Velocity and Location Information from Onboard Vibration Measurements of Rail Vehicles

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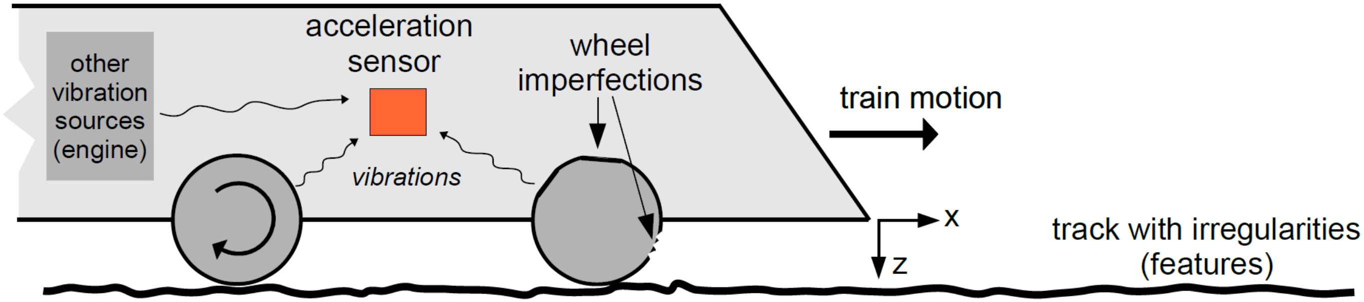
Vehicle Vibrations

- **Vehicle vibrations:** oscillatory motion of many different frequencies

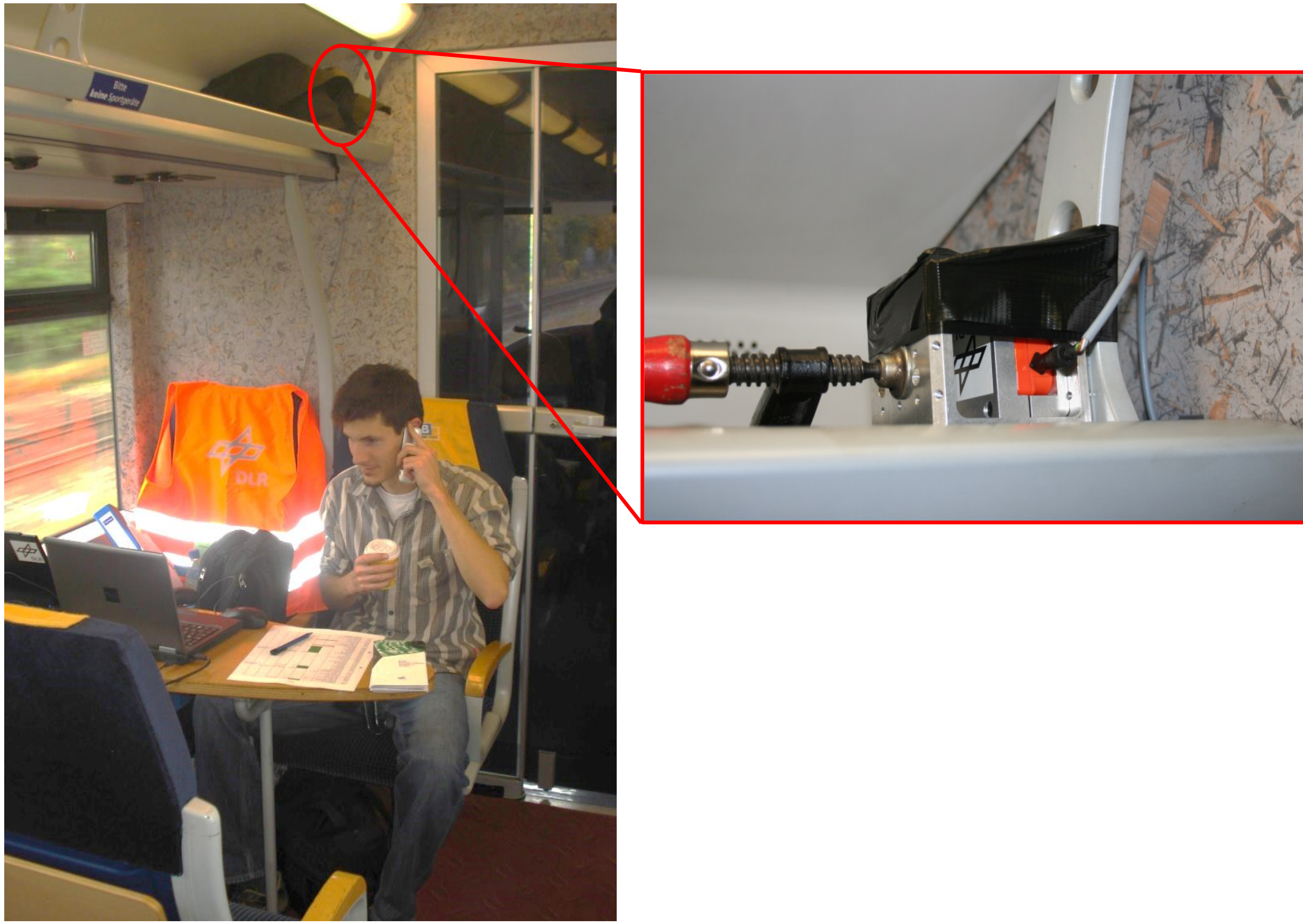


- **Often undesired** effect of a moving vehicle: "NVH engineering" in vehicle design

