Measurement Methods for Train Localization with Onboard Sensors

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Train Localization

State-of-the-art train localization uses elements in the railway environment (infrastructure-**based**)

Onboard train localization (Infrastructure-**less**)

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Visionary Applications
Enabled by Onboard Train Localization

Virtual Coupling

Visionary Applications
Enabled by Onboard Train Localization

Autonomous Train Formation

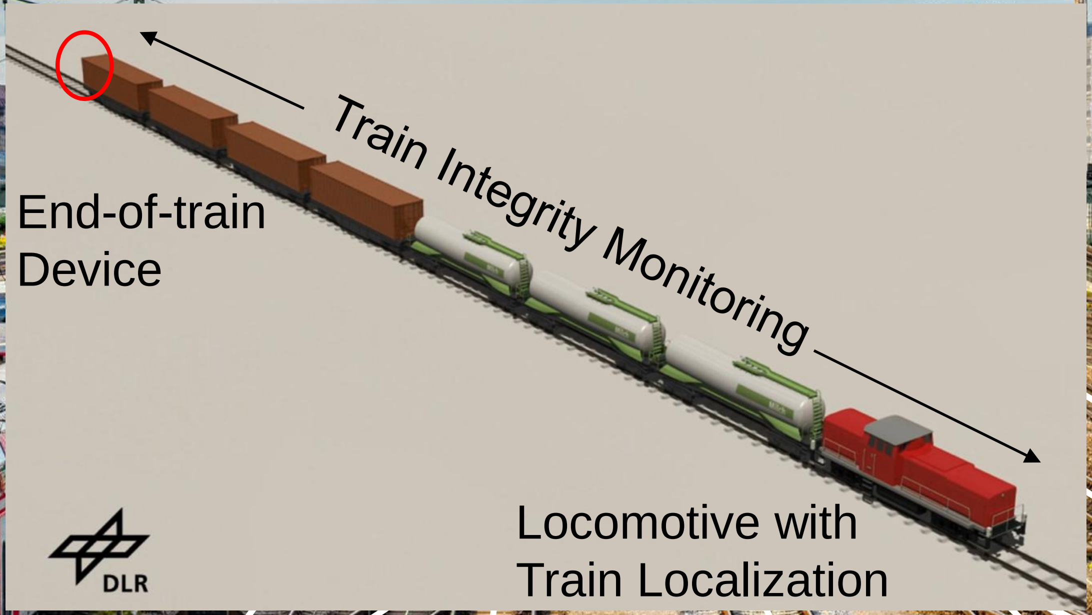
Applications Enabled by Onboard Train Localization

Railway Collision Avoidance System (RCAS)

Applications Enabled by Onboard Train Localization

Railway Collision Avoidance System (RCAS)

End-of-train Device for Cargo Trains



Applications Enabled by Onboard Train Localization

Railway Collision Avoidance System (RCAS)

End-of-train Device for Cargo Trains

Track Condition Monitoring with Regular Trains

Applications Enabled by Onboard Train Localization

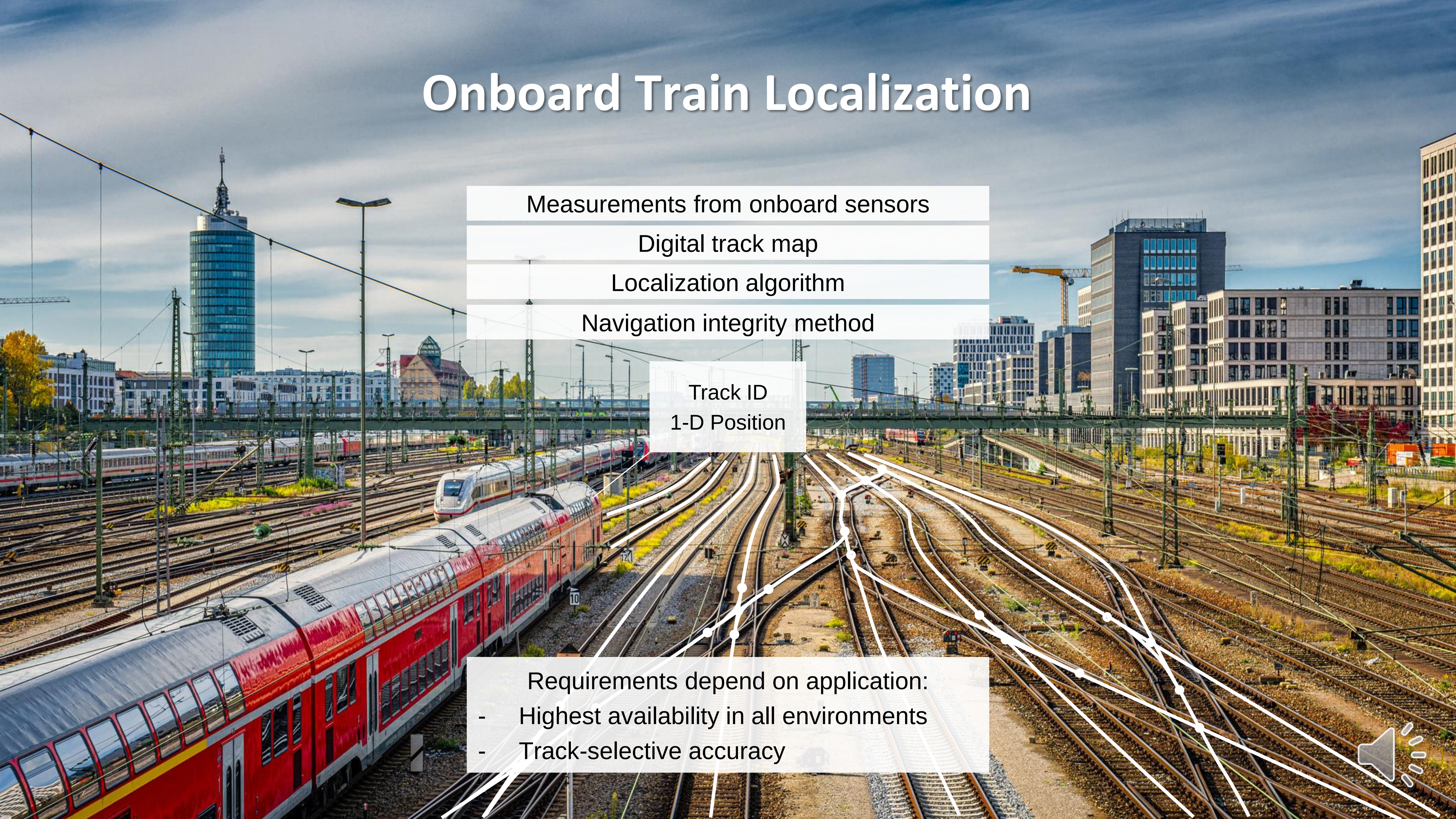
Railway Collision Avoidance System (RCAS)

