A Train Integrity Solution based on GNSS Double-Difference Approach

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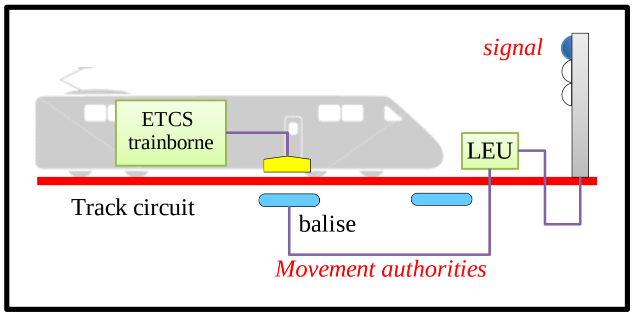
Roadmap

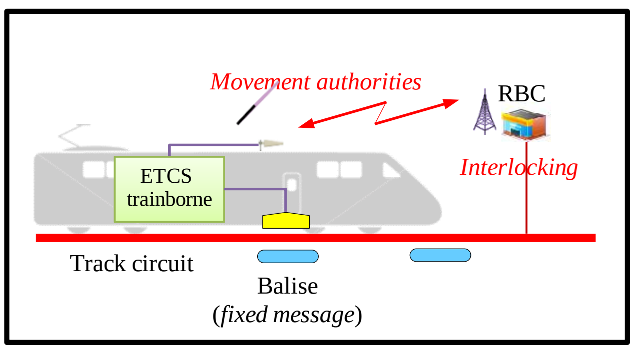
- Introduction to ERTMS/ETCS
- Train integrity issue
- Proposed solution
- Protection Level evaluation
- Simulation results
- Conclusions

ERTMS/ETCS

ERTMS / ETCS (European Railway Traffic Management System / European Train Control System) is the standard for European railways. There are three levels:



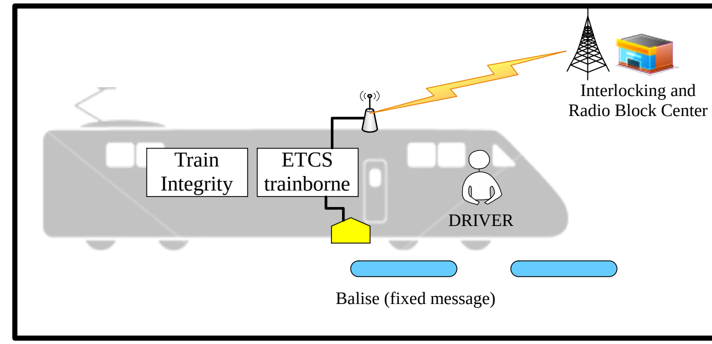
Level 1



Level 2

Present

future



Level 3

↓

Train must be able to evaluate its own position and to determine whether no carriage has been decoupled

↓

Virtual Track Circuit

Train Integrity

Issue:

With the term train integrity we mean the ability to determine whether all the carriages are still coupled each others.

Goal:

Define a Virtual Track Circuit to reduce operational cost and increase the line capacity.

Solution:

Use a double difference approach between a couple of GNSS receiver located respectively at the head and at the end of the train. In such a way it is possible to estimate the train length with a little time delay.

Why satellite technology?

Main advantages are:

- Reduction of operational and maintenance cost
- Increasing of line capacity

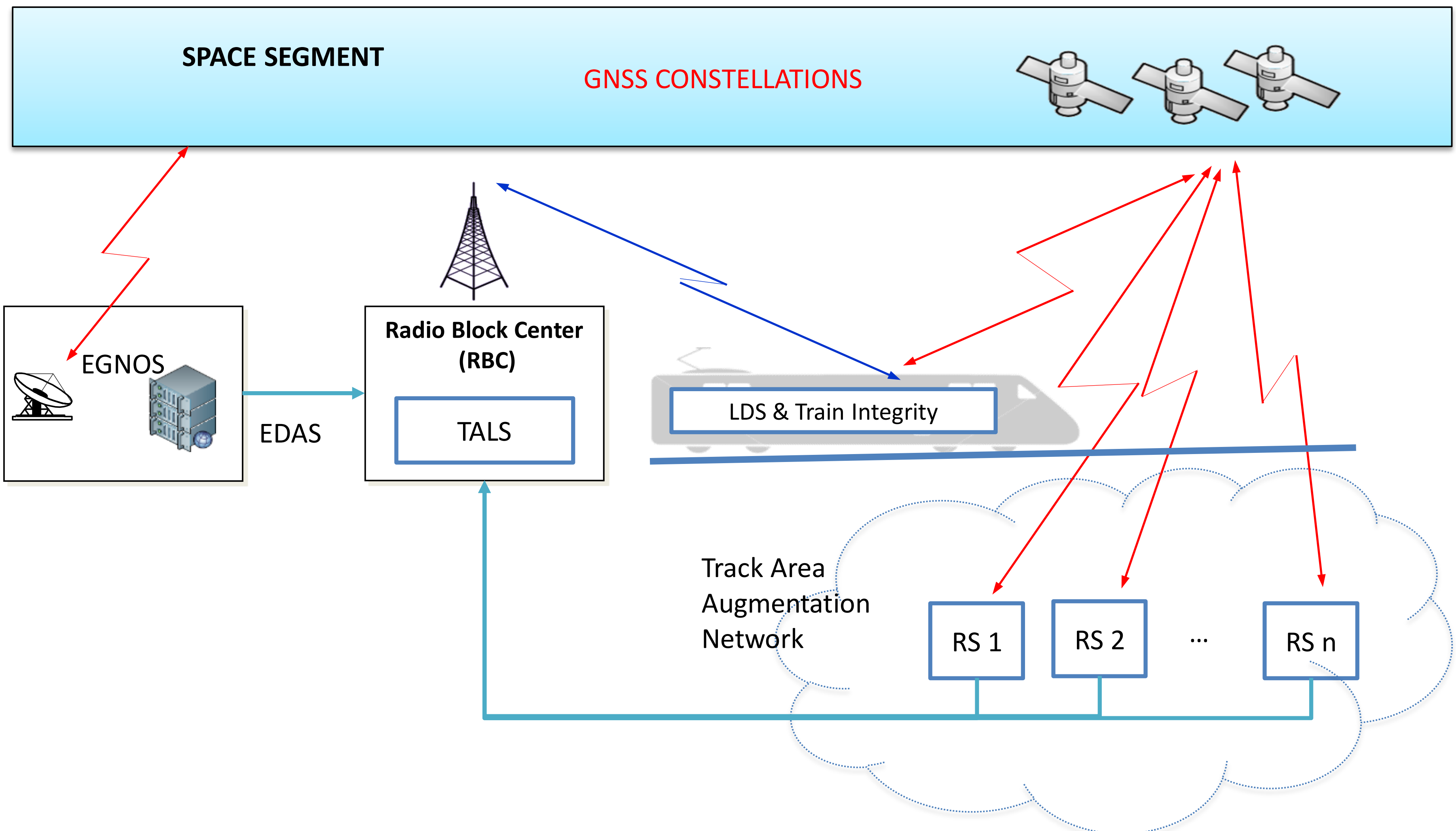
Market perspective:

- Cost-effective solution to increase safety on low traffic lines
- Increase traffic on high-speed lines

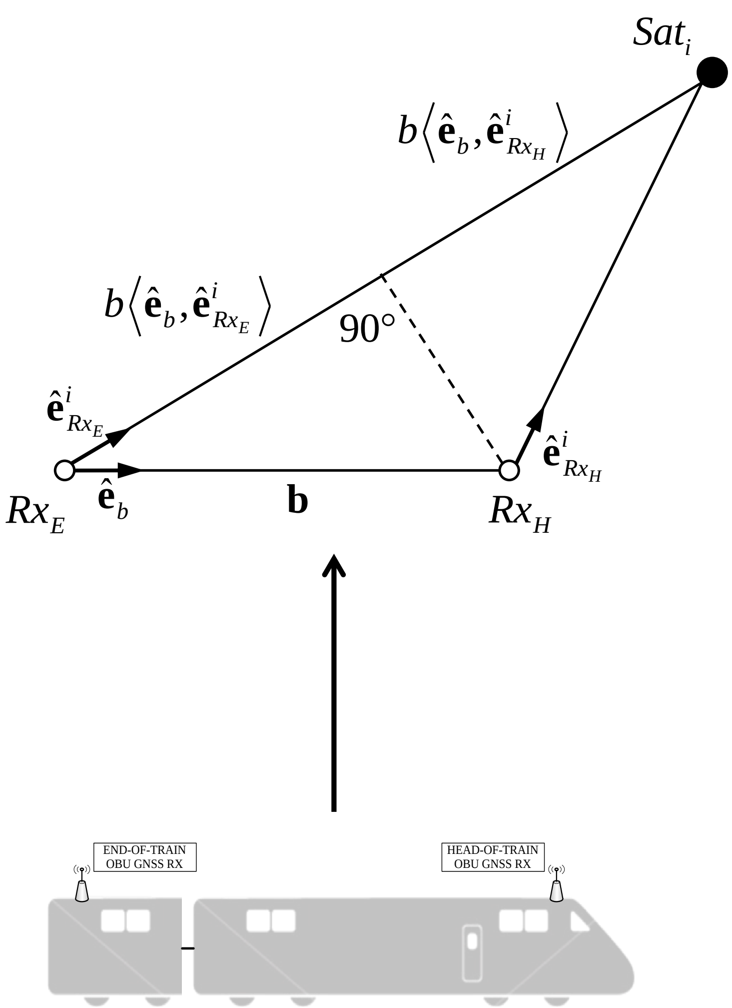
Main challenge:

- Fulfill the SIL-4 requirements in terms of THR (Tolerable Hazard Rate) imposed for railways (*i.e.* $THR \leq 10^{-9}/h$)

Reference architecture



Double Difference approach



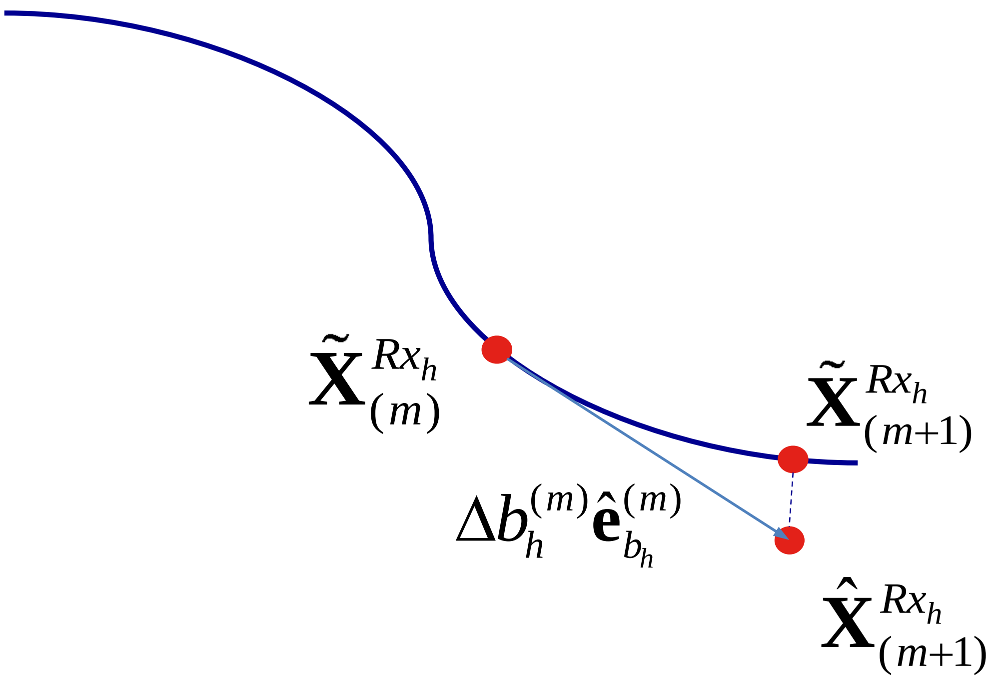
$$
\begin{aligned}
SD_i &= \left\| \mathbf{X}_i^{Sat}\left[T_i^{Sat}(k)\right] - \mathbf{X}^{Track}\left[s_H\left(T_i^{Rx_h}(k)\right)\right] \right\| - \\
&\quad + \left\| \mathbf{X}_i^{Sat}\left[T_i^{Sat}(k)\right] - \mathbf{X}^{Track}\left[s_E\left(T_i^{Rx_h}(k)\right)\right] \right\| = \\
&= r^i_{Rx_H}\left[1 - \left\langle \hat{\mathbf{e}}^i_{Rx_H}, \hat{\mathbf{e}}^i_{Rx_E} \right\rangle\right] - \left\langle \mathbf{b}, \hat{\mathbf{e}}^i_{Rx_E} \right\rangle,
\end{aligned}
$$

