \left(1 - \frac{1}{M}\right) \text{erfc} \left\{ \frac{\| \Gamma_i e \|}{2\sqrt{2}} \sqrt{N_0 \Delta b} \right\} \]

- **DGNSS - N_0 epochs, M equispaced, Rank Order Statistics Detector**

\[ P_e^{(N_0, II)} = 1 - \sum_{h=k_0}^{N_0} \binom{N_0}{h} (1 - P_e)^h P_e^{N_0-h} \]
A measurement campaign has been also performed in the framework of the 3InSat research project, by means of a diagnostic train CARONTE (CAR ON Technology) provided by the Italian Railway Operator RFI.

The experimental track error probability for the inter-track offset of 2 m. is about 0.15, in good accordance with the theoretical model (for $M=2$, $D_b=2$ m, the track error probability equals 0.158).
Track Determination: Low Complexity phase DD approach

1. Position Estimation for each track based on code only DGNSS

2. Track Detection: selection of the track for which the $L^2$ norm of the carrier phase double difference residuals is minimum

\[
\rho = \begin{cases}
V_{H_1} = \left[ \nabla \Delta \phi - H^\phi b_{H_1} \right] \mod 2\pi \\
V_{H_2} = \left[ \nabla \Delta \phi - H^\phi b_{H_2} \right] \mod 2\pi \\
V_{H_M} = \left[ \nabla \Delta \phi - H^\phi b_{H_M} \right] \mod 2\pi
\end{cases}
\]

Select the smaller

\[
\hat{H}_k = \begin{cases}
V_{H_1}^T R^{-1}_{\nu} V_{H_1} \\
V_{H_2}^T R^{-1}_{\nu} V_{H_2} \\
V_{H_M}^T R^{-1}_{\nu} V_{H_M}
\end{cases}
\]
Experimental Results

Synthetic scenario using raw data measured by three stations belonging to the IGS network: WTZR (used as Rover), BZRG and GOPE.
Experimental Results

- Dataset 1 (22/01/2014) consists on 900 samples:
  - No error in track detection

- Dataset 1 (1/01/2014) consists on 4500 samples:
  - No error in track detection
Train Integrity

- Train integrity means the ability to determine whether all the carriages are still coupled each other.

- **Goal**: to define a Virtual Track Circuit to reduce operational cost and increase the line capacity.

- **Approach**: Double difference between a pair of GNSS receivers located at the head and end of the train.
Double Difference approach

- The classic Double Difference Algorithms can be extended to account for the track constraint mapping the 3-D estimation problem into a 1-D estimation problem.
- Approach: iterative estimation of the baseline increments when the HoT and EoT receivers move along the track, respectively. *(Neri et Al. ION GNSS+ 2014)*

\[
\hat{\mathbf{X}}_{Rx_H}^{(m+1)} = \hat{\mathbf{X}}_{Rx_H}^{(m)} + \Delta b_{H}^{(m)} \hat{\mathbf{e}}_{b_H}^{(m)}
\]

\[
\hat{\mathbf{X}}_{Rx_E}^{(m+1)} = \hat{\mathbf{X}}_{Rx_E}^{(m)} + \Delta b_{E}^{(m)} \hat{\mathbf{e}}_{b_E}^{(m)}
\]

\[
\tilde{L}^{(m+1)}(k) = \tilde{s}_{H}^{(m+1)}(k) - \tilde{s}_{E}^{(m+1)}(k)
\]
Performance Assessment

\[ PL_e \approx \sqrt{2} \frac{b}{B} \sigma_{dd_{\text{Max}}} \gamma_{\text{Max}} \sqrt{\lambda_{\text{Max}}} + k_e \sigma_{\varepsilon_1} \]

\[ k_e = \sqrt{2} \text{erfc}^{-1} \left( \frac{R_{\text{TrainIntegrity}}^{\text{TH}_e}}{N_{\text{Dec}} D_{\lambda_{\text{RM}}^{-1}}^{\text{nc}}} \left[ D_{\lambda_{\text{RM}}^{-1}}^{-1} \left(1 - P_{fe}\right), \lambda_{\text{Max}} \right] P_{SF} \right) \]
Simulation results (0.5, 2.5km freight train)

- Results are provided for freight trains in two cases:
  - 0.5 m length train travelling at 108 km/h;
  - 2.5 km length train travelling at 80 km/h.
PL for single fault

• Simulations results indicate that:

\[ \sigma_{\text{dd}_\text{Max}} = 2 \]
\[ |g|_{\text{Max}} \leq 1 \]

\[ B = 50 \text{ km} \]
\[ b = 2.5 \text{ km} \]

\[ SLOPE = 0.14 \rightarrow PL \geq 7m \]

• Then, it is possible to derive the Virtual Circuit Length considering the dynamical model of the train (dynamic coupling junctions)
Gap Free Results

Short Train

Long Train

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Gap emulation

- Train constant speed
- One of the carriages decouples from the previous one
- The front train section continues its movement after the decoupling as if nothing has been occurred
- The tail section stops only by action of rolling resistance
- Track slope effect has been neglected
Gap affected Results

Short Train

Long Train

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Dynamic effect mitigation

• Reduction of outliers by increasing the time to alert

Train length $L=2500$ m
Conclusions

• Multi-constellation architectures relying on GPS, GLONASS and in perspective GALILEO offers an higher degree of flexibility to reach the SIL-4 level (mandatory for the railways applications).

• Nevertheless, the availability of an augmentation network is of paramount importance in reducing the PL.

• Moreover, increased accuracy is requested when additional capabilities, like parallel track discrimination are required.

• In this sense, availability of evolved SBAS SIS developed for aeronautical applications is of primary concern.
Conclusions

• As illustrated by the performance analysis, Two Tiers Integrity Monitoring and Augmentation Networks represent a cost effective means to satisfy the SIL-4 requirement.

• The Virtual Track Circuit concept, based on the estimate at the same time of the train position and its length, may represent a cost effective means to implement ERTMS L3 and optimize use of railway infrastructure.

• Simulations and experimental results indicate the feasibility of a GNSS based monitoring of the train integrity.
References


