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Signal Processing for Transportation Engineering Applications

2101553: Computer Applications in Transportation

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Outline

- Section I: Introduction

- Section II: (Some) Techniques in Signal Processing

- Section III: Hands-On Signal Processing

Learning Objectives

By the end of this class, you will be able to:

- Explain what signals are and why signal processing matters.
- Interpret signals in both time and frequency domains.
- Use MATLAB to analyze and extract information from real signals.

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Section I: Introduction

I: Signal… What is it?

- A **signal** is:
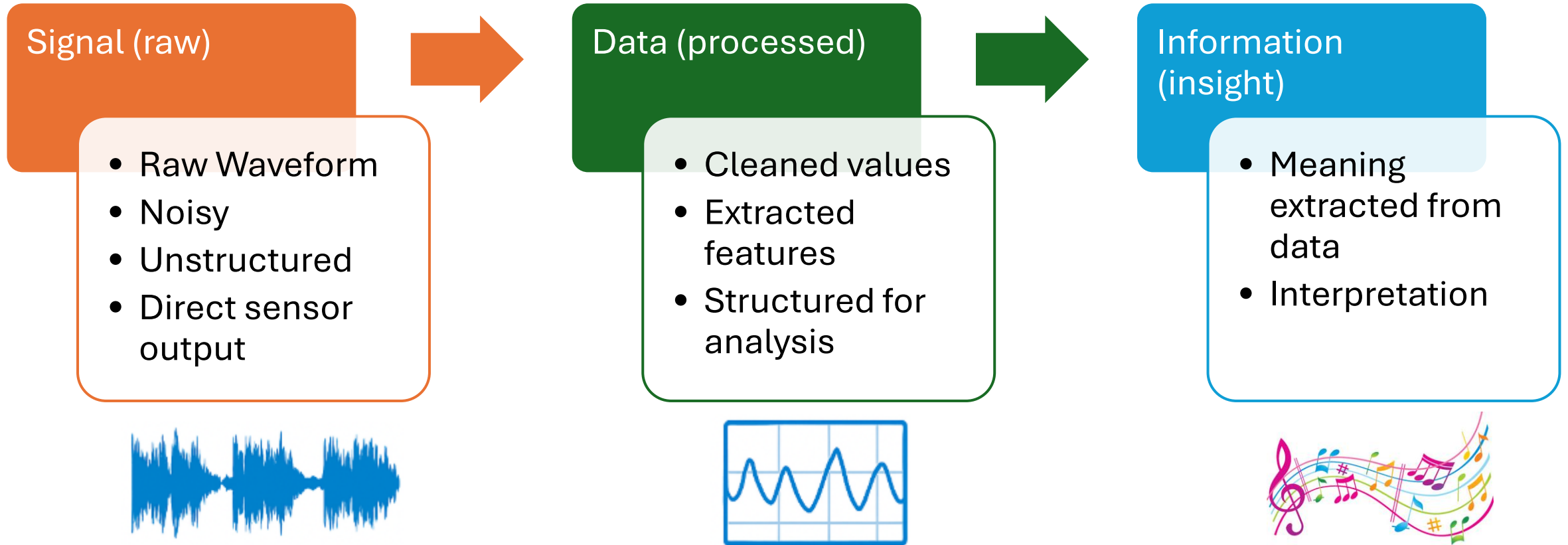
    *Any quantity that changes **over time** and can be **measured***

- Examples of quantities:
    - Sound amplitude
    - Acceleration
    - Velocity
    - Voltage
    - Light intensity
    - Temperature

    A signal is the *raw material* before we extract anything useful

I: Signal → Data → Information

Signal (raw)
- Raw Waveform
- Noisy
- Unstructured
- Direct sensor output

Data (processed)
- Cleaned values
- Extracted features
- Structured for analysis

Information (insight)
- Meaning extracted from data
- Interpretation

We measure <u>signals</u>, we analyze <u>data</u>, we understand <u>information</u>

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I: Why Signal Processing Matters

- Signals are **everywhere** (Sound, light, vibration, images, temperature, voltage)

- Signals are the **first layer of reality** we can measure.

- But raw signals are often **noisy, messy, or meaningless.**

- Signal processing helps us:
  - Extract meaningful **insights**
  - Make better **decisions** based on real-world observations

I: Where Do We See Signals in Everyday Life?

- Examples of everyday signals:
  - Your phone's microphone captures sound signals
  - Your smartwatch senses heart-rate signals
  - Cars use vibration signals for safety systems
  - Cameras capture image signals
  - Thermometers and weather stations record temperature signals
  - GPS devices track location signals

Signals are everywhere — that's why signal processing is everywhere

I: Let's LOOK at a Signal: Virtual Oscilloscope

- Real signals look like waveforms that change over time

- This oscilloscope visualizes a live audio signal

- Let's briefly see how sound appears as a waveform

https://academo.org/demos/virtual-oscilloscope/

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I: Signals as Time-Series

- A signal can be represented as a **time series waveform**:
  - **x-axis:** time
  - **y-axis:** measured value
  - This is the raw waveform that we will process later
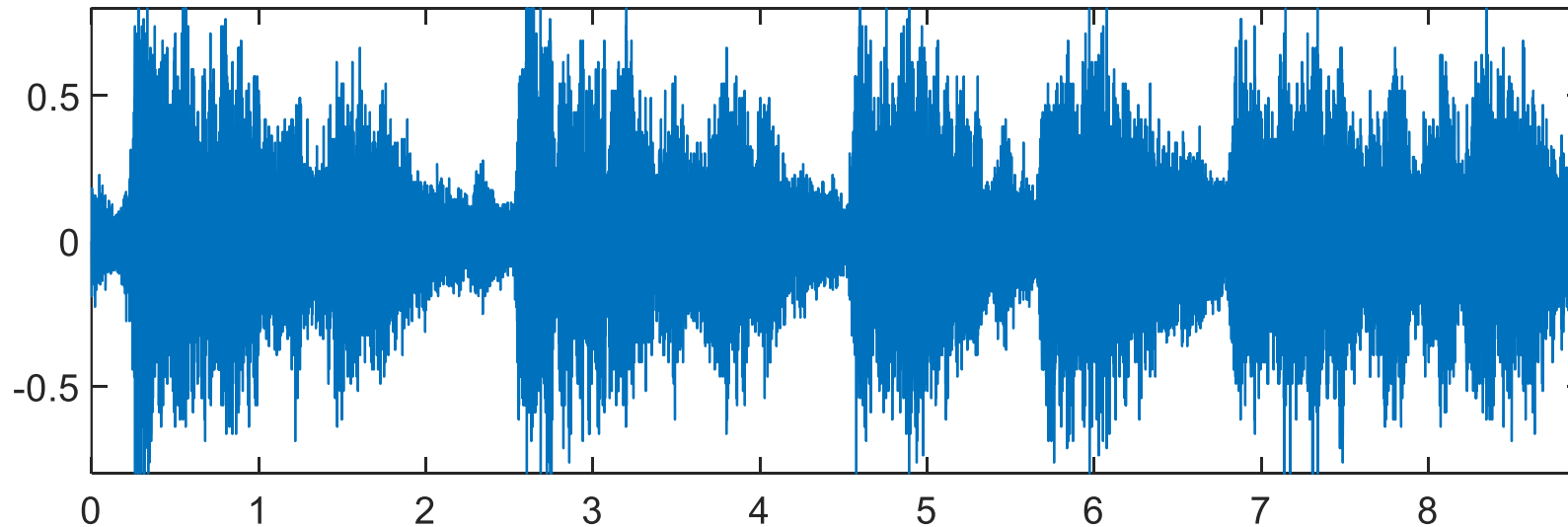
Let's SEE Frequencies: Spectrum Analyzer

- Every sound contains hidden frequency components

- A spectrum analyzer shows these components

- This is important for audio, vibration, mechanical systems, etc.

https://academo.org/demos/spectrum-analyzer/

I: What Can We Extract from a Signal?