- **Desired** vibrations
  - Feedback control
  - Mechanical fault diagnostics
  - Engine speed estimation
  - Terrain classification based on wheel vibrations (Robotics)
  - Vehicle speed measurement by driving over a street bumper

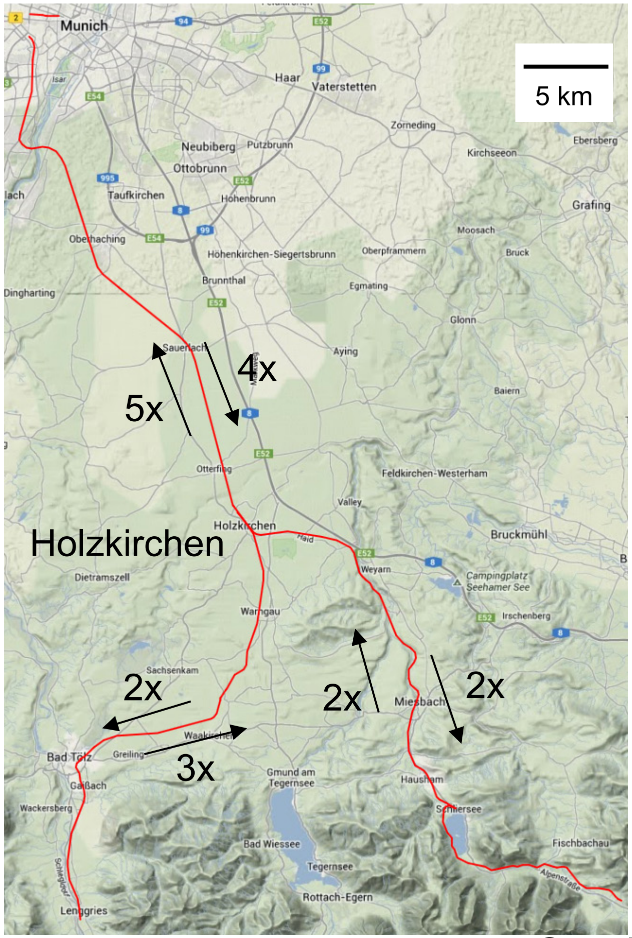
We propose: Using vibration information for velocity and location computation

