Cost-effective Localization of Railway Track Faults using GNSS Antenna under Train's Roof

Li ZHANG, Rudolf FROLOW, Volker SCHWIEGER
Institute of Engineering Geodesy, University of Stuttgart, Germany

Session: An Analog Earth in Digital Models: Capturing the World Around Us

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Motivation

Train accident in Garmisch 2022

Source: https://bahnblogstelle.com/196726/unfalluntersuchung-zum-zugunglueck-bei-garmisch-partenkirchen-laeuft-noch/

Track faults

Source: McCue, K. (2010). Assessing earthquake hazard and risk in australia. Australian Planner, 47(1), 52–53.

Track Recording Vehicles (VRV)

https://www.networkrail.co.uk/running-the-railway/looking-after-the-railway/our-fleet-machines-and-vehicles/new-measurement-train-nmt/

Early detection and precise localization of track faults is an important current research topic in the construction and maintenance of railways

➔ **Goal:** Continuous Track Monitoring system:

- cost-effective, board-autonomous
- permit-free (no special permission from railway authorities)
- installation on vehicles during regular service

Source : https://www.openpr.com/news/2939720/railway-maintenance-service-market-advance-technology-latest

Introduction - ConMoRAIL

- Project: Efficient Sensor-based **Con**dition **Mon**itoring Methodology for the Detection and Localization of Faults on the **Rail**way Track (ConMoRAIL)
- Partner:
  - Institute of Railway and Transportation Engineering, University Stuttgart (IEV)
  - Institute of Engineering Geodesy, University Stuttgart (IIGS)
  - Württembergische Railway Company (WEG)
- Funding: Deutsche Forschungsgemeinschaft (DFG, German Research Fondation)
- Duration: April 2023 – March 2026 (3 Years)

Where?

Which type?

Test

Stadler Reginal Shuttle of WEG

Challenges of Localization

Permit-free? ➔ GNSS antenna could not installed on the top of train ➔ GNSS antenna under Train's Roof

(a) (b)

(a) ublox ANN-MS GNSS antenna under the train's roof and (b) antenna vicinity in the train

Static Test

GNSS antenna under self-constructed cover plate using fiberglass-reinforced plastic (the same material as the train's roof)

(a) (b)

(a) Tallysman TW3972 antenna and (b) u-blox ANN-MS antenna and with GP

©u-blox

u-blux C102-F9R application board (~350 Euro)

Test on static objects in Campus University of Stuttgart

Static Test Results

~30 minutes **Test Scenario (on 08.11.2023)**

Session No. (Time)	Antenna Type	Cover Plate
1 (08:18-08:49)	Tallysman TW3920 +GP	without
2 (08:51-09:19)	Tallysman TW3920 +GP	with
3 (09:22-09:52)	u-blox ANN-MS+GP	without
4 (09:53-10:22)	u-blox ANN-MS+GP	with

Accuracy and Correctness

Quality parameter	Accuracy (Standard Deviation [mm])				Correctness (Mean of Difference [mm])		
Session No.	sΔdN	sΔdE	sΔdh	sΔd3D	mΔdN	mΔdE	mΔd2D
1	5.1	2.1	7.7	9.5	3.6	3.3	4.9
2	5.0	3.9	9.9	11.7	-5.2	5.0	7.2
3	3.7	3.6	5.4	7.5	-1.3	3.2	3.5
4	4.5	3.2	6.5	8.4	2.2	3.4	4.1

Number of Satellites and PDOP (max, mean, min)

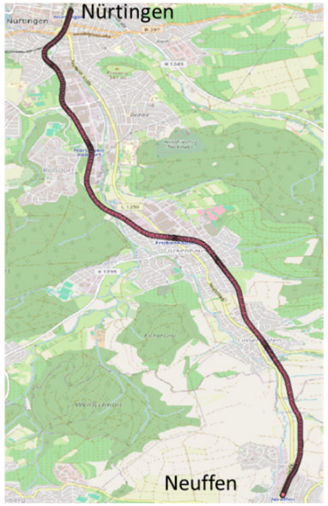
Session No.	Number of Satellites			PDOP		
	min	mean	max	min	Mean	max
1	21	22.5	24	0.8	0.9	1.0
2	20	22.1	24	0.9	1.0	1.3
3	18	21.0	23	0.9	0.9	1.1
4	18	20.7	23	0.8	0.9	1.0