End-of-train Device for Cargo Trains

Track Condition Monitoring with Regular Trains

Evolution of ETCS (European Train Control System) Virtual Balise

Onboard Train Localization



Measurements from onboard sensors

Digital track map

Localization algorithm

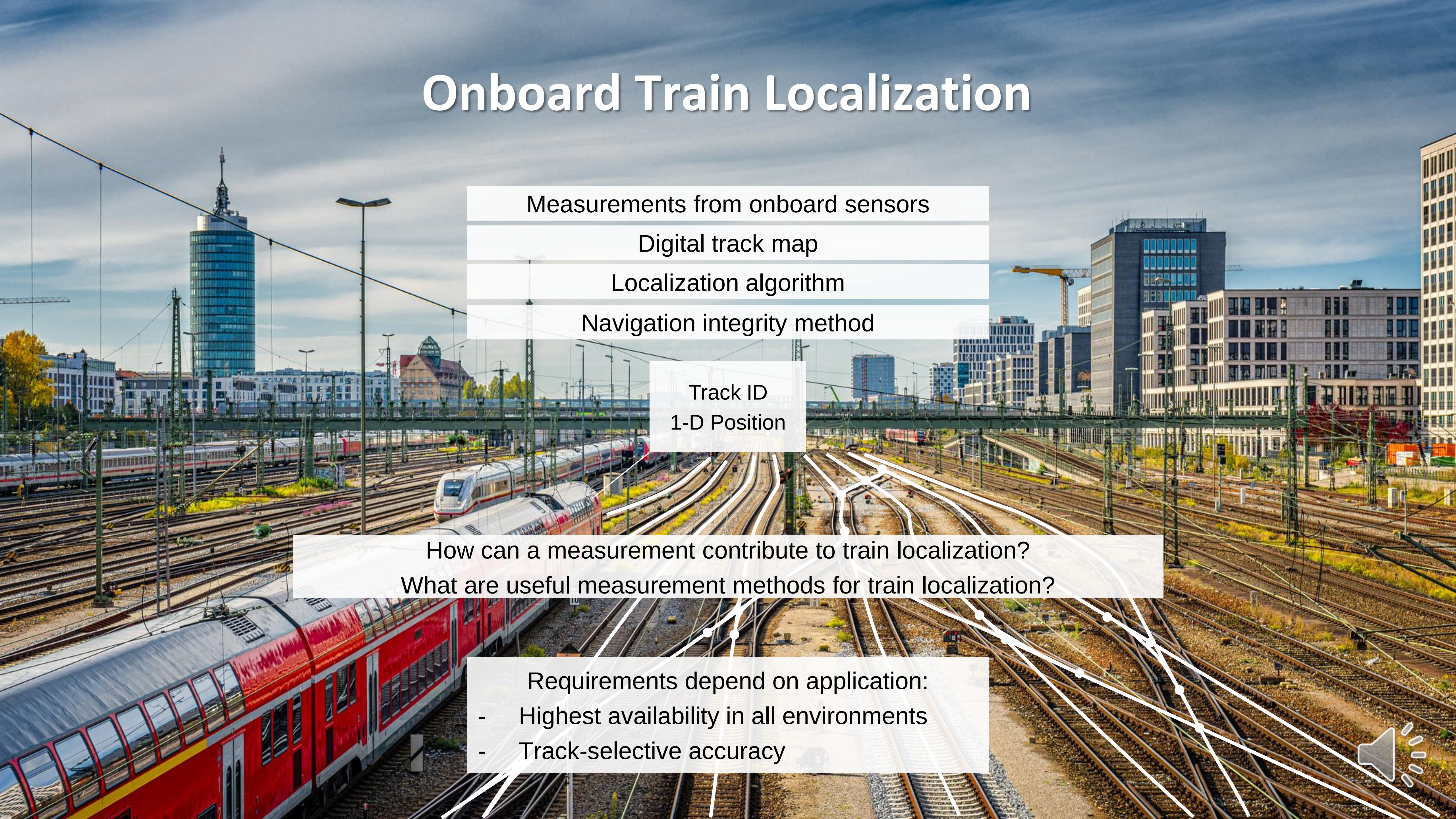
Navigation integrity method

Track ID
1-D Position

Requirements depend on application:

- Highest availability in all environments
- Track-selective accuracy

Onboard Train Localization



Measurements from onboard sensors

Digital track map

Localization algorithm

Navigation integrity method

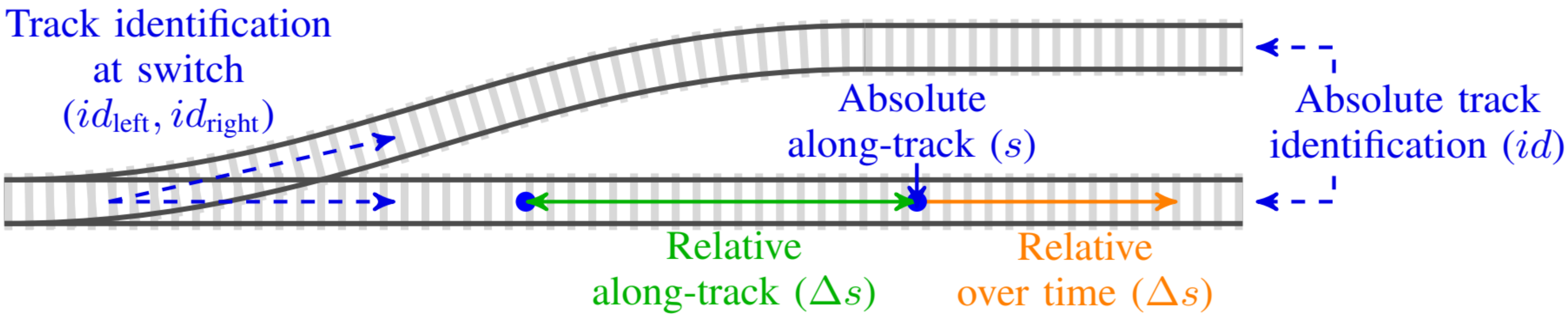
Track ID
1-D Position

How can a measurement contribute to train localization?
What are useful measurement methods for train localization?