$$
\begin{aligned}
DD^{ij}_{Rx_H Rx_E} &= SD_i - SD_j = \\
&= r^i_{Rx_H}\left[1 - \left\langle \hat{\mathbf{e}}^i_{Rx_H}, \hat{\mathbf{e}}^i_{Rx_E} \right\rangle\right] - \left\langle \mathbf{b}, \hat{\mathbf{e}}^i_{Rx_E} \right\rangle - \\
&\quad + \left[r^j_{Rx_H}\left[1 - \left\langle \hat{\mathbf{e}}^j_{Rx_H}, \hat{\mathbf{e}}^j_{Rx_E} \right\rangle\right] - \left\langle \mathbf{b}, \hat{\mathbf{e}}^j_{Rx_E} \right\rangle \right] = \\
&= r^i_{Rx_H}\left[1 - \left\langle \hat{\mathbf{e}}^i_{Rx_H}, \hat{\mathbf{e}}^i_{Rx_E} \right\rangle\right] - r^j_{Rx_H}\left[1 - \left\langle \hat{\mathbf{e}}^j_{Rx_H}, \hat{\mathbf{e}}^j_{Rx_E} \right\rangle\right] + \\
&\quad - \left\langle \mathbf{b}, \hat{\mathbf{e}}^i_{Rx_E} - \hat{\mathbf{e}}^j_{Rx_E} \right\rangle.
\end{aligned}
$$

Mitigation of most of the iono, tropo and clocks errors

Railway Constraint

We adopt a constrained positioning algorithm to map the 3-D estimation problem into a 1-D estimation problem

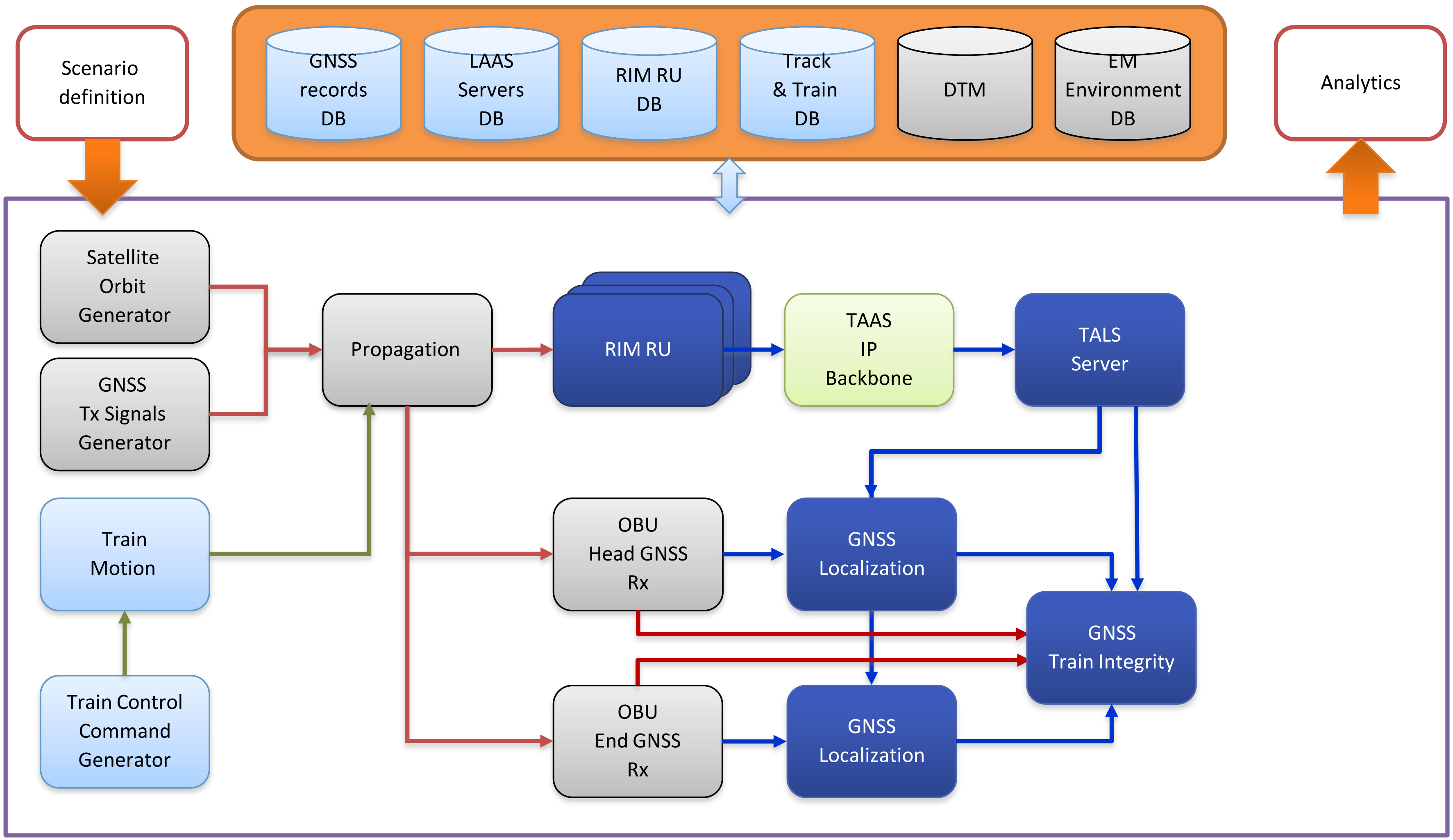


$$\mathbf{G}^{(m)} = \left[\hat{\mathbf{e}}_{b_H}^{(m)} \quad \hat{\mathbf{e}}_{b_E}^{(m)} \right],$$