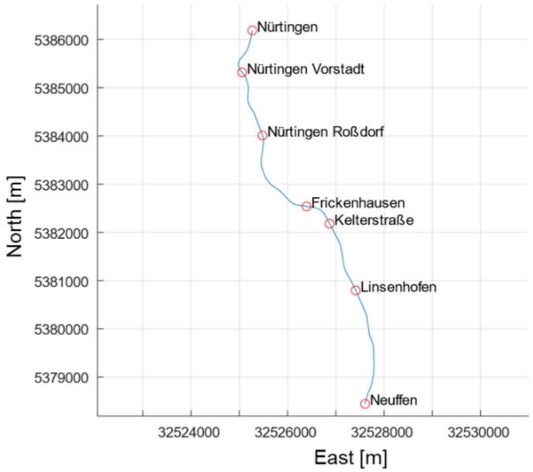
- Std. in the height is about a factor of 2-3 higher than in the horizontal and 3D std. ~ 1 cm
- With vs without cover plate (same antenna): The cover plate has slightly reduced the number of available satellites and increased PDOP➔ Accuracy (3D std.) 1.2 factors higher and correctness (difference to reference in 3D) 1.2-1.5 factors higher
- Comparison of antennas: accuracy of the u-blox ANN-MS antenna even better than the Tallysman TW3920

Kinematic Test

Integration of GNSS and IMU using ESKF (Error State Kalman Filter)

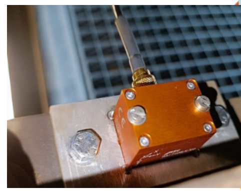
- GNSS antenna under the train's roof (1Hz)
- One IMU on the bogie and one IMU inside the train (300 Hz)
- Real-time Computer





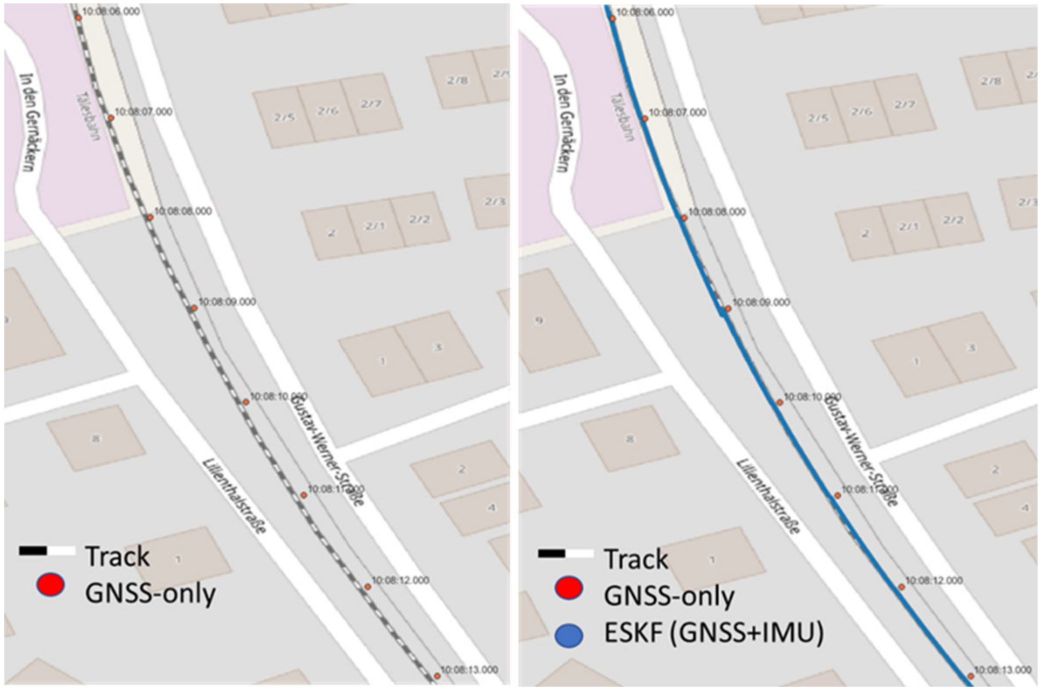
Overview of total trajectory between Nürtingen und Neuffen
(~8.9 km, ~12 minutes, max. velocity 70 km/h)

