Collision Avoidance, Virtual Coupling of Trains, Autonomous Trains − Novel Train Localization Methods for Next Generation Railways

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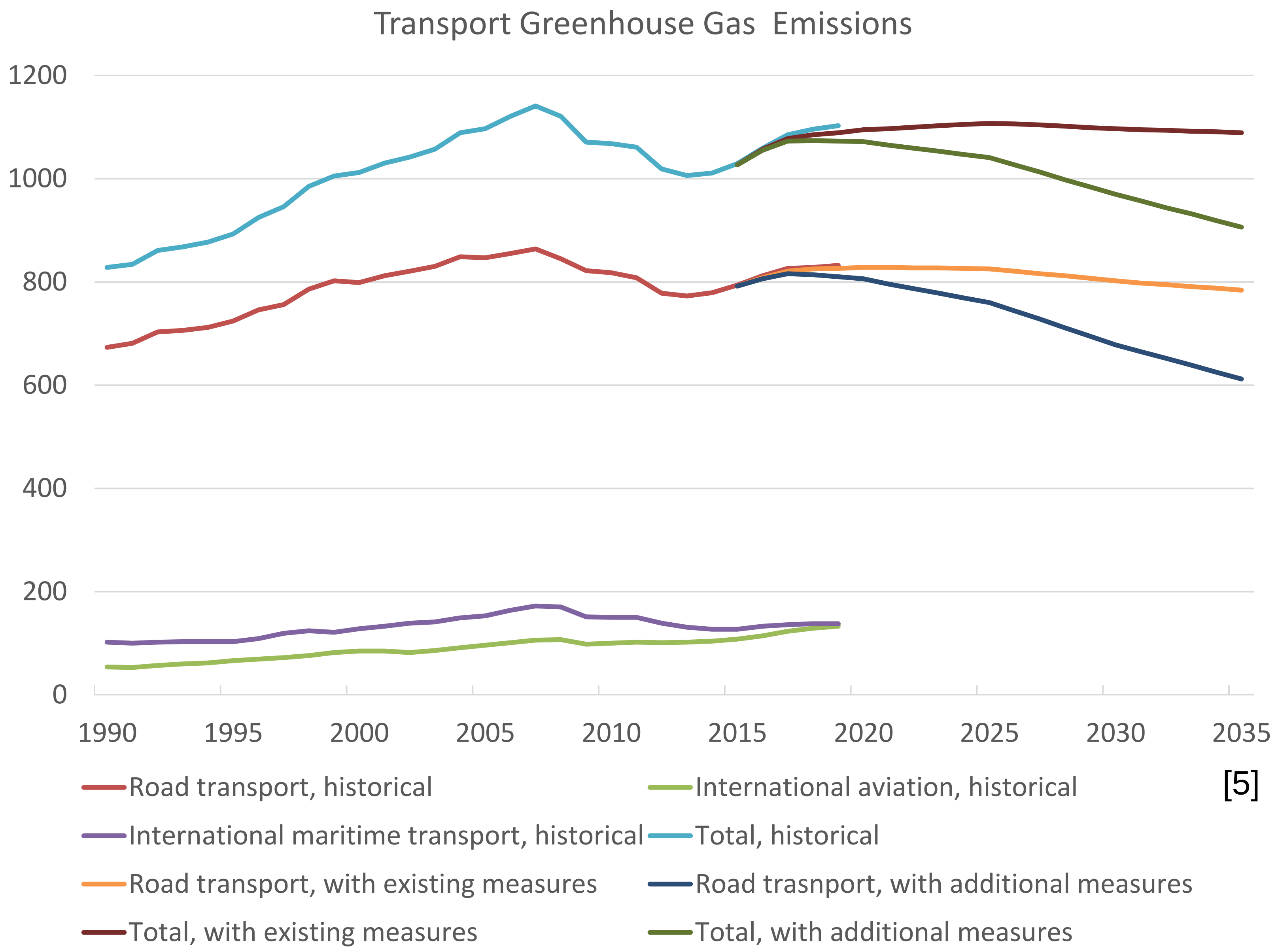
Motivation

Climate change:
Mitigate adverse effects on humans

- EU-27 greenhouse gas (GHG) emissions:
  - -55% of 1990 by 2030
  - Climate neutral by 2050
- Transport sector responsible for approx. 25% GHG emissions
  - Road 72%
  - Railways 0.5%

➔Shift traffic from road to rail



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Traffic Situation Road vs. Railway

Current situation in road traffic:

- 76% of freight, 92% of passengers
- Dense, efficient use of roads
- Many accidents, traffic jams, less energy efficient, 72% GHG emissions

Current situation in railway traffic:

- 18% of freight, 8% of passengers
- Inefficient use of railways: traditional safety systems
- Safer, more energy efficient, 0.5% GHG emissions

Railways Today

Communications systems:

- Analog train communication: Narrowband-FM
- TETRA
- GSM
- GSM-R:
  - 1992 Standard maintained by International Union of Railways
  - Data transmission for European Train Control System (ETCS)

➔ Replacement by 2030 with Future Railway Mobile Communication System based on 5G

Track side localization systems:

- Axel counters:
  In and out of section
- Balise/Magnets:
  Train on top of equipment
- Cable loops:
  cross over every 100m
  ~ 100m accuracy

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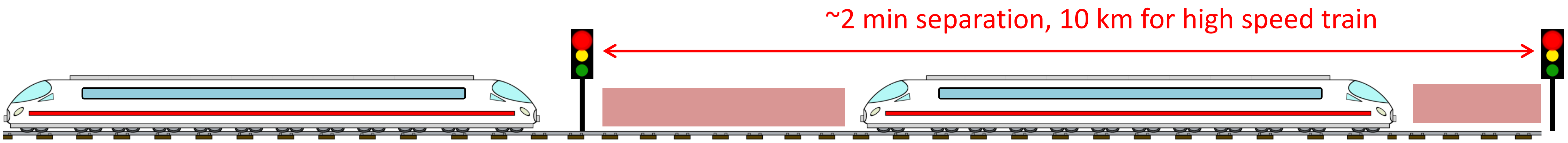
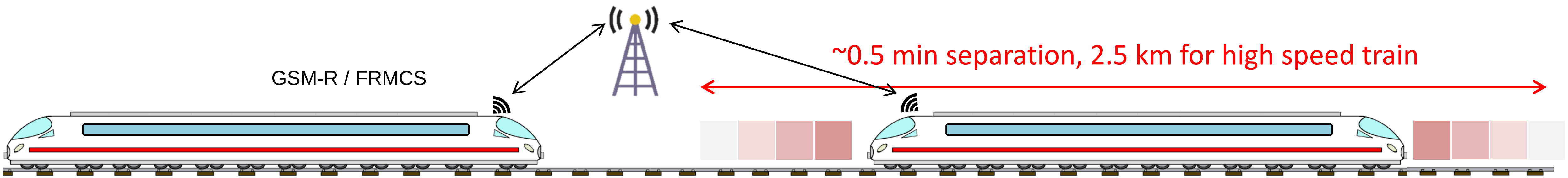
[9]

Railway Safety Systems: Today and Future

Classic safety system: Interlocking system, European Train Control System (ETCS) Level 2, GSM-R



Future safety system: Moving Block, ETCS Level 3, GSM-R, reliable onboard train localization



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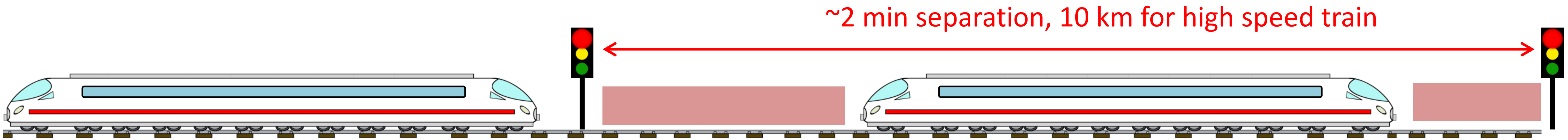

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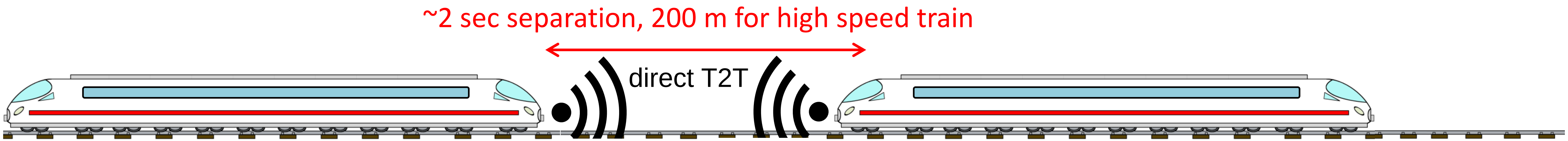
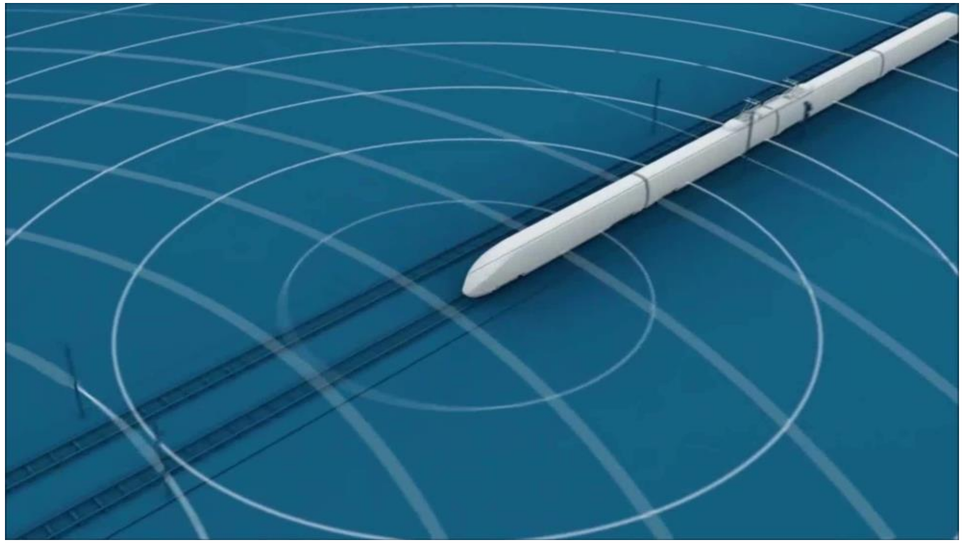


Virtually Coupled Trains: Platooning, direct train-to-train (T2T) communication, reliable onboard train localization

Next Generation Railways

- **Goal:** Use existing tracks more efficiently without reducing safety
- **Approach:** Train-to-Train (T2T) communication and reliable onboard train localization
- **Applications:**

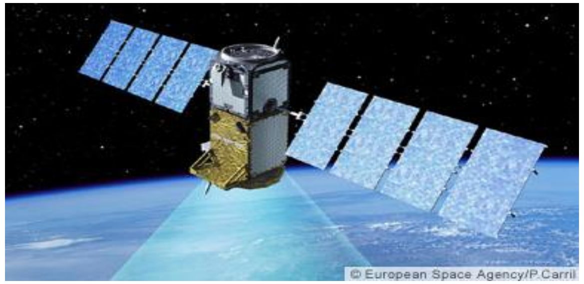
Autonomous trains: Collision avoidance



intelligence on wheels

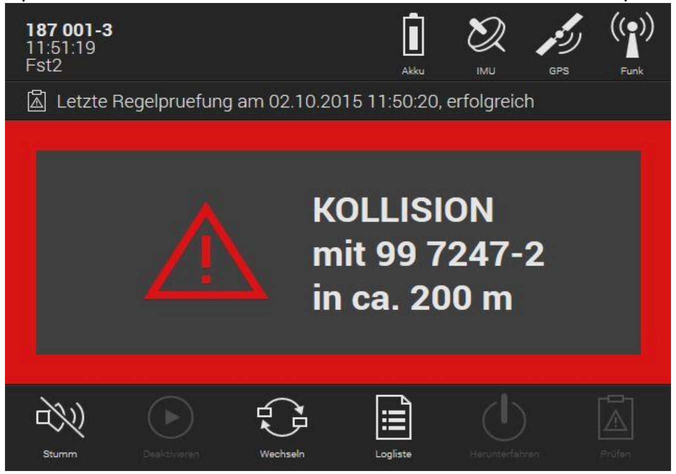
Next Generation Railways Today
Collision Avoidance − Driver Assistance