- **Signal processing reveals what's hidden inside the waveform**
  - **Amplitude** → How strong is the signal?
  - **Frequency** → What patterns repeat over time?
  - **Phase** → When do those patterns happen?
  - **Shape/Envelope** → Does it change suddenly or smoothly?
  - **Energy/Power** → How intense is it overall?
  - **Trends/Anomalies** → Are there sudden jumps or drops?
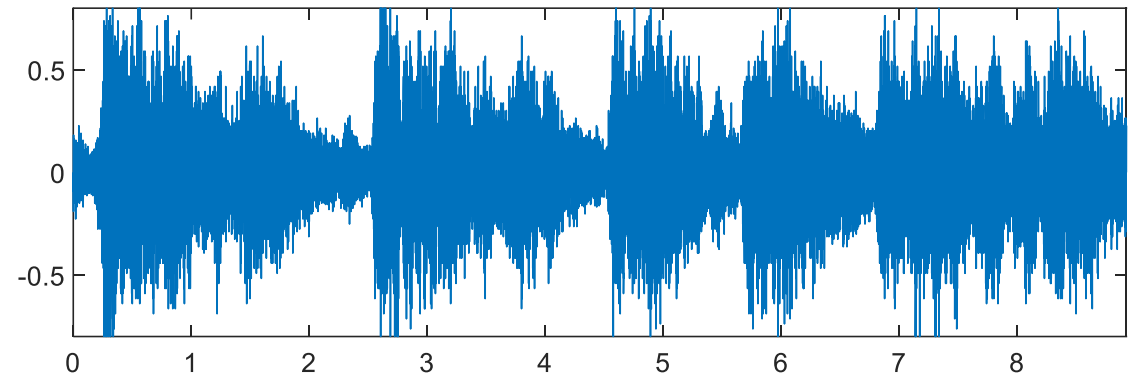
I: Everyday Applications of Signal Processing

- Noise Cancelling Headphones

https://www.youtube.com/watch?v=s09xkfKRBwg

I: Everyday Applications of Signal Processing

- Voice Recognition

https://www.youtube.com/watch?v=6altVgTOf9s

I: Applications of Signal Processing in Transportation

- **Train vibration signals (Axle Box Acceleration)**

Vertical ABA
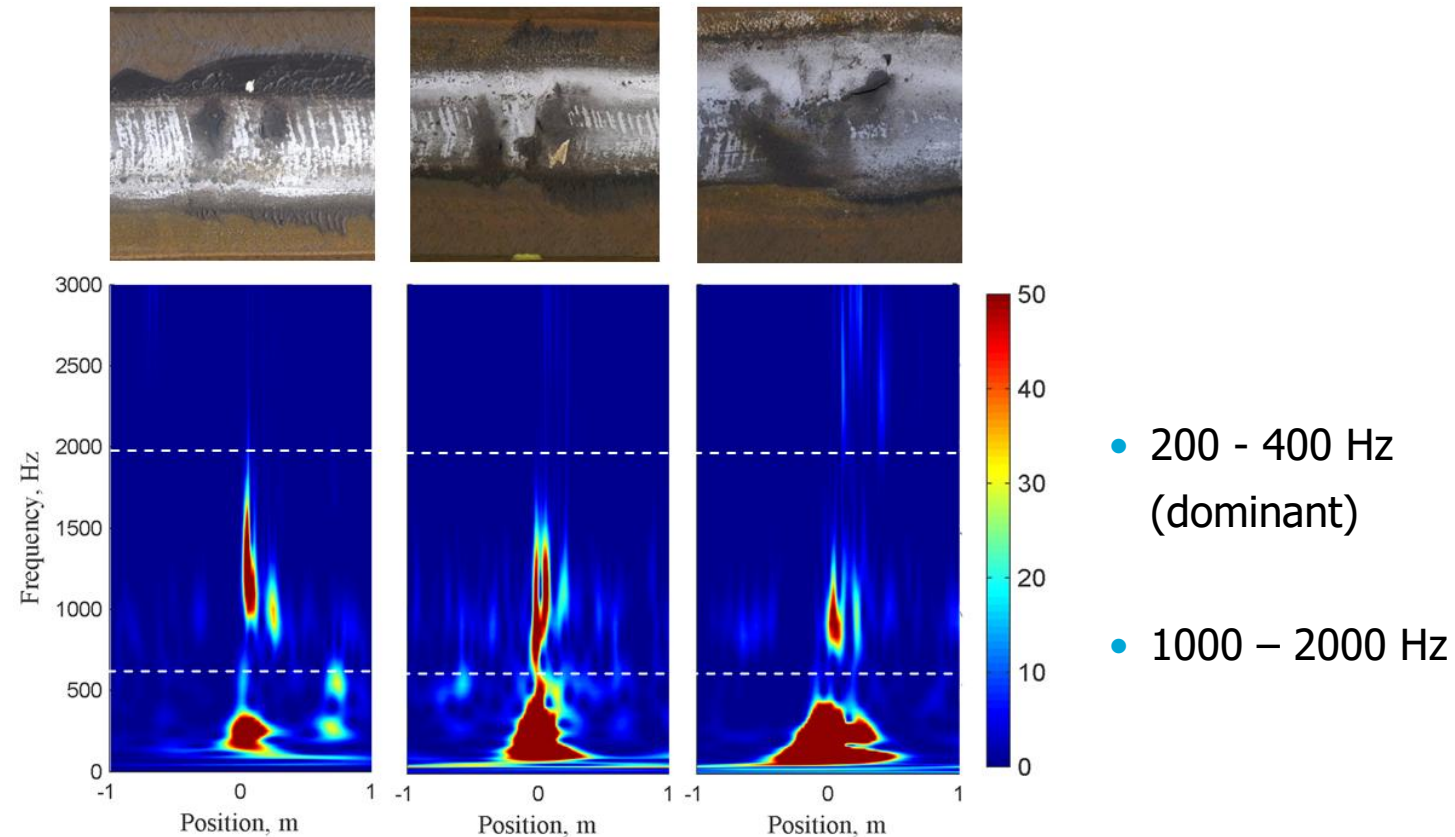
- 200 - 400 Hz (dominant)

- 1000 – 2000 Hz

Z. Li, M. Molodova, A. Núñez, and R. Dollevoet, "Improvements in axle box acceleration measurements for the detection of light squats in railway infrastructure". IEEE Transactions on Industrial Electronics 62(7): 4385-4397, 2015. DOI:10.1109/TIE.2015.2389761

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I: Applications of Signal Processing in Transportation

- **Train vibration signals (Axle Box Acceleration)**
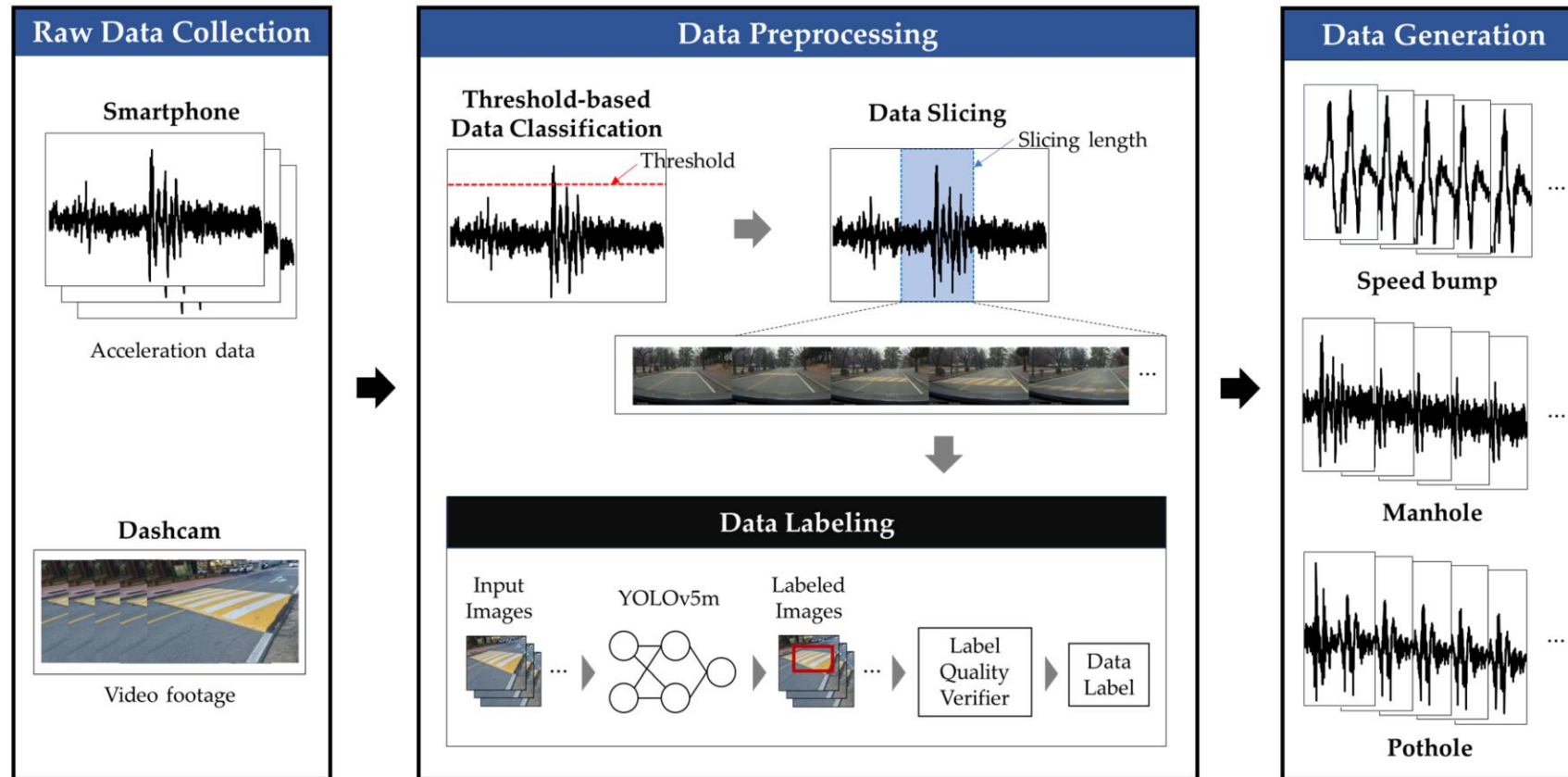
https://www.mdpi.com/1424-8220/24/7/2099?utm_source=chatgpt.com

Section II:
(Some) Techniques in Signal Processing

II: Looking at a time series waveform is not enough

- Many signals contain hidden repeating patterns

- Some changes are easier to detect in the frequency view than in the time view

- Frequency analysis helps reveal what components make up a signal

II: Fourier Transform — What Is Frequency?

