ERSAT GGC

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A MULTI-SENSOR AUTONOMOUS INTEGRITY MONITORING APPROACH FOR RAILWAY AND DRIVER-LESS CARS

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European Global Navigation Satellite Systems Agency

HORIZON 2020

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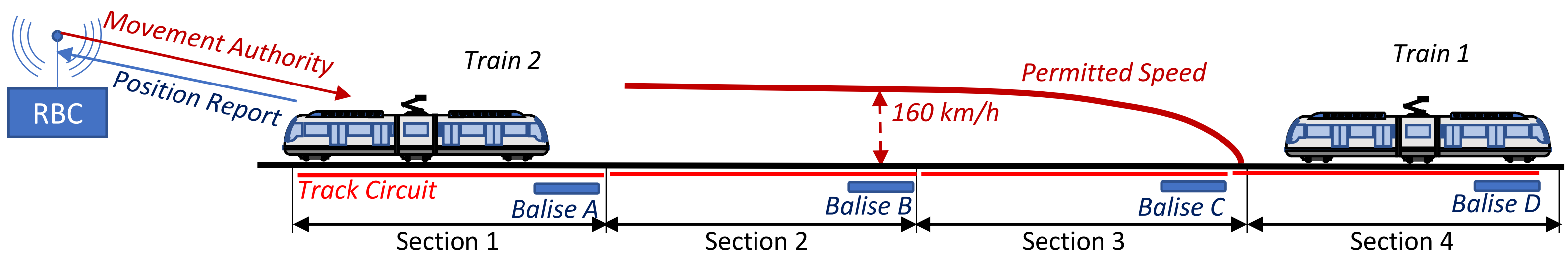
ROMA TRE UNIVERSITÀ DEGLI STUDI

Contents

- Rail & Road Accuracy and Integrity Requirements
- EM Scenario
- Space Diversity based Multipath Detection & Exclusion
- GNSS vs. Odometry based Multipath Detection & Exclusion
- Experimental results
- Conclusions

RAIL - SAFETY CRITICAL Requirements



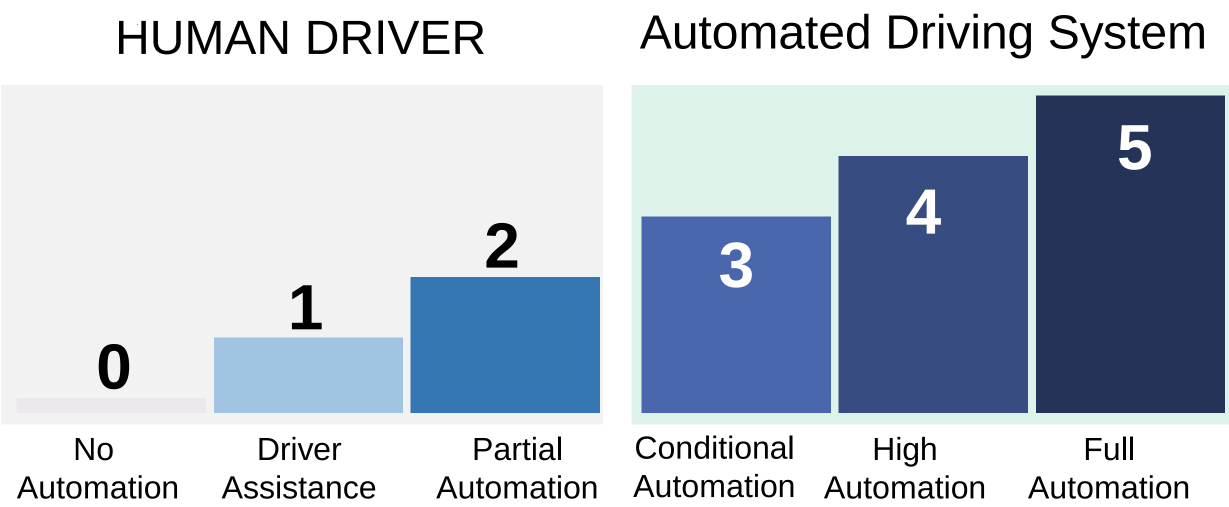
ERTMS/ETCS

Safety Integrity Level SIL-4

THR <10^{-9} [hazard/(h x Train)]

GNSS Functionality	Alert Limit	Accuracy
VB detection VITAL	**1** m	25 cm
VB detection NON VITAL	**5** m	125 cm
Track discrimination	**2** m	50 cm

ROAD - SAFETY CRITICAL Requirements



KPI	Value
Lateral ALERT LIMIT	**< 25 cm**
Longitudinal ALERT LIMIT	**2 m**
Speed accuracy	**?**
Trajectory handshake latency	<100 msec
Status message latency	<10 msec
Status message loss rate	$< 10^{-6}$
Status message rate	> 10 Hz

ELECTRONIC HORIZON

Vehicles and Road users

- Position, speed
- acceleration
- direction (heading)
- Yaw rate

Static obstacles

- Position

Infrastructure

- **High Accuracy Digital map**

From other sources

- traffic
- weather information

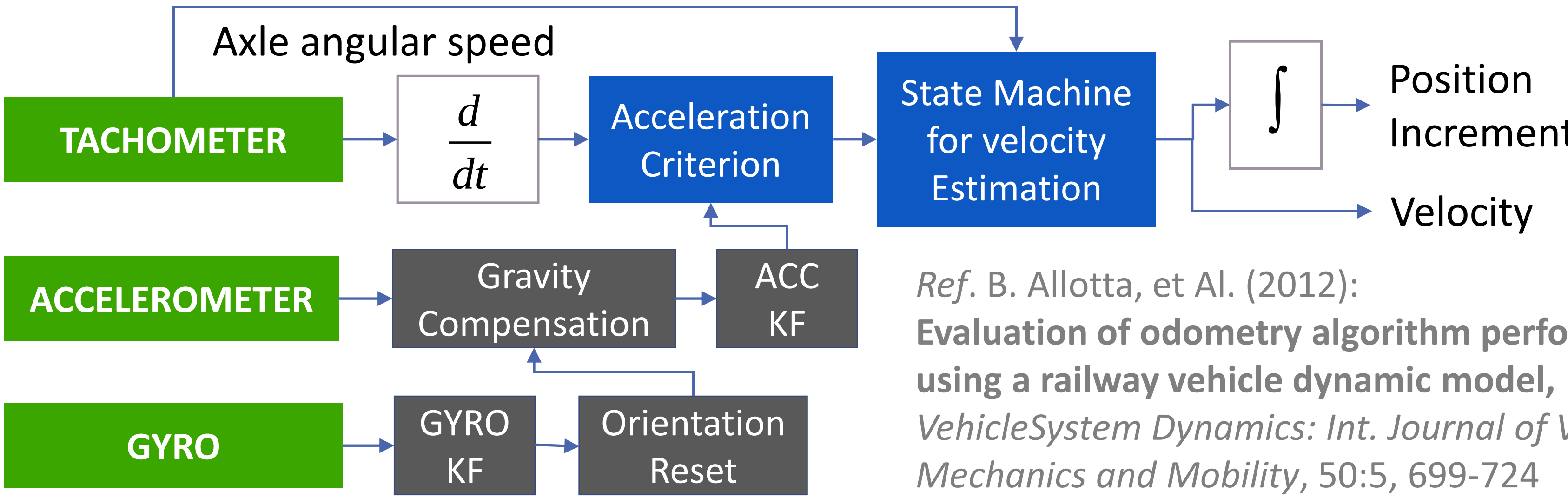
Railway EM scenario

- **MULTIPATH** is a Major Hazard

Yellow: Unconstrained RTK (GPS)
Red: IMU+GPS

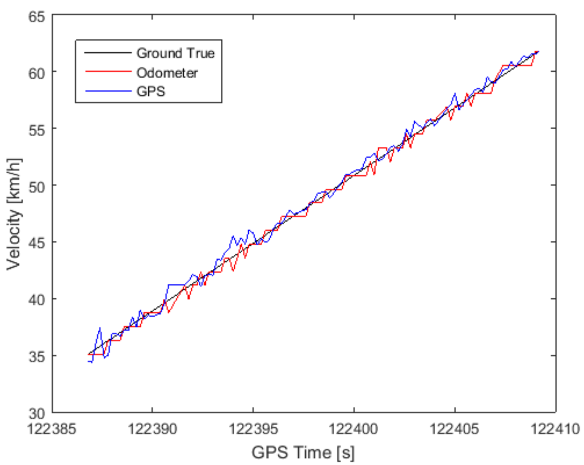
The EM scenario

Enhanced Odometers



Ref. B. Allotta, et Al. (2012):
Evaluation of odometry algorithm performances using a railway vehicle dynamic model,
VehicleSystem Dynamics: Int. Journal of Vehicle Mechanics and Mobility, 50:5, 699-724