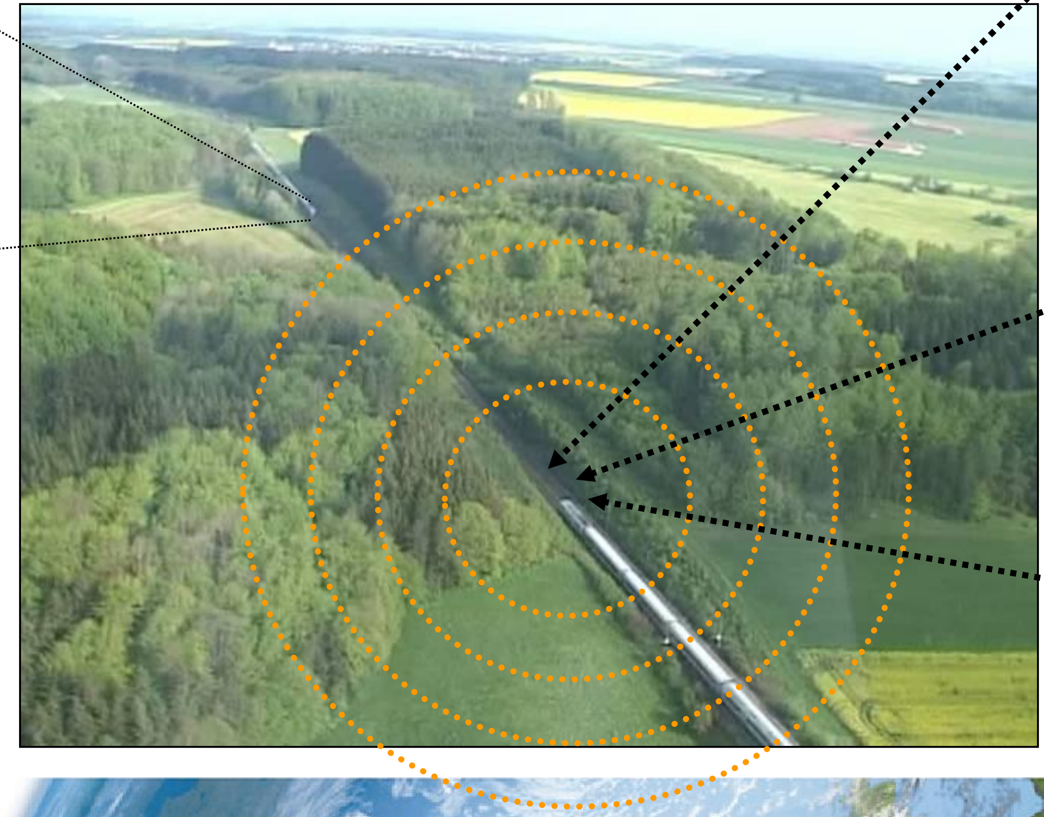
- Developed by DLR and
- DLR Spin-Off Intelligence on Wheels
- Transfers TCAS-System from aviation to railways



Galileo/EGNOS

+





Sensors
(IMU, Mag, …)

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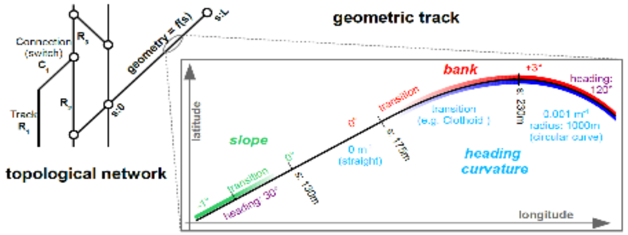


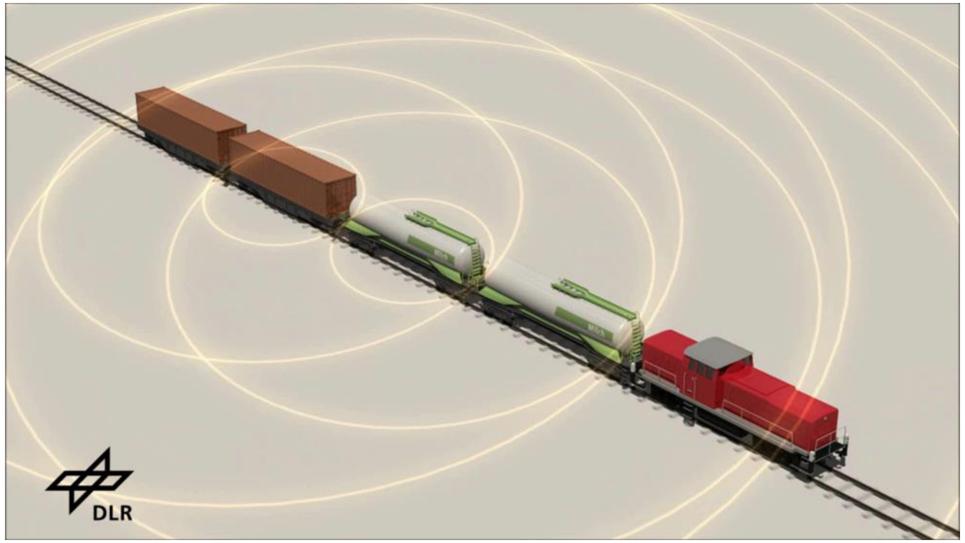
Digital Map

DLR

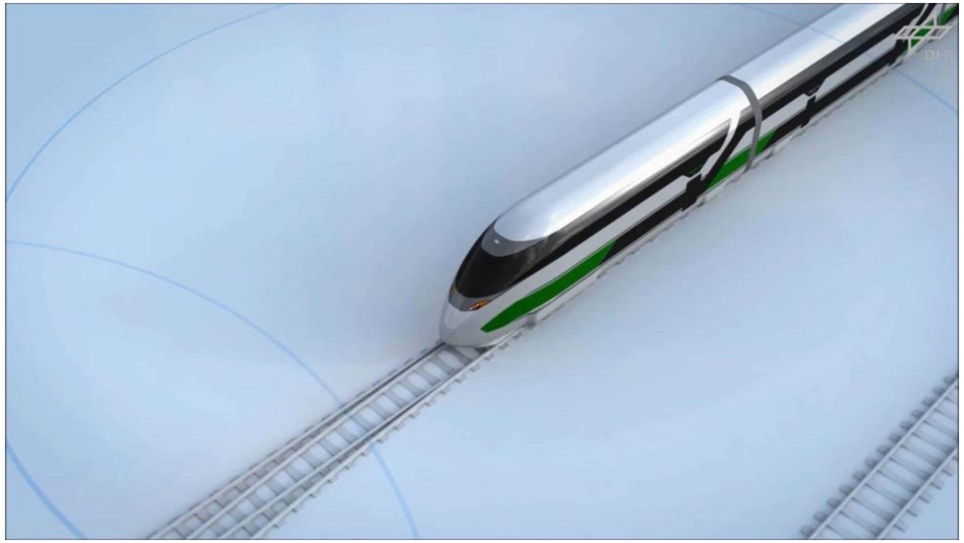
Next Generation Railways

- **Goal:** Use existing tracks more efficiently without reducing safety
- **Approach:** Train-to-Train (T2T) communication and reliable localization
- **Applications:**

Automatic train coupling



Virtual coupling



Train Localization with Onboard Sensors

Sensors

- GNSS receiver
- IMU
- Magnetometer

Map

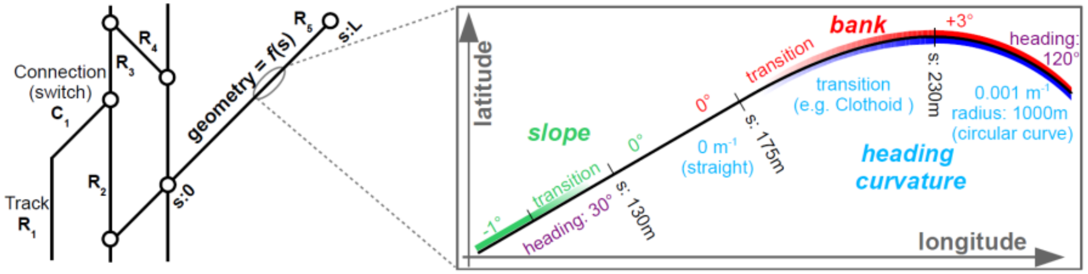
- Topological coordinates
  - Track ID
  - Track position

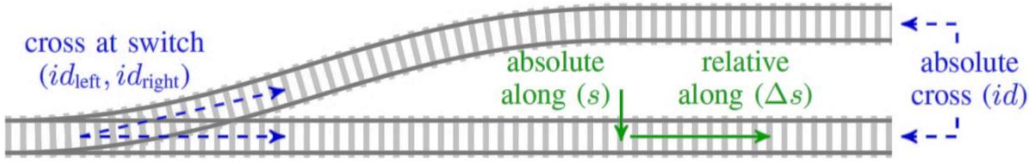
Methods

- INS
- Signature based localization
- Multi sensor fusion

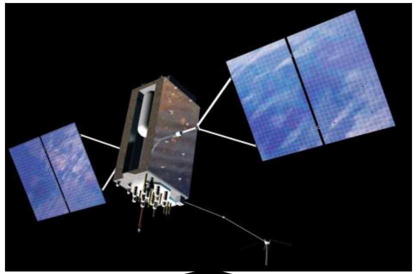
Evaluation

- Measurement campaigns
- Ground truth reference
- Analysis:
  - Accuracy
  - Availability





Why not simply use GNSS?



Blocked

[10]

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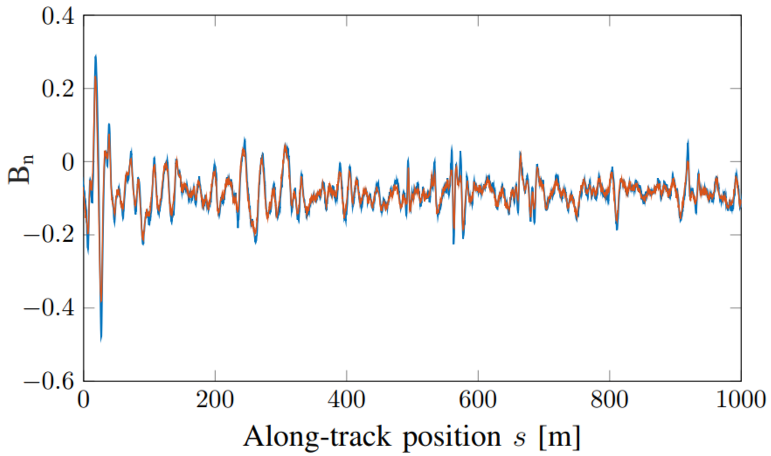
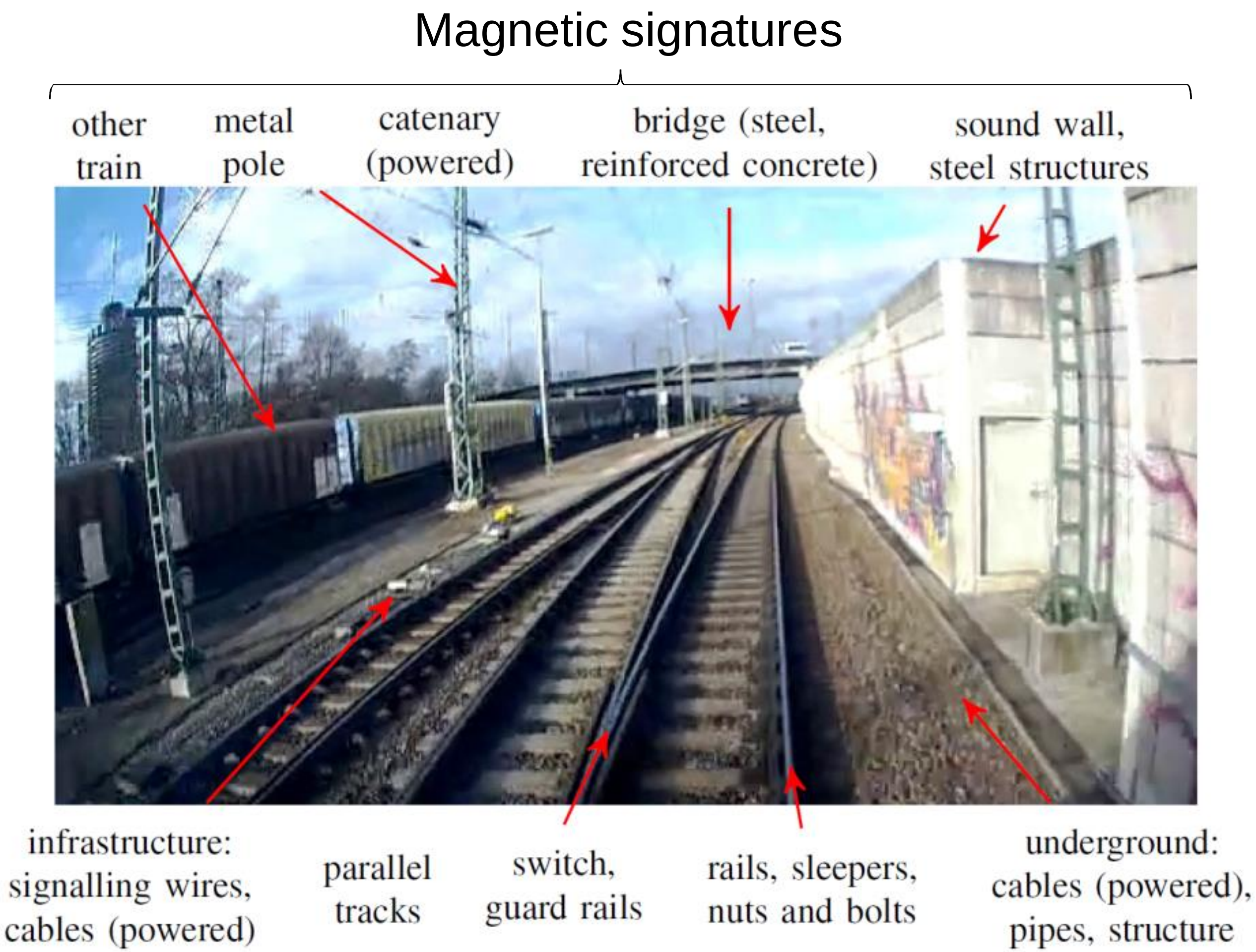
➡ **GNSS signals not available or strongly degraded**