Requirements depend on application:

- Highest availability in all environments
- Track-selective accuracy

How can a Measurement Contribute to Train Localization?

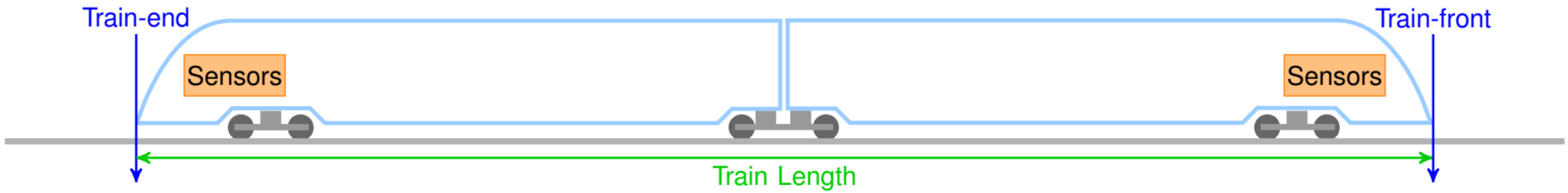


Train Speed, Relative over Time	
Speed measurement	d/dt s
Travel distance over time	Δs
Dead reckoning	$\Sigma\ \Delta s$

Relative Train Localization	
Distance measurement between two positions on track	Δs

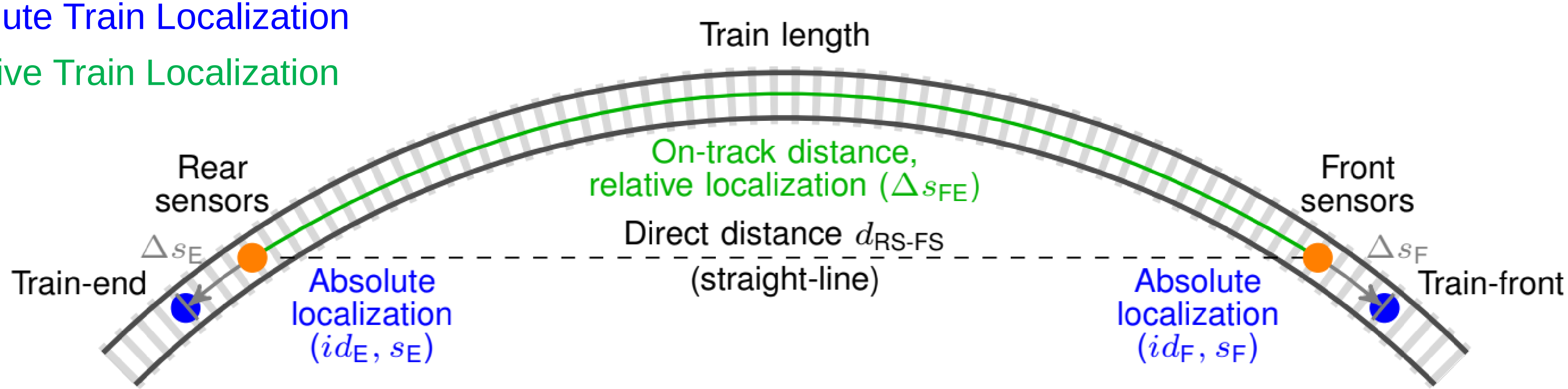
Absolute Train Localization	
Absolute along-track	s
Absolute track identification	id
Track identification at switches	id

Absolute and Relative Train Localization

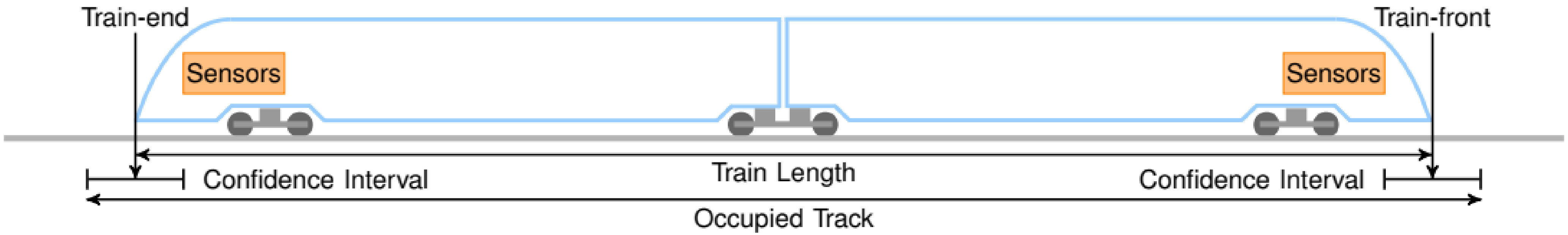


Absolute Train Localization

Relative Train Localization



Robust and Safe Train Localization



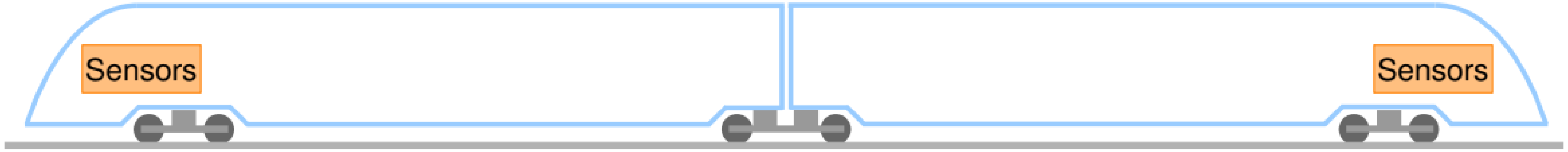
- Safe train localization uses confidence intervals and a defines an occupied track
  - redundant measurements
  - navigation integrity monitoring

- Navigation integrity method computes protection levels based on measurement analysis, failure detection and exclusion and a sensor fusion monitoring
  - Confidence interval is the protection level in along track direction
  - Navigation integrity guarantees, that true location is within the confidence interval with very low error probability

- An application is safe when the confidence interval (protection level) is smaller than a limit (alert limit) that is defined by the application and use-case requirements

Measurement Methods Overview

- Sensors (selection)
    1. GNSS,
    2. IMU,
    3. Magnetometer,
    4. Terrestrial radio ranging
- Some methods require a map, pre-processing, or multiple measurements
- Paper contains further links to publications