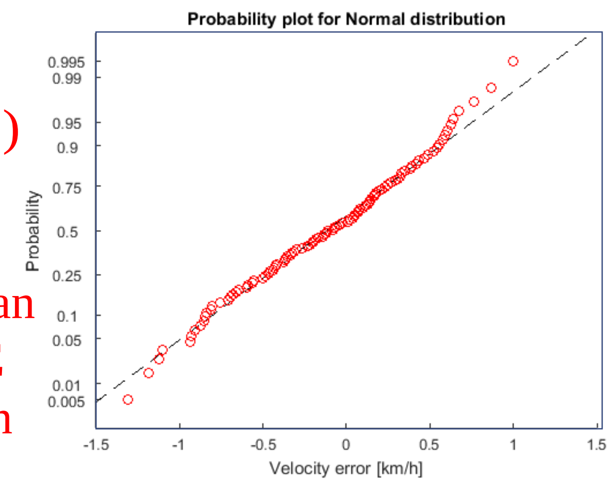
- Velocity measurement model



$$v_{OD}^{en}(t_k) = v(t_k) + \beta(t_k) + \eta_S(t_k)$$

zero mean **NARROW BAND** Gaussian process

zero mean **WHITE** Gaussian Process



GNSS vs. ODOMETER

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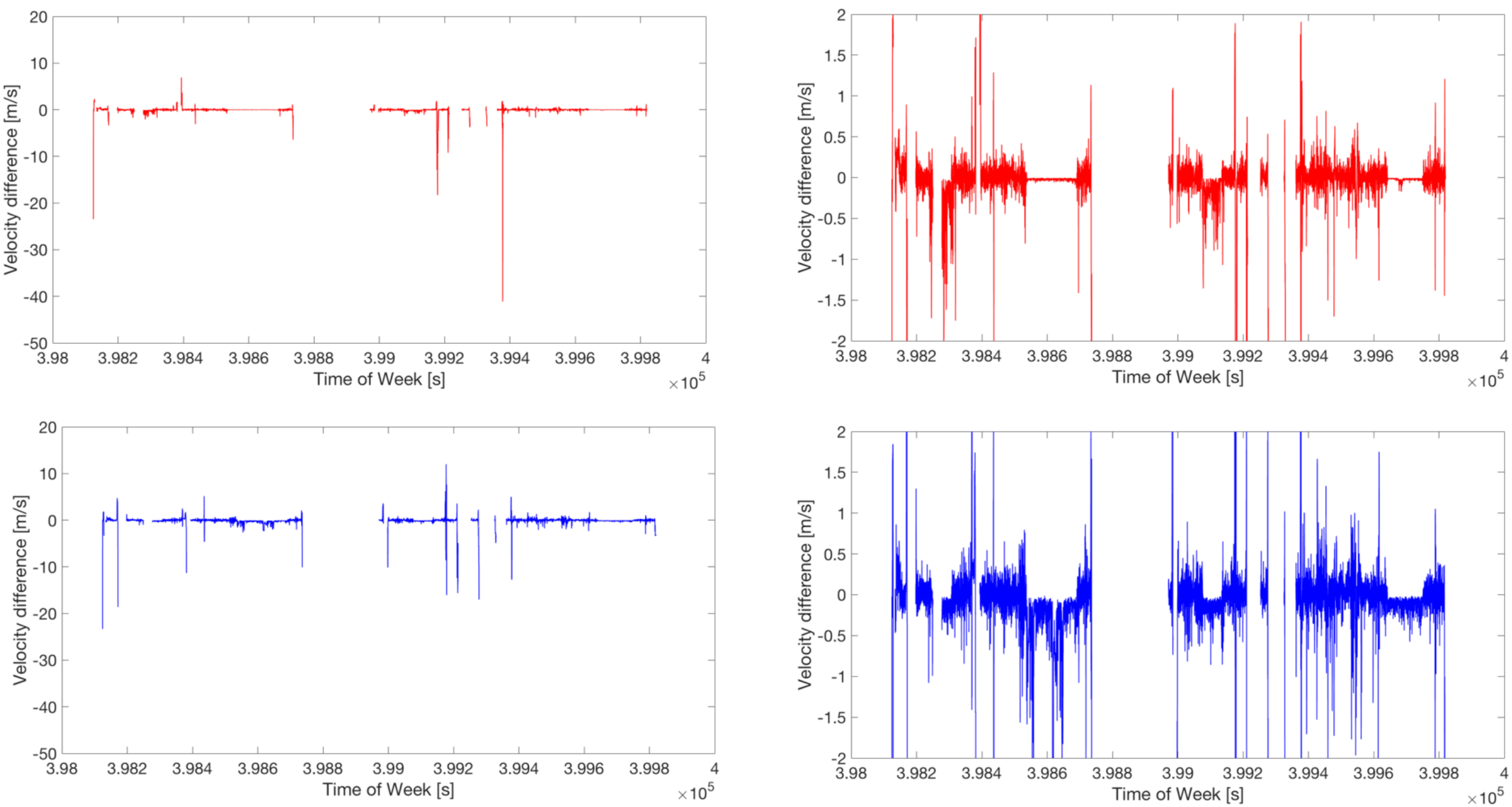
Difference between GNSS and ODOMETER velocity estimates



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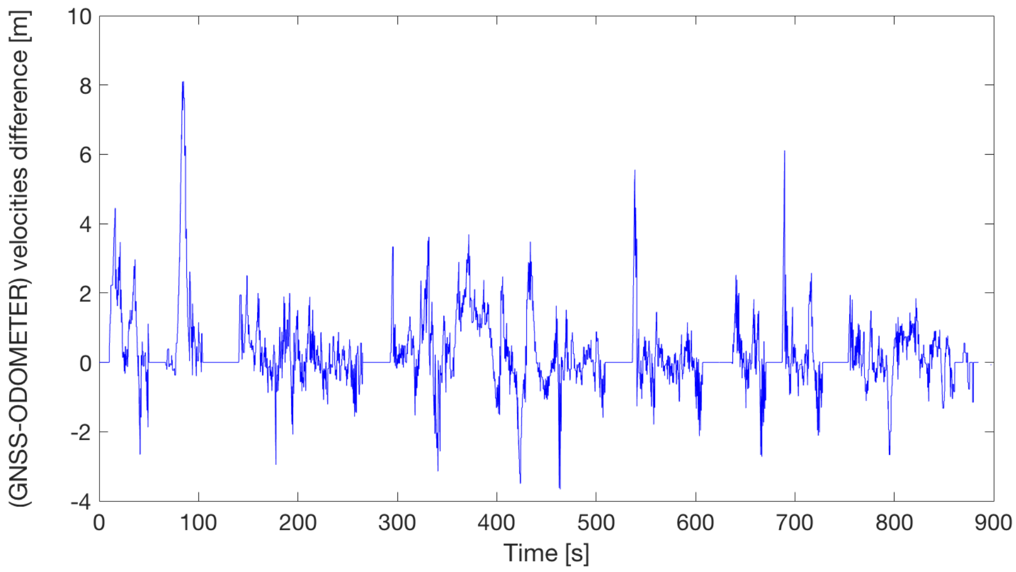
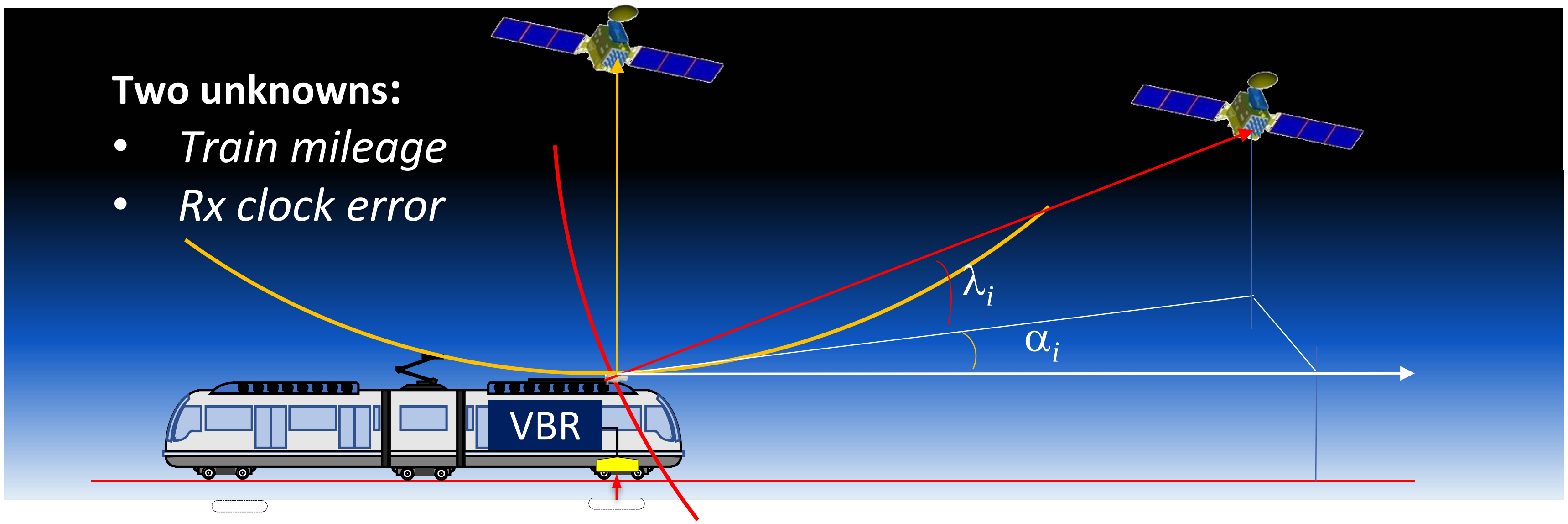