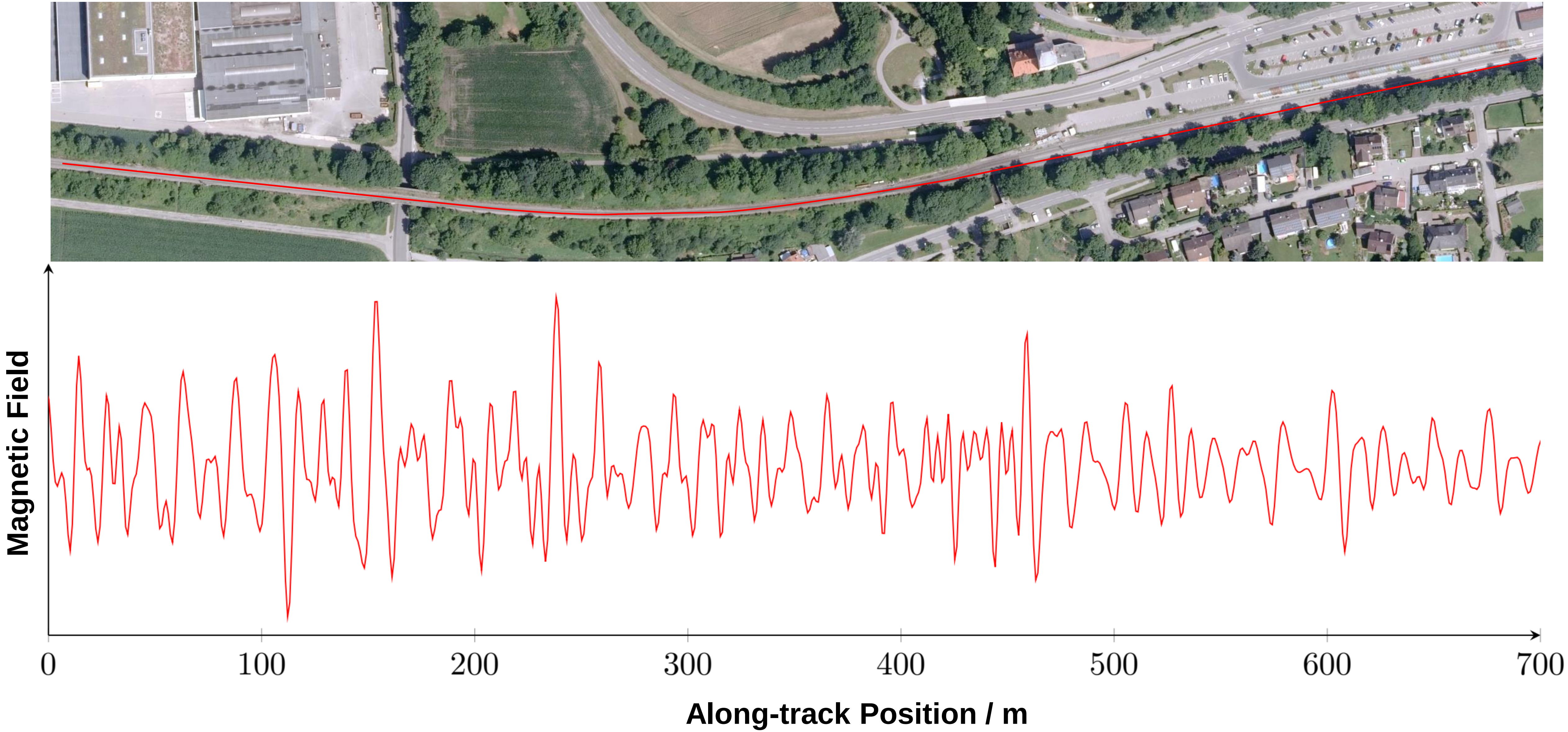
Magnetic Field in Railway Environments

- Ferromagnetic materials
  ➔ distortions of earth magnetic field
- Distortions location dependent and characteristic for specific part of track
  ➔ magnetic signatures
- Magnetic signatures: time invariant for days/weeks
  ➔ Map magnetic signatures for train localization





Magnetic Signatures of Railway Tracks



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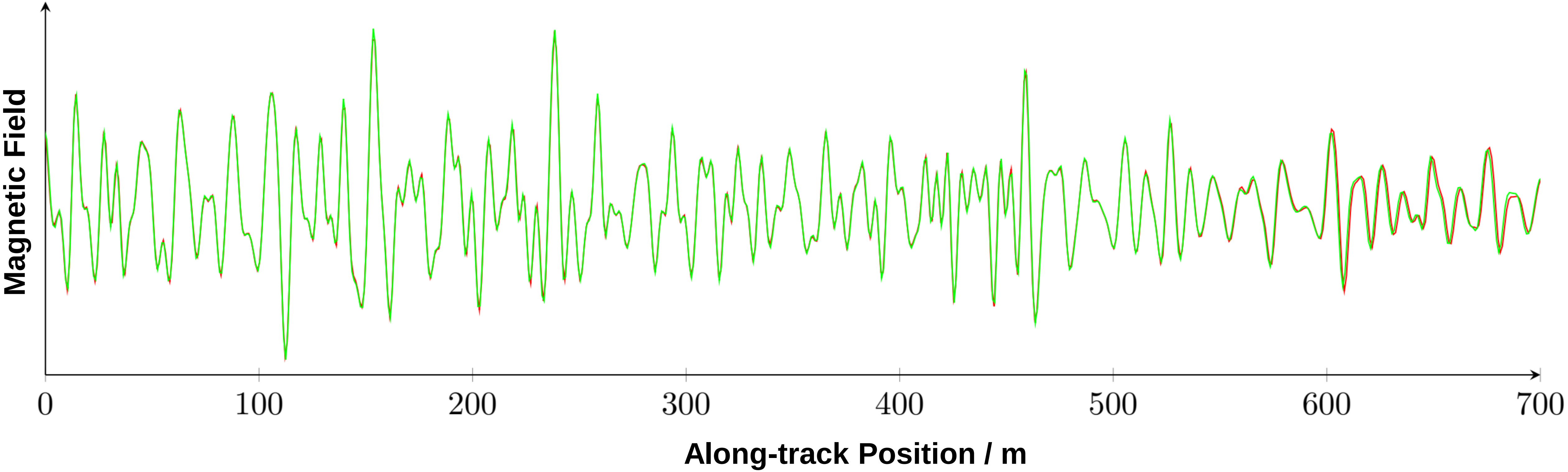

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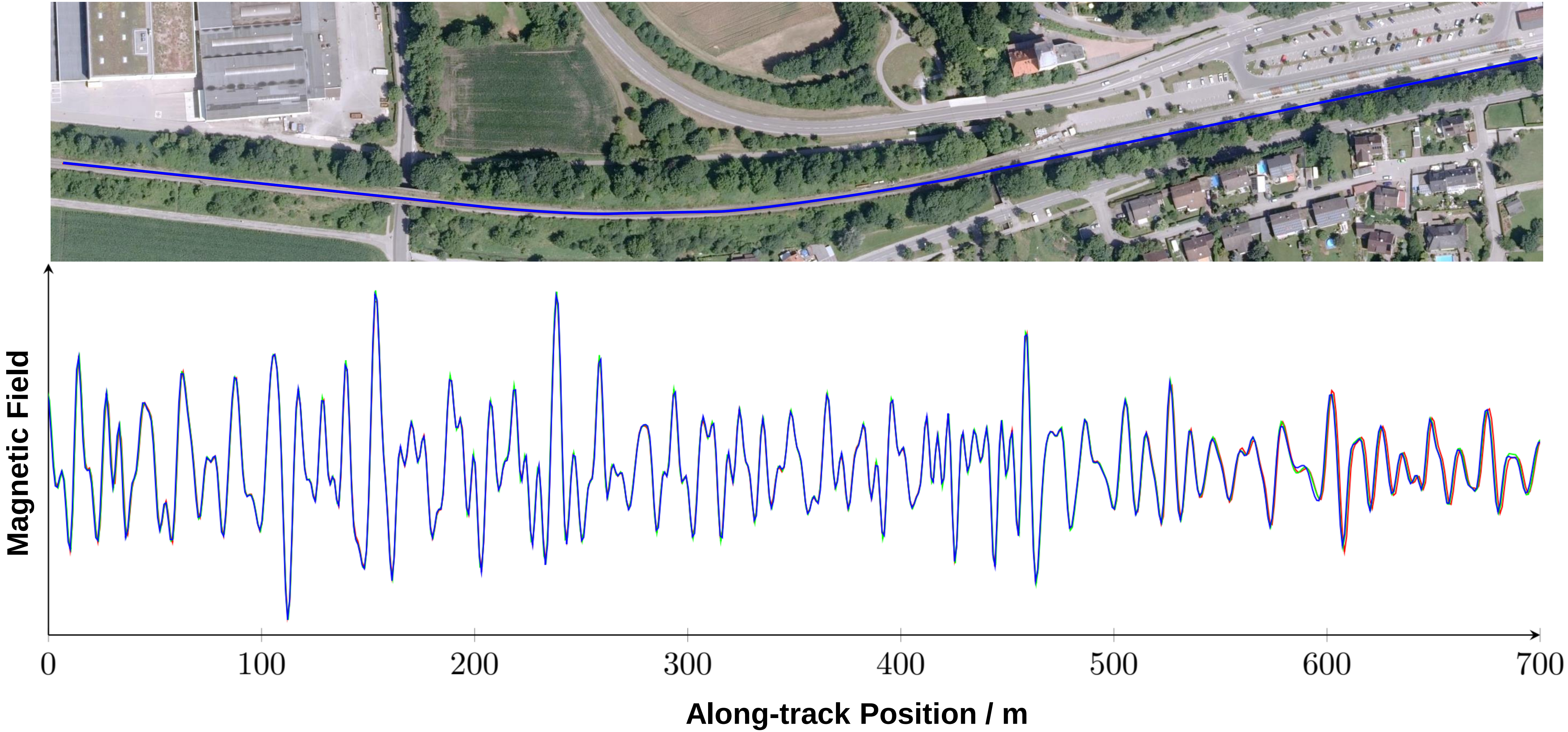

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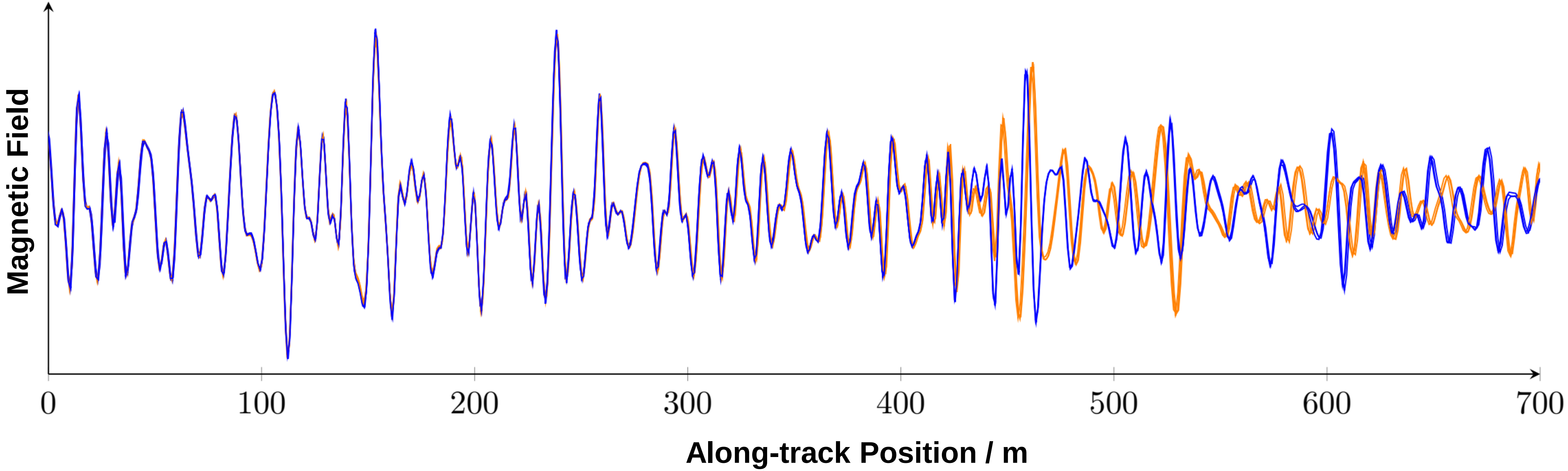
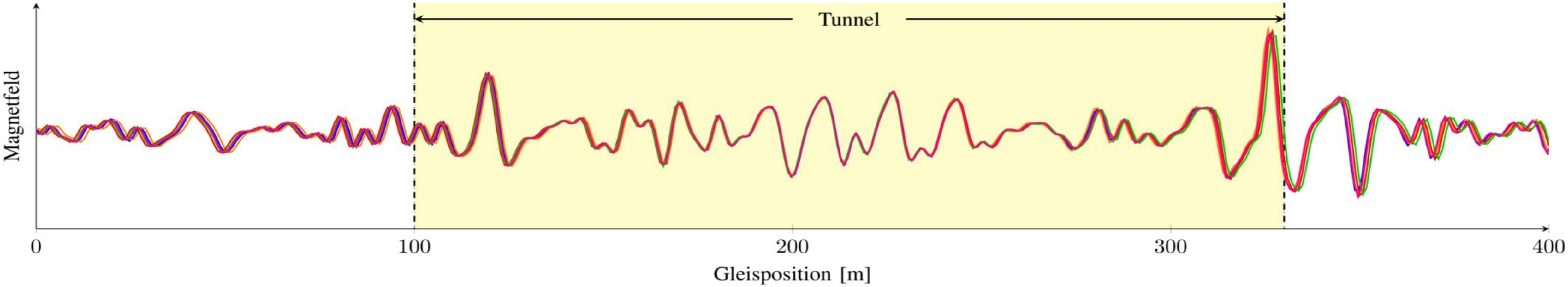