$$\begin{cases} \hat{\mathbf{e}}_{b_H}^{(m)} = \left[\dfrac{\partial \mathbf{X}^{Rx_H}}{\partial s} \right]_{s=\tilde{s}_H^{(m)}(k)} \\ \hat{\mathbf{e}}_{b_E}^{(m)} = \left[\dfrac{\partial \mathbf{X}^{Rx_E}}{\partial s} \right]_{s=\tilde{s}_E^{(m)}(k)} \end{cases}$$

$$H_{constr}^{(m)} = H^{(m)} \cdot G^{(m)}$$

Simulation tool

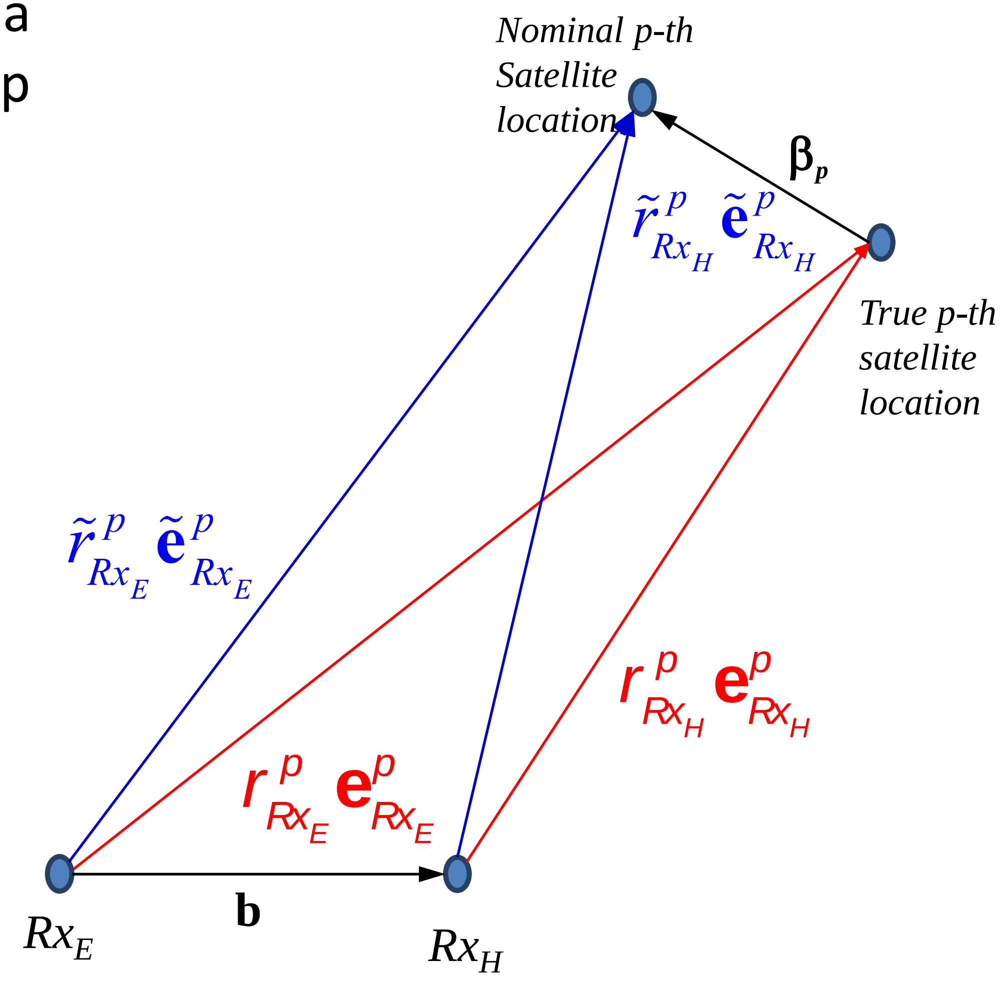


Protection Level Evaluation

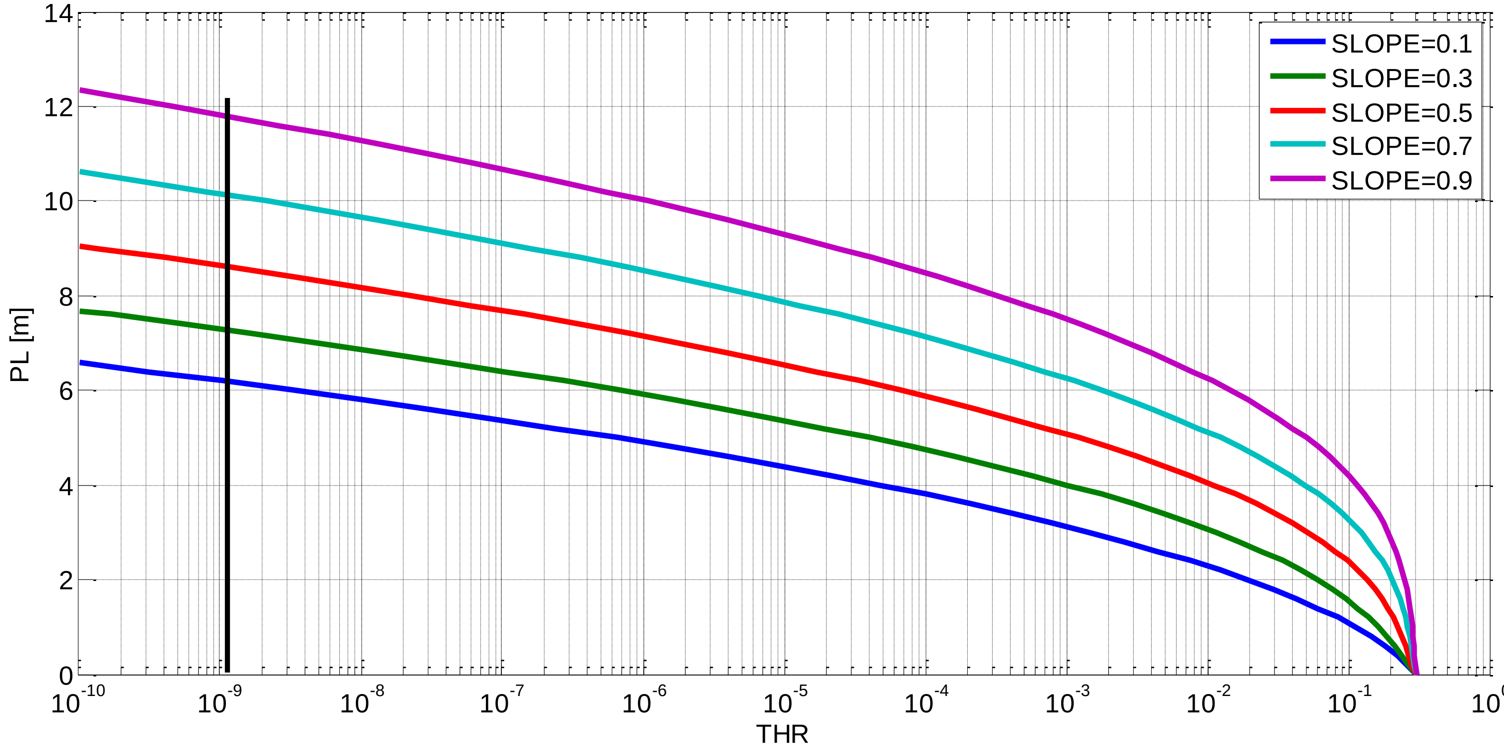
We can define protection as a statistical over bound of the gap estimation error. In fact