Measurement setup on over-head rack



Data recording experiment

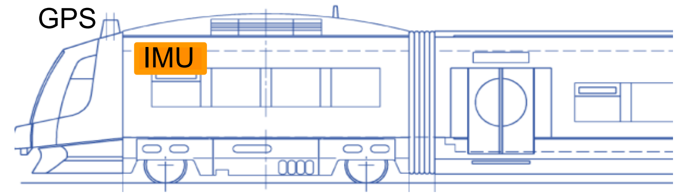
Munich

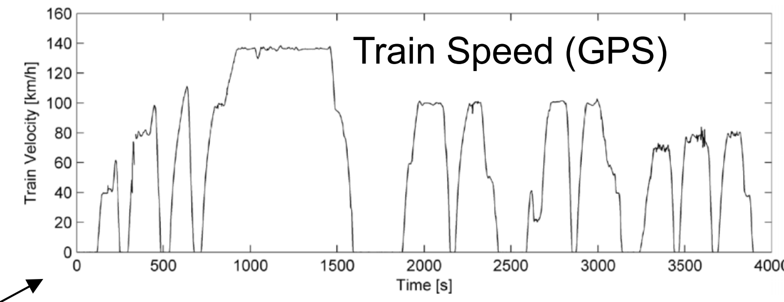


Lenggries

Alps

Osterhofen

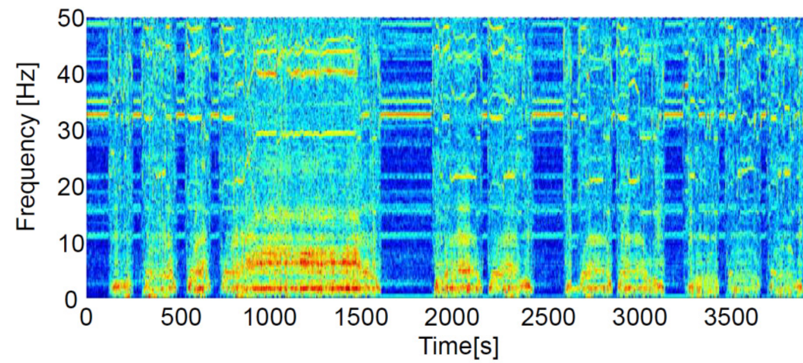




Munich

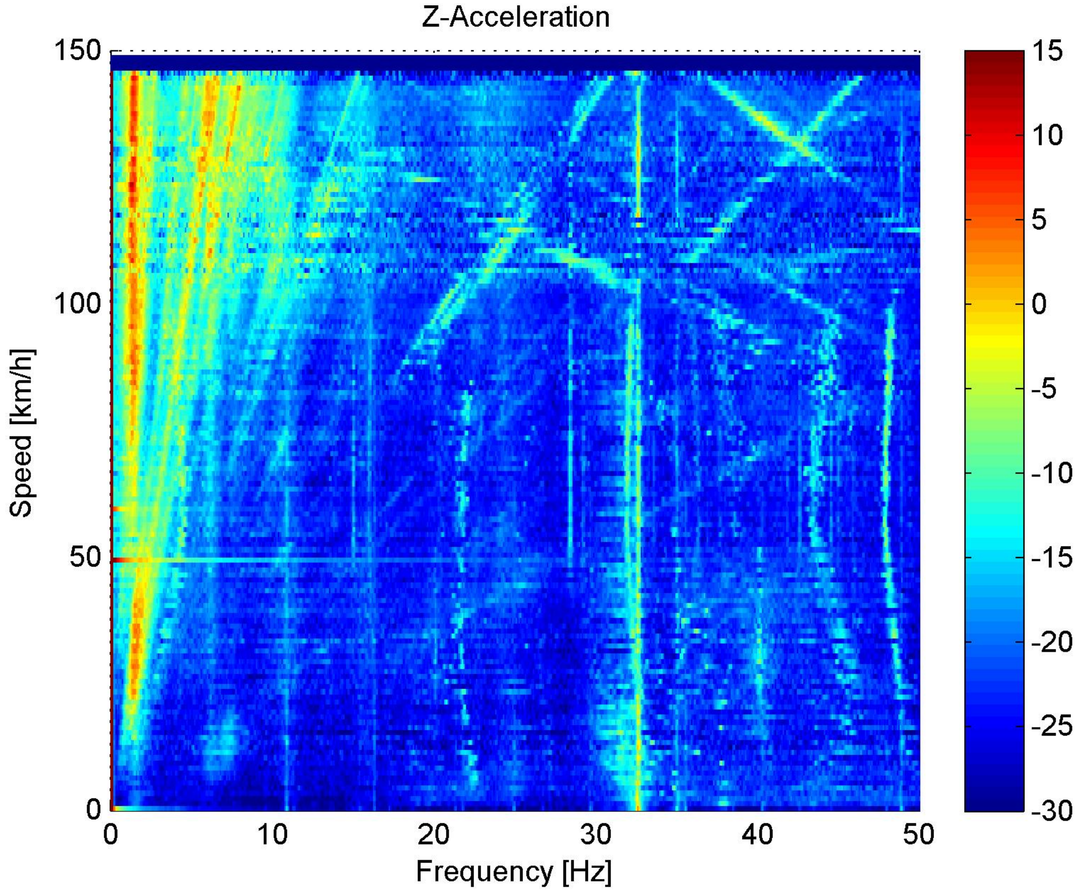
Lenggries

Spectrogram of Z acceleration



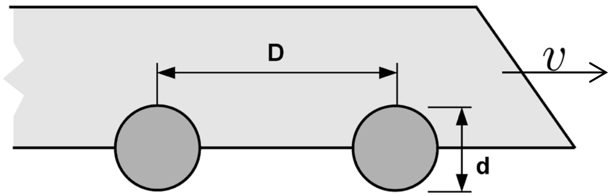
Spectrogram: speed over Z-Acceleration (f)

- data sequences of 1024 samples: 10,24s at 100Hz
- power spectral density (PSD) of each sequence
- sorted into speed bins by mean GNSS speed of sequence
- 150 bins of 1km/h width, multiple PSDs in one bin are averaged



