351 – Data Acquisition with LabVIEW

Acquired core competencies:

1. You will learn the basics of working with LabVIEW and use it to record various elementary signals. **Important for experiments 352 through 355!**
2. You will perform Fourier transforms and identify the frequency components of periodic signals in the spectrum. **Important across the board in physics!**
3. You will become familiar with the sampling theorem and gain an intuitive understanding of the aliasing effect. **Important for automatic data acquisition!**

1 Tasks

1. Continuously record a sinusoidal input signal with constant amplitude. Display the time trace and the frequency spectrum. Increase the frequency and describe your observations.
2. Generate a mixture of a sinusoidal signal and white noise. Characterize the signal and the noise. Evaluate the signal's interpretability at various signal-to-noise ratios.
3. Measure the current and the voltage from a Pt100 sensor using LabVIEW. Convert the determined resistance to a temperature and display it graphically.

2 Fundamentals

Keywords: Sampling theorem, Fourier transform, signal-to-noise ratio (SNR), white noise, pink noise, current-based and voltage-based measurements

2.1 LabVIEW

LabVIEW is a graphical programming language for automating data acquisition and control tasks. It is suitable for solving numerous problems in the laboratory. Figure 1 shows a simple LabVIEW program. A distinction is made between the **Front Panel** (the user interface) and the **Block Diagram**, where the actual program is coded. Unlike other programming languages, in LabVIEW the individual program commands are graphically connected to one another.

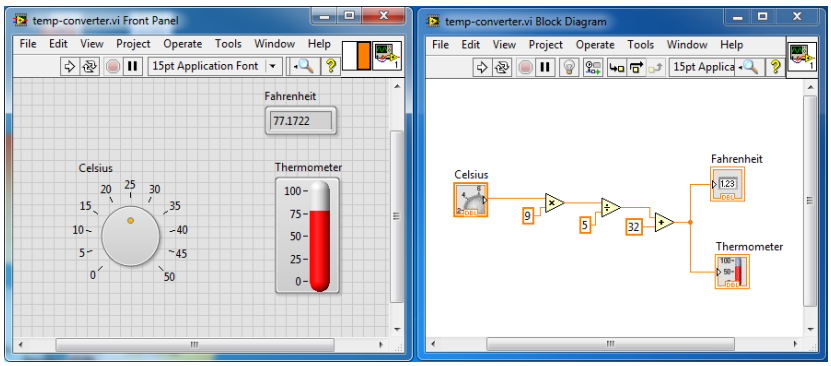


Figure 1: Simple LabVIEW program for the conversion between °C and °F.

2.2 Data acquisition using a PC

In many cases, it is necessary to process analog signals using a computer. An analog-to-digital converter (ADC) converts the continuous analog signal into a discrete digital signal. An n-bit converter can represent 2^n different states (non-negative integers from 0 to $2^n - 1$). With a maximum input voltage of $U_{\max}$, this results in a voltage resolution ΔU of:

$$\Delta U = \frac{U_{\max} - U_{\min}}{2^n - 1} \xrightarrow{\text{for } U_{\min} = 0} \frac{U_{\max}}{2^n - 1} \tag{1}$$

In order to reconstruct a signal after digitization, at least 2 values must be recorded per period. Therefore, to avoid losing any information during sampling when dealing with a mixture of signals with a maximum signal frequency of $f_{\max}$, the signal must be recorded at a sampling frequency f_{sample} of:

$$\boxed{f_{\text{sample}} \geq 2 \cdot f_{\max}} \tag{2}$$

This condition is referred to as the **sampling theorem** or **Nyquist–Shannon theorem**. If, however, higher signal frequencies are applied, the signal frequency cannot be derived unambiguously from the data (see Fig. 2). The incorrect interpretation of the signal frequency due to an insufficient sampling frequency is called aliasing.

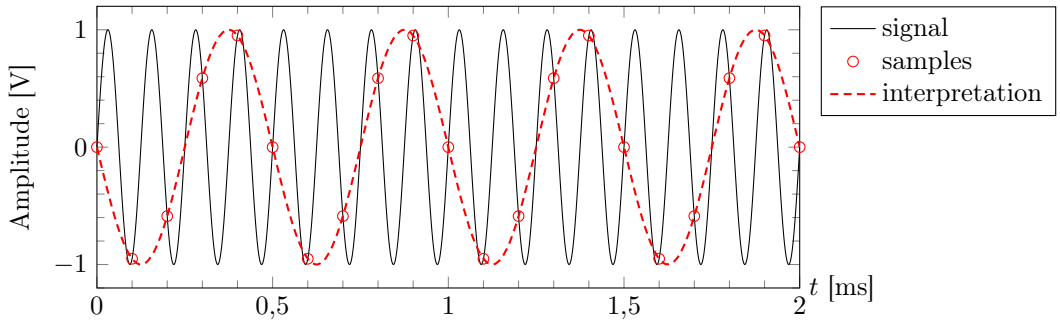


Figure 2: Sampling of a signal with an insufficient sampling frequency. The plotted points ○ correspond to the sample values. It is evident that an incorrect signal frequency is reconstructed when the sampling theorem (2) is violated.