Magnetic Signatures in Tunnel

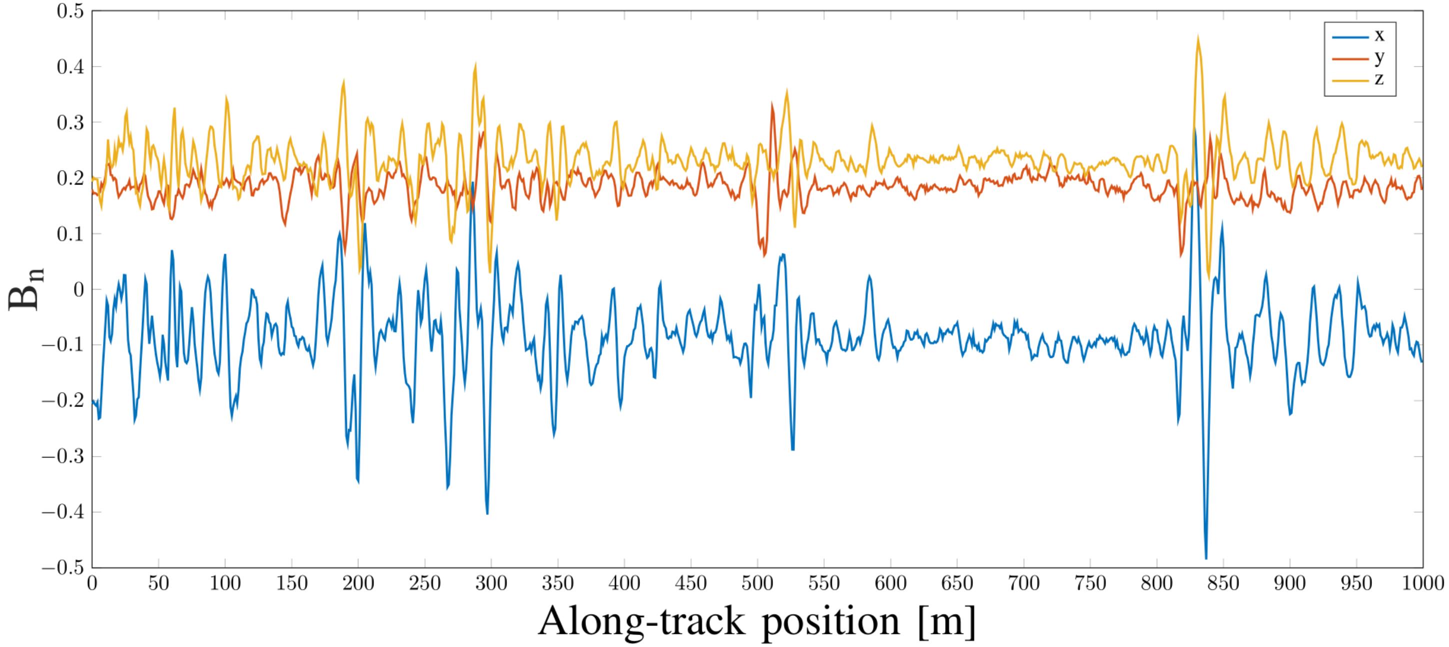


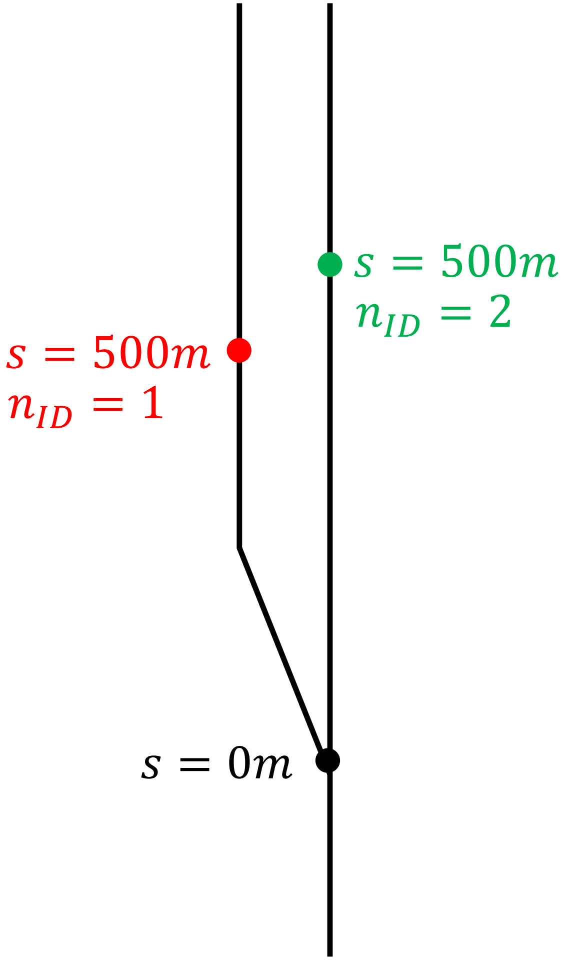
5 runs through tunnel overlayed ➔ localisation in tunnel possible

Magnetic Signatures: Map Creation

Map:

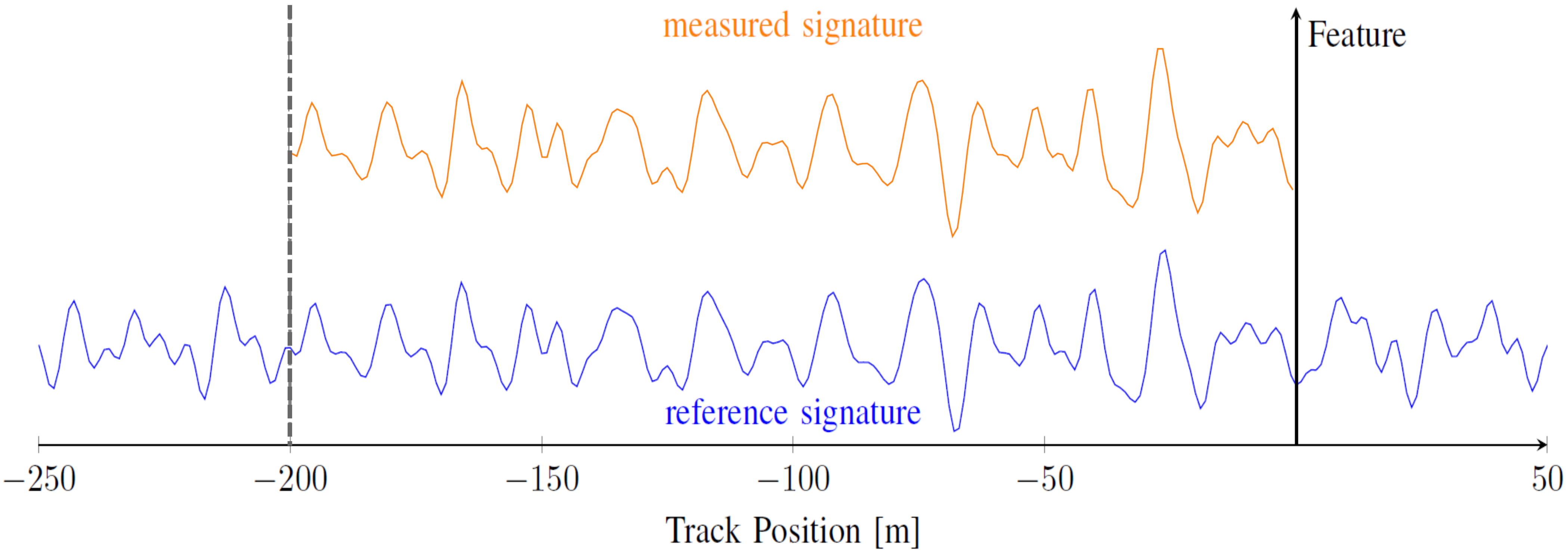
- 1-D along-track position and track number
- Magnetic vector field





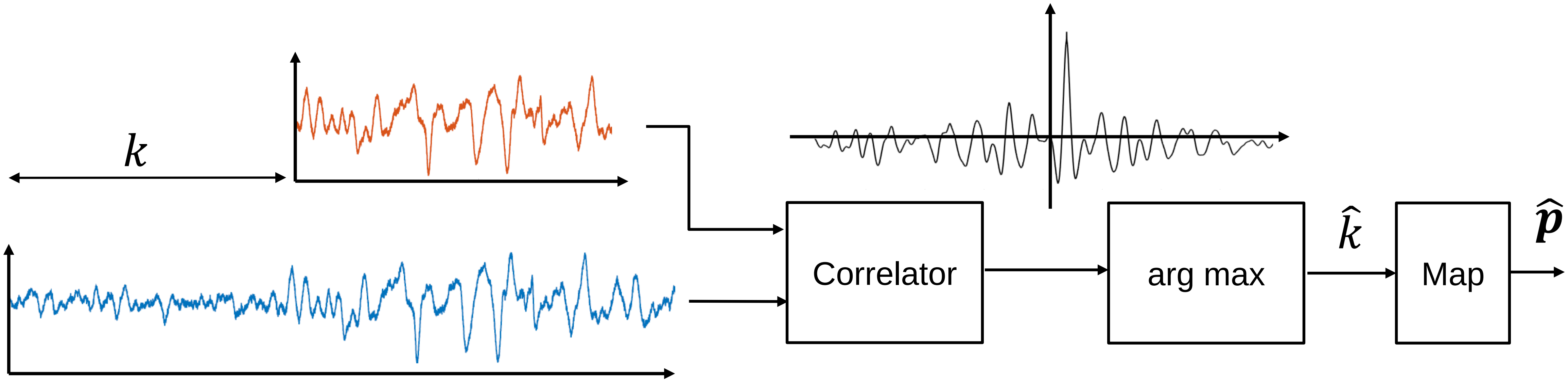
Along-track position

Magnetic Signatures: Signature Matching



Magnetic Signatures: Signature Matching and Position Estimation

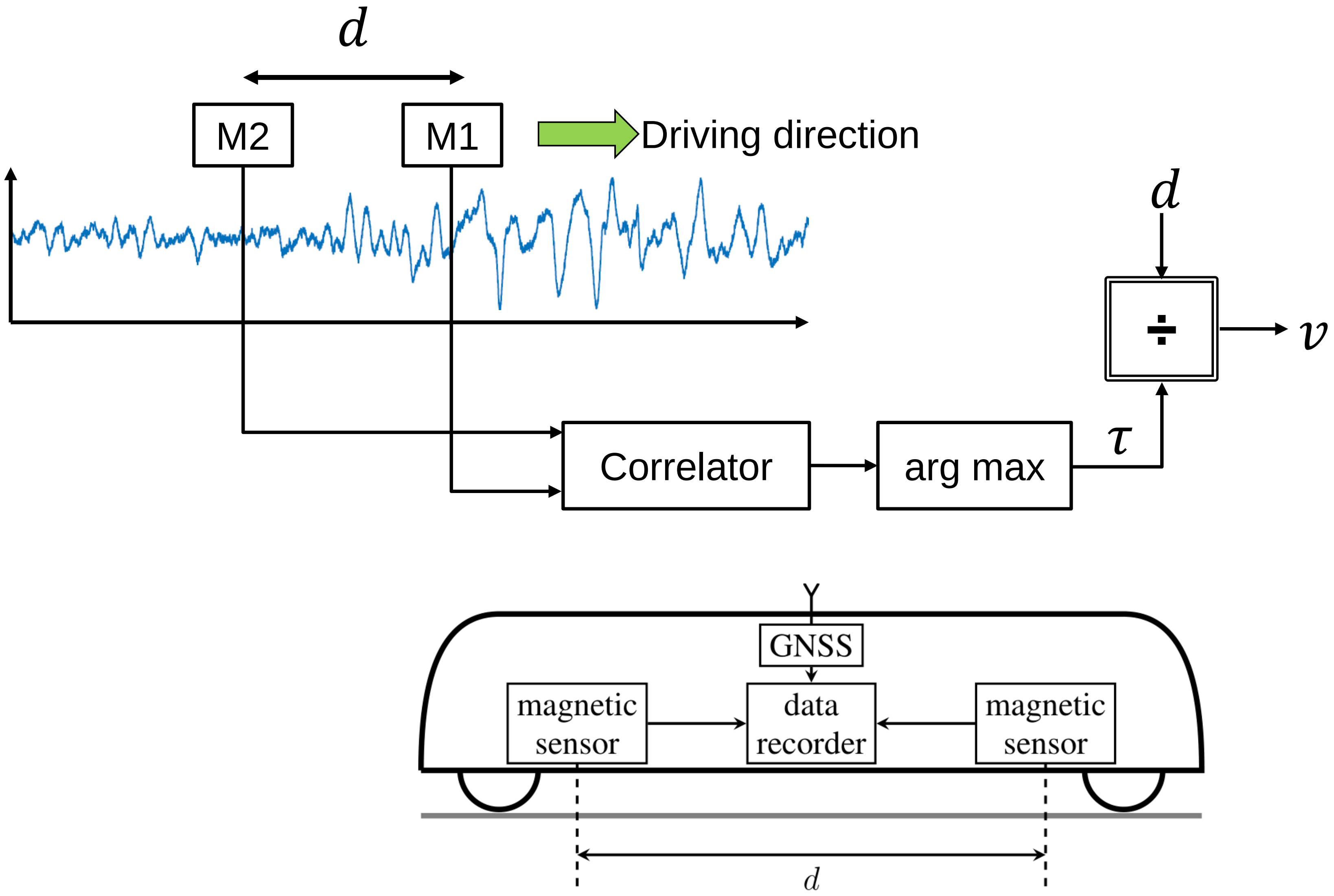
- Spatial transform: Direct comparison of map and online signature
- Matching: Simple cross correlation
- Position estimate: Lag with the highest correlation value



Magnetic Signatures: Speed Estimation

- Train driving with speed v
- Two magnetic sensors at fixed, known distance d
- 2nd magnetic sensor measures same magnetic signatures with delay $\tau = d / v$