IMU on the bogie



IMU inside the train

First Results of Kinematic Positioning of Train



GNSS-only (float solutions) vs. ESKF (GNSS+ IMU) for one track section

- **Float**

7s float solution

Dataset	Std. ([m])
GNSS-only	0.98
ESKF (GNSS+IMU)	0.17

- **Fixed**

Deviations to the maps (OSM): several centimeters to several decimeters, mean of the deviations is ~ 3 to 4 dm

?

Accuracy of OSM: 1-2 meters?

➔ More accurate reference for evaluation

Conclusion and Outlook

- The train's roof reduces the quality of GNSS measurement, but not dramatically
- Reference data by track measurement vehicle (summer 2025) and evaluation
- Unscented Kalman Filter instead of ESKF
- Map-Matching for improving the positioning
- Update the map with track faults

ACKNOWLEDGEMENTS

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The most relevant SDGs related to the presentation and theme of this session

1st relevant SDG: 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

2nd relevant SDG: 8 DECENT WORK AND ECONOMIC GROWTH

3rd relevant SDG: 10 REDUCED INEQUALITIES

SUSTAINABLE DEVELOPMENT GOALS | International Federation of Surveyors supports the Sustainable Development Goals

Thank you for your attention!

Questions?

Contact:
Dr.-Ing. Li Zhang
Email: li.zhang@iigs.uni-stuttgart.de
Institut für Ingenieurgeodäsie
Geschwister-Scholl-Str. 24D
70174 Stuttgart, Germany

STEP 1: SELECT HERE THE THREE MOST RELEVANT SDGs
STEP 2: COPY THE SDG INTO PREVIOUS SLIDE

1 NO POVERTY
2 ZERO HUNGER
3 GOOD HEALTH AND WELL-BEING
4 QUALITY EDUCATION
5 GENDER EQUALITY
6 CLEAN WATER AND SANITATION
7 AFFORDABLE AND CLEAN ENERGY
8 DECENT WORK AND ECONOMIC GROWTH
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
10 REDUCED INEQUALITIES
11 SUSTAINABLE CITIES AND COMMUNITIES
12 RESPONSIBLE CONSUMPTION AND PRODUCTION
13 CLIMATE ACTION
14 LIFE BELOW WATER
15 LIFE ON LAND
16 PEACE, JUSTICE AND STRONG INSTITUTIONS
17 PARTNERSHIPS FOR THE GOALS

Reallabor – IMU

- Inertial Measurement Unit (IMU) = 3-axis Accelerometer + 3-axis Gyroscope
- ✓ Acquired Signals: $\ddot{x}, \ddot{y}, \ddot{z},\ \dot{\phi}, \dot{\theta}, \dot{\psi}$
- ✓ Sensors mounted both on the bogie and on the car body.

- **ASC IMU 7.025LN.300 - 6 DOF Inertial Measurement Unit (Bogie)**
  - Measuring range:

  Acceleration ± 25 [g] Gyro rate: ± 300 [°/s]

- **ASC IMU 7.002LN.150 - 6 DOF Inertial Measurement Unit (Car body)**
  - Measuring range:

  Acceleration ± 2 [g] Gyro rate: ± 150 [°/s]

ASC IMU 7.025LN.300
ASC IMU 7.002 LN.150

IMU	Measurement Range Acceleration	Measurement Range Rational Rate
7.025LN.300 (bogie)	± 25 [g]	± 300 [°/s]
7.002LN.150 (train)	± 2 [g]	± 150 [°/s]