The Track constraint



- The location of the train is completely determined by its **MILEAGE** from the terminus station

Track Parametric Equations

$$\mathbf{X}_{Rx} = \mathbf{X}_{Rx}(s)$$

Train mileage (s)

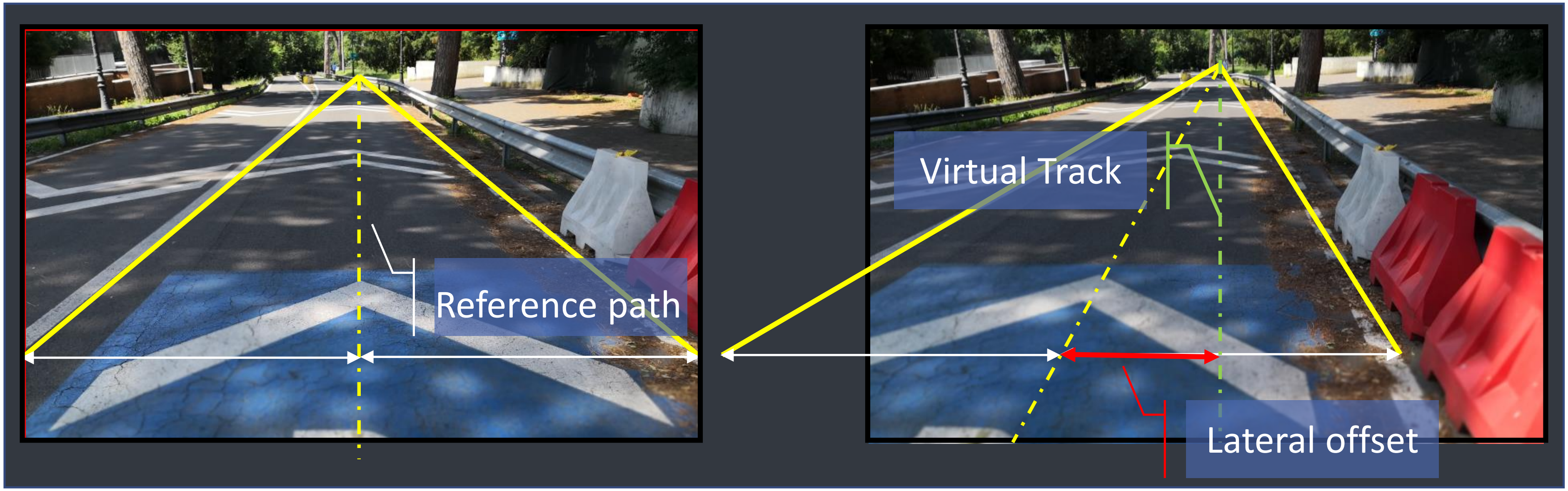
Track Constrained Positioning

$$\Delta\tilde{\boldsymbol{\rho}}_{Rx} = \mathbf{H}\begin{bmatrix} \Delta s \\ c\delta t_{Rx} \end{bmatrix} + \boldsymbol{\varepsilon}$$

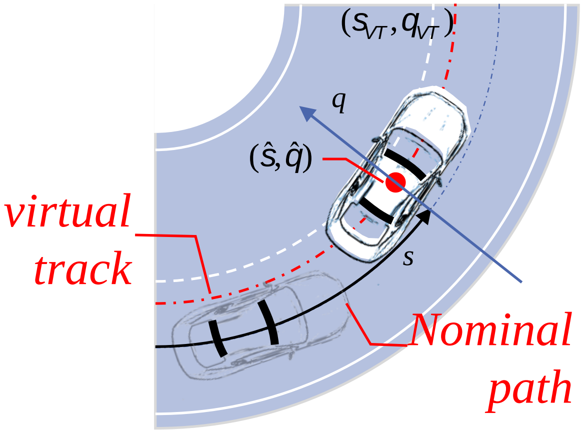
$$\mathbf{H} = \begin{bmatrix} \mathbf{E}_{Rx}^{T} \dfrac{\partial \mathbf{X}_{Rx}}{\partial s} & \mathbf{1}_{N_{Sat}} \end{bmatrix}$$

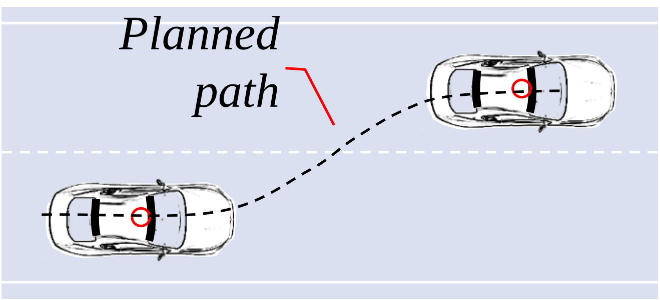
Virtual Track Concept

Use of Imaging to estimate the lateraL OFFSET



Vehicle Position determined by Its curviinear coordinates based on lane middle line

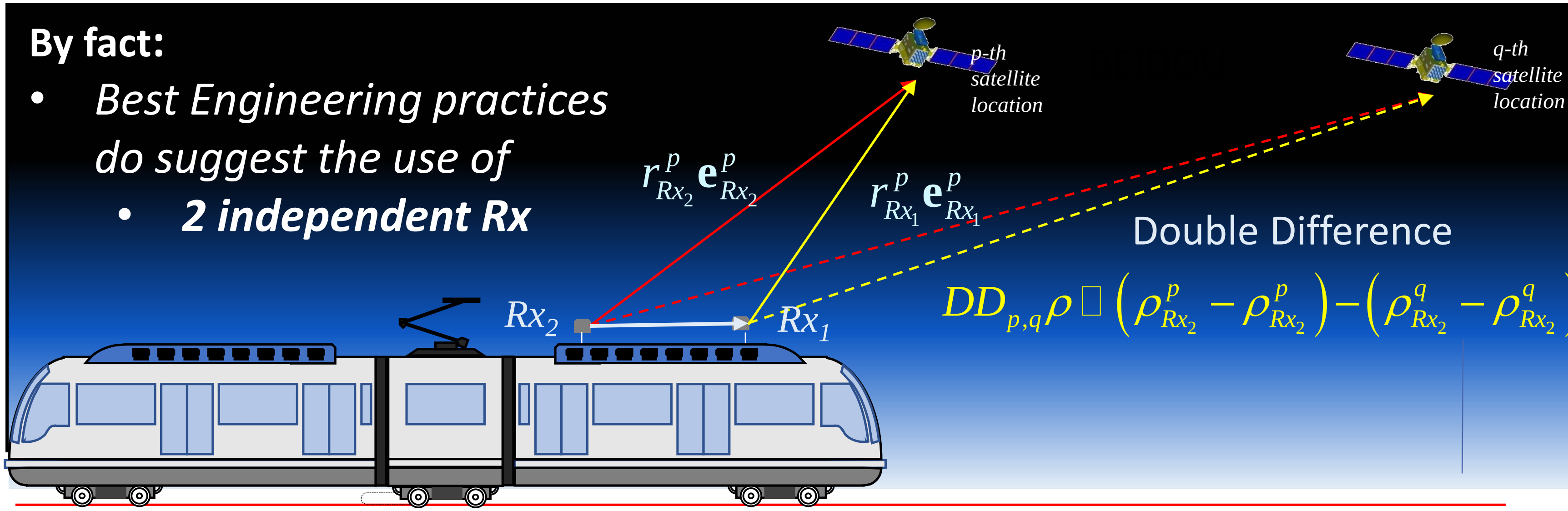




Space Diversity Multipath Resilience

By fact:

- *Best Engineering practices do suggest the use of*
  - ***2 independent Rx***



- Pseudorange Double Difference equations

$$DD_{p,q}\rho \cong \left\langle \mathbf{b}, \mathbf{e}^{q}_{Rx_2} - \mathbf{e}^{p}_{Rx_2} \right\rangle + \nu_{p,q}$$

$$\nu_{p,q} \cong \underbrace{n^{Rx_1}_{p} - n^{Rx_2}_{p} - n^{Rx_1}_{q} + n^{Rx_2}_{q}}_{\text{Thermal noise}} + \underbrace{\mu^{Rx_1}_{p} - \mu^{Rx_2}_{p} - \mu^{Rx_1}_{q} + \mu^{Rx_2}_{q}}_{\text{Multipath error}}$$

- Pseudorange difference Multipath Indicator

$$\left[\zeta^{\rho}_{p}\right]_{q} = DD_{p,q}\rho - \left\langle \hat{\mathbf{b}}_{k/k-1}, \hat{\mathbf{e}}^{q}_{Rx_2} - \hat{\mathbf{e}}^{p}_{Rx_2} \right\rangle$$