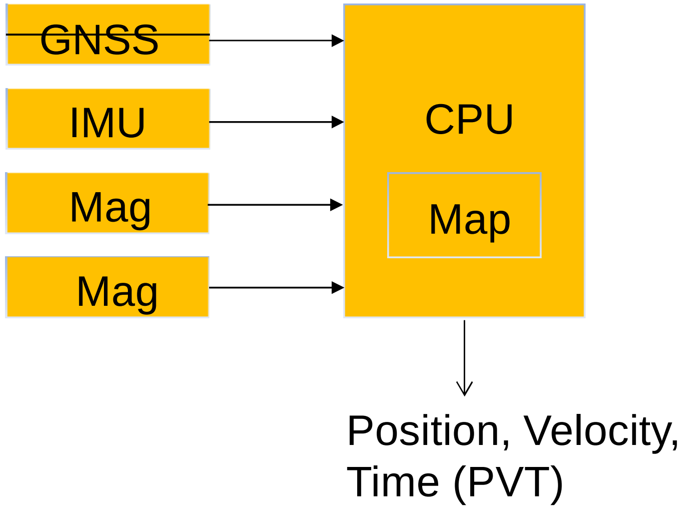
➔ Speed estimation $v = d / \tau$

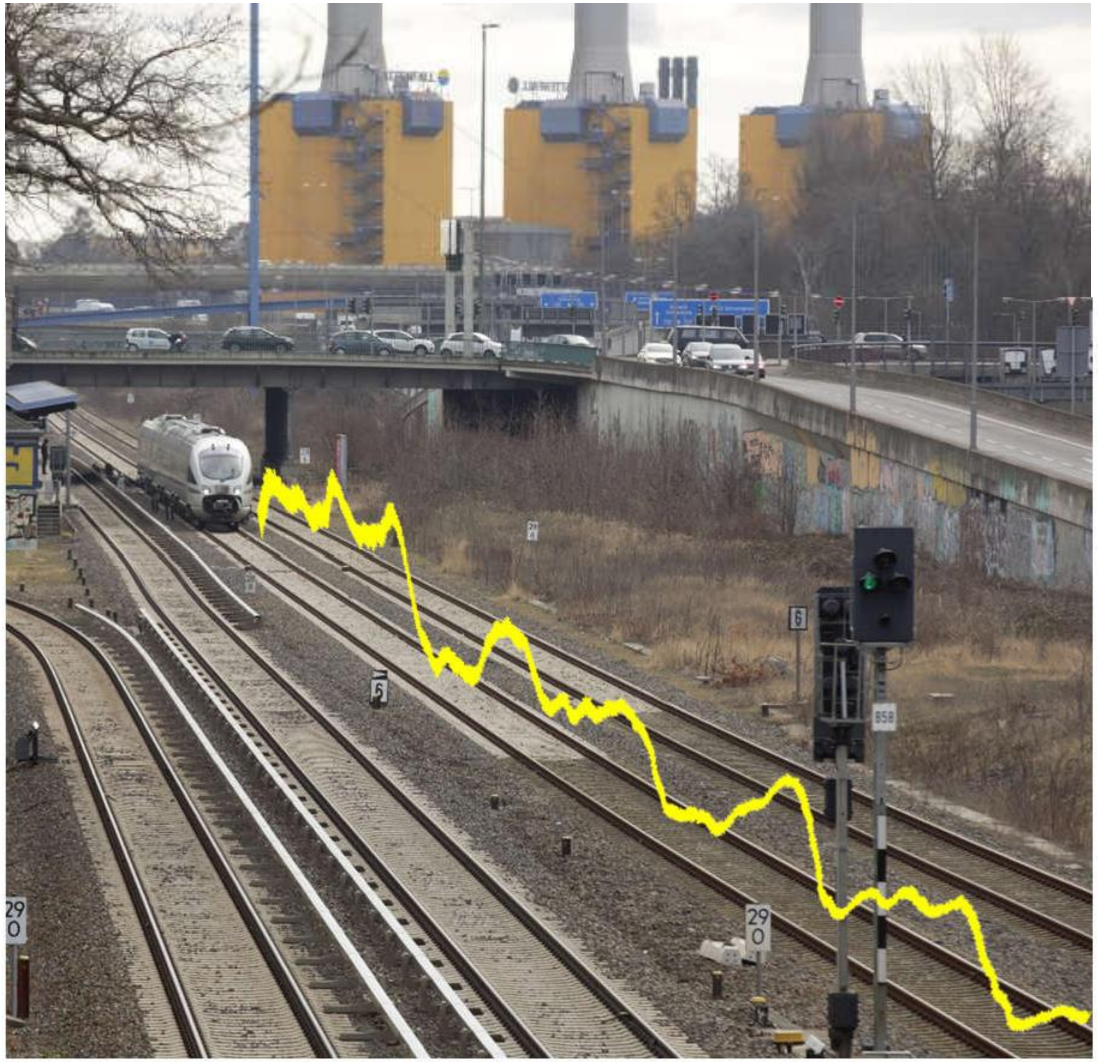


Magnetic Signatures: GNSS Independent Localization

1x Magnetometer + Map → Position

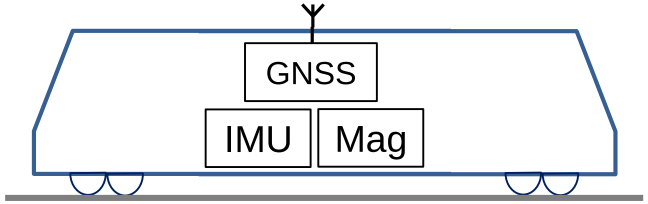
2x Magnetometer → Speed



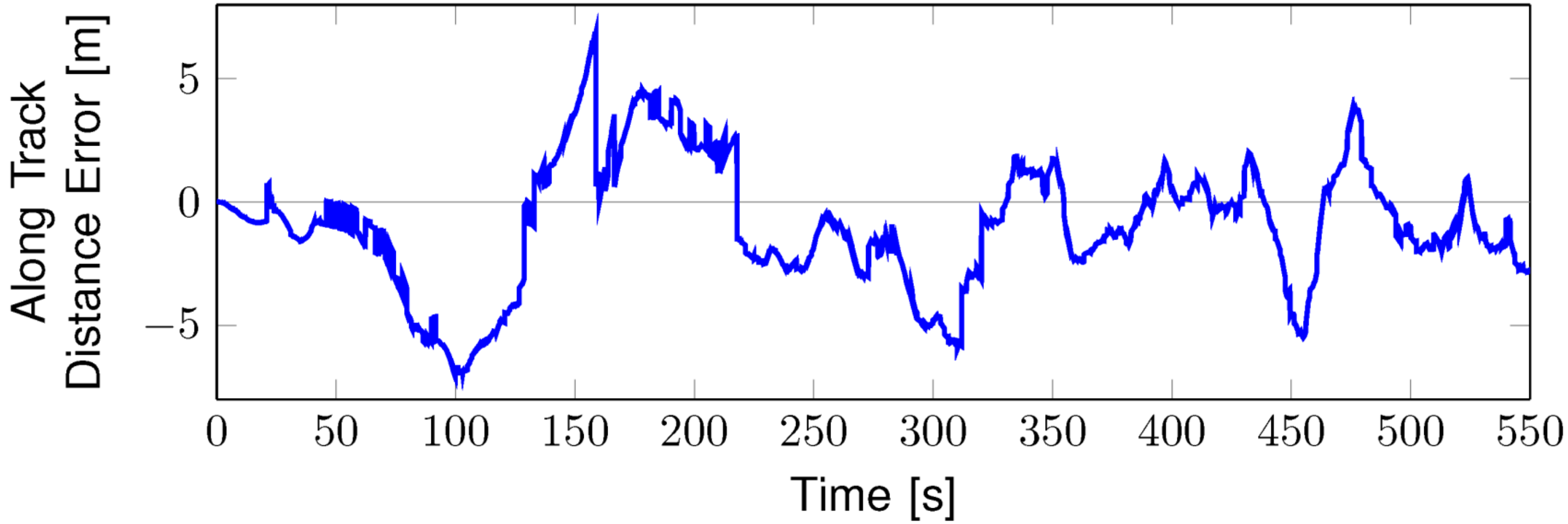


Bounding INS Positioning Errors with Magnetic-Field-Signatures [13]

- Sensors on cabin floor of diesel train
- Train driving in rural area
- Speed 0-50 km/h
- IMU KVH 1750 @100Hz
- 2 Xsens MTi-G-700 magnetometers 100Hz
- Reference: GNSS receiver u-blox LEA-M8T
- Evaluation on 13 km track

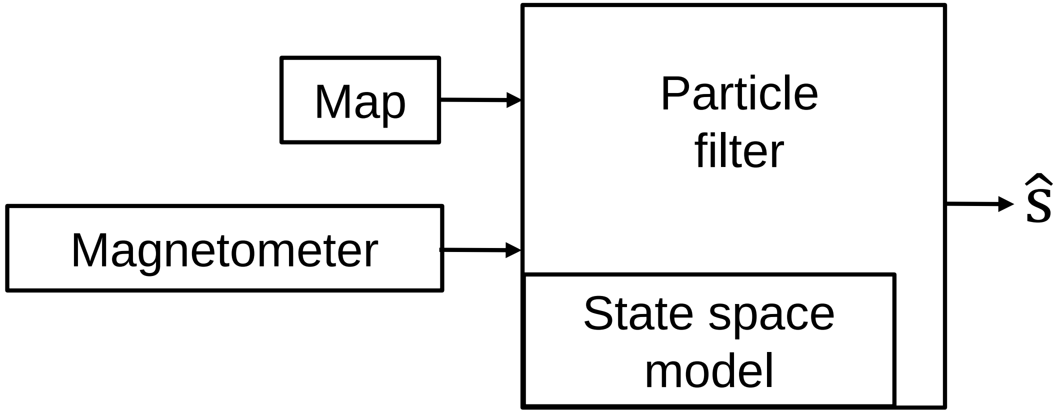


- Error state Kalman filter (ESKF) input: Inertial navigation system (INS), map-based magnetic signature matching, and speed estimation

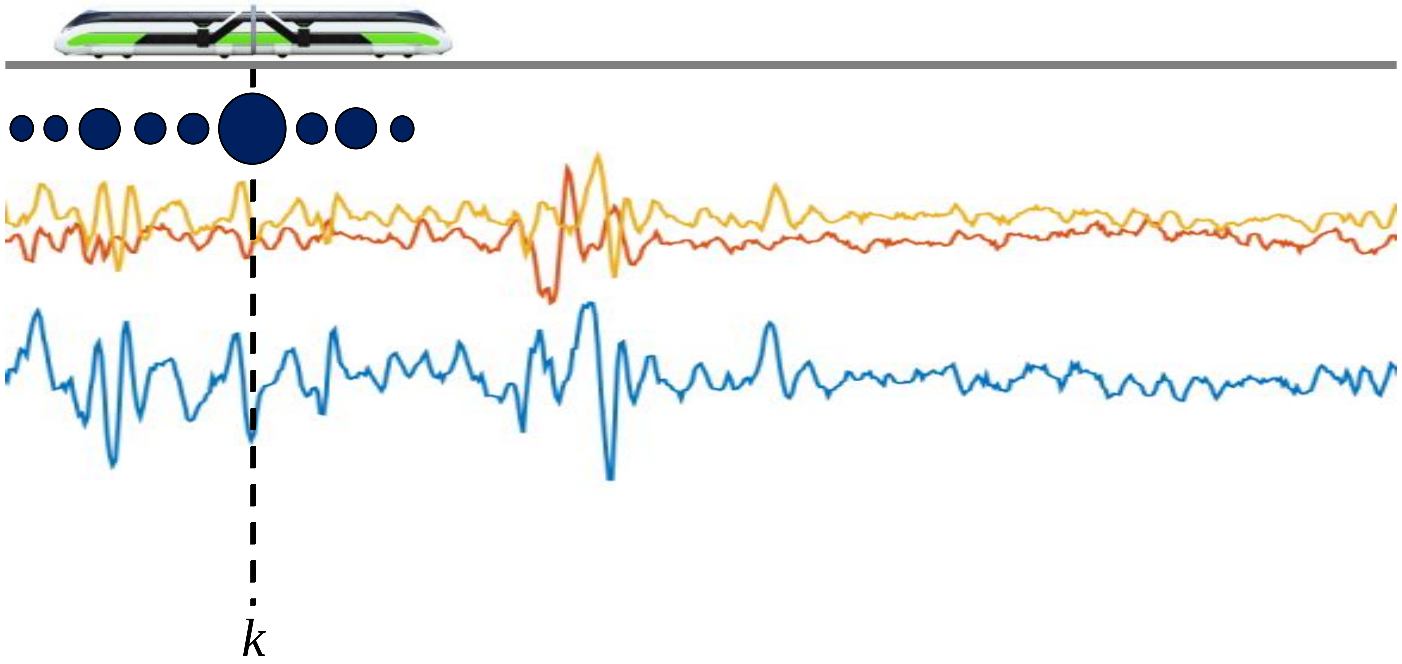


➔ RMSE < 3.7 m

Along-track Position Estimation with Particle Filter



$$\mathbf{d} = \begin{bmatrix} s & \dot{s} & \ddot{s} \end{bmatrix}^T$$



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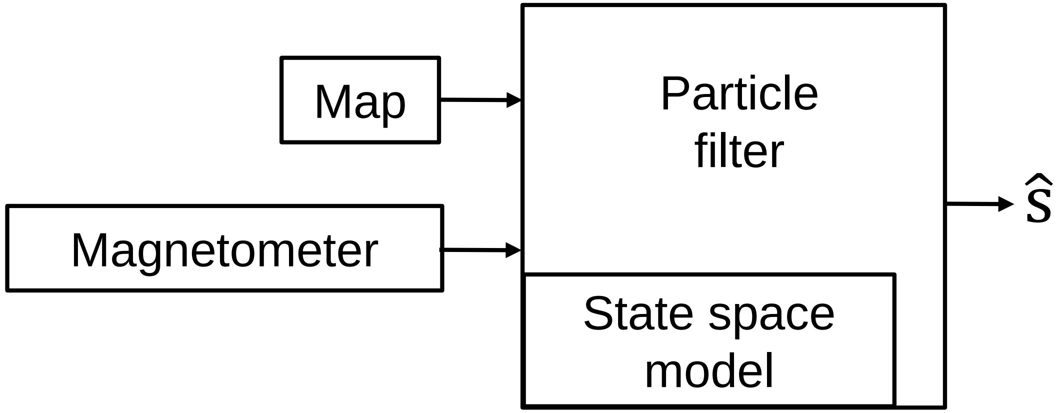