Vehicle vibration model

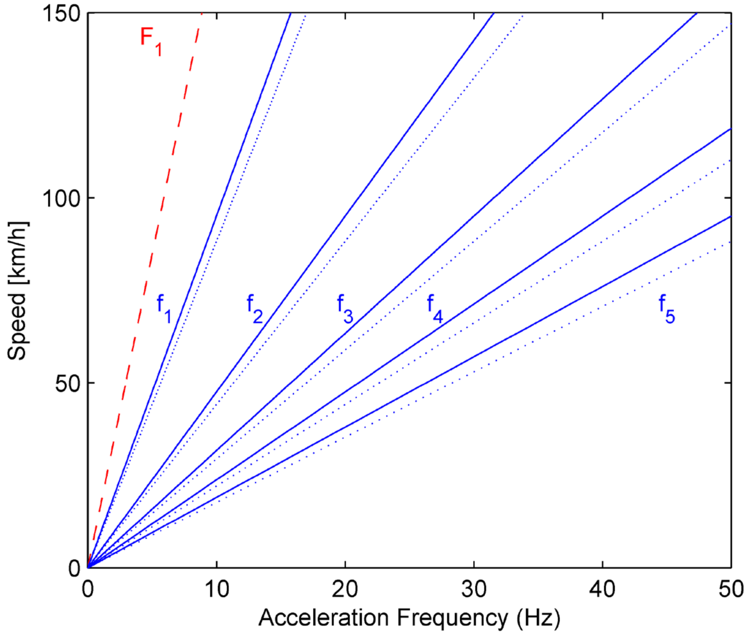
$$F_n = \frac{v}{D} n$$

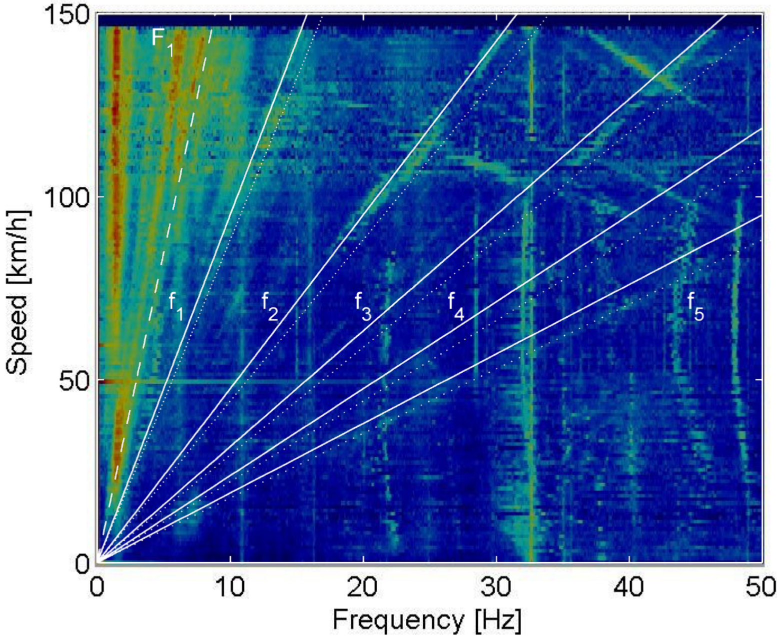


$$f_n = \frac{v}{d \cdot \pi} n$$

train datasheet: D=4.7 m

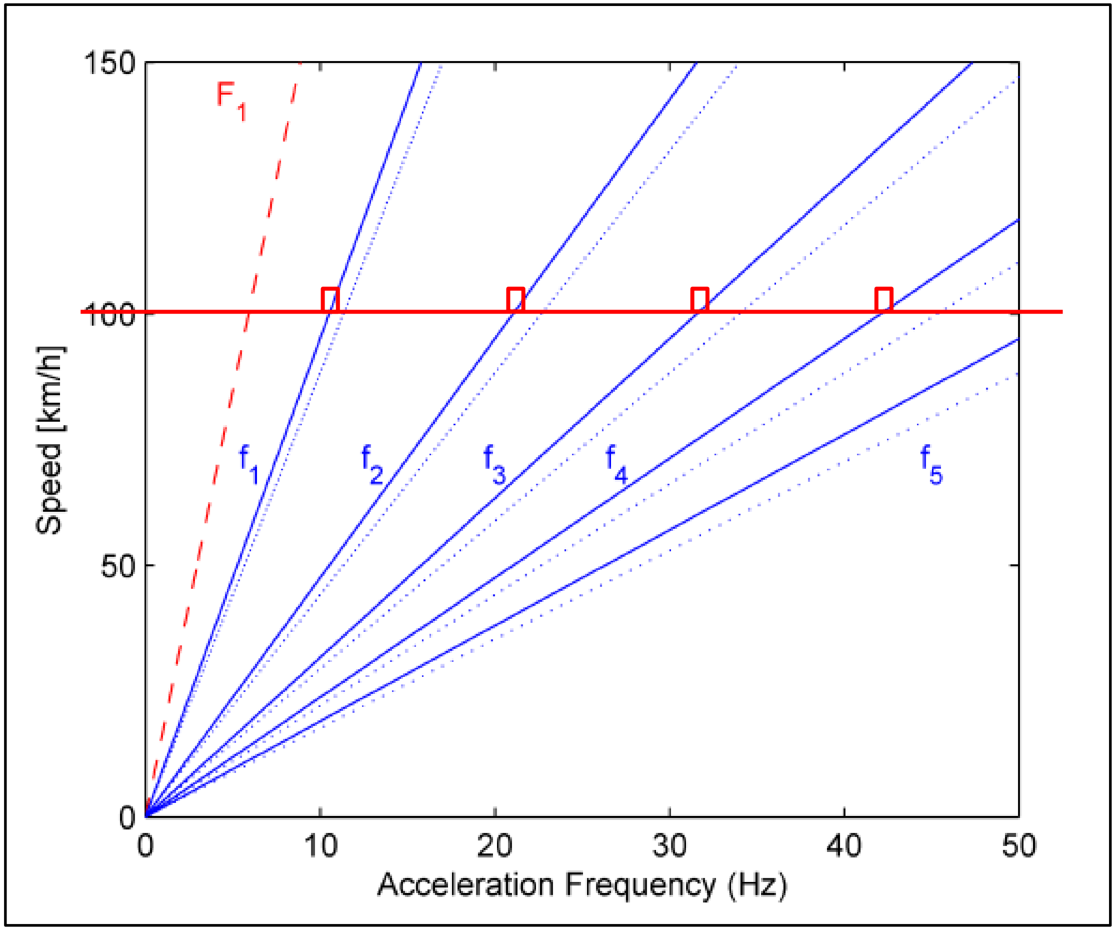
d_{new}=0.84 m d_{EOL}=0.78 m



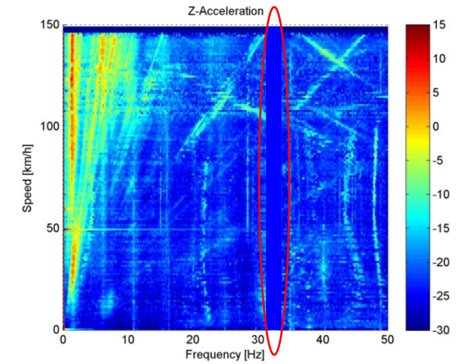


Application: speed measurement

hypothesis: $\hat{v}$



Speed measurement processing



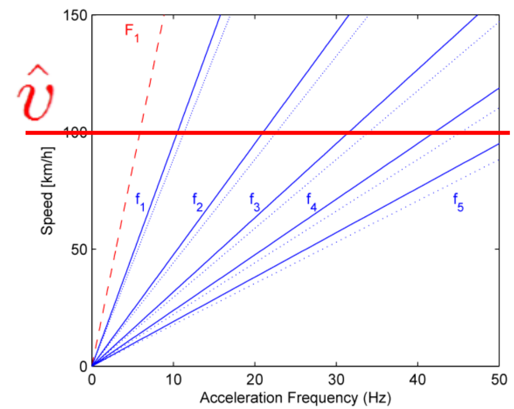
1. Sequence of data (e.g. 100 samples)