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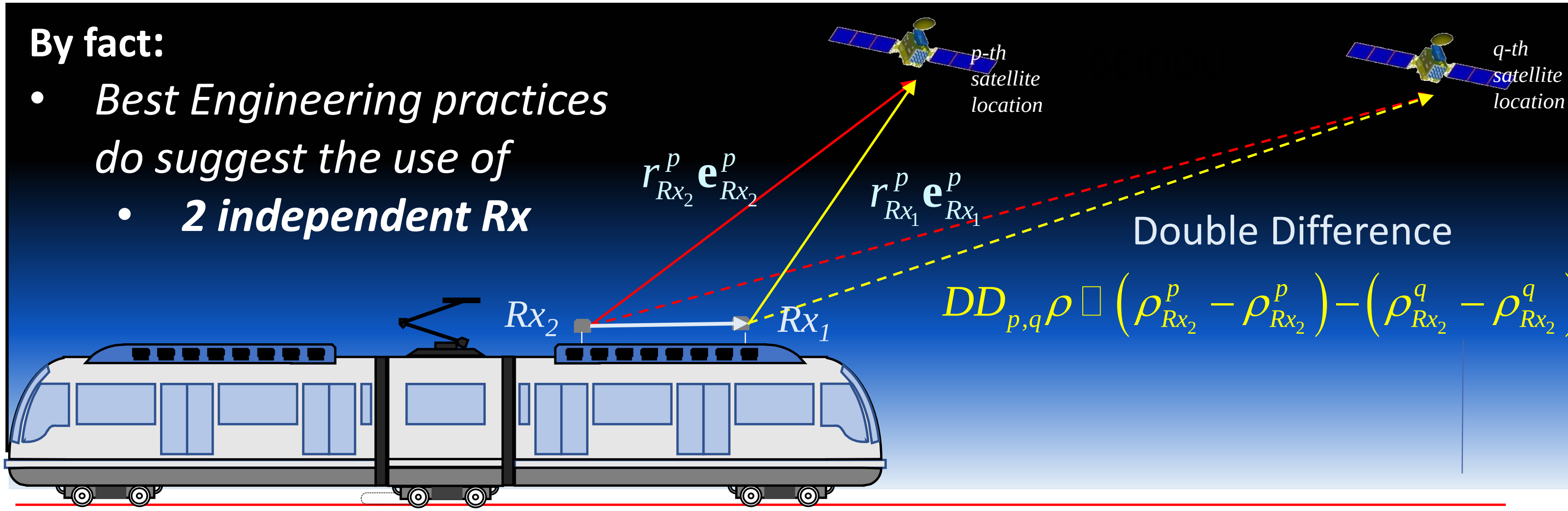

- **DOPPLER** Double Difference equations (negligible rotations)

$$DD_{p,q}f_D \cong DD_{p,q}f_D^{MP} + DD_{p,q}f_D^{n}$$

Multipath error Thermal noise

- **DOPPLER** difference Multipath Indicator

$$\left[\zeta_p^{DOP}\right]_q = DD_{p,q}f_D$$

ODOMETRY Based Multipath Resilience

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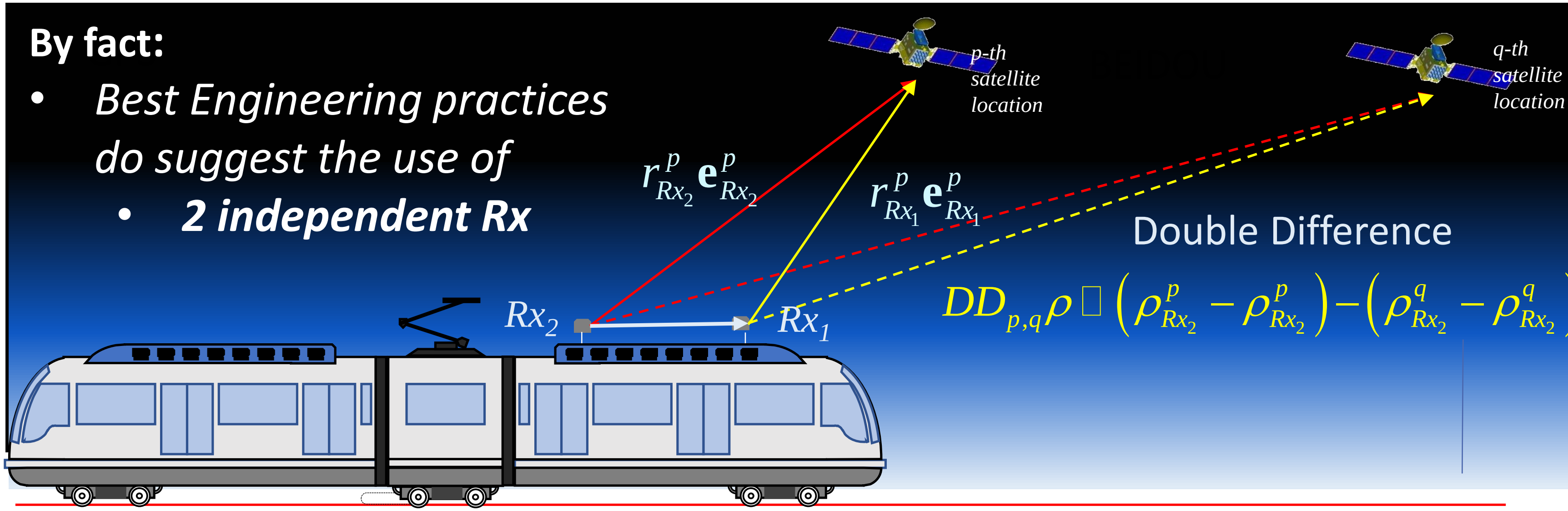


- **DOPPLER – ODOMETER** Difference equations

$$SD_{p,q} f_D = SD_{p,q} f_D^{ODO} + SD_{p,q} f_D^{MP} + SD_{p,q} f_D^{n}$$

$$f_{D_p}^{ODO} = \frac{f_C}{c + \left\langle \mathbf{v}^p_{Sat}, \mathbf{e}^p_{Rx} \right\rangle} \left[\left\langle \mathbf{v}^p_{Sat}, \mathbf{e}^p_{Rx} \right\rangle + \left\langle \mathbf{v}_{ODO}, \mathbf{e}^p_{Rx} \right\rangle \right]$$

- **DOPPLER – ODOMETER** Multipath Indicator

$$\left[\zeta_p^{ODO}\right]_q = SD_{p,q} f_D - SD_{p,q} f_D^{ODO}$$

Multipath Detection and Exclusion

- Multipath detection is performed by thresholding $|\zeta_p|$
- To avoid **masking** of SIS of weak multipath by SISs with stronger Multipath an the **iterative procedure** that removes at each iteration the effects produced by those satellites whose signal is already classified as *faulty* is adopted

a. Initialize the set $S^{Healthy}$ of healthy satellites to the set of visible satellites with elevation greater than the elevation mask.

b. Repeat

- for each satellite in $S^{Healthy}$ compute $|\zeta_p|$

c. Select the satellite with the largest $|\zeta_p|$

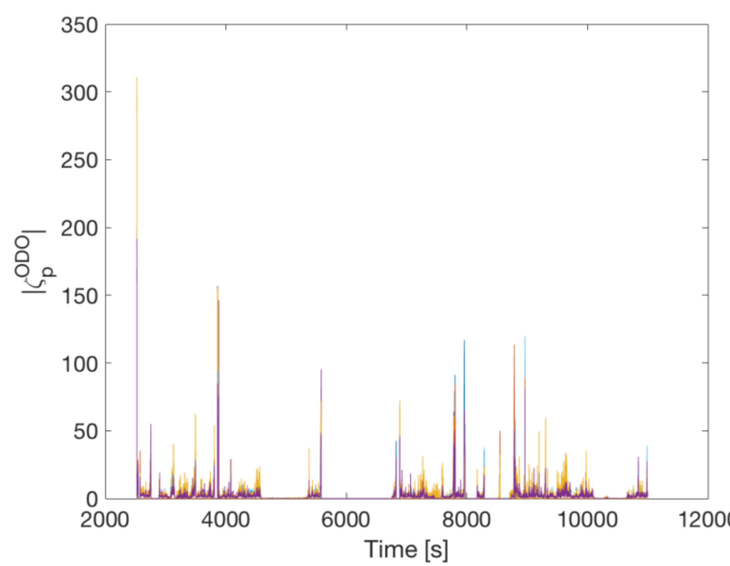
$$\hat{p} = Arg\left\{ \underset{p \in S^{Healthy}}{Max}\left[|\zeta_p| \right] \right\}$$

d. If $|\zeta_{\hat{p}}|$ exceeds a predefined threshold γ_ζ

- remove $\hat{p}$ from the healthy set $S^{Healthy}$
- and mark the satellite as *unreliable*.

until $|\zeta_{\hat{p}}| > \gamma_\zeta$ and $S^{Healthy}$ is non empty.