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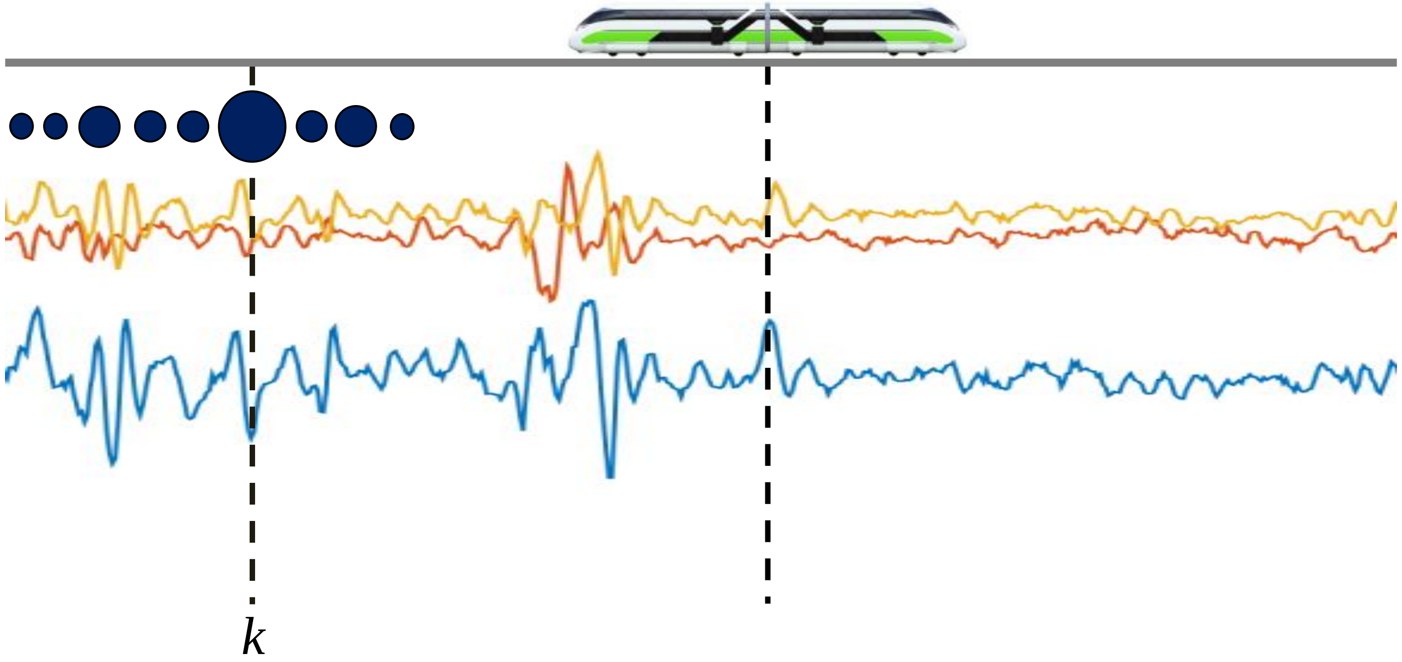

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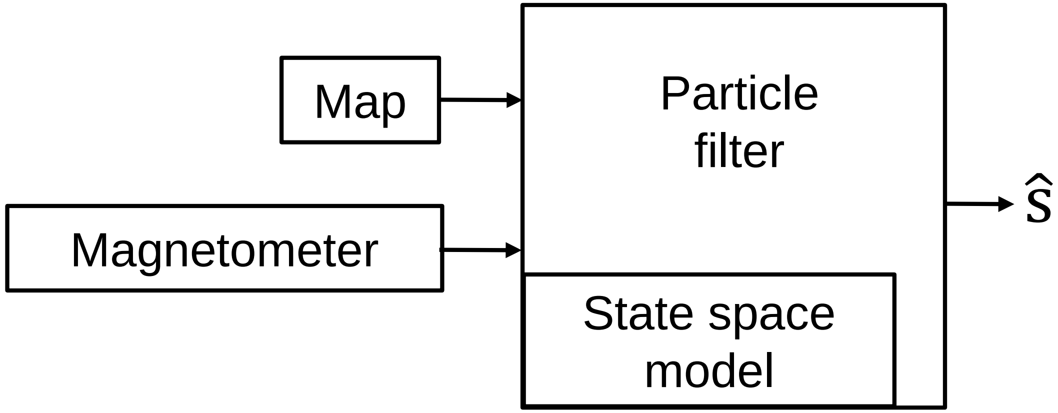

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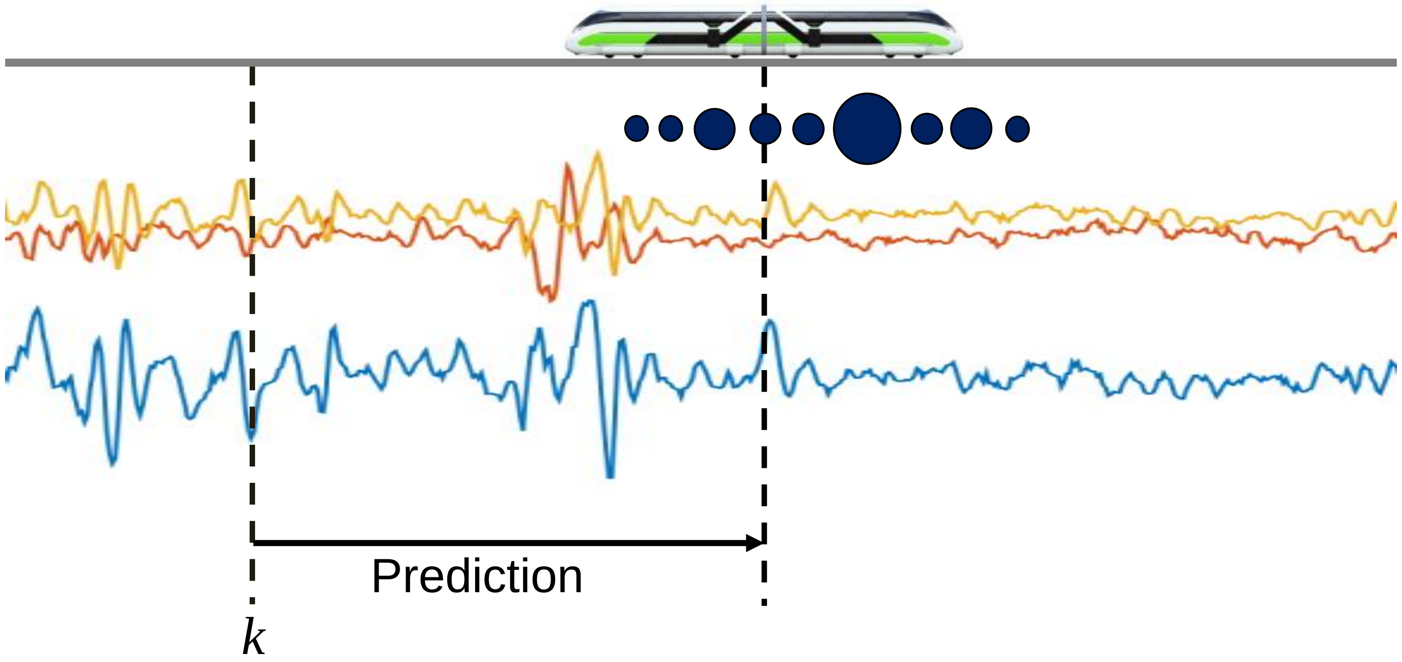

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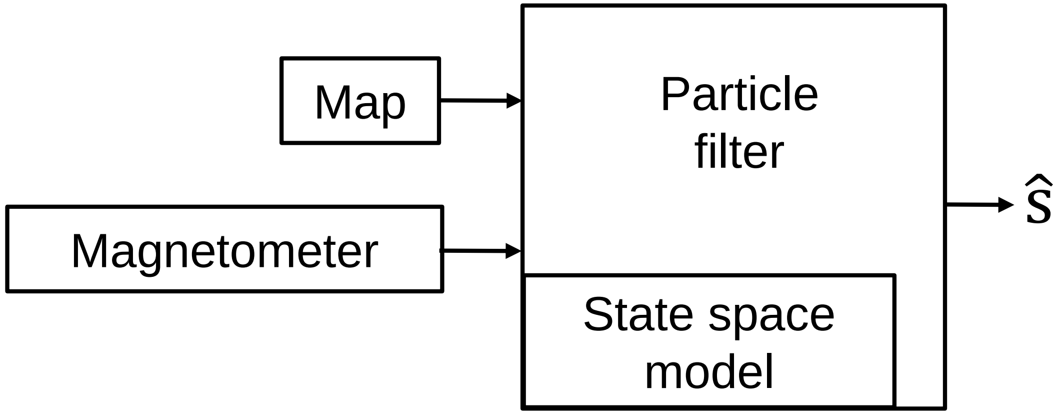
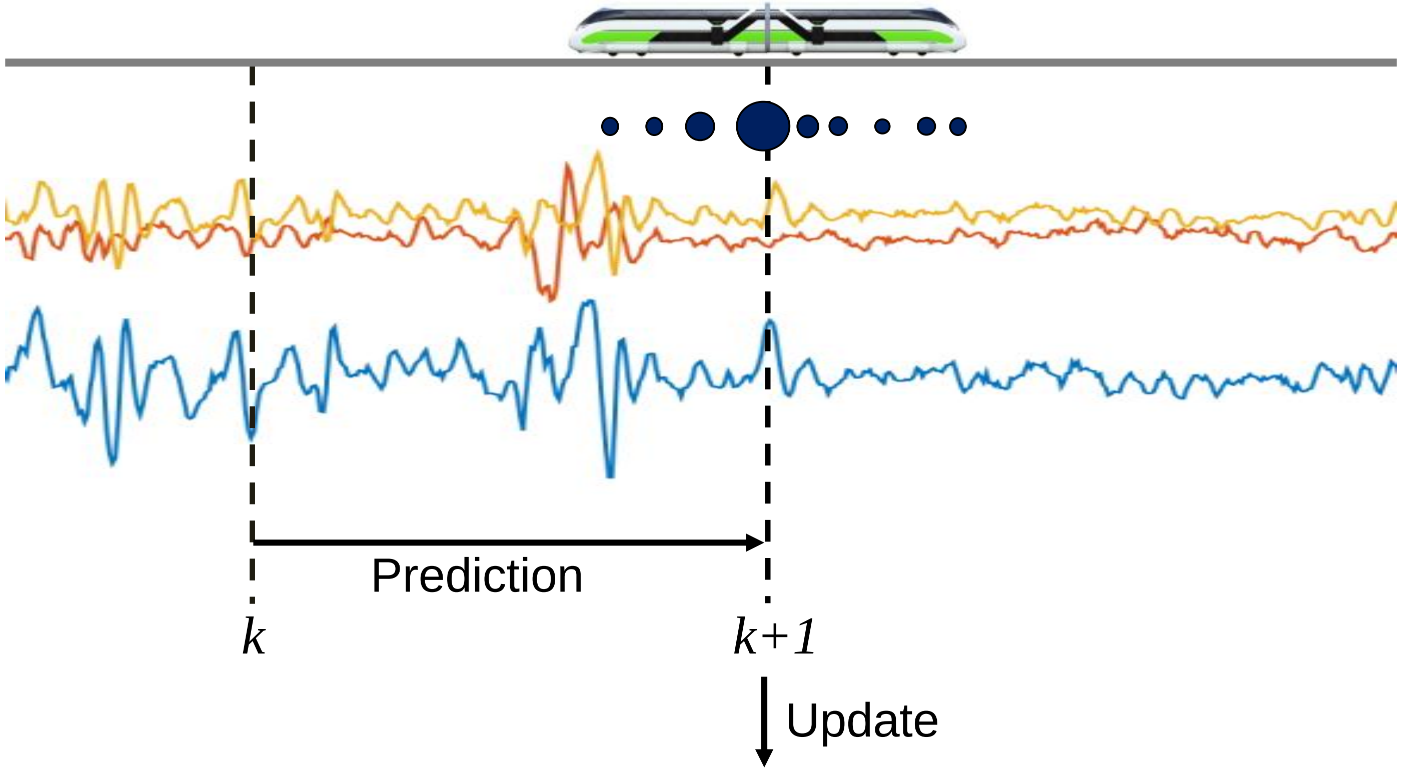




$$\mathbf{d} = \begin{bmatrix} s & \dot{s} & \ddot{s} \end{bmatrix}^T$$

$$w_{k+1}^i \propto w_k^i \cdot p(\mathbf{z}_{k+1} | \mathbf{d}_{k+1}^i, \mathrm{m})$$