$$\hat{L} \underset{coupled}{\overset{decoupled}{\gtrless}} \eta$$

We have to link the train integrity issue with the satellite integrity issue



Performance Assessment



$$PL_e \simeq \sqrt{2}\,\frac{b}{B}\,\sigma_{\overline{dd}\,Max}\,|\gamma|_{Max}\sqrt{\lambda_{Max}} + k_e\sigma_{\varepsilon_L}$$

$$k_e = \sqrt{2}\,erfc^{-1}\left(\frac{R_{TH_e}^{TrainIntegrity}}{N_{Dec}D^{nc}_{\chi^2_{N_{RIM}-1}}\left[D^{-1}_{\chi^2_{N_{RIM}-1}}\left(1-P_{fe}\right),\,\lambda_{Max}\right]P_{SF}}\right)$$

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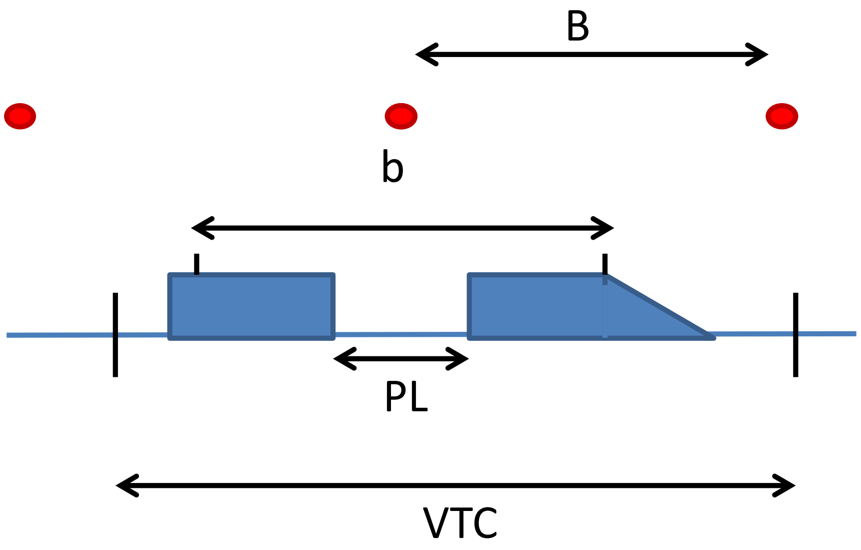
Protection Level for single fault

To have a numerical reference of the protection level let us consider:

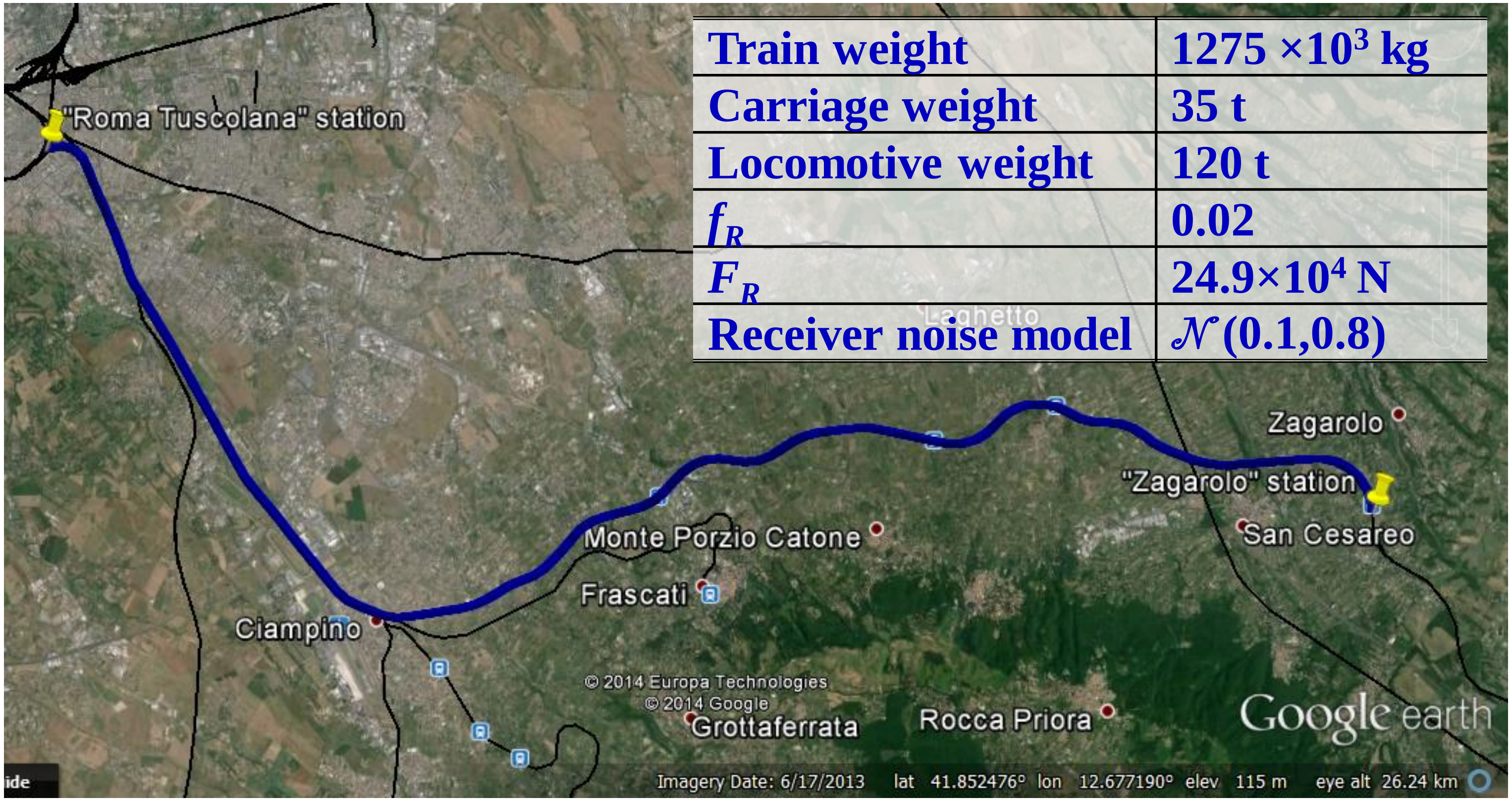
$$\left.\begin{aligned} &\sigma_{\overline{dd}_{Max}} = 2 \\ &|\mathbf{g}|_{Max} \le 1 \\ &B = 50\ km \\ &b = 2.5\ km \end{aligned}\right\} \quad SLOPE = 0.14 \longrightarrow PL \cong 7m$$