2. Multi-Notch filter: removal of from speed independent vibratior (horizontal lines)

3. 150 defined speed hypotheses from 0 to 150 km/h (1 km/h width): $\hat{v}$

4. Computation of multiple band pass filters for each speed hypothesis

$$\hat{A}_{\hat{v}}(k) = f_{\text{multi-bandpass}}(A(k), \hat{v})$$

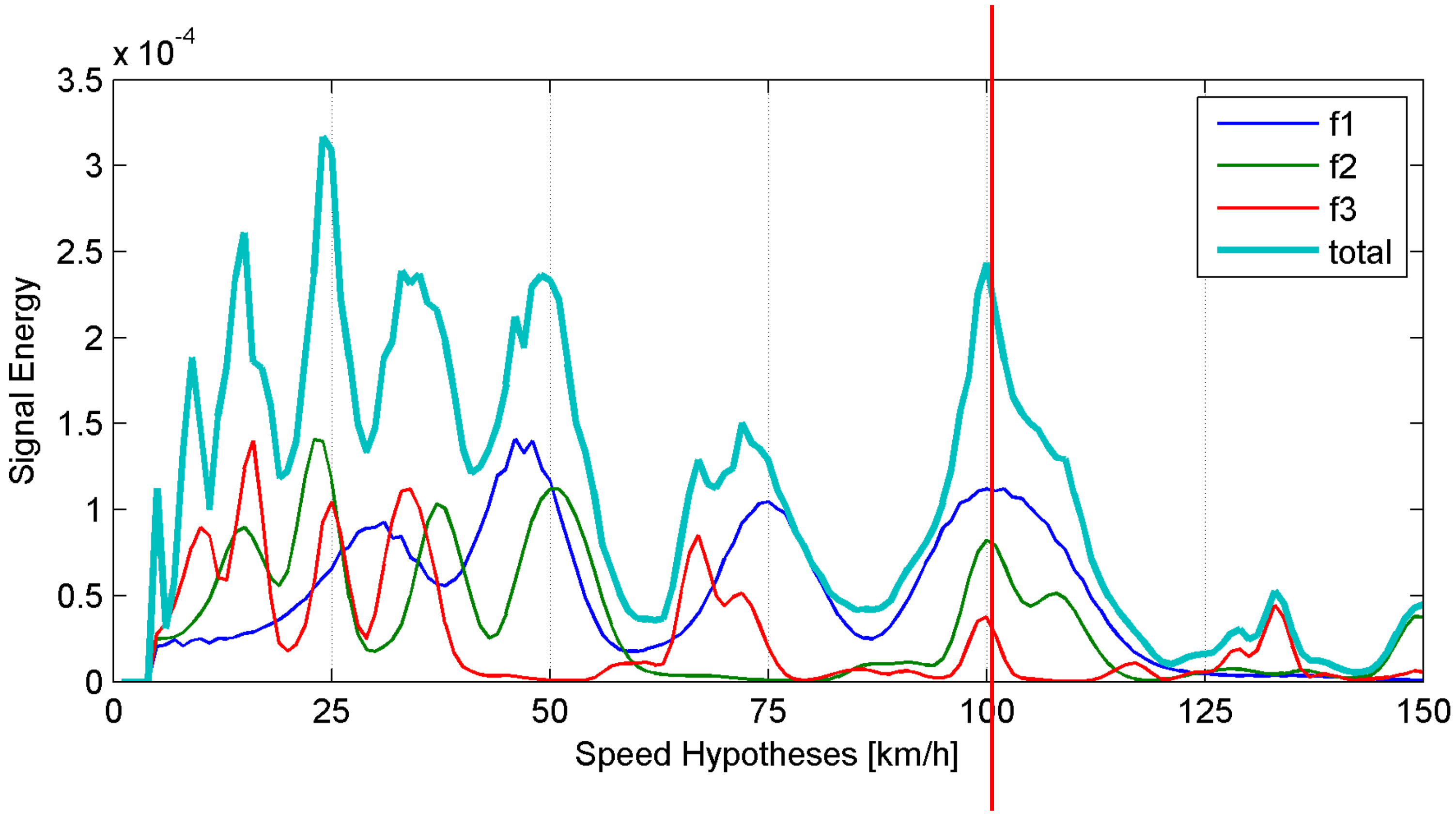


5. Compute signal energy of every speed hypothesis:

$$E_{\hat{v}} = \sum_{n=-\infty}^{\infty} |\hat{A}_{\hat{v}}(n)|^2$$

6. Search the maximum

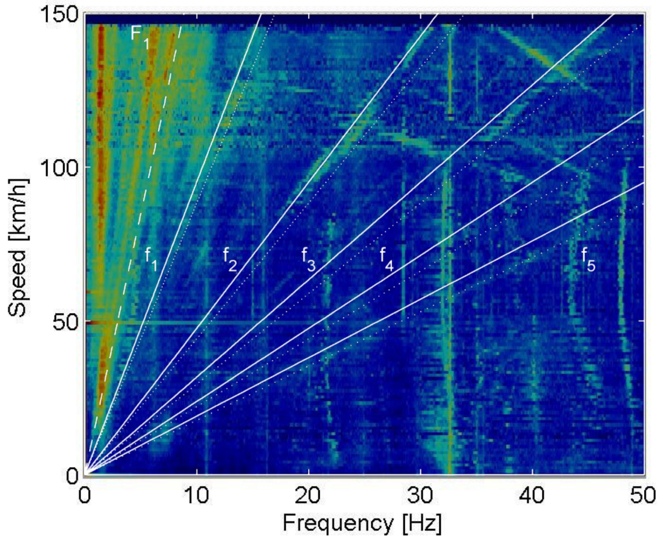
Speed measurement results

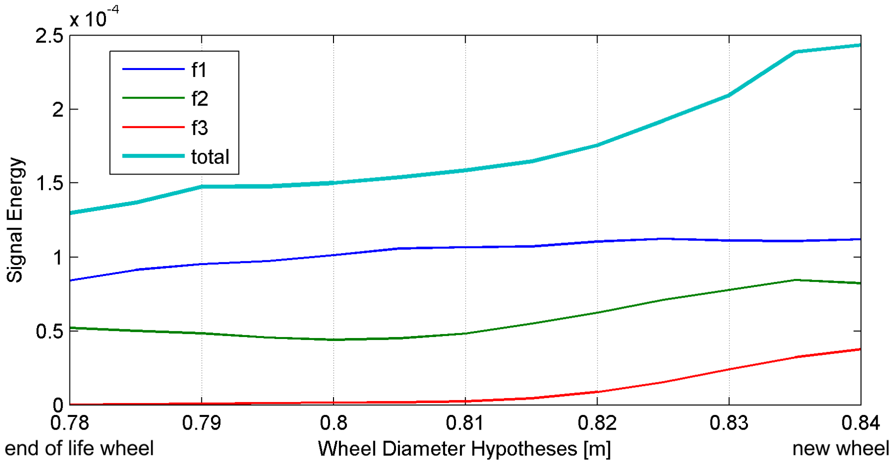


true speed (GPS): 101 km/h

Wheel radius measurement

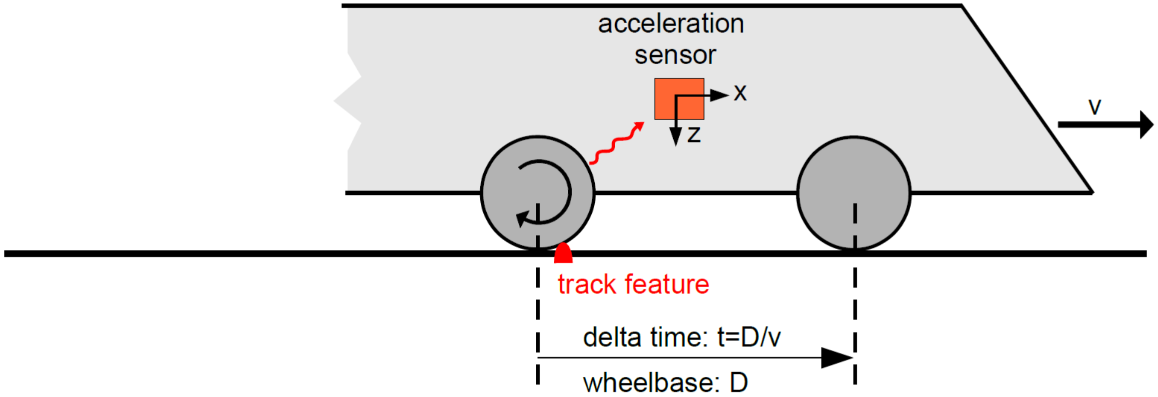
- Now: speed is known (odometer / GPS)
- Application: **Monitoring the wheels**
- Train's datasheet: 0.78 m for used wheels, 0.84m for new wheels