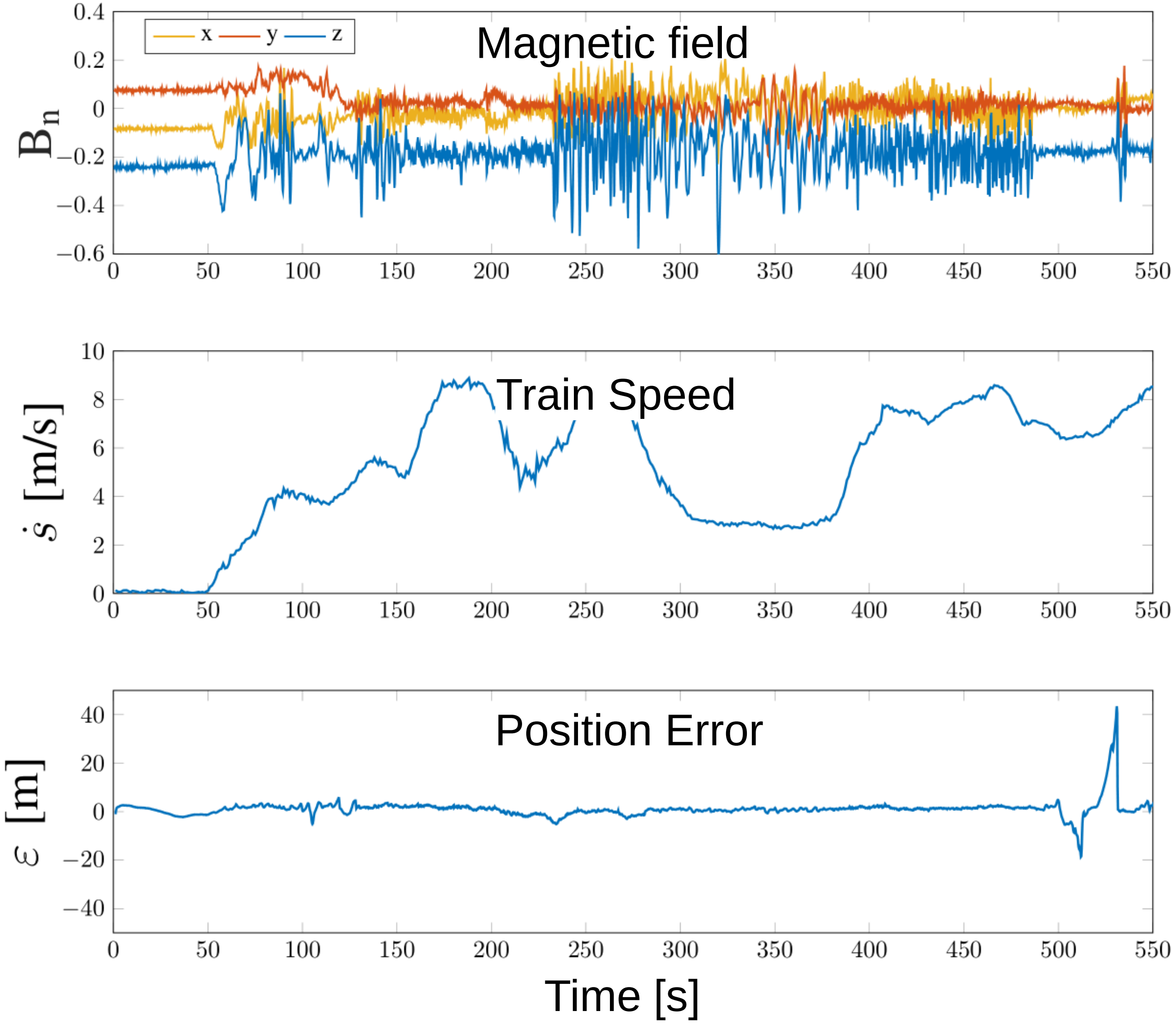
➡ **Nonlinearities: Sampling importance resampling (SIR) particle filter**

Train Localization with Particle Filter and Magnetic Field Measurements [14]

- SIR particle filter:
  - 2000 particles, 10 Hz update rate
  - Real time on PC in MATLAB

- Speed RMSE < 0.5 m/s

- Position RMSE < 5.5 m



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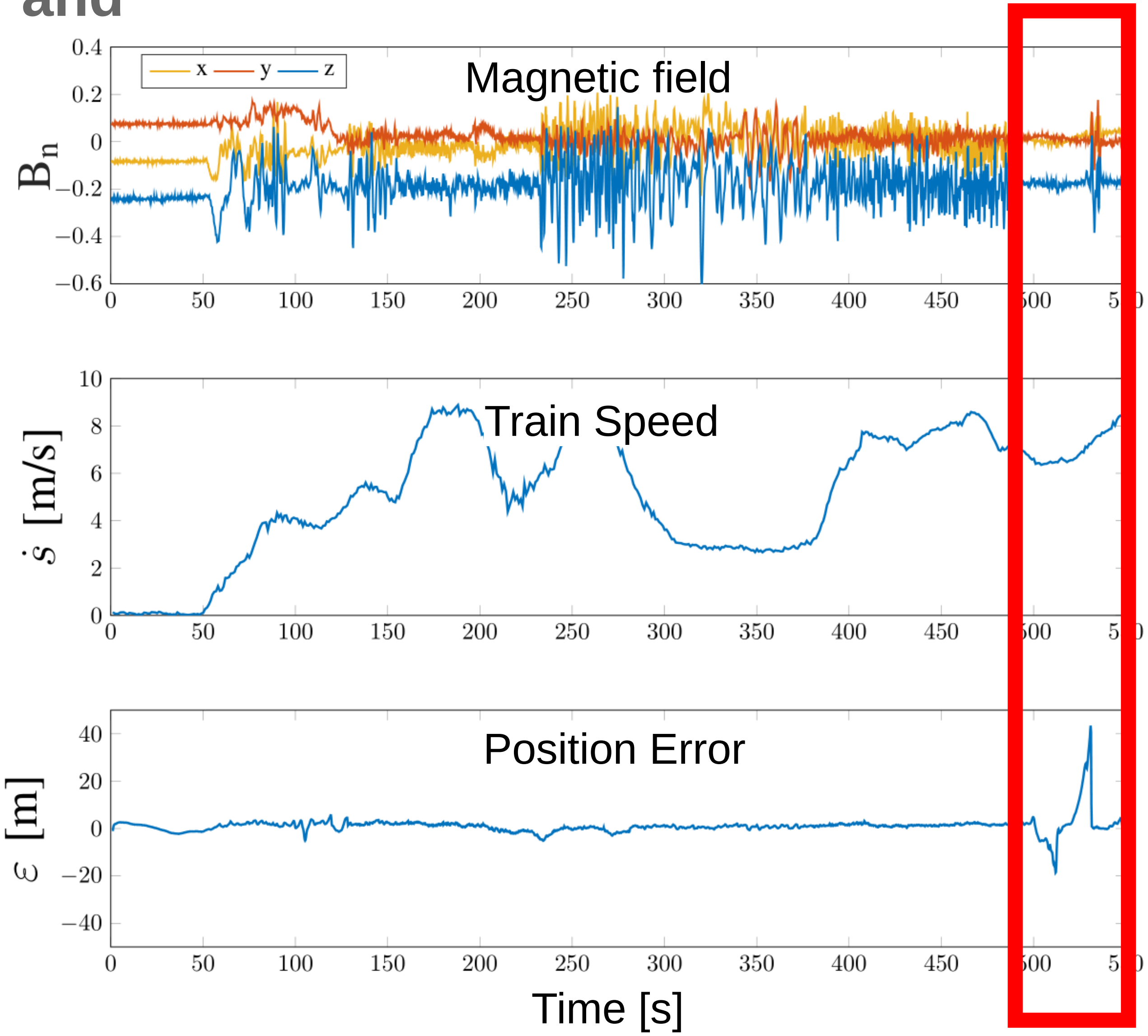

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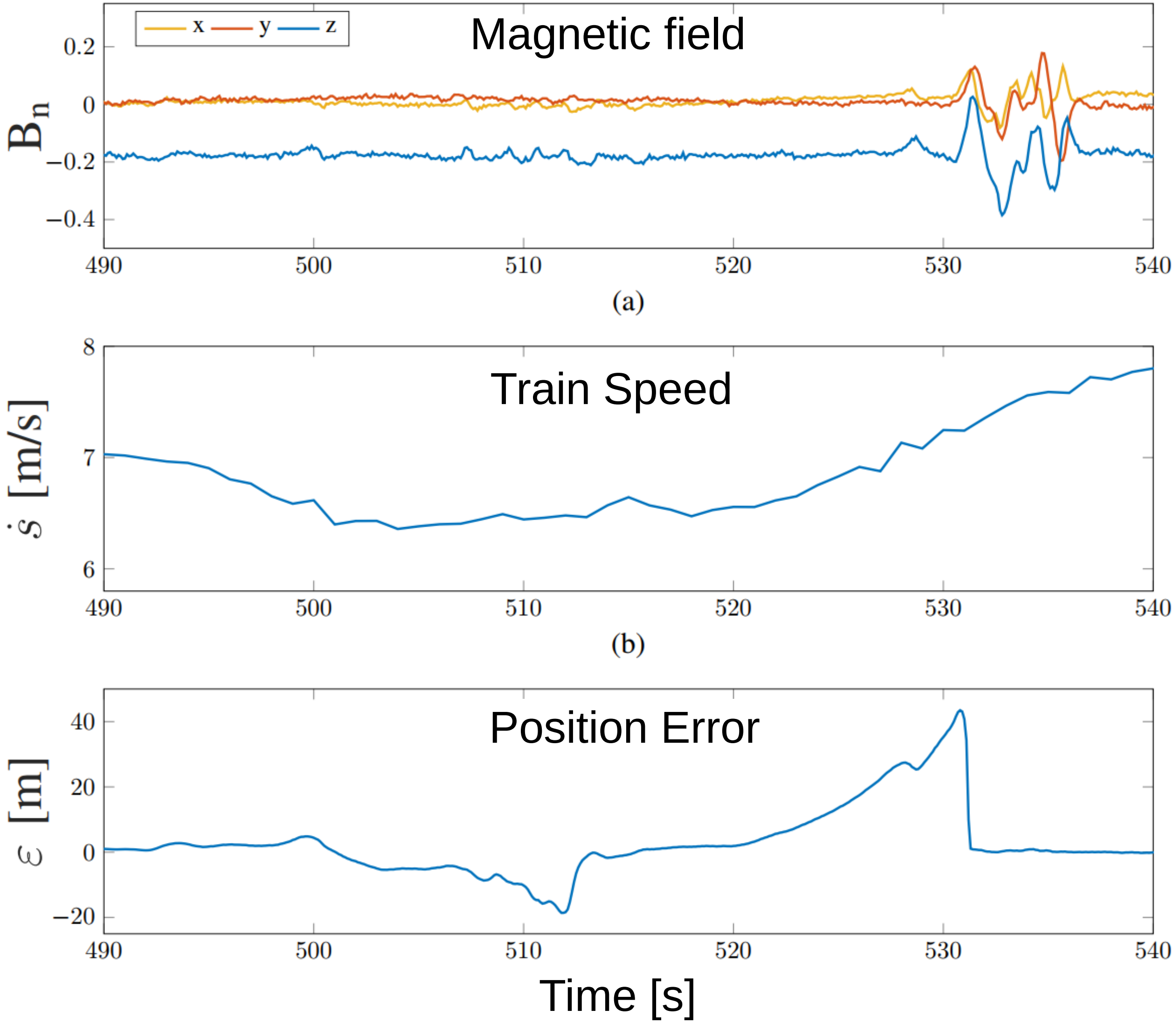


Joint Train Localization and Track Identification based on Earth Magnetic Field Distortions [15]

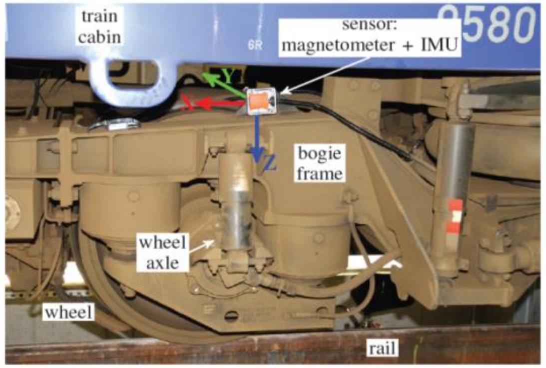
- Magnetometer triad, 1 accelerometer in driving direction, and map of magnetic signatures

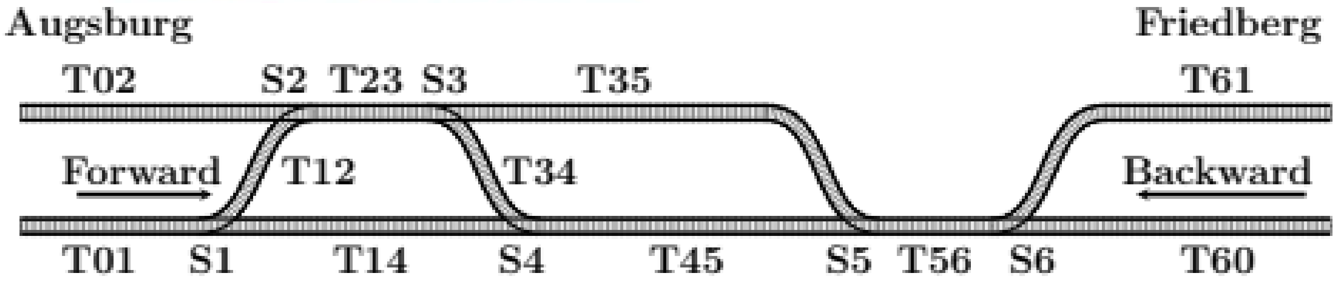
- SIR particle filter:
  - 3000 particles, 10 Hz update rate
  - Real time on PC in MATLAB
  - Switch:
    1. Copy of particle filter for hypotheses: “left switchway”, “right switchway”
    2. Likelihood ratio test to remove hypothesis