In such a way it is possible to derive the Virtual Circuit Length considering the dynamical model of the train (dynamic coupling junctions)



Simulation results

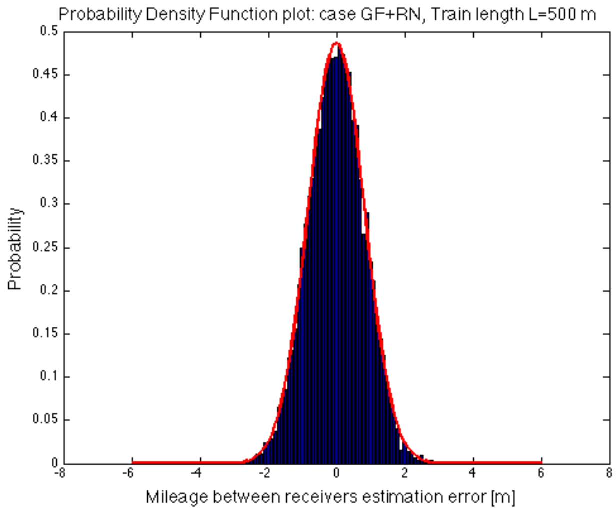
Results are provided for both a typical passenger train (500 m length travelling at 108 km/h) and a heavy freight one (2500 m length with cruise speed of about 80 km/h)



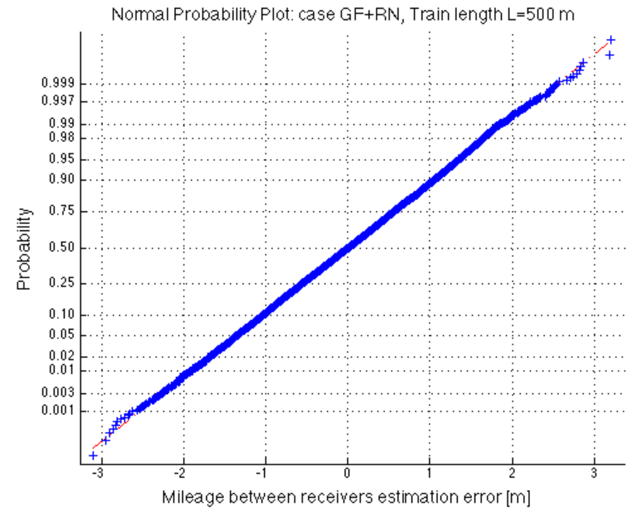
Train weight	**1275×10^3 kg**
Carriage weight	**35 t**
Locomotive weight	**120 t**
f_R	**0.02**
F_R	**24.9×10^4 N**
Receiver noise model	**$\mathcal{N}(0.1,0.8)$**