Train Speed, Relative over Time

	Type	Method	Sensor
S.1	GNSS	Doppler, time differenced carrier phase	GNSS receiver
S.2	Magnetic	periodic wheel signal	magnetometer
S.3	Magnetic	speed signature	magnetometer
S.4	Magnetic	magnetic signature	2x magnetometer
S.5	Vibration	speed signature	inertial
S.6	Vibration	vibration signature	2x inertial
S.7	Cellular RF system	Doppler, base station to mobile	mobile terminal

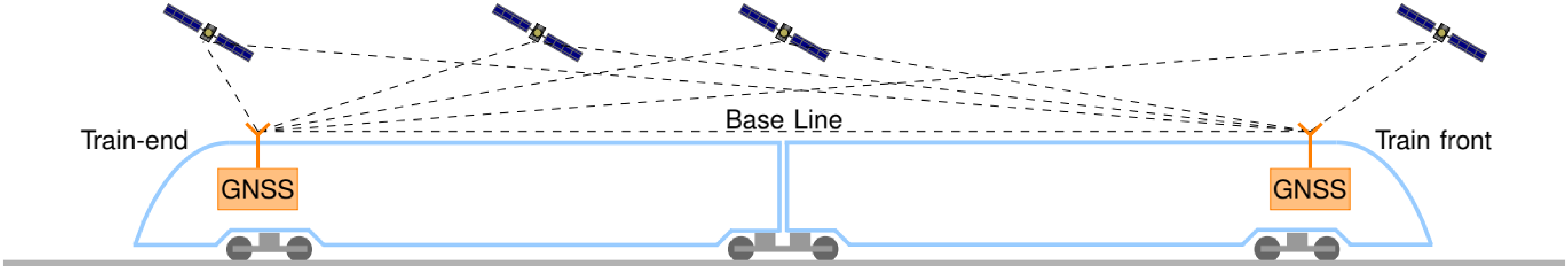
Relative Train Localization

	Measurement Method	Type of Localization	Sensors, Map
R.1	GNSS relative	relative on tracks, train to train / front to end	2x GNSS (SBAS), map
R.2	Baseline GNSS	relative, direct distance	2x GNSS
R.3	INS relative	relative on tracks	IMU, (GNSS,X,odometer,map)
R.4	Inertial signature	relative on tracks	2x IMU, (odometry)
R.5	Magnetic signature	relative on tracks	2x magnetometer, (odometry)
R.6	Radio ranging on train	relative, direct distance train to train / front to end	2x RF tranceivers
R.7	Cellular base station	relative, direct distance train to train / front to end	2x cellular mobile terminal, map

Absolute Train Localization

	Measurement Method	Type of Localization	Sensors, Map
A.1	GNSS loosely	absolute on tracks, loosely coupled with map	GNSS position, (SBAS), map
A.2	GNSS tightly	absolute on tracks, tightly coupled with map	GNSS pseudorange, (SBAS) map
A.3	INS/GNSS	absolute on tracks	IMU, GNSS, map
A.4	INS/X/map	absolute on tracks	IMU, (odometer), map X: e.g. magnetom., vibrations
A.5	Inertial signature	absolute on tracks	IMU, (odometry), map
A.6	Magnetic signature	absolute on tracks	magnetometer, (odometry), map
A.7	Cellular base station radio ranging	absolute on tracks, loosely coupled with map	cellular mobile terminal, map
A.8	Cellular base station radio ranging	absolute on tracks, tightly coupled with map	cellular mobile terminal, map

1. GNSS - Global Navigation Satellite System



A GNSS receiver measures pseudorange, Doppler and carrier phase to multiple satellites in view.

Train Speed, Relative over Time	
Train speed via Doppler	GNSS
Train speed via time-differenced carrier phase	GNSS

Relative Train Localization	
Relative on tracks	2x GNSS
Baseline GNSS, double differencing	2x GNSS

Absolute Train Localization	
GNSS position, loosely coupled with map	GNSS
GNSS pseudorange, tightly coupled with map	GNSS

2. IMU – Inertial Measurement Unit

Measurements: accelerations, turn rates in three axes (x,y,z)