    - first harmonic f1 at 150km/h: new wheel 15.8Hz, end-of-life wheel: 17.0 Hz





- Here: "snapshot in time"

Application: Localization



- Signal preprocessing
  - transformation from time to spatial samples (known speed) by interpolation:

$$A(s) = f_{\text{interp}}(k, A(k), s)$$

  - **Matched filter: 2 Dirac-Delta** functions with distance of wheelbase D (4.7m)

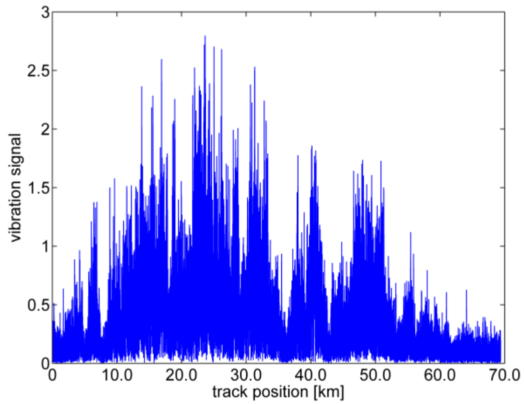
$$\tilde{A}(s) = f_{\text{MF}}(A(s))$$

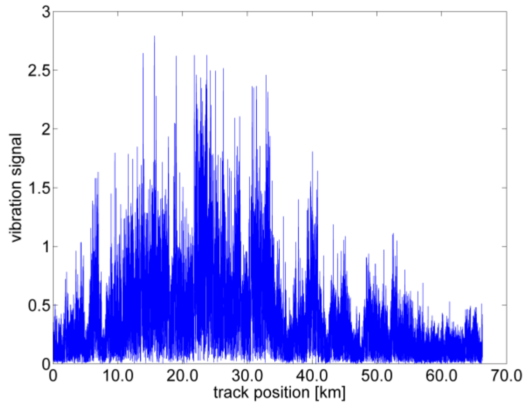
  - Removing the phase information (better S/N): computing the signal envelope:

$$\hat{A}(s) = |\tilde{A}(s) + j \cdot f_{\text{Hilbert}}(\tilde{A}(s))|$$

Localization Processing

1. Prior track map recording:





2. Correlation of hypothetical signal (from map) and measured signal:

$$C_{\text{hypo}}(s) = \sum_{m=1}^{L} \left(\hat{Z}_{\text{path}}(m) \cdot \hat{A}_{\text{hypo}}(s+m) \right)$$