- Frequency is the number of occurrences of a repeating event per unit of time.

- 1 Hz (hertz) is equal to one occurrence of a repeating event per second.

Adapted from TU Delft slide

II: Fourier Transform — What Is Frequency?

- Frequency is the number of occurrences of a repeating event per unit of time.

- 1 Hz (hertz) is equal to one occurrence of a repeating event per second.

$$x(t) = \cos(2\pi f t)$$

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Adapted from TU Delft slide
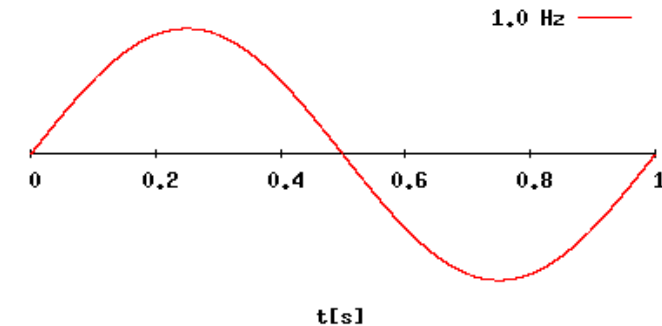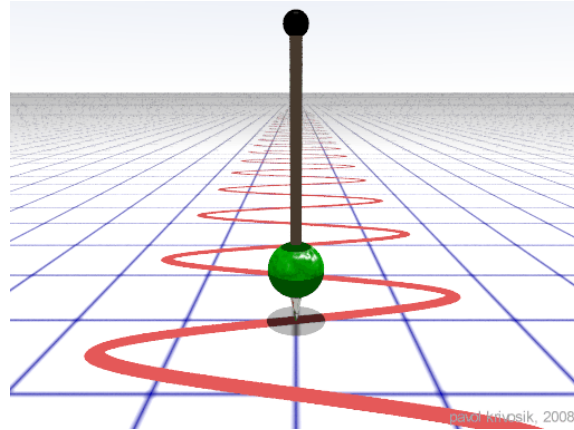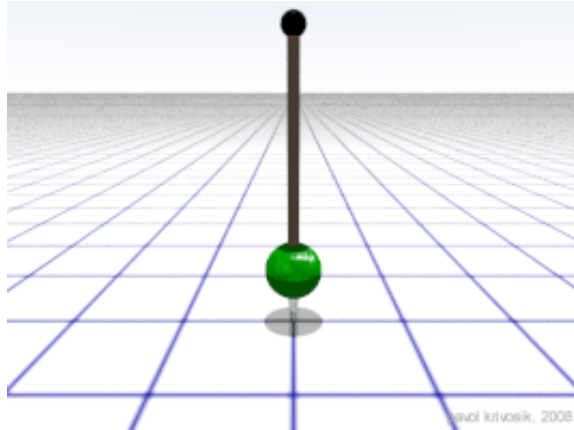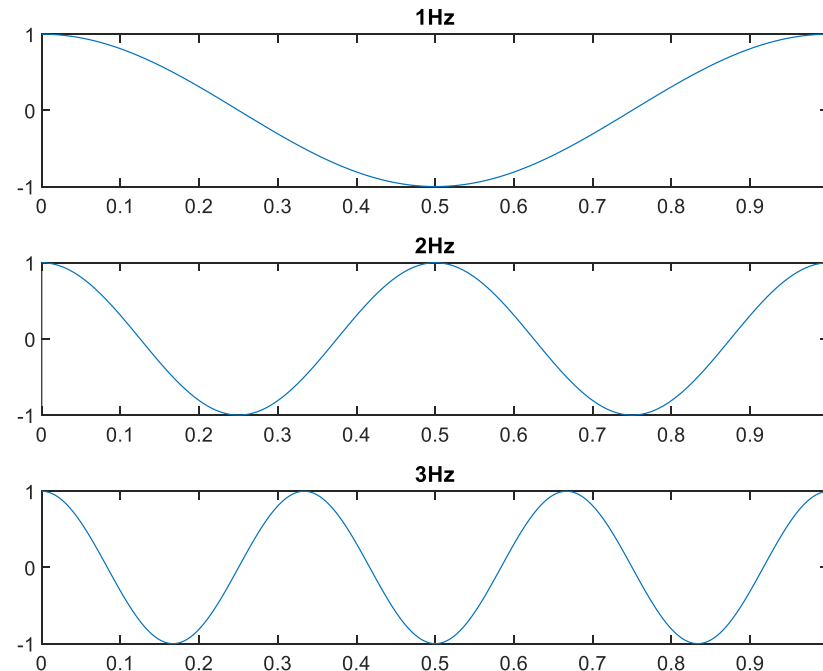
II: Fourier Transform – what is it?

Fourier transform of $x(t)$:

$$\hat{x}(\omega) = \int_{-\infty}^{\infty} x(t)e^{-i\omega t}\,dt$$

Angular frequency: $\omega = 2\pi f$ (Frequency f)

Imaginary number: $i^2 = -1$

Euler's formula $\quad e^{-i\omega t} = \cos(x\omega) - i \cdot \sin(x\omega)$

Inverse transform: $\quad x(t) = \int_{-\infty}^{\infty} \hat{x}(\omega)e^{i\omega t}\,d\omega$
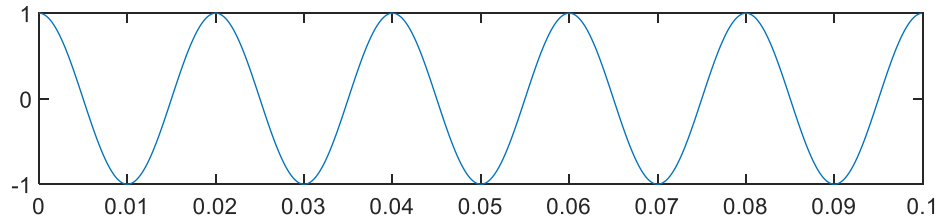
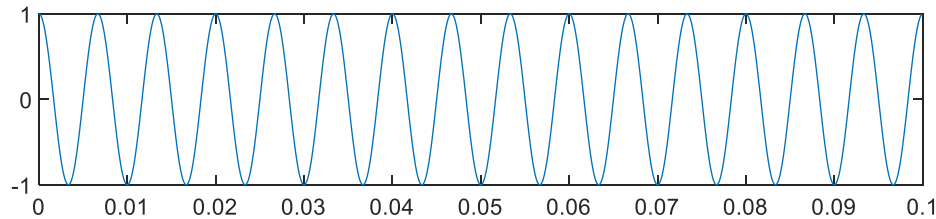Jean-Baptiste Joseph Fourier

21 March 1768 – 16 May 1830

Adapted from TU Delft slide

II: Fourier Transform – what is it?

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Adapted from TU Delft slide
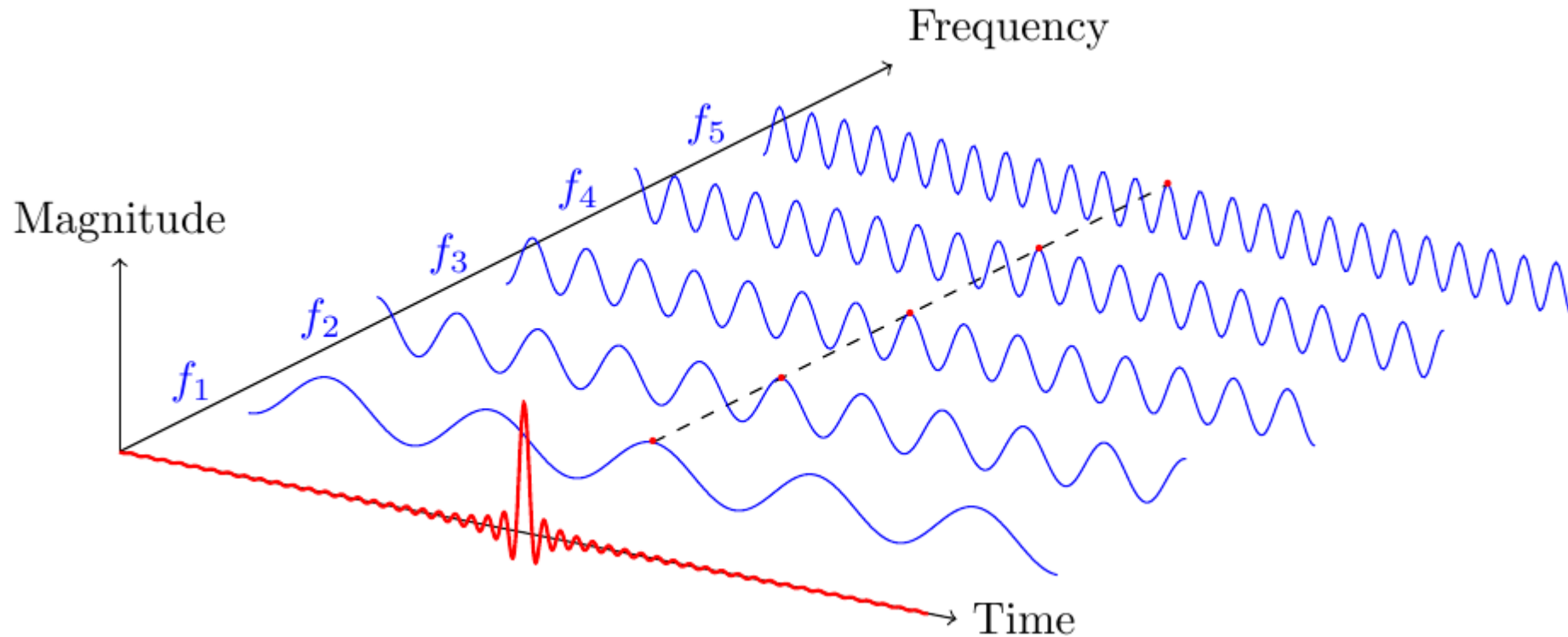
II: Fourier Transform – what is it?