The Fourier transform establishes a relationship between the time and frequency domains. It can be used to assign a frequency spectrum to any time trace. Both representations contain the complete information of the signal. In electronics, it is often helpful to represent signal information in the frequency domain. The time trace $f(t)$ and the frequency spectrum $F(\omega)$ are related by the following pair of transformations:

$$F(\omega) = \int_{-\infty}^{+\infty} f(t) e^{-i\omega t} \, \mathrm{d}t \tag{3}$$

$$f(t) = \frac{1}{2\pi} \cdot \int_{-\infty}^{+\infty} F(\omega) e^{+i\omega t} \, \mathrm{d}\omega \tag{4}$$

2.3 Noise and its characterization

Noise is defined as a statistical fluctuation in a measured quantity. The frequency spectrum of a noise signal is typically very broad.

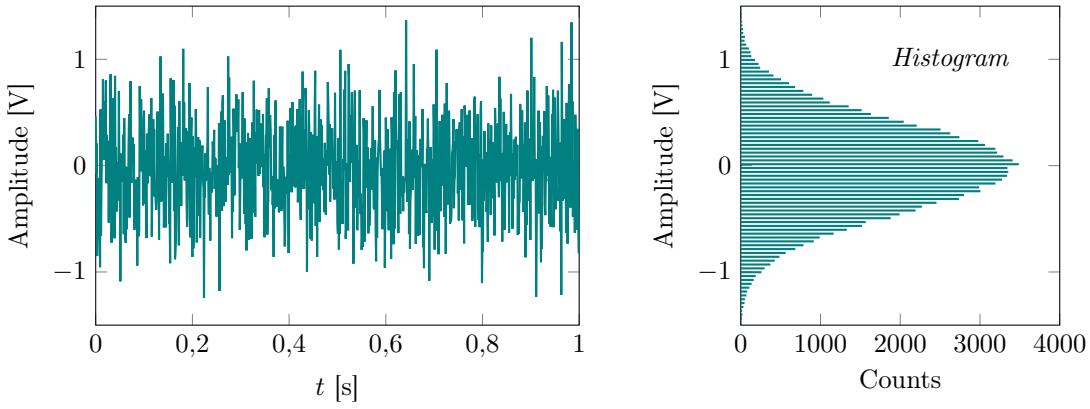


Figure 3: Time trace and histogram of noise fed from the Agilent 33210A.

Figure 3 shows a schematic time trace of a noise signal. The values are evenly distributed around a mean value:

$$\text{arithmetic mean:} \quad \langle U \rangle = \lim_{T\to\infty} \frac{1}{T} \cdot \int_{t_0}^{t_0+T} U(t)\,\mathrm{d}t \tag{5}$$

On average over time, a noise signal exhibits as many positive as negative values, so the arithmetic mean disappears. This value therefore *cannot* be used to characterize noise levels. One possible characterization is based on the variance:

$$\text{variance:} \quad \langle U^2 \rangle = \lim_{T\to\infty} \frac{1}{T} \cdot \int_{t_0}^{t_0+T} \left(U(t) - \langle U \rangle\right)^2 \,\mathrm{d}t \tag{6}$$

The integrand in equation (6) is ≥ 0, so the variance is nonzero and allows for a characterization of the noise level. To enable a comparison of amplitude values, the standard deviation is often used:

$$\text{standard deviation:} \quad \sigma = \sqrt{\langle U^2 \rangle} = \sqrt{\lim_{T\to\infty} \frac{1}{T} \cdot \int_{t_0}^{t_0+T} \left(U(t) - \langle U \rangle\right)^2 \,\mathrm{d}t} \tag{7}$$

Noise processes are classified based on their frequency spectrum, see Fig. 4. Many noise processes have a constant frequency spectrum; this is referred to as white noise, since all frequency components are present in equal amounts, i.e., the noise power density S is constant:

$$S_{\text{white}}(f) = \text{const.} \tag{8}$$

In so-called pink noise, on the other hand, low-frequency components are more prominent than high-frequency components. In many cases, the noise power density behaves like

$$S_{\text{pink}}(f) \propto \frac{1}{f^n} \qquad \text{(mostly with } n \leq 2\text{)} \tag{9}$$