Iteration #1



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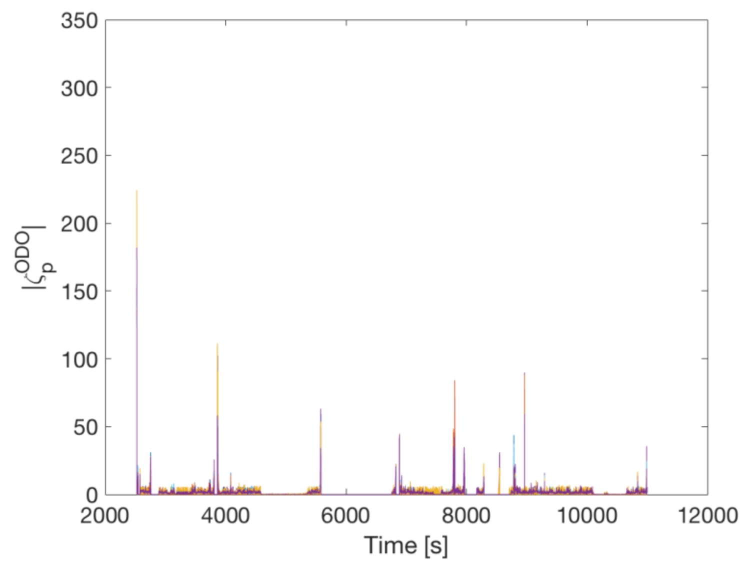
Iteration #2



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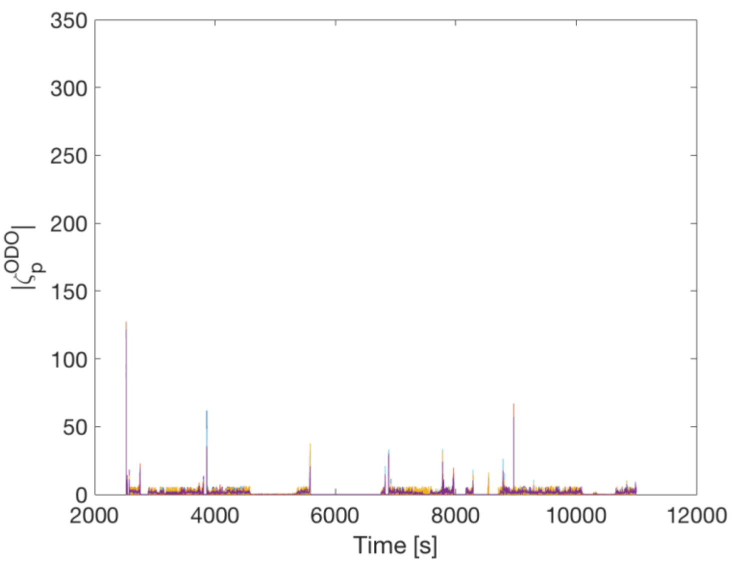
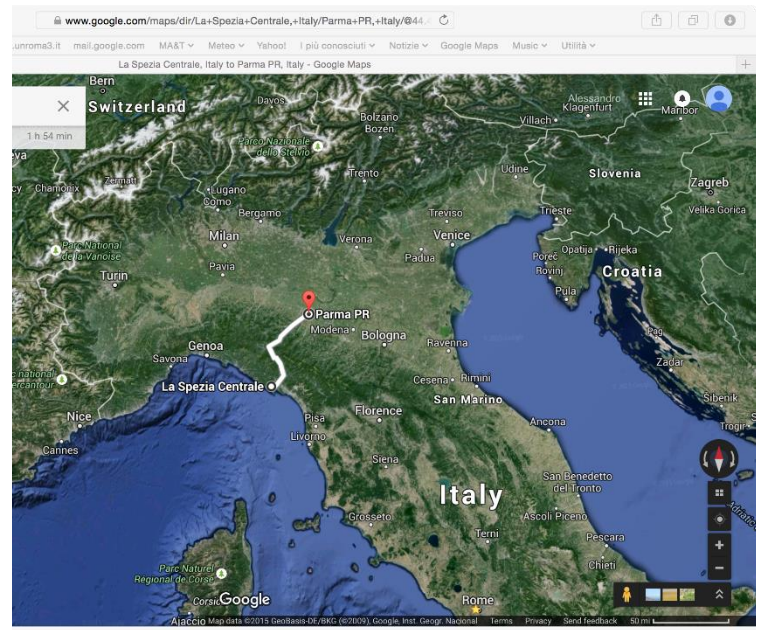
Iteration #3



Multipath in rail environment

- PONTREMOLESE line
- Line length: 120 km
- Physical Balises: about 500
- Track AreaAugmentation Network
  - 3 RIMs equipped with 2 GPS receivers each
- Trains:
  - 2 Ale.642 tractions equipped with 2 GPS receivers each
- Track Database based on RTK positioning survey



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- Trains:
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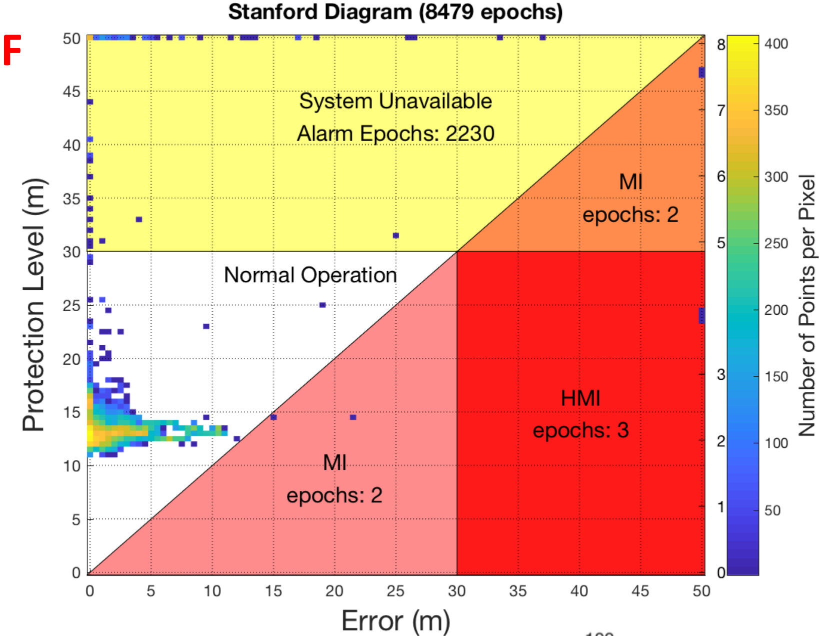
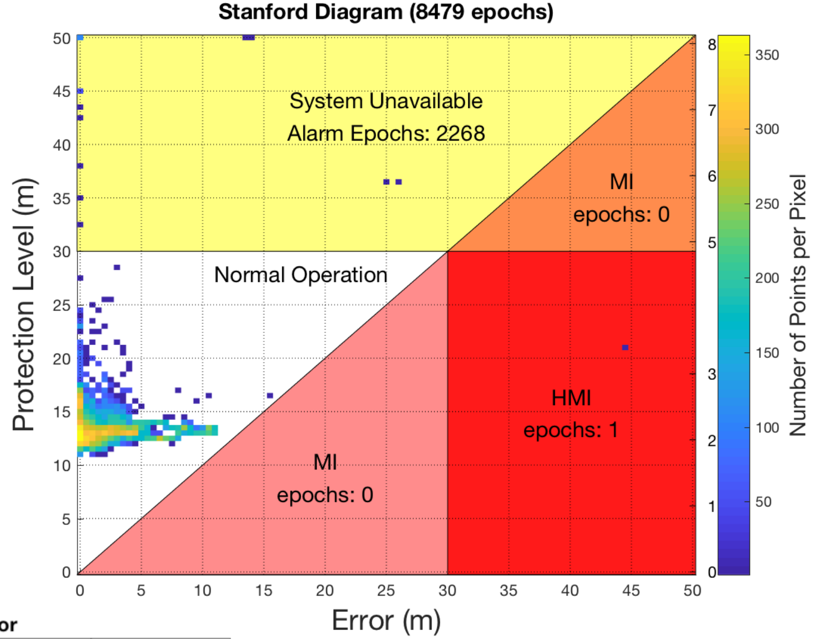
- Track Database based on RTK positioning survey
- Challenging environment w.r.t. multipath
  - Tunnels
  - Sky occlusions

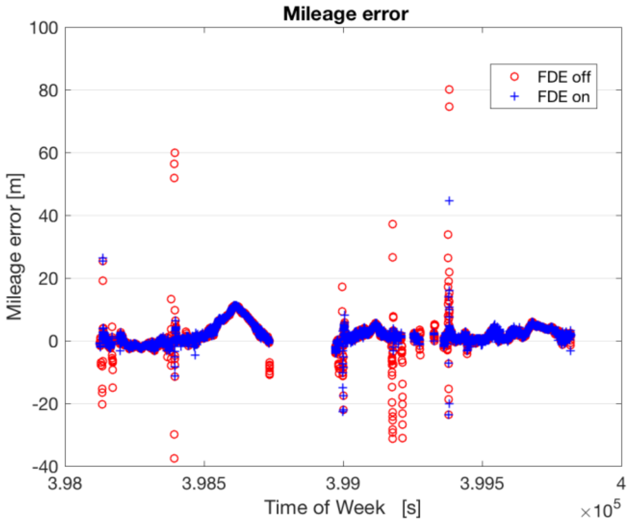
Results: Doppler Double Diff. (2 Rx)