1. Inertial Navigation System (INS/GNSS, INS/X/map):

- INS/GNSS computes position, velocity and attitude

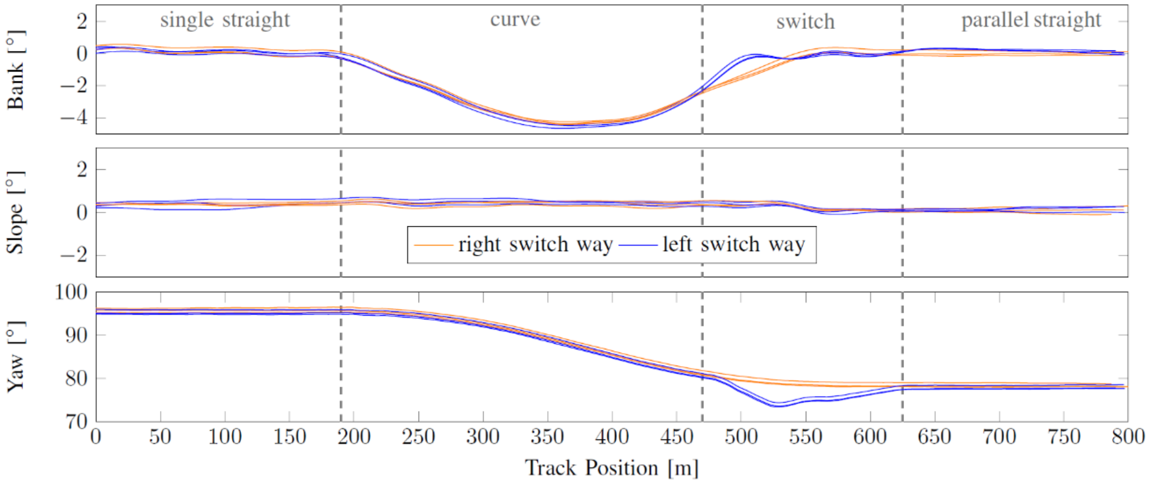
2. Kinematics of track geometry

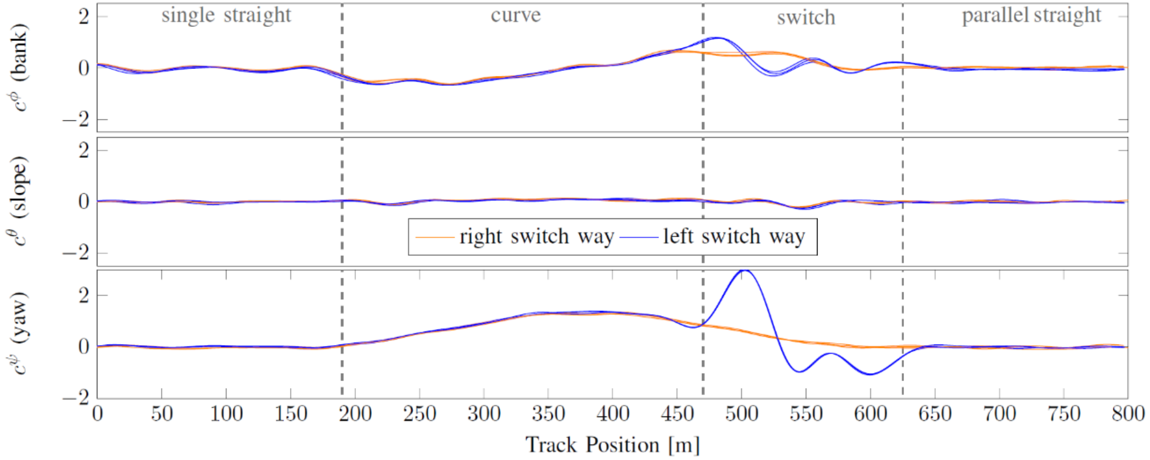
- No integration required: suitable for low-cost MEMS IMUs
- Curvatures can be processed from turn rates and velocity

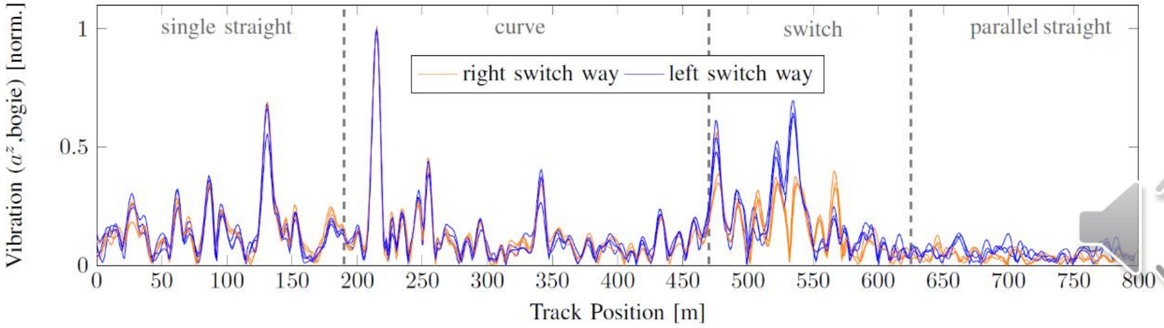
3. Vibrations

- Characteristic vibration intensity

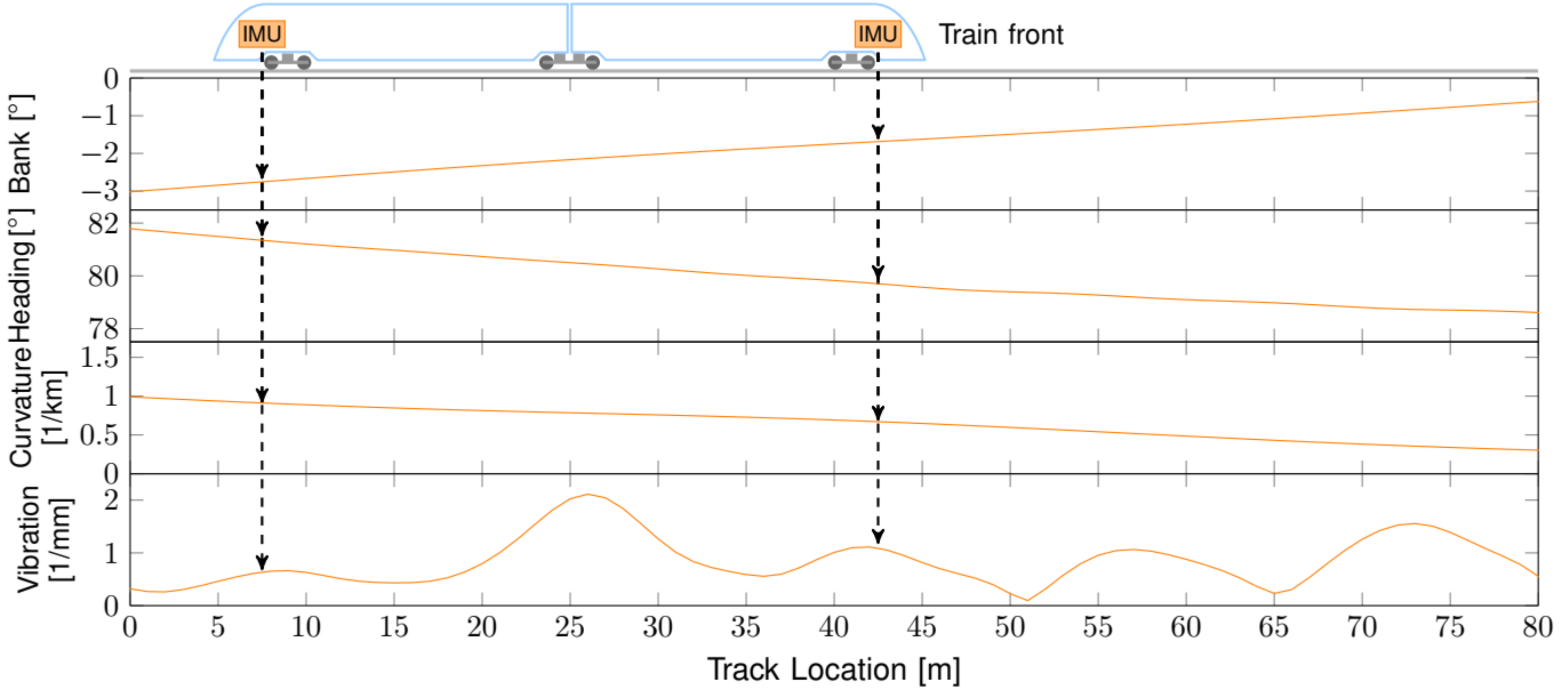
Inertial Signatures







2. IMU Measurement Methods



Train Speed, Relative over Time	
Along-track acceleration, integration over time	IMU
Vibration speed signature, comparison of speed dependent patterns	IMU
Vibration signature comparison with known distance between sensors	2x IMU

Relative Train Localization	
Inertial signature relative on tracks	2x IMU (odometry)