3. Localization computation
   - Track: search for the hypothesis with the highest correlation

$$C_{\text{ML}} = \arg\max_{\text{hypo}} \tilde{C}_{\text{hypo}}(s)$$

   - Track position: peak position

$$\tilde{s} = \arg\max_{s} \tilde{C}_{\text{ML}}(s)$$

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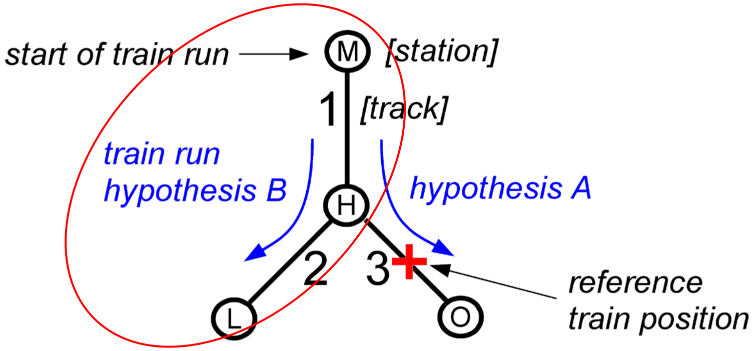
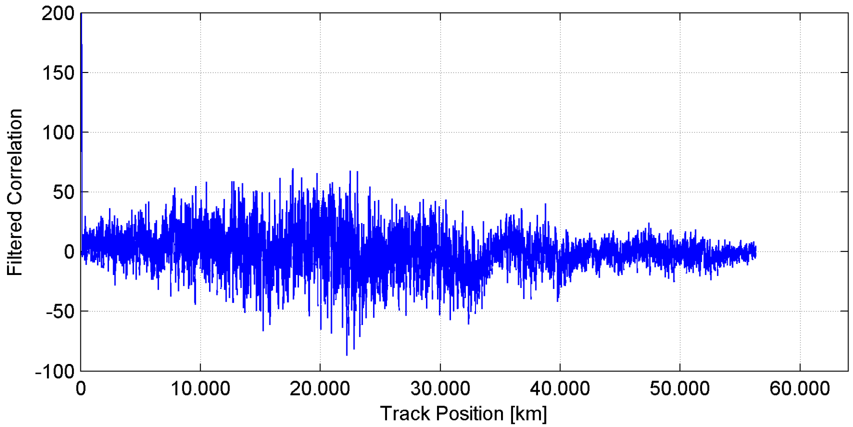
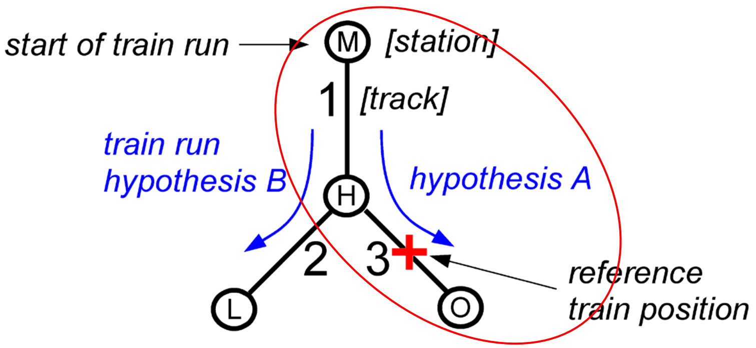
Localization results