- Speed RMSE < 0.4 m/s

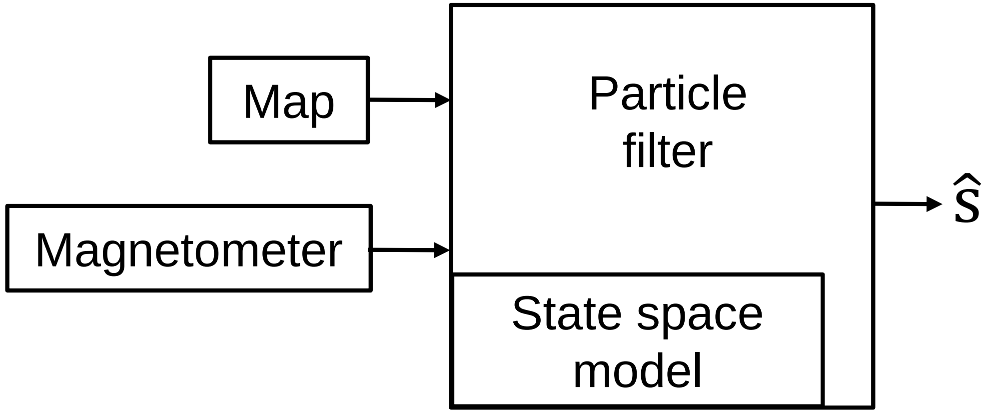
- Position RMSE < 6.5 m

- Track identification after 2.6 – 6.5 s or 26 – 112 m

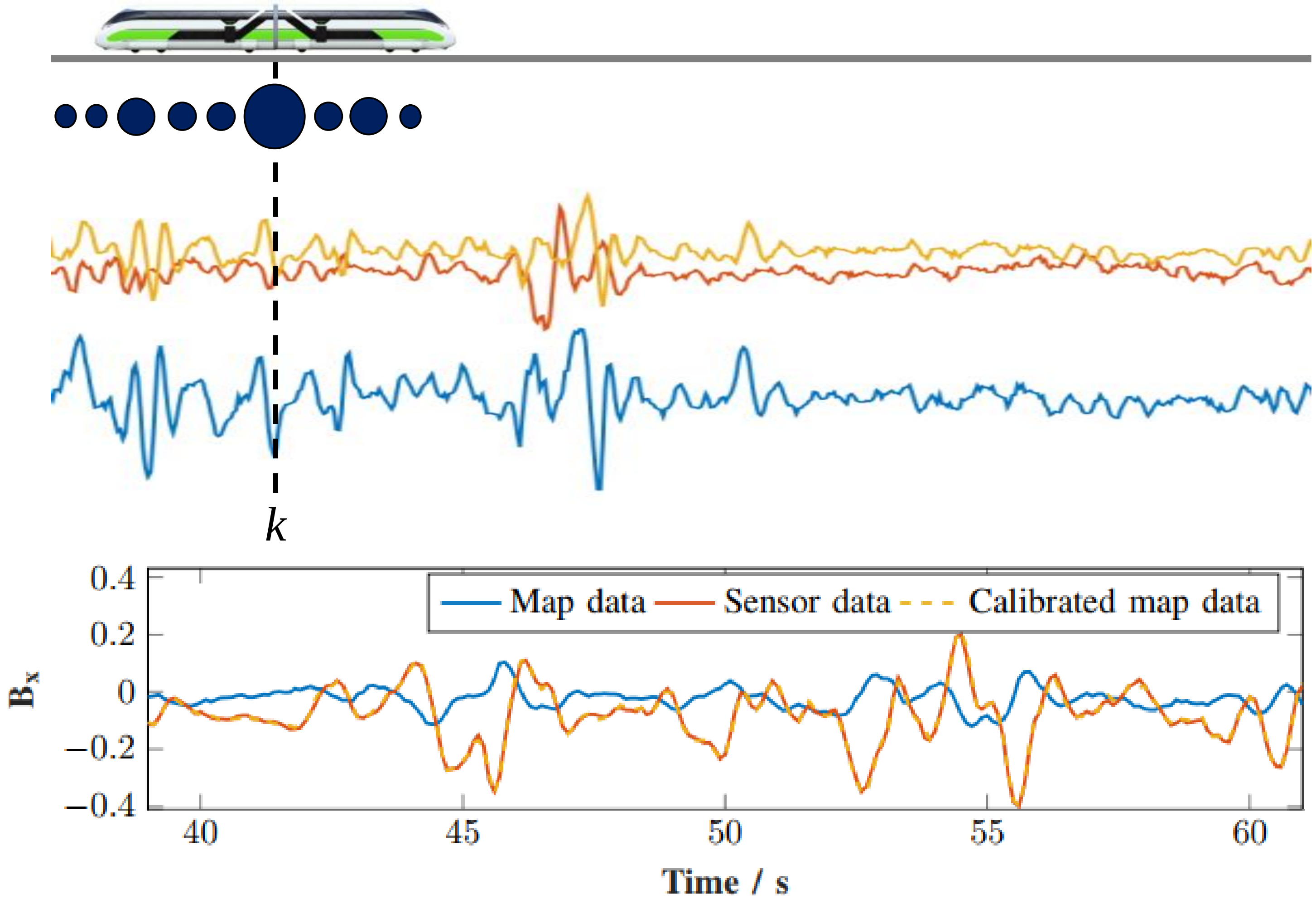




Along-track Position Estimation with Particle Filter for different Magnetometers or Trains



$$\mathbf{d} = [s \quad \dot{s} \quad \ddot{s}]^T$$



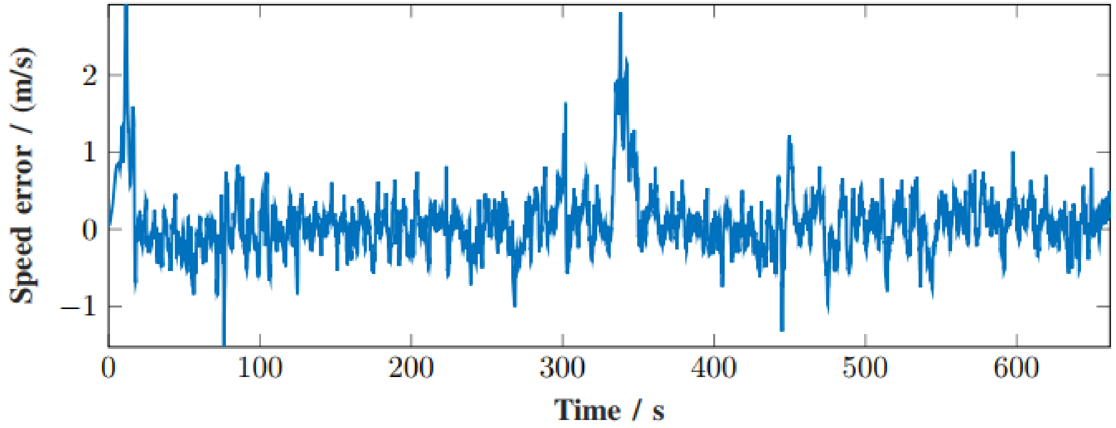
Calibrated magnetometers: One map for all different train types

Evaluation of Simultaneous Localization and Calibration of a Train Mounted Magnetometer [16]

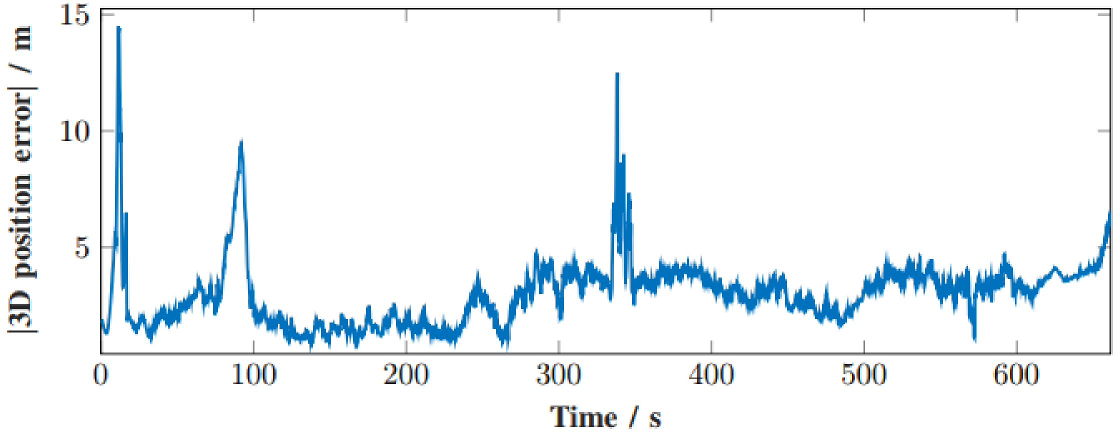
- Magnetometer:
  - At back of steam locomotive, 1.5 m above ground
  - On cabine floor of diesel railcar, 1 m above ground

- Rao-Blackwellized particle filter:
  - Particle filter: Along-track position estimation
  - Kalman filter: calibration parameter estimation
  - 2000 particles, 10 Hz update rate
  - Real time on PC in MATLAB
- Speed RMSE < 0.5 m/s
- Position RMSE < 3.5 m

Speed Error



Position Error



Conclusions

- Magnetic Signatures:
  - Location dependent disturbances of earth magnetic field
  - Standalone localization of trains with magnetometer only
    - Along-track position
    - Track identification

- Simultaneous localization and calibration of magnetometers: Reuse of magnetic map for different train types

- GNSS independent localization: Independent errors
  ➔ Improved availability, redundancy, and integrity for robust and reliable onboard train localization

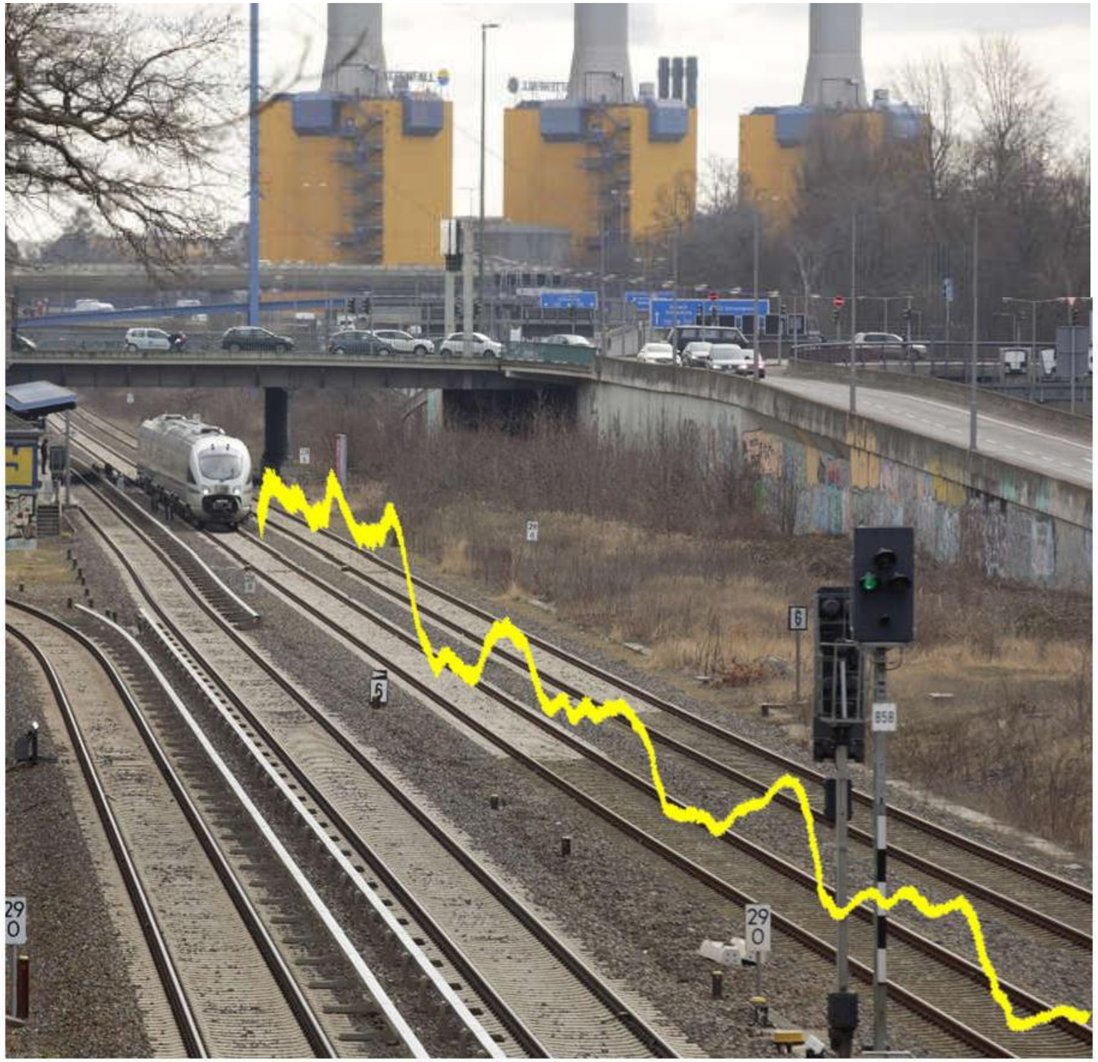
➔ Virtual coupling of trains and next generation railways for more environmentally friendly transport

Outlook

Worldwide unique measurement campaign with DB advanced TrainLab in March 2021

- 8 days, 2242 km, 30 magnetometers (3D)
- Halle, Berlin, Kassel, Göttingen, Munich, Augsburg
- 98 km tachymeter reference (cm) incl. tunnels; odometry, fiber-optical gyros, multi-frequency, multi-constellation GNSS receivers with real-time kinematic positioning
- Electrified (DC/AC)/ non-electrified, urban/ suburban/ rural, rail and road traffic scenarios
- Track change inside tunnels with switches, magnetic track brake maneuvers

Goal: Robust and reliable magnetic signature based onboard train localization



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References

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[5] European Environment Agency (EEA), National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism

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References

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