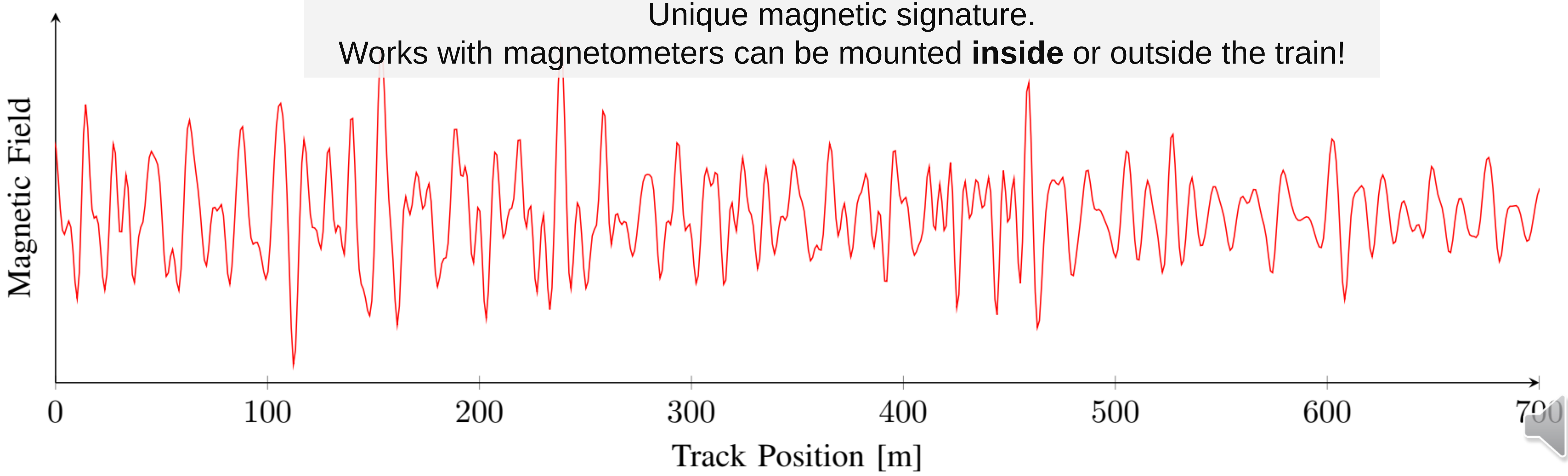
Absolute Train Localization	
Inertial signature (attitude, curvature, vibration)	IMU, map (odometry)

3. Magnetometer

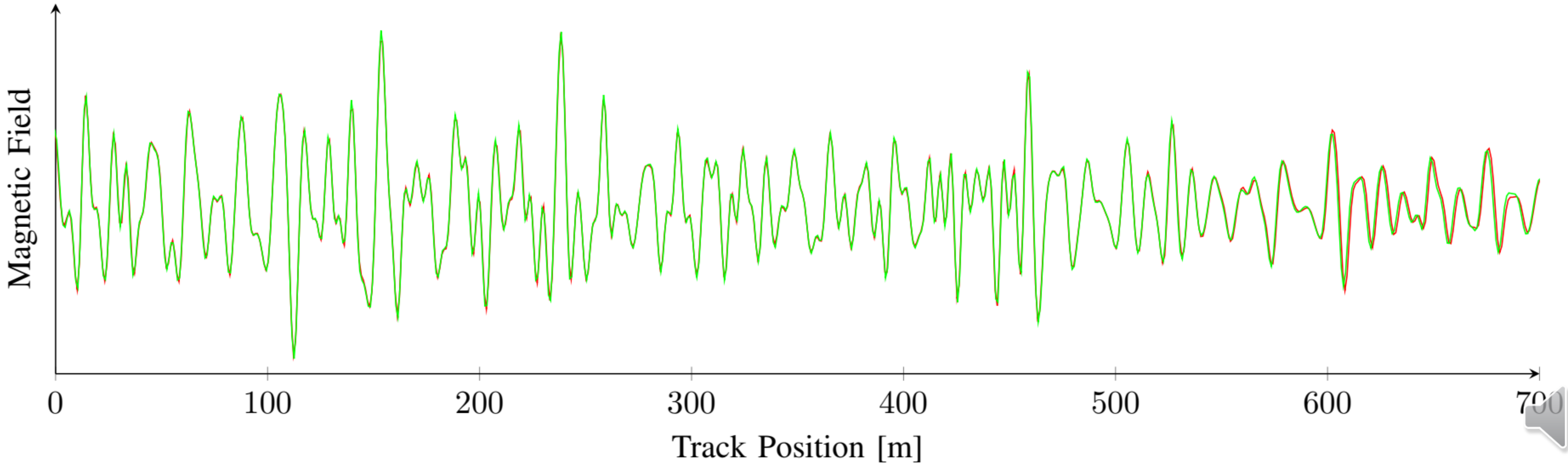
- Measurements: magnetic field density (Tesla) in three axes (x,y,z)
- Sensor elements are used in an electronic compass
- Railway environment creates characteristic distortion of the magnetic Earth field

3. Magnetometer: Magnetic Signature, 1st Run

Unique magnetic signature.
Works with magnetometers can be mounted **inside** or outside the train!