OFF



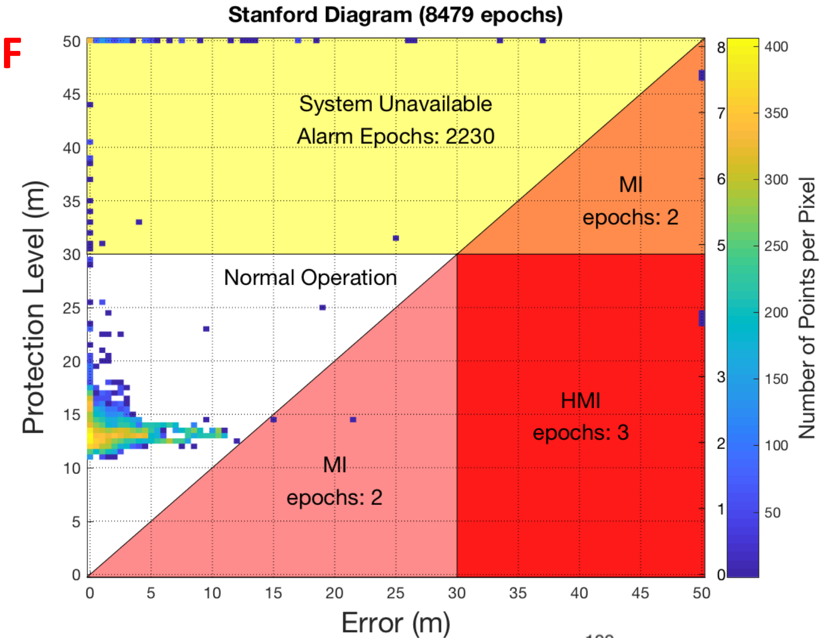
ON



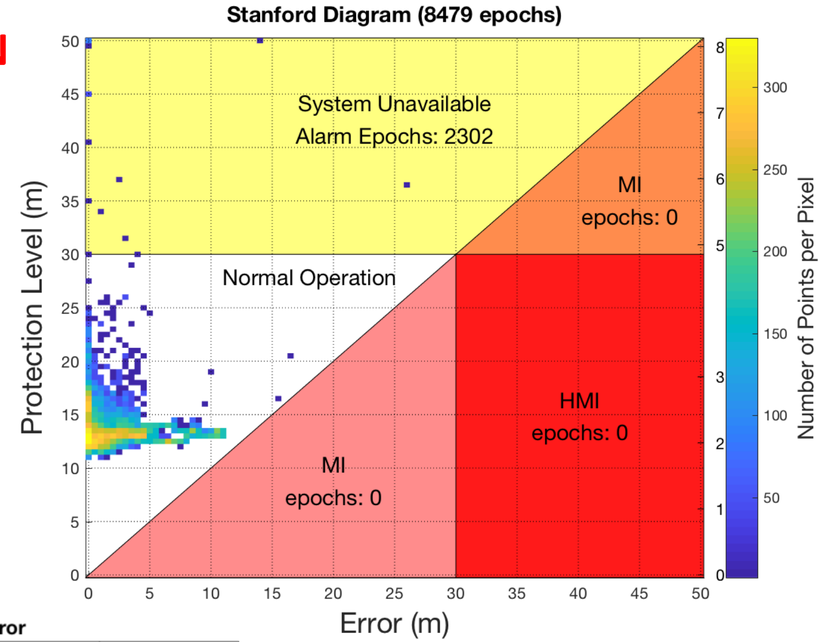


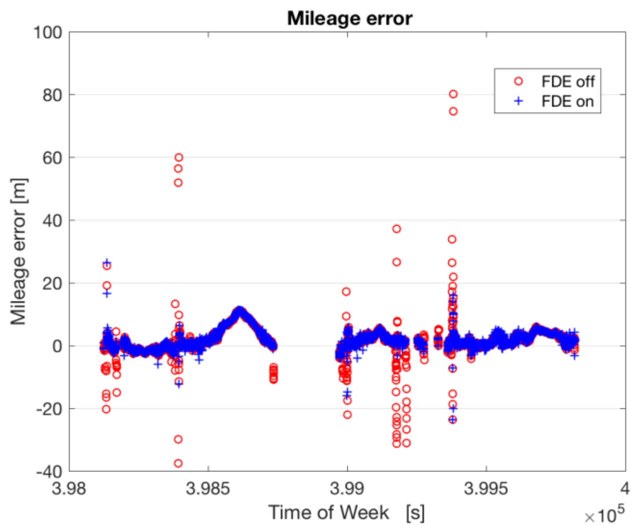
Results: Odometry based FDE

OFF

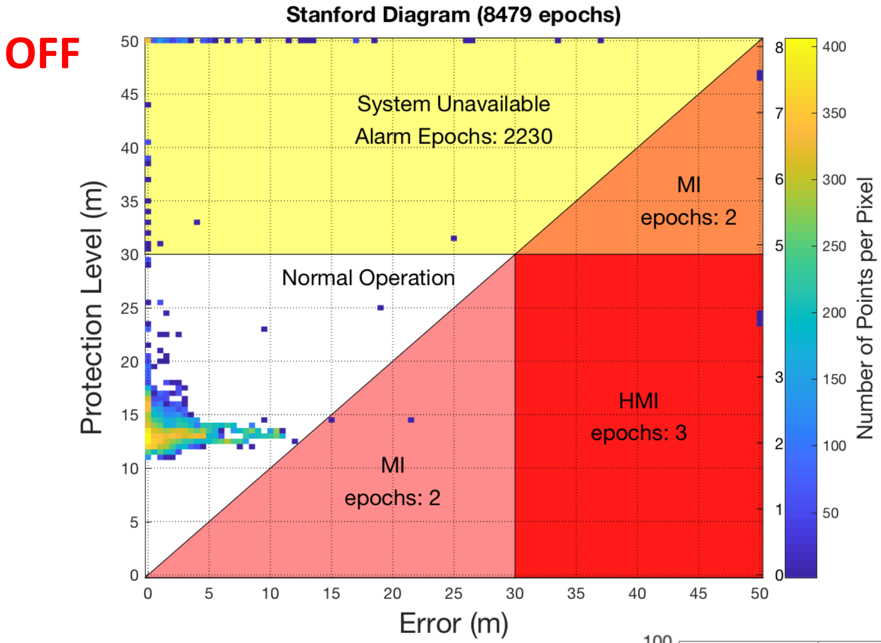


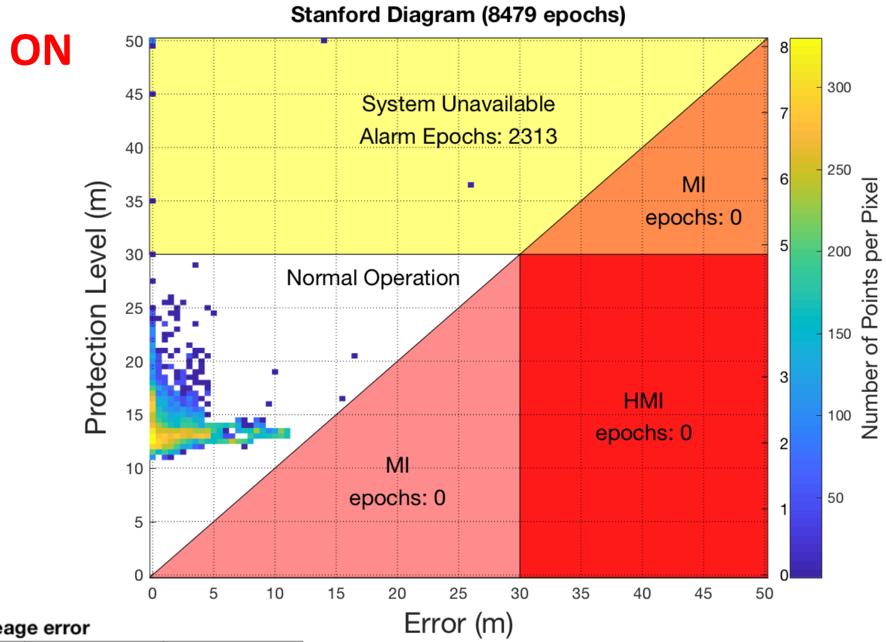
ON

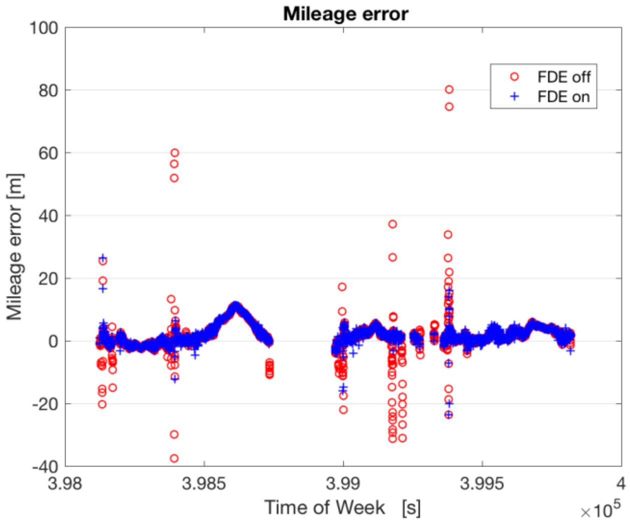




Results: Doppler Double Diff. + Odometry