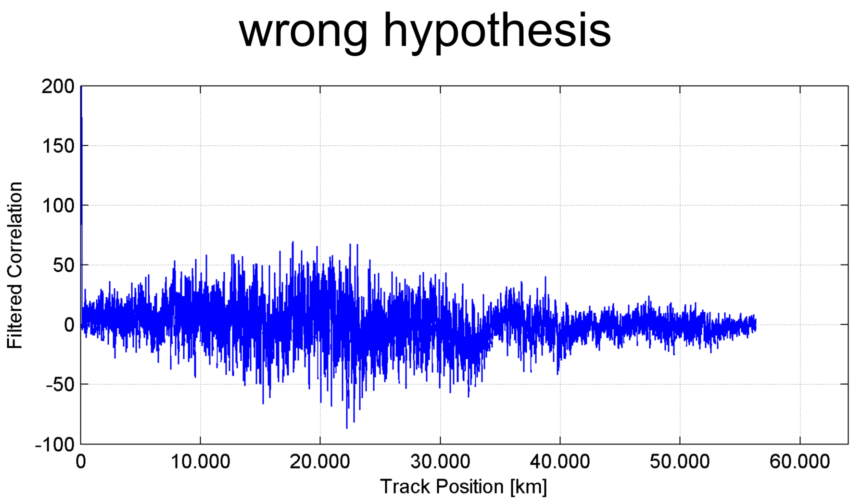


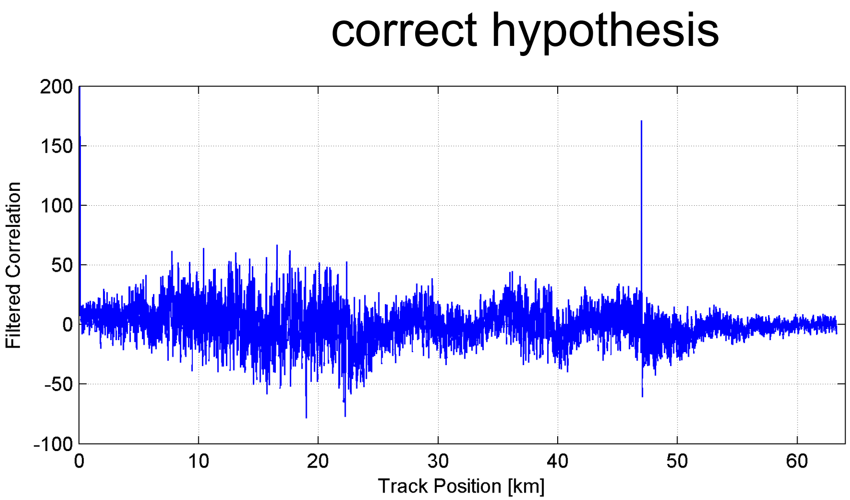
wrong hypothesis



Localization results

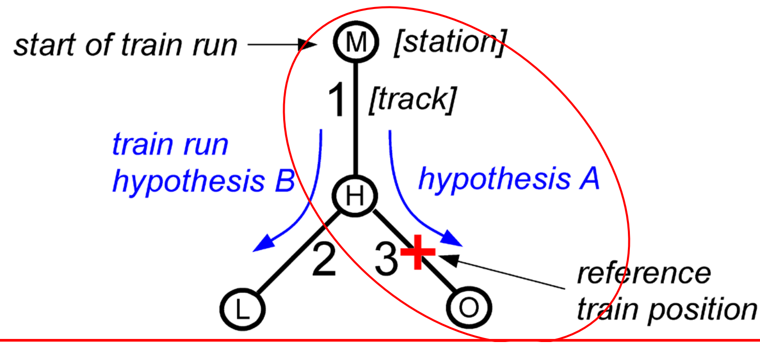


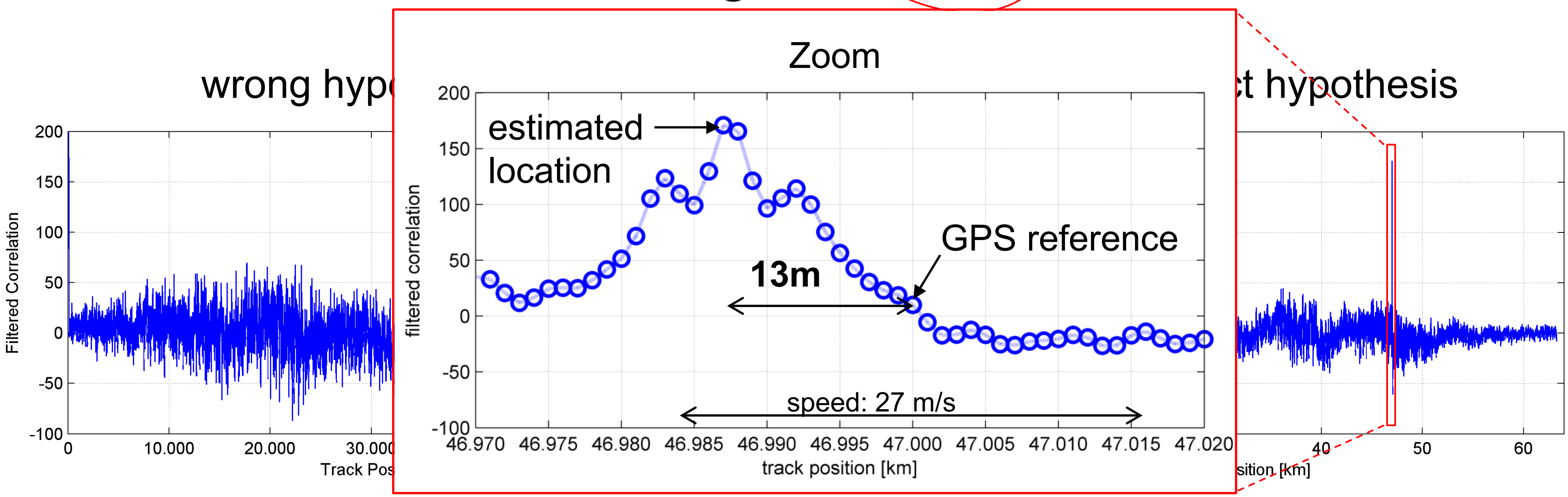




Snapshot in time, no prior knowledge of past position !

Localization results





Snapshot in time, no prior knowledge of past position !

Key benefits

- **independency** from other measurements (e.g. GNSS, low frequent IMU, Camera)
- **absolute vehicle speed and localization for track-selective localization**
- **augment** strapdown navigation approaches, IMU bias observation
- add-on to navigation systems: no additional hardware required, **low cost approach**
- **low installation complexity & high installation flexibility**

Approach of vibration navigation

- Approach by accident
    - over-head rack measurements
    - first approach: snap-shot speed/location estimation

- Future: Measurement improvements
    - enhanced **pre-filter**
    - optimized **sensor placing**
    - **higher sampling frequency**

- Future: Algorithmic improvements (FUSION'14+):
    - Advanced **algorithms for speed** estimation
    - **Tracking** of the **speed** hypothesis and **position**
    - **Multisensory fusion** (GPS, IMU, Vibration method)

Summary and conclusions

- Vertical mounted acceleration sensor shows horizontal speed dependency in frequency domain

- We presented an approach and a proof of concept for:
    - absolute speed computation
    - wheel size monitoring
    - absolute, track selective location computation

- Matched filter (wheelbase) is the key for using vibrations for localization

- It was possible to compute speed and location from a over-head rack mounted sensor

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„One man‘s noise is another man‘s data“,
B. Parkinson (GPS chief architect)

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