$$x(t) = \cos(2\pi f t)$$

$$\left|\hat{x}(f)\right|$$

f=50Hz

f=150Hz

f=300Hz
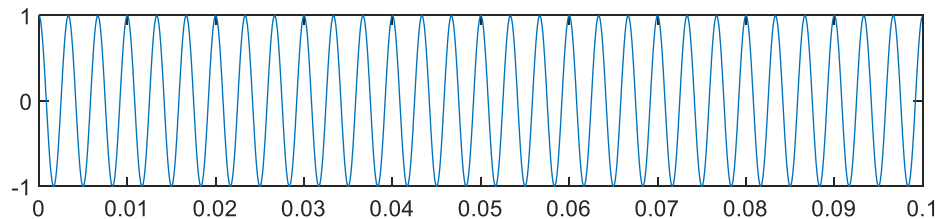
Time *t* (s)

*Sampling frequency 10,000 Hz
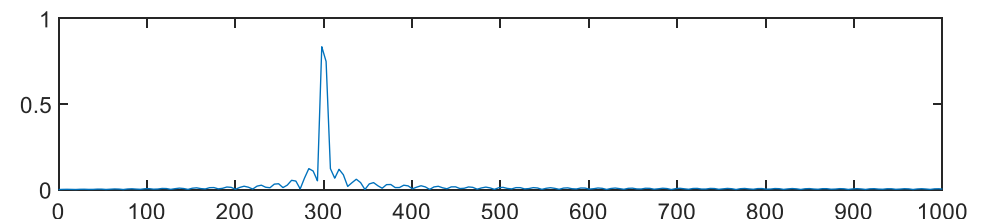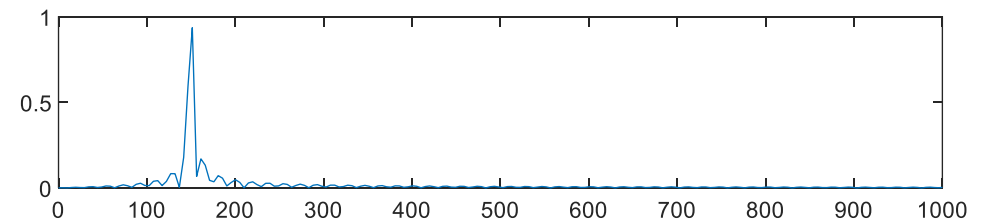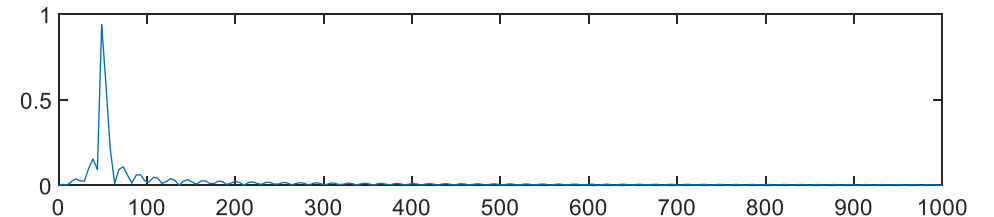
Frequency *f* (Hz)

Adapted from TU Delft slide

II: Fourier Transform – what is it?

Row 1 in the Time Domain

f=50Hz

Row 2 in the Time Domain

f=150Hz

$x(t)$

50Hz + 150Hz

Time (s)

How does the $\left|\hat{x}(f)\right|$ look like?

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Adapted from TU Delft slide

II: Fourier Transform – what is it?

Row 1 in the Time Domain — f=50Hz

Row 2 in the Time Domain — f=150Hz

$x(t)$ — 50Hz + 150Hz

$\left|\hat{x}(f)\right|$

Time (s)