Reallabor

Component	Cost [EUR]
Echtzeitrechner NI CompactRIO 9042	7208.90
Netzteil Mean Well RS-75-24 (x2)	40.00
Analogeingangsmodul NI 9205	927.00
Serielles Kommunikationsmodul NI 9870	1103,13
Trägheitsmesseinheit ASC IMU 7.025LN.300	3973.40
Trägheitsmesseinheit ASC IMU 7.002LN.150	3973.40
GNSS-Empfänger + Antenne	355.81
Feldrechner	2913.12
Gesamt	20534.76

NI-9205

NI-9870

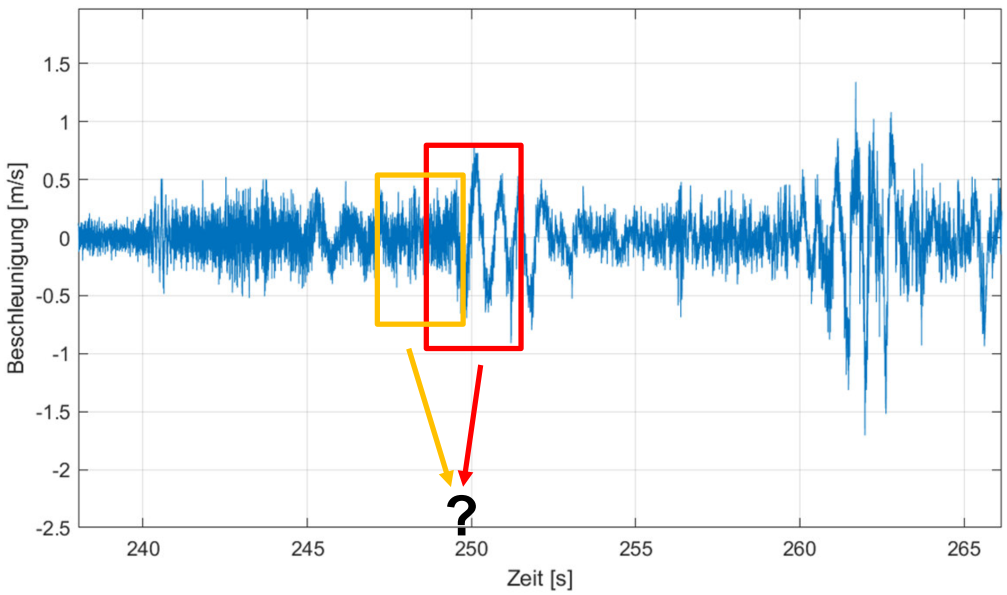
NI cRIO-9042

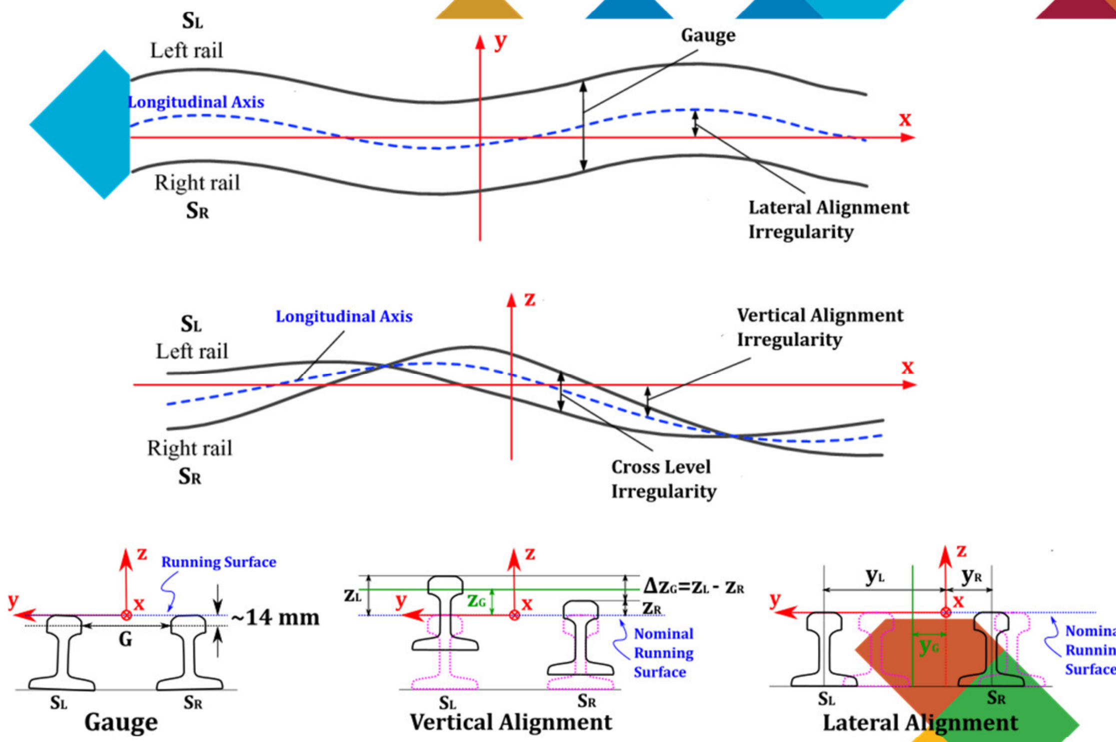
Ublox Antenne

ASC IMU 7.025LN.300
ASC IMU 7.002 LN.150

Mean Well RS-75-24

Reallabor





Overlapping faults? ➔ high positioning accuracy

Monitoring Scope

- The system must be able to detect and identify **middle-length track defects.**

Type of Defect	Specific Defect	Wavelength Range λ [m]
Superficial Rail Defects	Short Wavelength Corrugation	0.03 - 0.10
	Long Wavelength Corrugation	0.10 - 1.00
	Long Waves and rolling defects	1.00 - 3.00
Track Defects	Structural Defects, Track Irregularities	3.00 - 25.00
	Track Irregularities	25.00 - 70.00
Design Geometry	Track Layout	>70.00

- Track faults within the wavelength interval from 3 m to 70 m (frequency range between 0 Hz and 30 Hz for a vehicle speed up to 350 km/h)
- Most of the structural and geometrical vertical track defects are included:

Geometrical defects

1. Medium-wavelength vertical irregularities (vertical alignment)
2. Medium-wavelength horizontal irregularities (horizontal alignment)