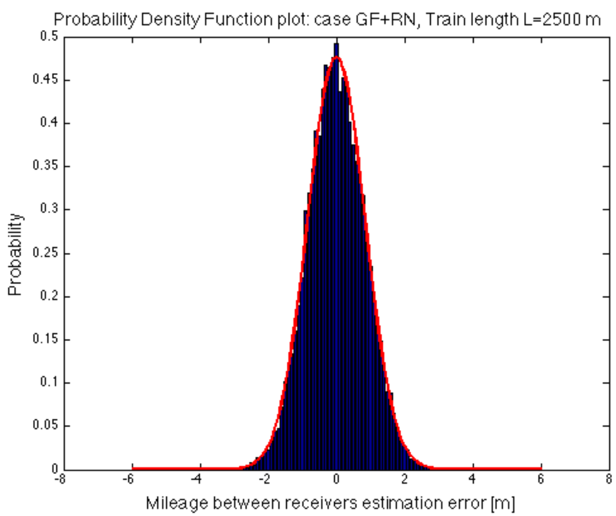
Train Length estimation error

Scenario with all coupled carriages

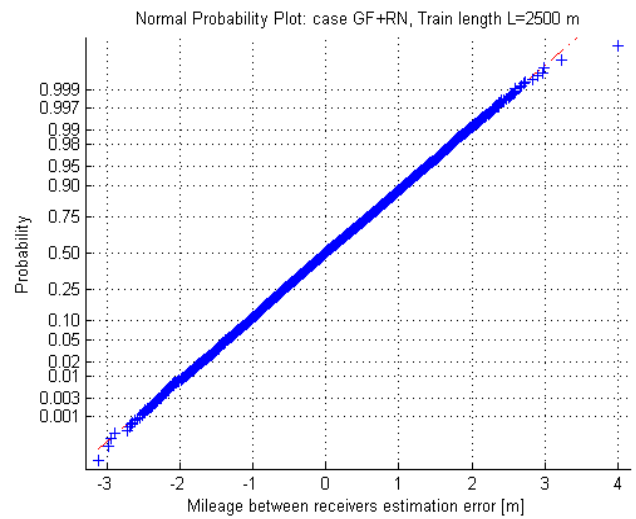


Short Train





Long Train



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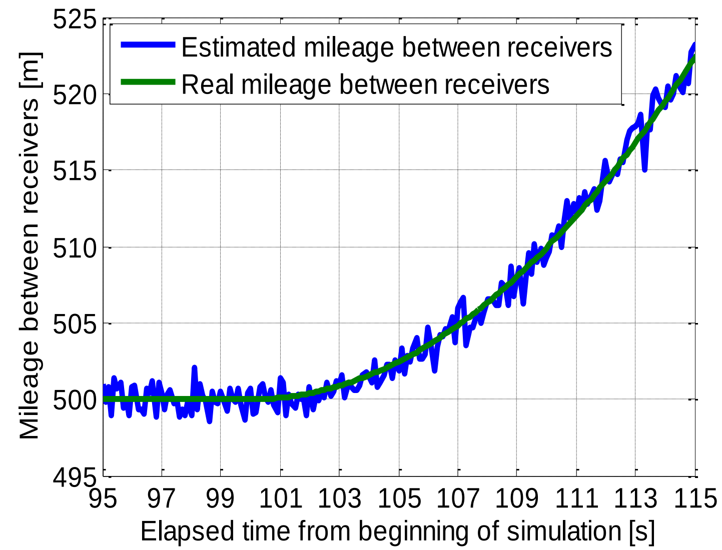
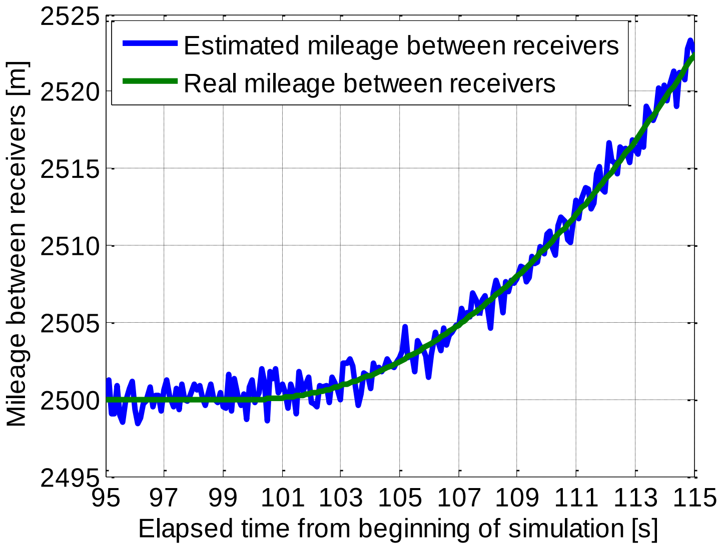
Intercarriage gap vs time to alarm

We considered the following scenario:

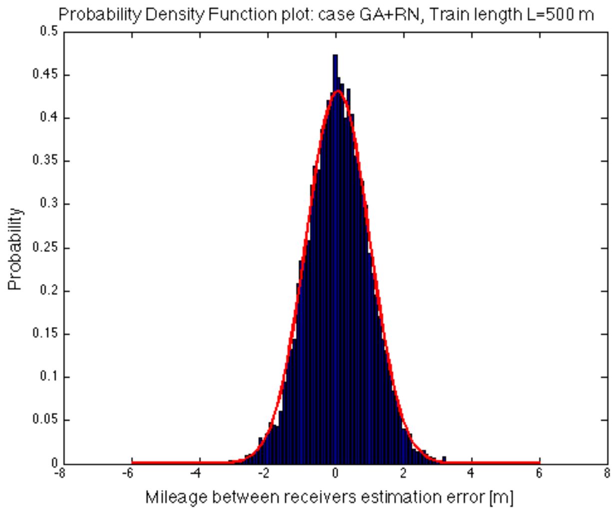
- The train moves at constant speed
- The train is a rigid block (no dynamic coupling between carriages)
- One of the carriages decouples from the previous one
- The front train section continues its movement after the decoupling as if nothing has been occurred
- The tail section stops only by action of rolling resistance
- Track slope effect has been neglected