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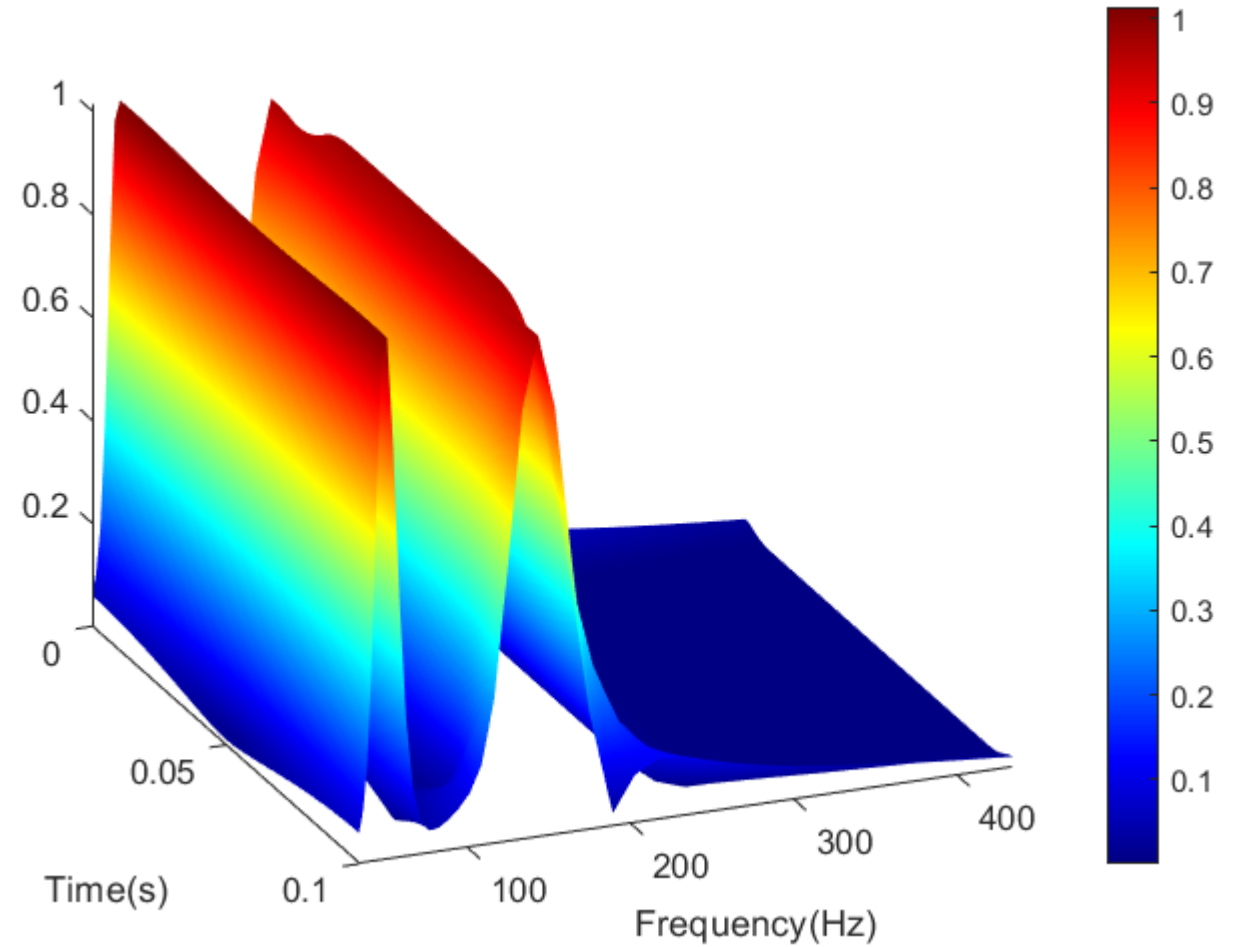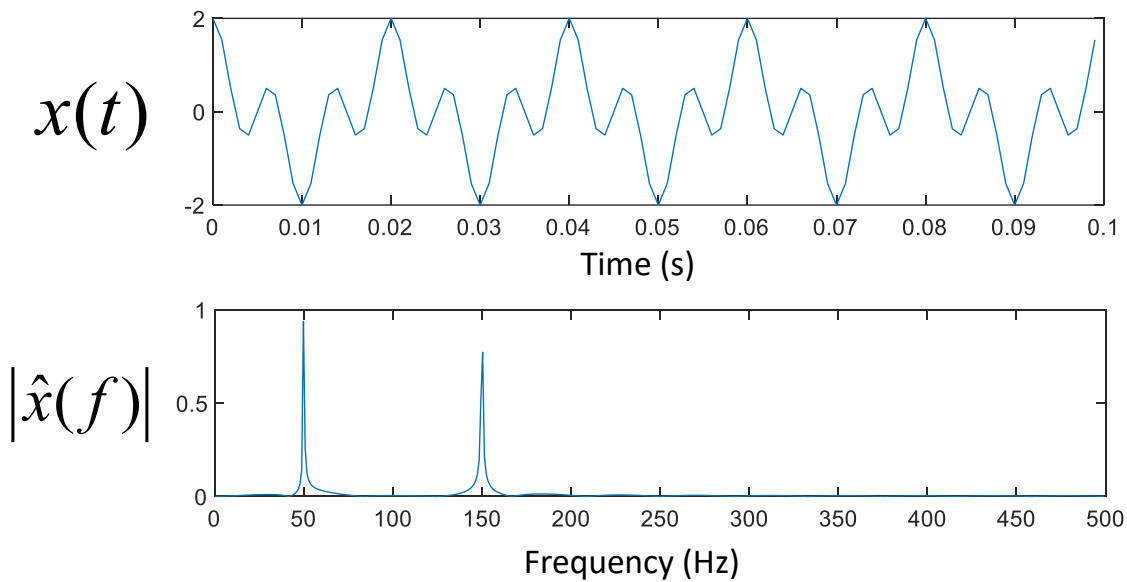
Adapted from TU Delft slide
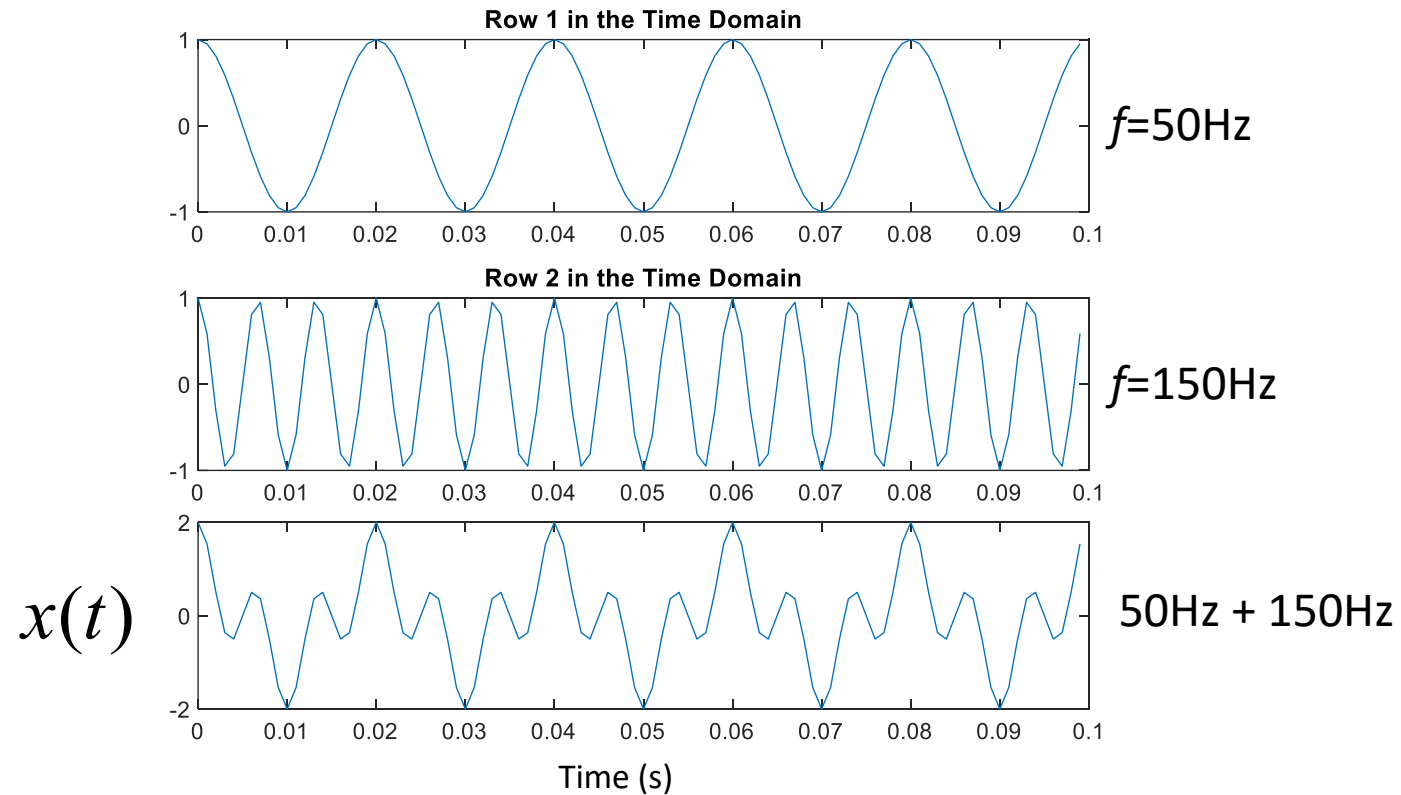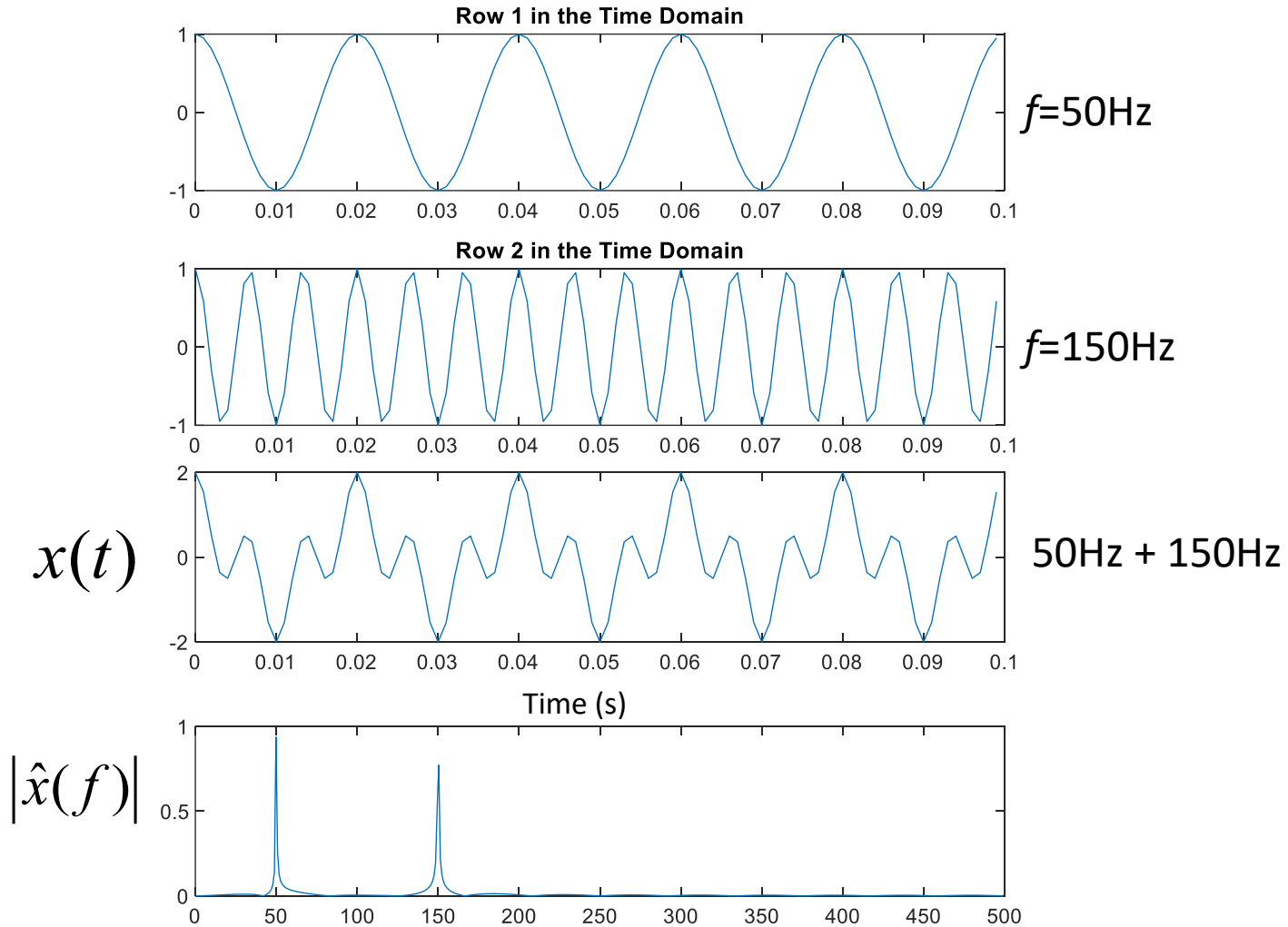
II: Fourier Transform – limitations