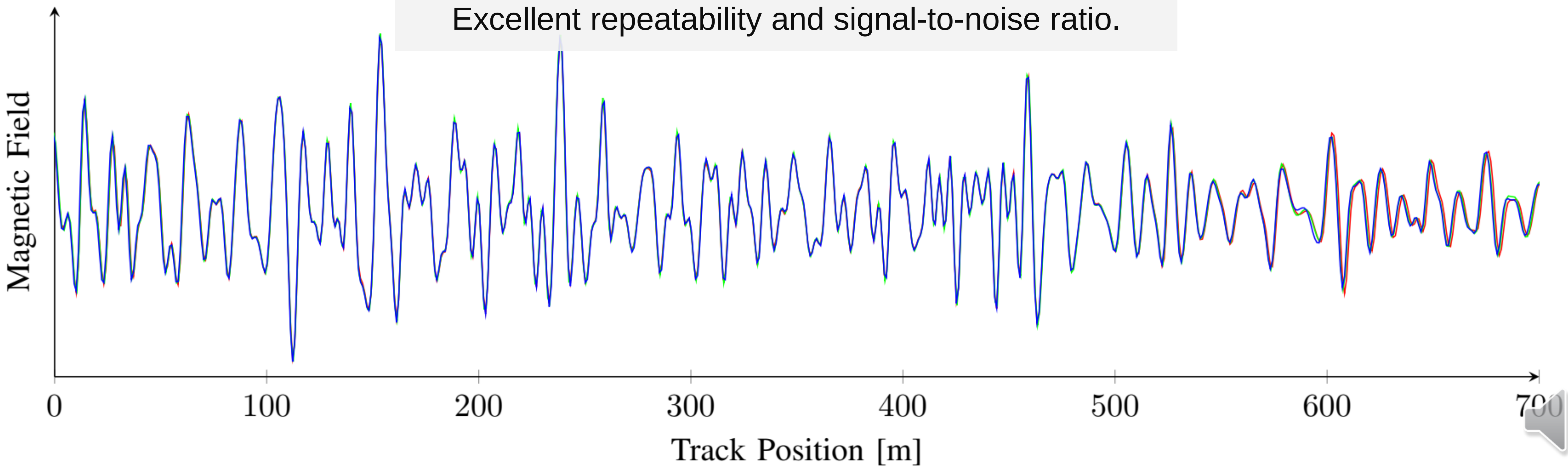


Magnetometer: Magnetic Signature
1st Run + 2nd Run

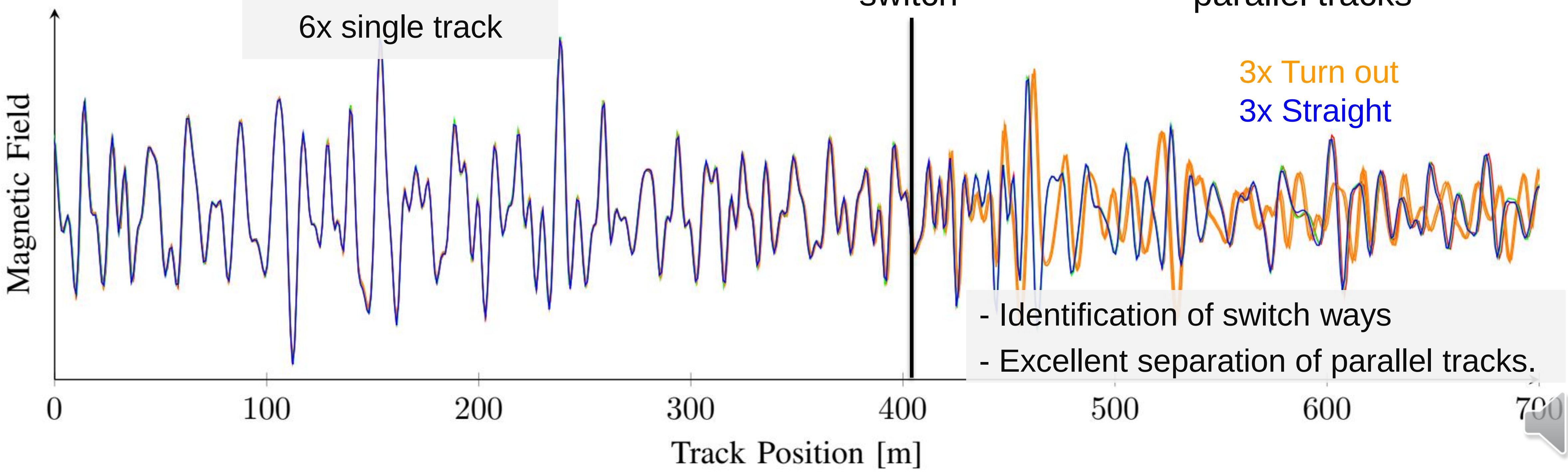


3. Magnetometer: Magnetic Signature
1st Run + 2nd Run + 3rd Run

Excellent repeatability and signal-to-noise ratio.

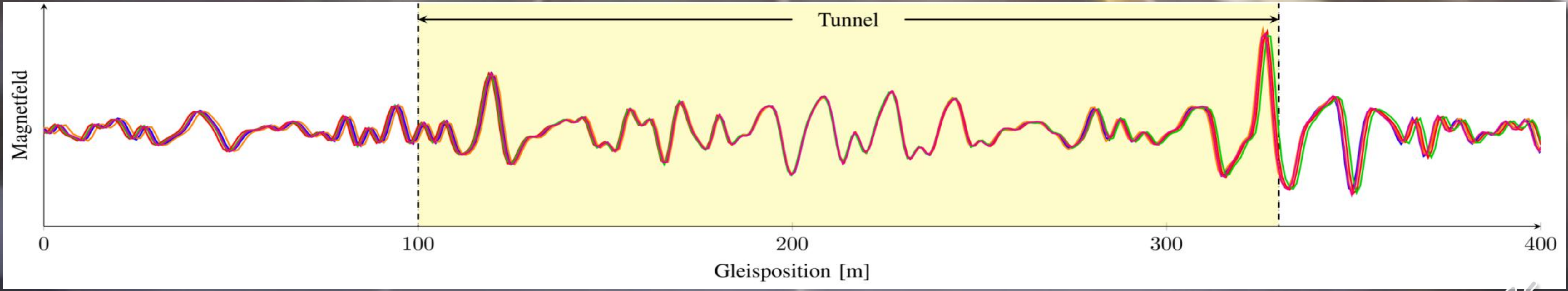


3. Magnetometer: Magnetic Signature
6 rain runs



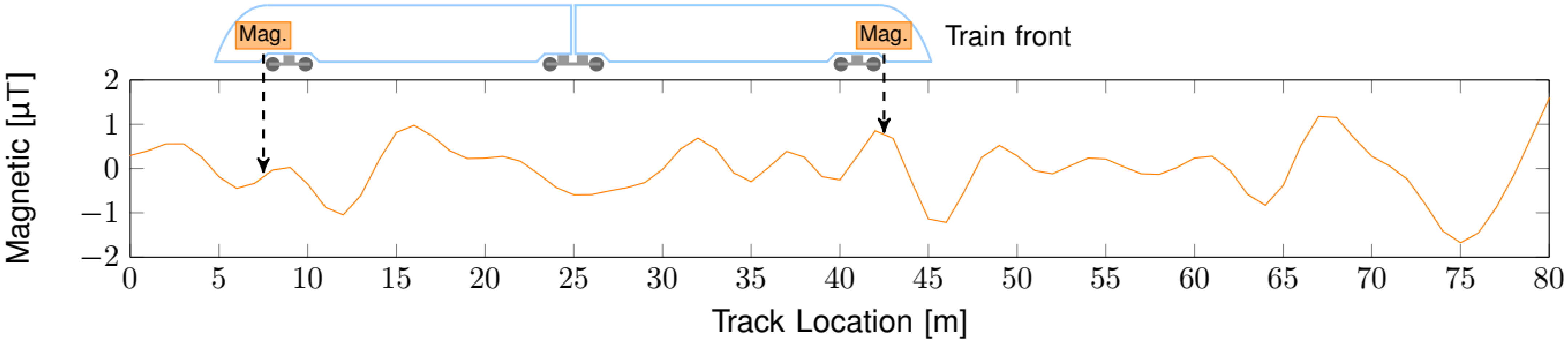
- Identification of switch ways
- Excellent separation of parallel tracks.