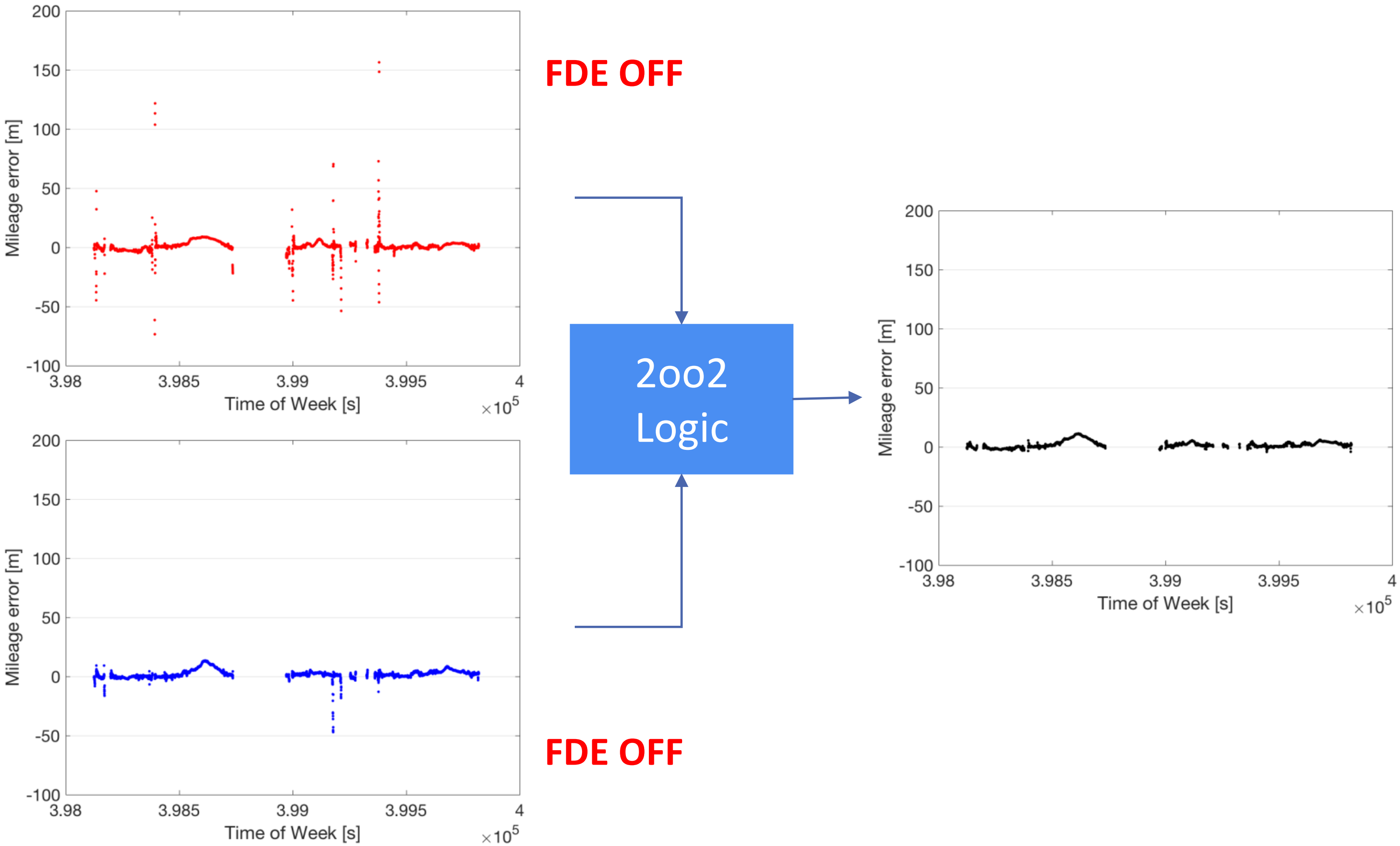






Results

2oo2 Logic: The two estimates of the train mileage provided by the two receivers are considered to be valid if the magnitude of their difference falls below a threshold



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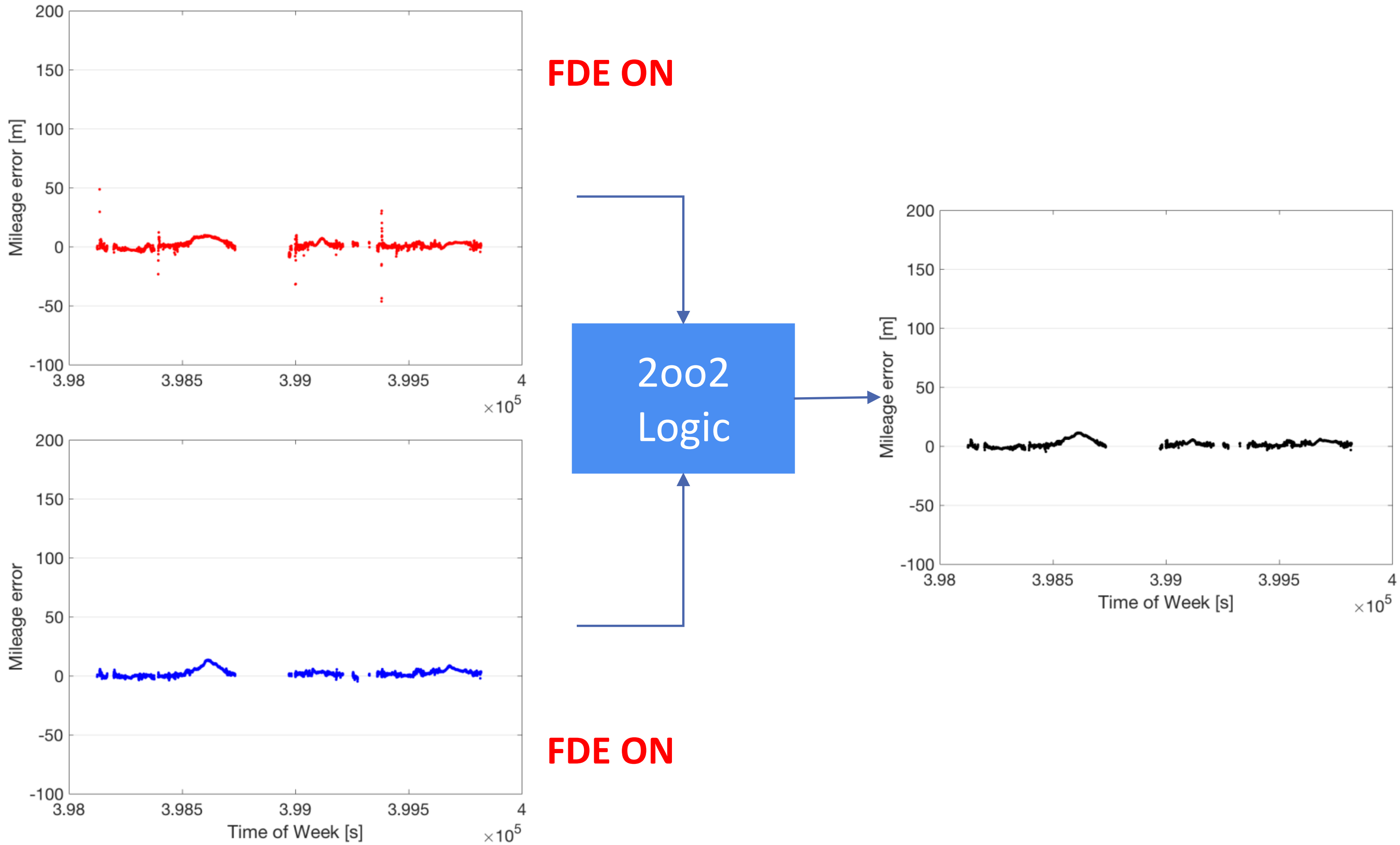
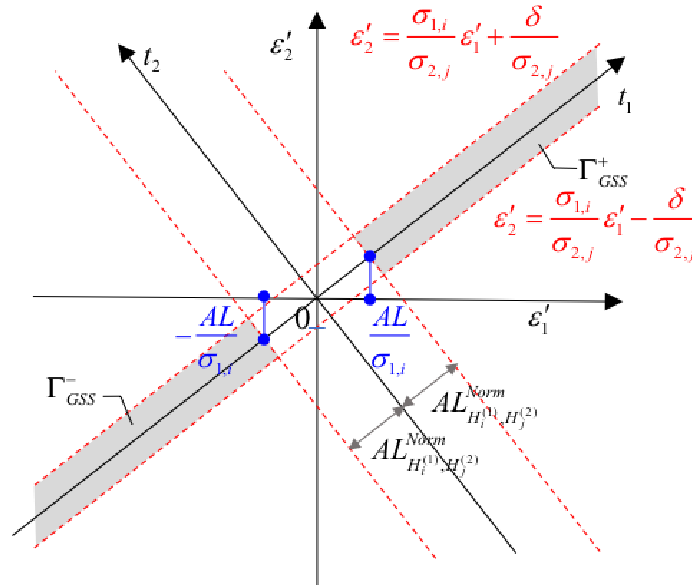