Electronic noise is always present and superimposes on the signal being measured. An important parameter in this context is the signal-to-noise ratio (SNR). The SNR is defined as the ratio of signal **power** to noise **power**:

$$\text{SNR} = \frac{P_{\text{signal}}}{P_{\text{noise}}} \tag{10}$$

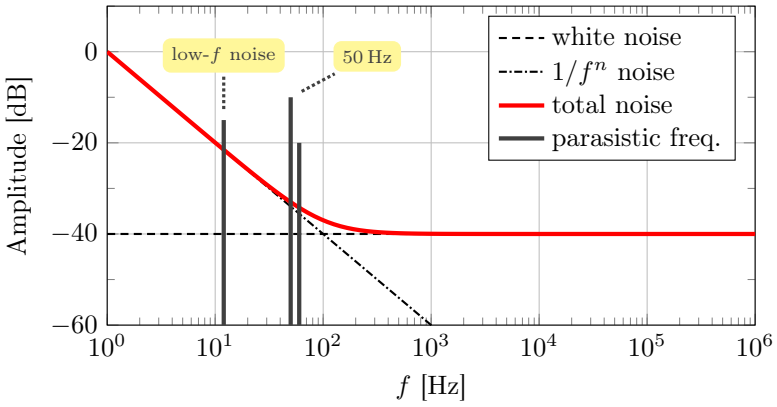


Figure 4: Spectral representation of superimposed white and pink noise. Some additional parasistic frequency peaks are shown schematically. The vertical axis is also logarithmically scaled here, since the unit dB is defined using the common logarithm.

If the signal and noise are measured at the same ohmic resistance R, the result is:

$$\mathrm{SNR} = \frac{U^2_{\mathrm{signal}}/R}{U^2_{\mathrm{noise}}/R} = \frac{U^2_{\mathrm{signal}}}{U^2_{\mathrm{noise}}} \tag{11}$$

Since the SNR is determined by averaging over time, the U^2 terms in the numerator and denominator can be interpreted as the **variances** $\langle U^2 \rangle$ of the signal and the noise, respectively. **Pt100:** As you prepare for the experiment in advance, download the 👉 Pt100 data set; you can also find it as a table in Experiment 350. Perform a linear fit $R(T) = R_0 + m \cdot T$ on the data, see Fig. 7. You will need the parameters R_0 and m during the course of this experiment.

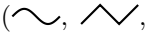
3 Experimental procedure

👉 The programming assignments will be completed in close collaboration with the instructors. LabVIEW also offers comprehensive online help. Therefore, you do not need to familiarize yourself with LabVIEW before the experiment begins. The following assignments are intended to give you a brief introduction to LabVIEW.

👉 Save each stage of your program's development so that you can reuse it at any time.

👉 **Always display the input signals simultaneously on the oscilloscope.**

The instructors will demonstrate how to program tasks 1 through 3. Listen carefully and follow along with all the steps on your own computer, making sure to comply with the instructions exactly. Complete the following measurement tasks on your own and analyze your data.

1. Apply a sinusoidal signal ($f = 100\,\mathrm{Hz}$, amplitude $1\,\mathrm{V}$) to the **AI 0** input of the NI BNC-2120 measurement system. Use the Agilent 33210A function generator as a signal source and enable the generator's output (**Output** key). Now record signals with different waveforms (). Save the time traces and the frequency spectra for your analysis, and plot both for each waveform. Discuss the similarities and differences. What is the frequency dependence of the noise in this case?

2. Apply a sinusoidal signal again ($f = 100\,\mathrm{Hz}$, amplitude $1\,\mathrm{V}$). Gradually increase the signal frequency up to $20\,\mathrm{kHz}$ and observe the time trace and the frequency spectrum. Discuss your observations.

3. Now connect the right BNC jack on the mixer box (Fig. 5) to the **AI 0** input of the NI BNC-2120 measurement system.

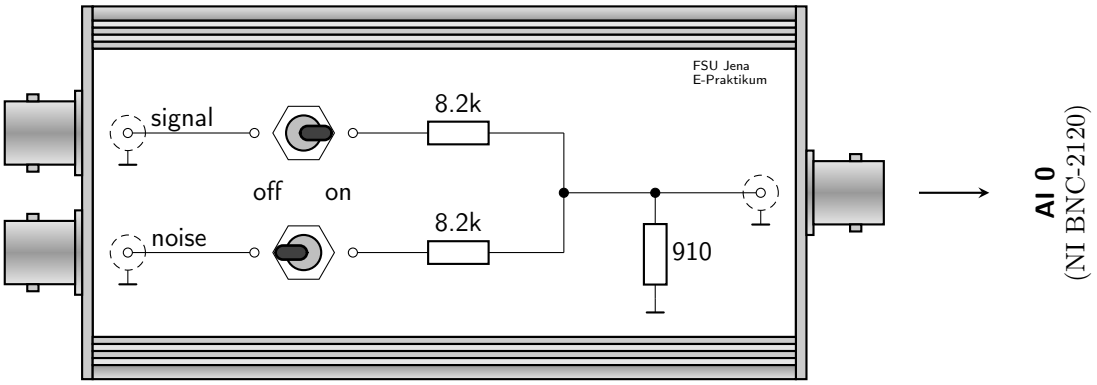


Figure 5: Mixer box for adding two signals (referred to here as "signal" and "noise").