- Fourier Transform shows what frequencies are present

- BUT it does not tell us when those frequencies happen

- This is a problem for non-stationary signals, where:
  - Frequencies change over time
  - Events happen suddenly (impacts, defects, shocks, braking, bumps)

- Example:
  - A signal contains of 50 Hz and 150 Hz
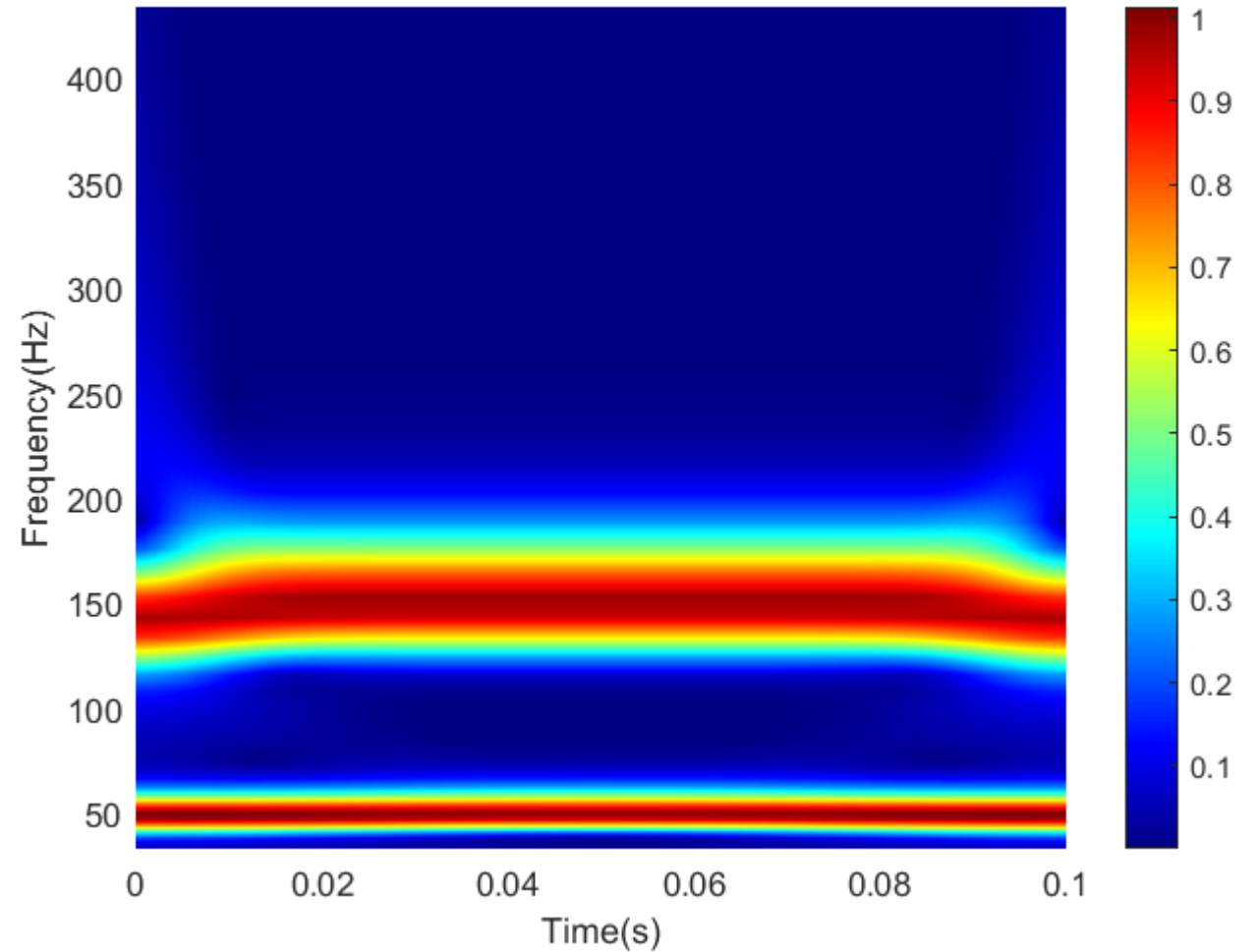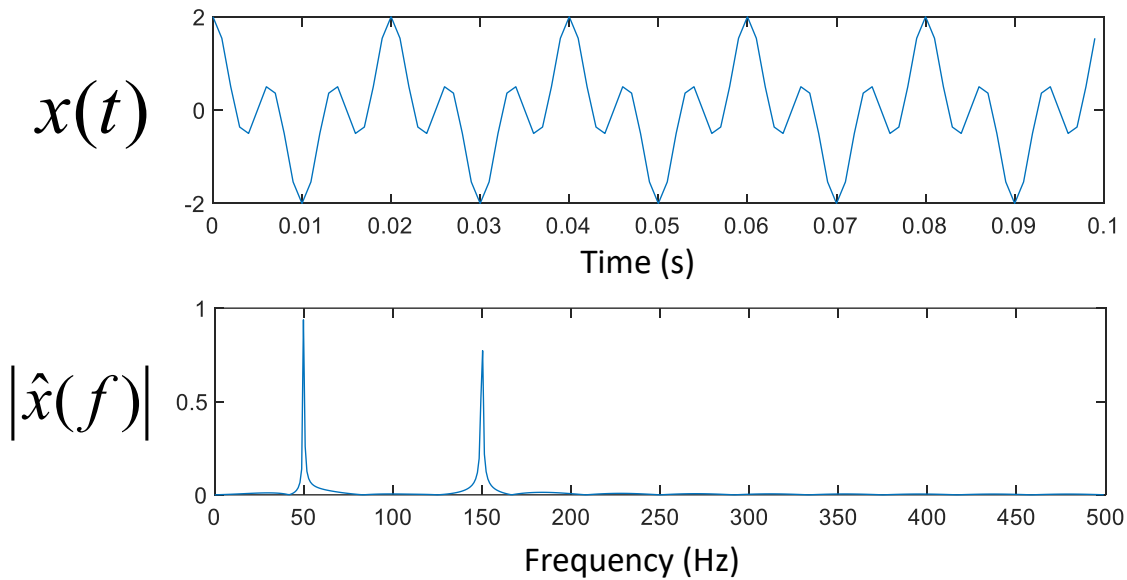 - Fourier Transform shows both, but hides the moment of change

II: Time–Frequency Analysis — Why Do We Need It?

- Many transportation signals are non-stationary (their characteristics change over time)