2oo2 Performance

- O2O Mileage linear combination

$$\hat{s}_0 = \frac{\sigma_2^2}{\sigma_1^2+\sigma_2^2}\hat{s}_1 + \frac{\sigma_1^2}{\sigma_1^2+\sigma_2^2}\hat{s}_2$$

- Then Misleading Information Probability is



$$P_{GSS}^{HMI}(s) = \sum_{i=0}^{h^{(1)}}\sum_{j=0}^{h^{(2)}} \Pr\left\{FD_i^{(1)}=0, FD_j^{(2)}=0\right\} P^{GSS}_{MI/s,H_i^{(1)},H_j^{(2)}} P_{H_i^{(1)},H_j^{(2)}}$$

$$P^{GSS}_{MI/s,H_i^{(1)},H_j^{(2)}} = \Pr\left\{\left|s-\hat{s}_0\right| > AL, \left|\hat{s}_2-\hat{s}_1\right| \le \delta \,\middle|\, s, H_i^{(1)}, H_j^{(2)}\right\}$$

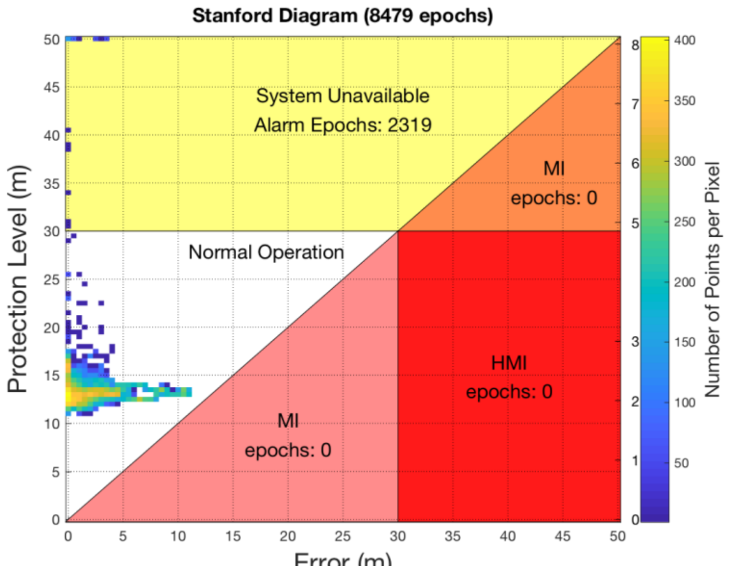
- Let $\varepsilon_1' = \frac{\varepsilon_1}{\sigma_{1,i}}$ $\quad \varepsilon_2' = \frac{\varepsilon_2}{\sigma_{2,j}}$

$$P^{MI}_{GSS/H_i^{(1)},H_j^{(2)}} = \frac{1}{2} erfc\left[\frac{AL_{i,j}^{Norm} + \tilde{\mu}_{i,j}^{(1)}}{\sqrt{2}}\right] + \frac{1}{2} erfc\left[\frac{AL_{i,j}^{Norm} - \tilde{\mu}_{i,j}^{(1)}}{\sqrt{2}}\right]$$

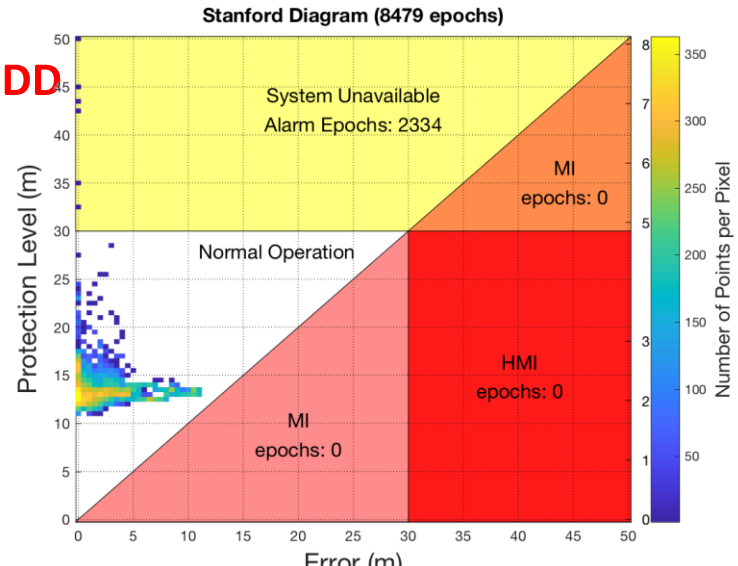
$$P^{MD}_{GSS/H_i^{(1)},H_j^{(2)}} = 1 - \left\{\frac{1}{2} erfc\left[\frac{\delta_{i,j}^{Norm} + \tilde{\mu}_{i,j}^{(2)}}{\sqrt{2}}\right] + \frac{1}{2} erfc\left[\frac{\delta_{i,j}^{Norm} - \tilde{\mu}_{i,j}^{(2)}}{\sqrt{2}}\right]\right\}$$

Results: Doppler Double Diff. + Odometry

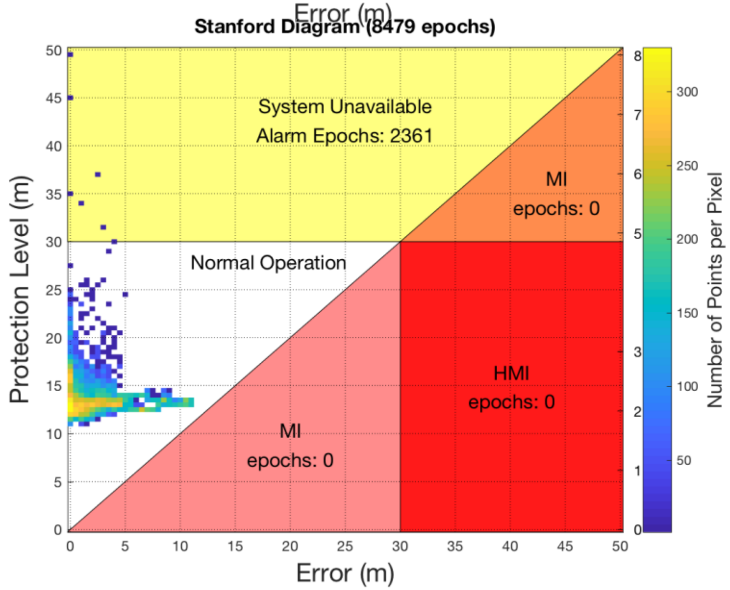
OFF



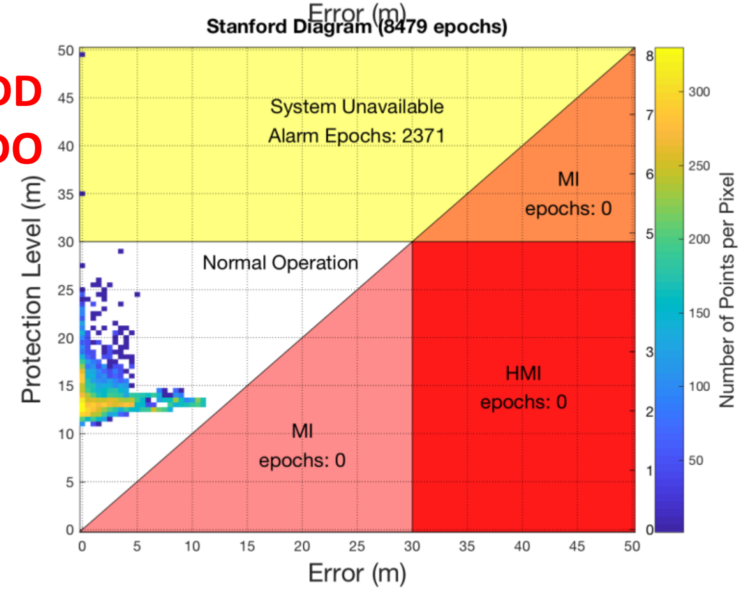
Doppler DD



ODO



Doppler DD + ODO



Conclusions

- **EXPLOITATION** of the two GNSS receivers of independent manufacturer usually deployed to reduce HW/SW Hazards allows to increase location AVAILABILITY even with single constellation
- **GEOREFERENCED KNOWLEDGE** of the railway is not essential when doppler are compared (pseudorange comparison requires a guess of the baseline between the receivers)
- **ODOMETER- GNSS DOPPLER comparison** is an effective means to face Multipath even when just one receiver is available
- **COMPARISON** of the positions provided by two receivers dramatically improves resilience.
- The proposed Multipath Detection & Exclusion is fully **COMPATIBLE** with other means to mitigate multipath.

Thank you for your attention

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