3. Magnetometer: Tunnel



Works in Tunnels!

3. Magnetic Measurement Methods

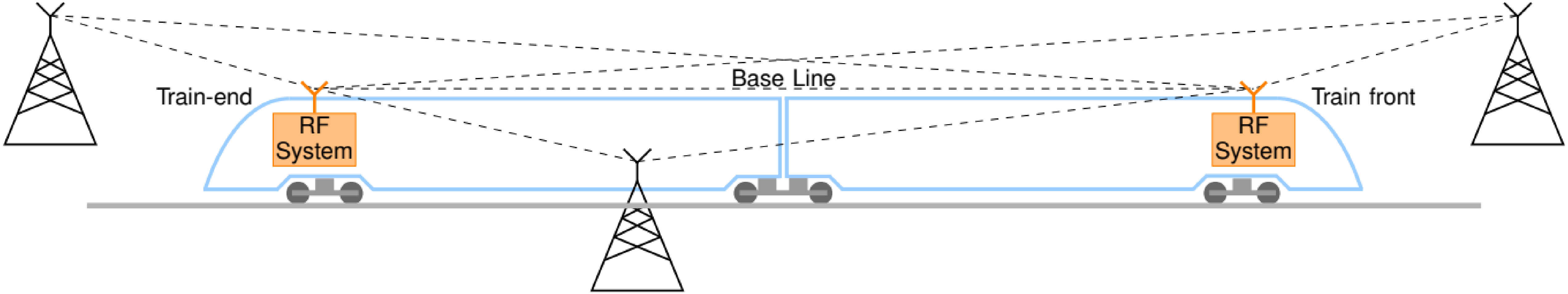


Train Speed, Relative over Time	
Magnetic periodic wheel signal	1x Mag.
Magnetic speed signature	1x Mag.
Magnetic magnetic signature	2x Mag.

Relative Train Localization	
Magnetic signature relative on tracks	2x Mag. (Odometry)

Absolute Train Localization	
Magnetic signature absolute on tracks	Mag., map (odometry)
INS/magnetic/map	Mag, IMU (odometry)

4. Terrestrial Radio Ranging Measurement Methods



- Measurements: Ranges (Round-trip Delays), Doppler

Train Speed, Relative over Time	
Cellular RF system, Doppler of base station to mobile terminal	mobile terminal

Relative Train Localization	
Radio ranging on train	2x RF trans.
Cellular base station, difference	2x mobile terminal, map

Absolute Train Localization	
Cellular base station ranging, map-matched position, loosely coupled	mobile terminal, map
Cellular base station ranging, tightly coupled	mobile terminal, map

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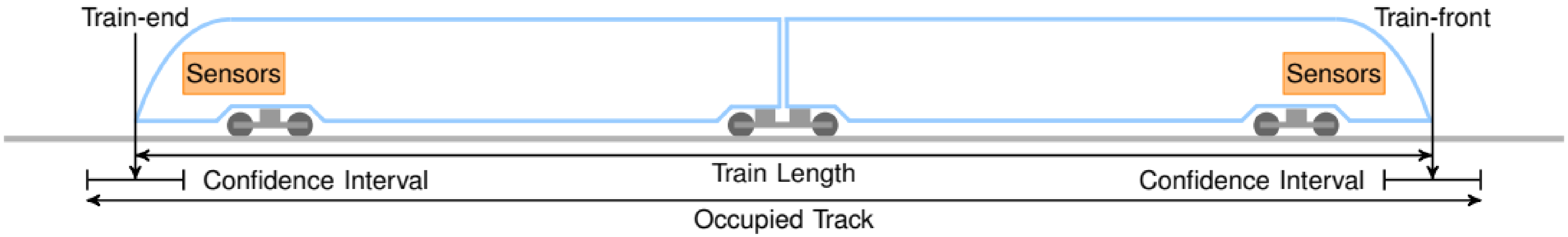
Current & Future Work



- Measurement methods from GNSS, IMU, magnetometer and terrestrial radio ranging.

- Current & future research focuses on:
  - Localization algorithms based on a digital track map with INS/GNSS, inertial and magnetic signatures for a reliable train speed, train location and train integrity monitoring with highest availability in all environments
  - Safe train localization with navigation integrity methods for railways with advanced sensor models

Measurement Methods for Train Localization with Onboard Sensors

Oliver Heirich · Benjamin Siebler · Stephan Sand · Andreas Lehner · Omar García Crespillo

Q&A Session: D2 Rail Navigation,
Day 1 (Monday, 23.11) 19:00-19:20 CET

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Links to all our publications:
elib.dlr.de

Measurement Methods for Train Localization with Onboard Sensors

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Track: Rail Navigation

Abstract: *Real-time train localization with onboard mounted sensors is a basis for future railway applications. In contrast to infrastructure based train localization with way-side sensors, the onboard train localization uses only train-side sensors and a digital map of the railway tracks. Therefore, the trains are equipped with sensors, e.g. near the train-front and near the train-end. The train-front location and the train-end location are determined on the tracks in track coordinates with absolute train localization methods. A distance on tracks between two locations is determined with relative localization methods. This distance on the tracks can be used to monitor the train length and also to observe the distance between trains. This paper contains an overview of different measurement methods for speed measurement, absolute train localization and relative train localization based on GNSS (Global Navigation Satellite System), IMU (Inertial Measurement Unit), magnetometers and RF (radio frequency) ranging.*

1. Introduction

Future train applications with real-time localization aim at an increase of safety and efficiency. An onboard train localization contains all components and computation onboard the train. In contrast to infrastructure based localization with beacons, cable loops or radio balises, the onboard train localization requires a map of the railway tracks. Applications with demand for real-time and onboard train localization are manifold such as: general train control and signalling, automated maneuvering, automated driving, collision avoidance warning systems [1], train-end monitoring as well as moving block and virtual coupling [2] that target on an increase of efficiency with shorter sequences of trains. Furthermore, a continuous and automated track condition monitoring requires an association of the measurements and anomalies to the position on the track.

Figure 1: Train with train-front, train-end, train length and occupied track definitions.

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