3. Cross level irregularities
4. Gauge irregularities

Structural defects

1. Track punctual defects and local instabilities (loss of track stiffness)
2. Rail joints and breakages

Out of the scope:

- Short-wavelength (high-frequency) corrugation.
- Long-wavelength low-frequency design geometry

Wavelength Content and Minimal Sampling Rate

Frequency Range of the vertical defects

- For $v = 70 \left[\frac{km}{h}\right]$ (nominal speed on the Tälesbahn line):

$$f = 0{,}28 \; \ldots \; 6{,}48 \, [Hz]$$

- For $v = 350 \left[\frac{km}{h}\right]$:

$$f = 1{,}39 \; \ldots \; 32{,}41 \, [Hz]$$

The frequency range of interest for this project:

$$f = 0 \; \ldots \; 30 \, [Hz]$$

Nyquist minimum sampling rate:

$$f_N = 2f = 60 \, [Hz]$$

Rule of Thumb in Instrumentation:

$$\boldsymbol{f_{S,min} = 10f = 300 \, [Hz]}$$

$$\boldsymbol{f = v/\lambda}$$

- Frequency f of the excitation signal on the railway vehicle produced by passing on the track defect with a speed v.
- It is not necessarily the frequency of the measured signals on the vehicle.
- It represents a good starting point to know the frequency interval in which the measurements should be done.
- Due to the effect of the primary and secondary suspensions (low-pass filter), the actual spectral content of the measured signals is lower.
- It is necessary to determine the cut-off frequency at the bogie and at the car body.