- Examples:
  - Train passing a defect
  - Smartphone hitting a pothole

- We need a method that shows:
  - What frequencies exist
  - When they occur

II: Time–Frequency Analysis

$x(t)$

$|\hat{x}(f)|$

Adapted from TU Delft slide

II: Time–Frequency Analysis

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Adapted from TU Delft slide

II: Time–Frequency Analysis

50Hz   150Hz

$x(t)$

$|\hat{x}(f)|$

Adapted from TU Delft slide

II: Time–Frequency Analysis
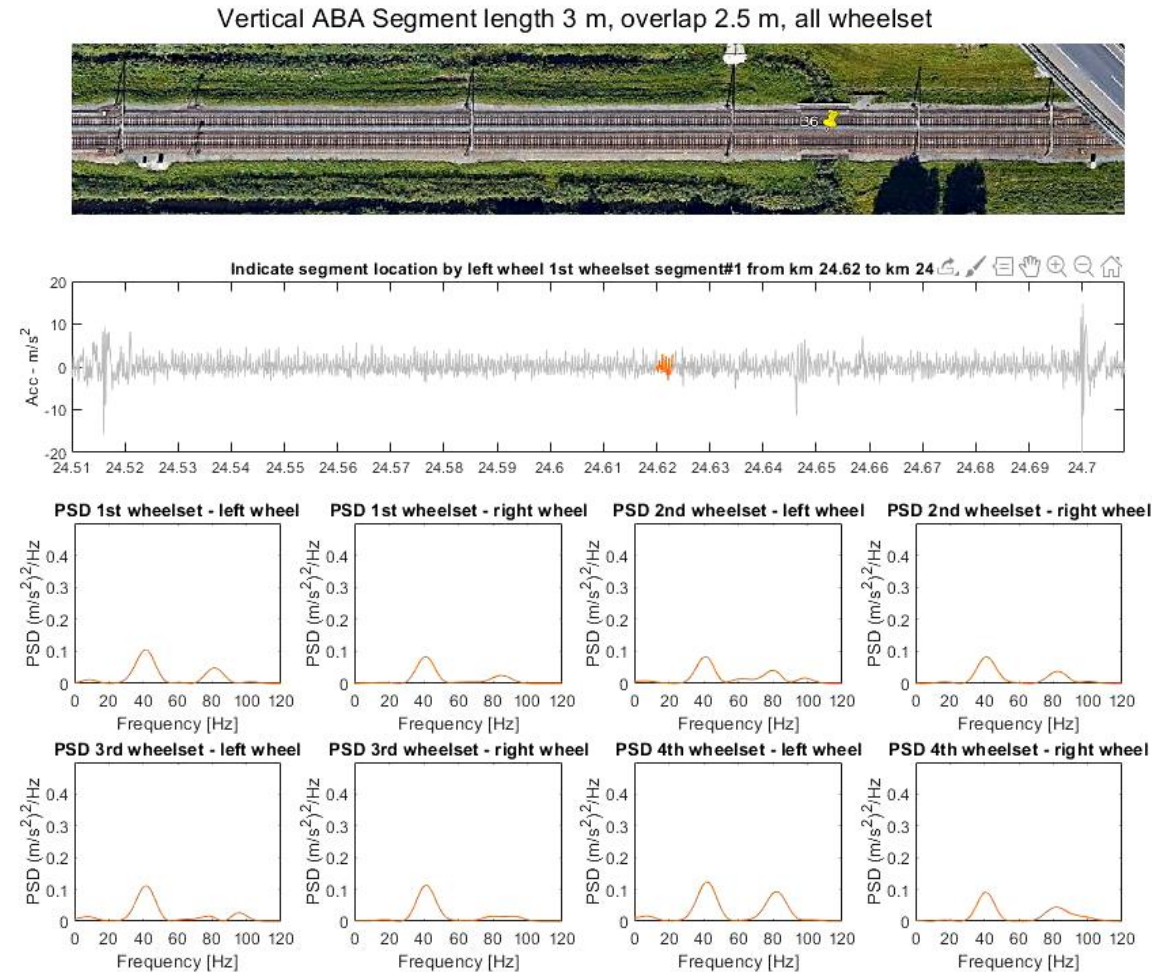
Adapted from TU Delft slide
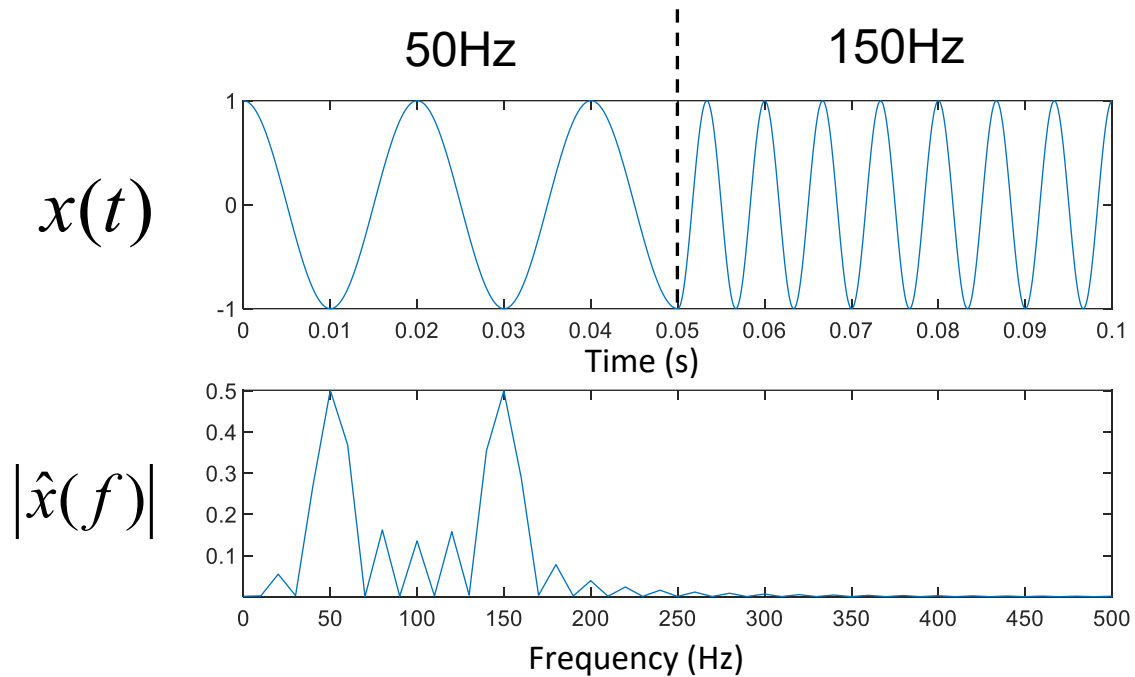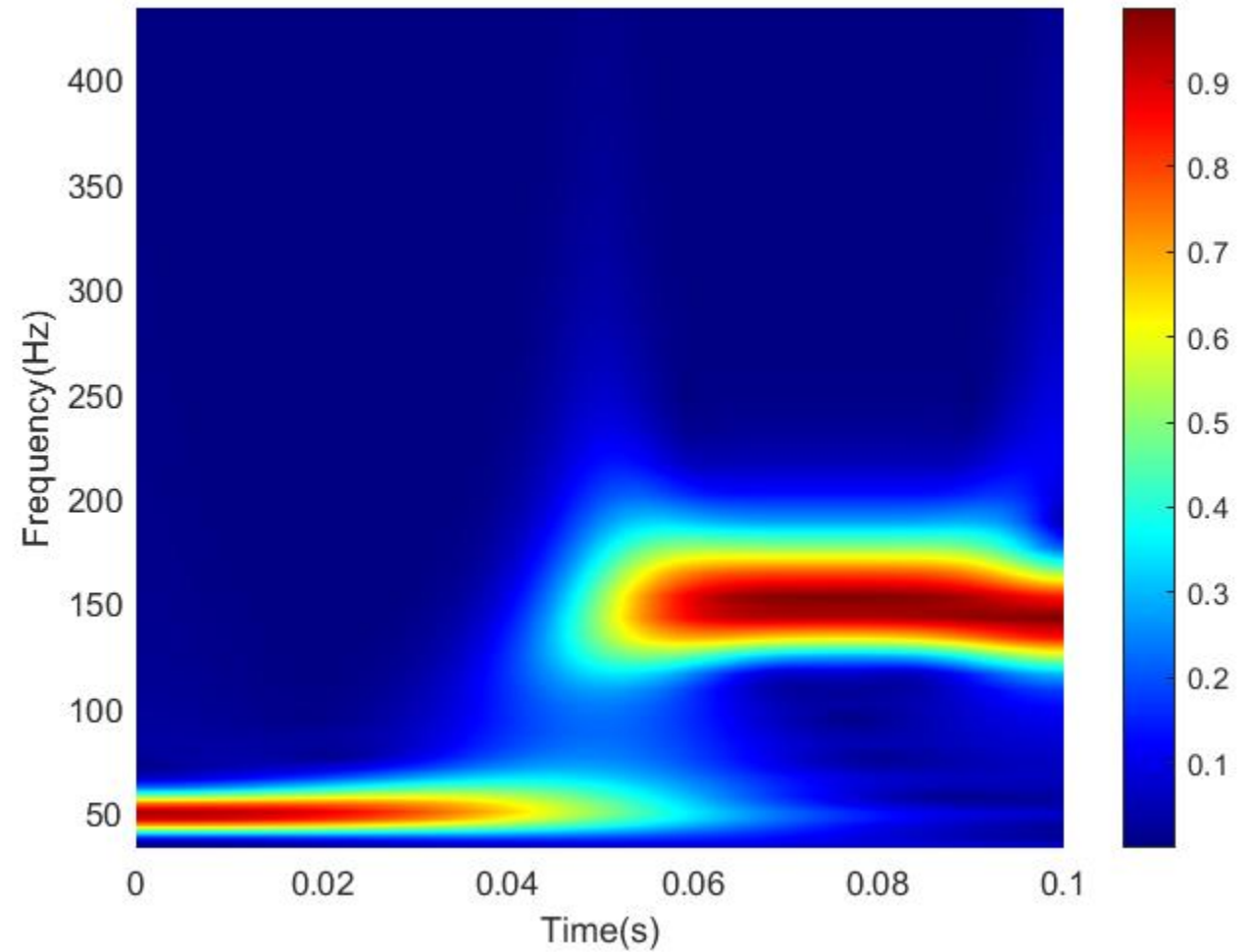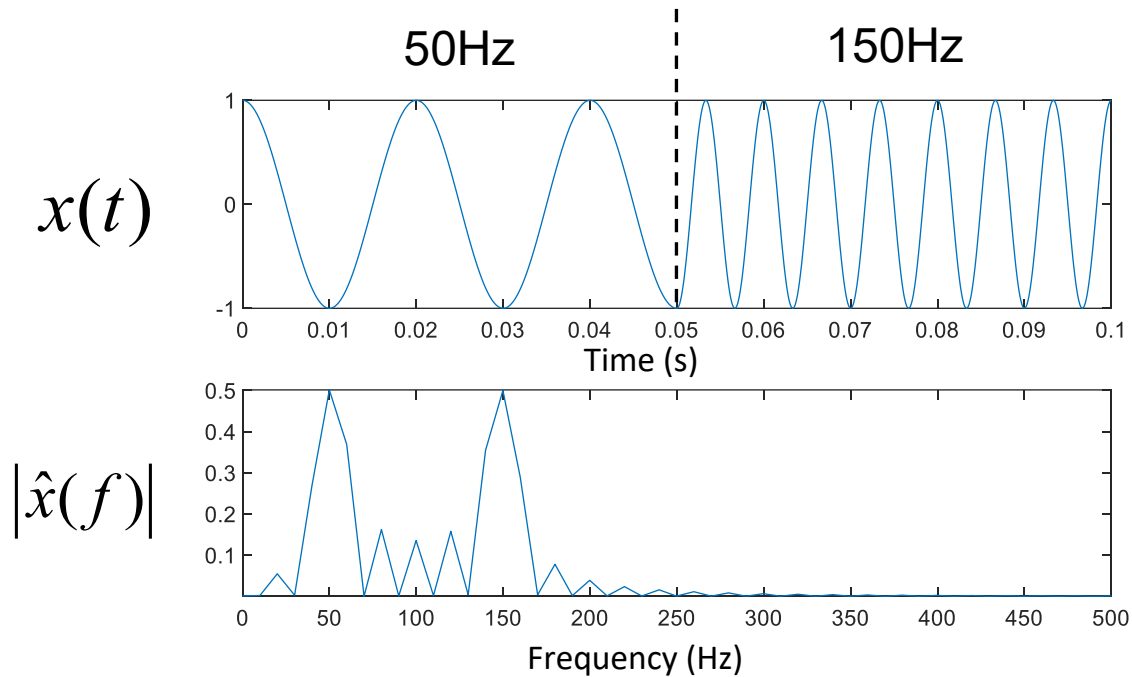
II: Time–Frequency Analysis