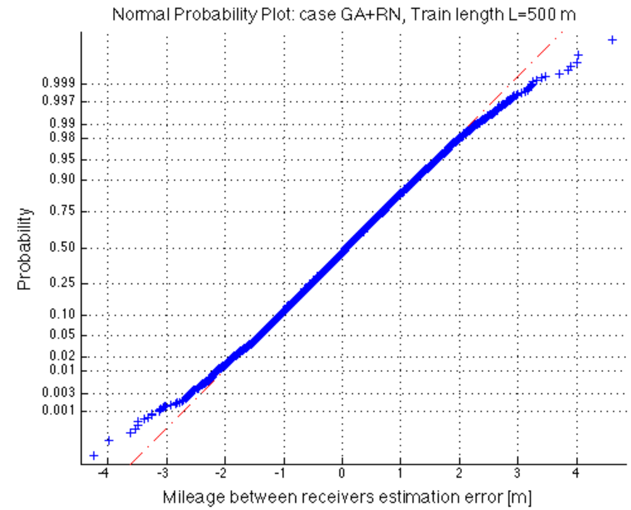


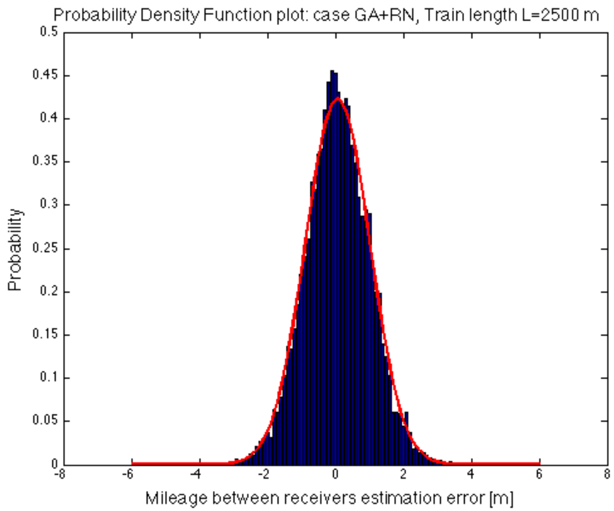
Train Length estimation error

Scenario with one decoupled carriage

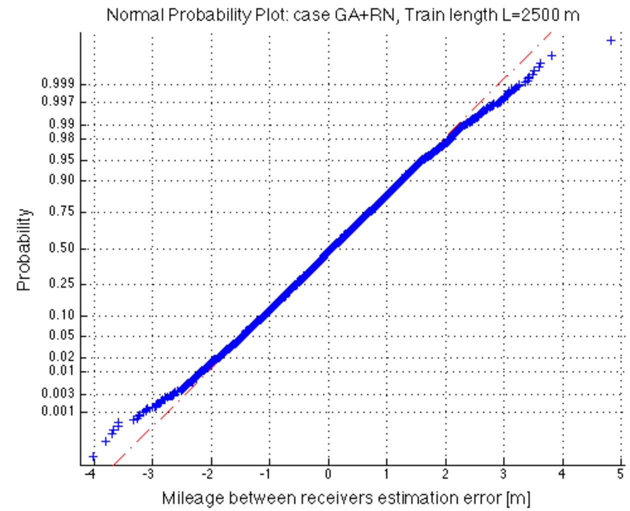


Short Train





Long Train



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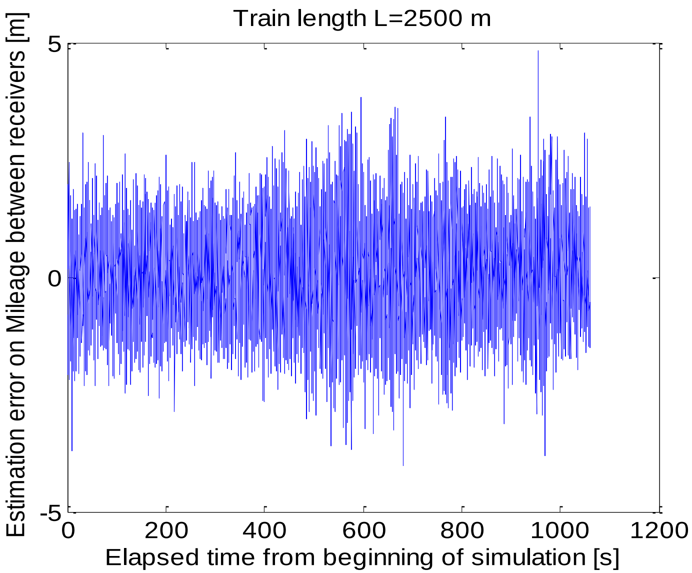
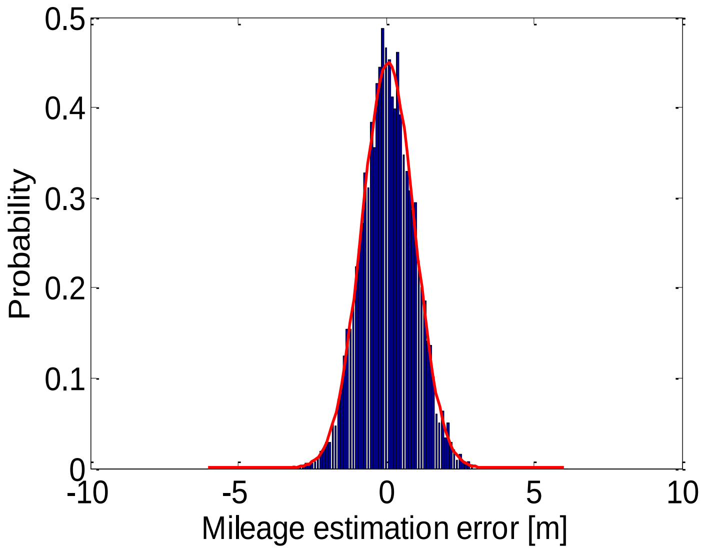
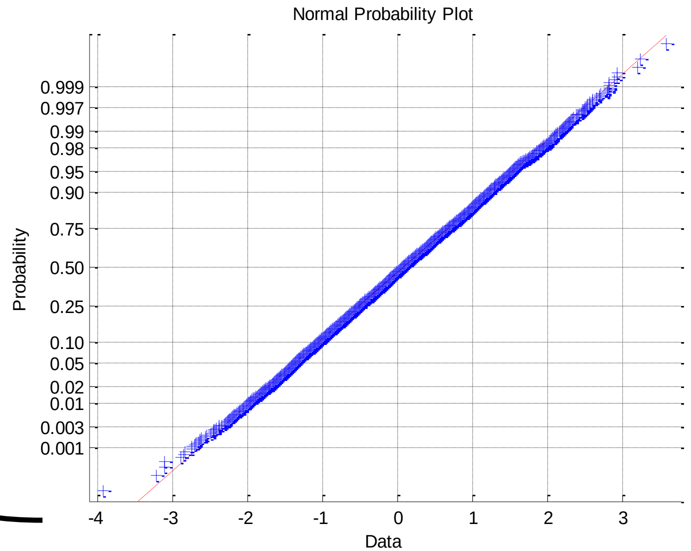
Dynamic effect mitigation



Median Filter





We use a median filter with window size equal to 10 epochs. In this way we reduce the outlier number in the error distribution by increasing the time to alert

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Conclusions

- Train Integrity function is key for the introduction of the ERTMS L3 system with GNSS technology
- We focused on the Virtual Track Circuit definition to estimate at the same time the train position and its length by the:
  - computation of Protection Level to evaluate the gap that can be protected by Virtual Track Circuit
  - verification that the theoretical model fulfils the SIL-4 (Safety Integrity Level 4) requirements
- Computer-based simulations have demonstrated the performance in terms of estimation error with different train lengths:
  - 250 m
  - 2500 m
- A median filter approach has been introduced to minimize the outlier number in the distribution by increasing the time to alert

Thank You for your kind attention