Technique	Description
Short-Time Fourier Transform	Breaks down a signal into short segments and performs a Fourier transform on each segment, providing information about the frequency content of the signal as it changes over time.
Wavelet Transform	Uses small waves (wavelets) to analyze and represent signals, providing a time-frequency representation that allows for localization in both time and frequency domains.
Wigner-Ville Distribution and Its Variants (Quadratic time-frequency representation)	A class of time-frequency analysis method that provides a time-frequency representation of a signal by calculating the energy distribution over both time and frequency, offering high resolution but suffering from cross-term interference.

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Adapted from TU Delft slide

II: Example in transportation application

- Applications for track maintenance decision support at transition zones

Vertical ABA Segment length 3 m, overlap 2.5 m, all wheelset

S. Unsiwilai, L. Wang, A. Núñez, and Z. Li, "Multiple-axle box acceleration measurements at railway transition zones". Measurement, Volume 213, May 2023, 112688.

II: Example in transportation application
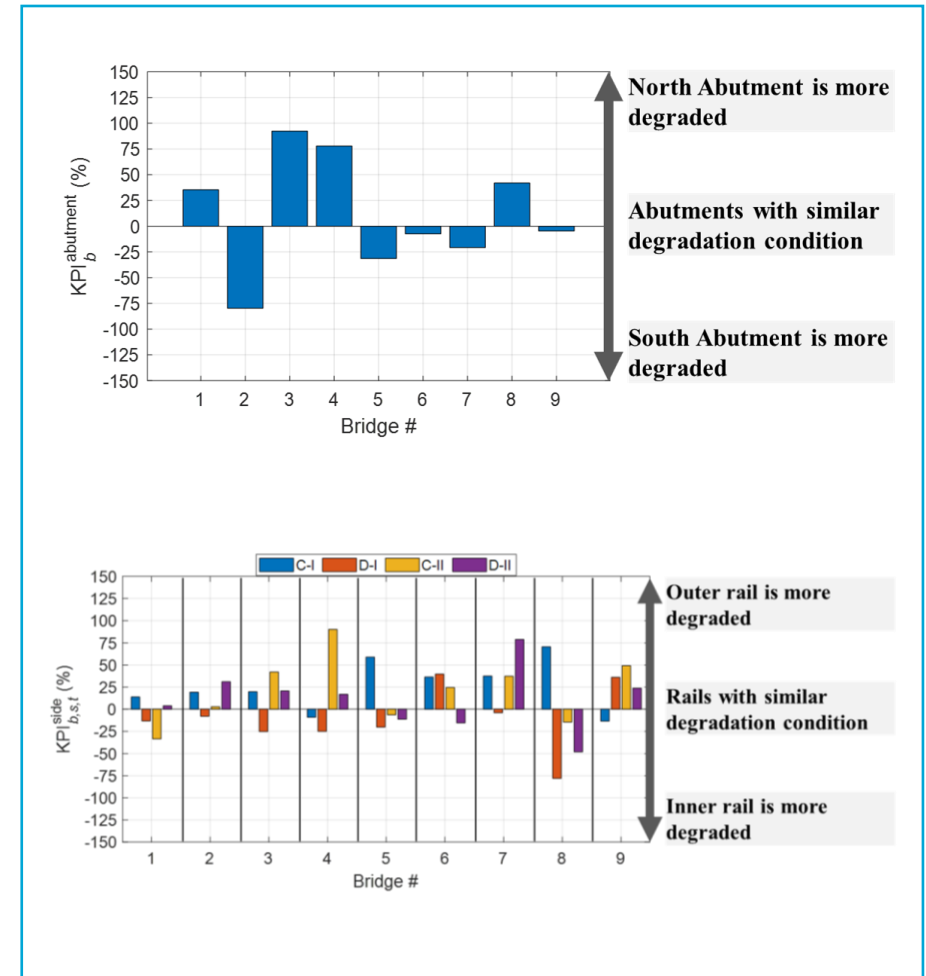
- Applications for track maintenance decision support at transition zones

Feature extraction from measurement signal → **Key Performance Indicators (KPIs)**
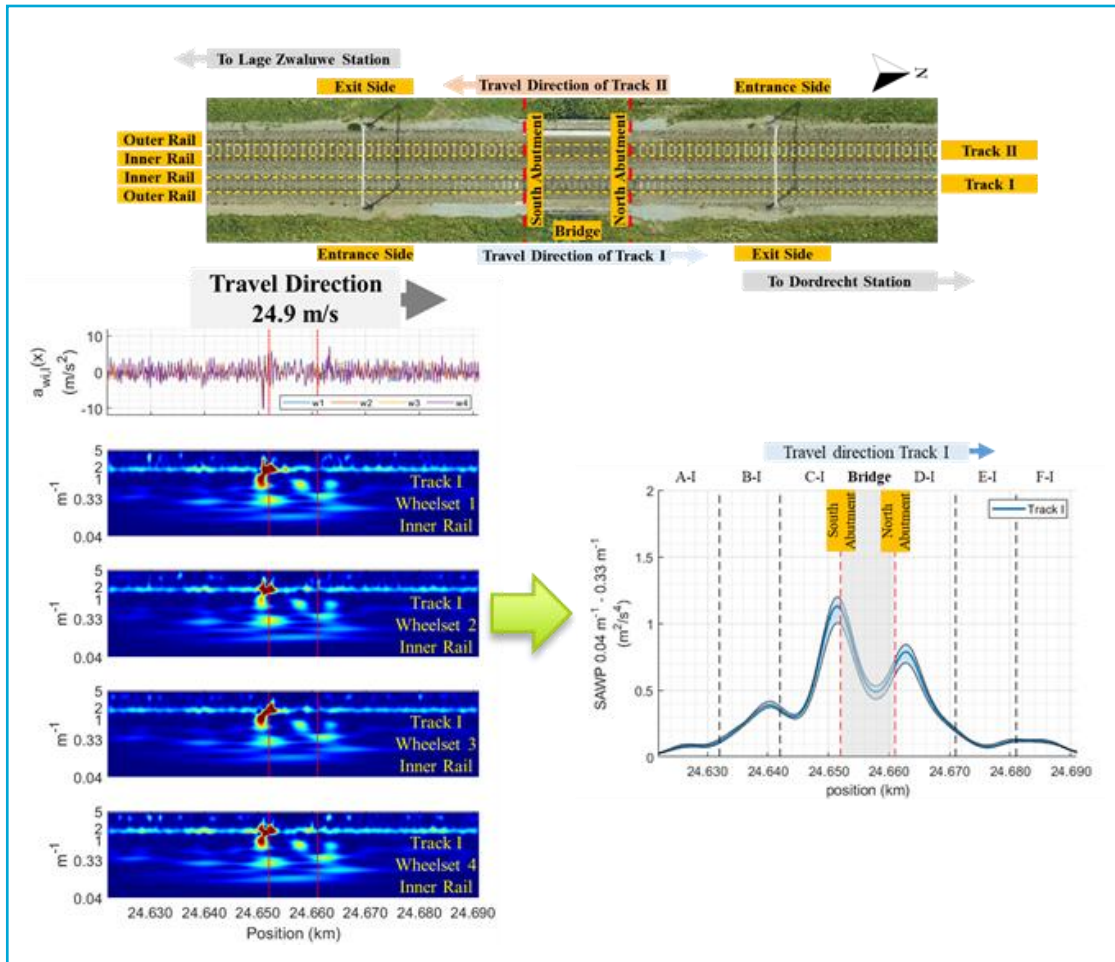
S. Unsiwilai, L. Wang, A. Núñez, and Z. Li, "Multiple-axle box acceleration measurements at railway transition zones". Measurement, Volume 213, May 2023, 112688.

Section III:
Hands-On Signal Processing

III: MATLAB Advantages for Signal Processing

- Rich Signal Processing Toolbox with ready-to-use functions

- Immediate visual feedback

- Fast prototyping

- Easy integration

- Widely used in engineering

IV: Hands-On Experience

- We will explore key MATLAB functions for signal processing

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Thank you for your attention!

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