☞ Using the mixer box (Fig. 5), a signal and noise can be superimposed. For the signal ($f = 100\,\mathrm{Hz}$, $U = 1\,\mathrm{V}$), use the Hameg HM8030 frequency generator, and for the noise, use the Agilent 33210A function generator (Noise: $10\,\mathrm{V_{pp}}$).

☞ In the following sections a), b), and c) of this task, **always** record the mean value, the standard deviation, the variance, the time trace, and the frequency spectrum.

a) signal on, noise off.

b) signal off, noise on.

c) signal on + noise on.

→ In part c), vary the amplitude of the signal to set the following three signal-to-noise ratios: $\mathrm{SNR}_1 = 1$; $\mathrm{SNR}_2 = 0{,}1$; $\mathrm{SNR}_3 < 0{,}1$. For SNR_3 adjust the settings so that in the time trace *no* signal is detectable, but a significant peak at the signal frequency is still present in the frequency spectrum. ☞ Measure the proportion of noise and signal, respectively, by turning off the signal or the noise.

→ Which measured quantities are suitable for characterizing noise, and which are not?

→ Evaluate both the signal time trace and the information content of the frequency spectrum. Up to what SNR can the signal still be detected in the time domain and in the frequency domain?

4. In this task, a quantity to be measured (in this case, temperature) shall be electronically recorded on a computer and processed further. To do this, set up the circuit shown in Fig. 6. Use the measuring rod with the Pt100 sensor from Experiment 350. The voltage U across the Pt100 sensor is recorded directly by the NI BNC-2120 measurement system (input **AI 0**). The current I is measured as a proportional voltage across the series resistor (input **AI 1**). Since we are processing DC signals here, it is sufficient to read a single value per sample. Make sure that the inputs of the NI BNC-2120 AD converter are set to **GS** (small toggle switches below each BNC input).

⚠ Note: Work through the task step by step and test the circuit using digital multimeters as described in Experiment 350. First, read the voltage at the Pt100 sensor and display it on a numerical indicator. Once the measured value is correct, add the current measurement also including a numerical indicator. Does the resistance of the Pt100, determined from U and I, make sense?

⚠ The AD converter card can process incoming data only sequentially. When reading from the two channels (**AI 0**, **AI 1**), a specific order must therefore be implemented in the program (e.g., using a flat sequence structure).

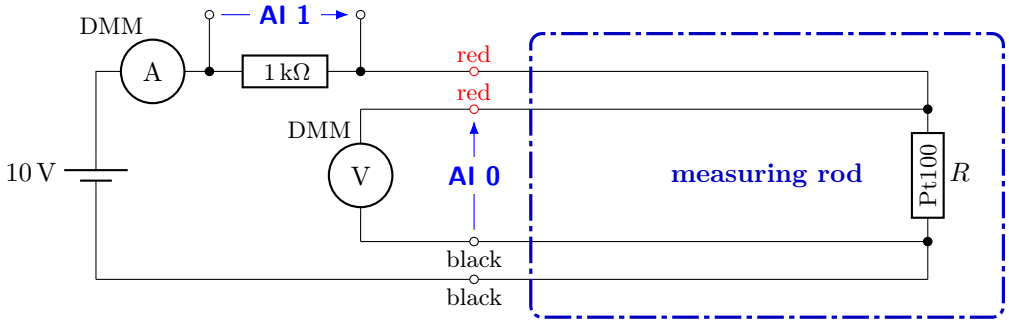


Figure 6: Temperature measurement using a Pt100 sensor. The two digital multimeters (DMMs) are used to **verify** the values displayed in LabVIEW. Choose **appropriate measuring instruments** for current and voltage measurements.

- Use LabVIEW to determine the resistance from U and I by means of Ohm's law, and display the resulting R in ohm. Convert the value to a temperature using your prepared linear fit of the Pt100 data set (based on the linear relationship $R(T) = R_0 + m \cdot T$; see Fig. 7) and display the measured temperature in °C.
- Possible extensions: minimum/maximum display, temperature over time, variations in the display (thermometer, analog gauge, ...)

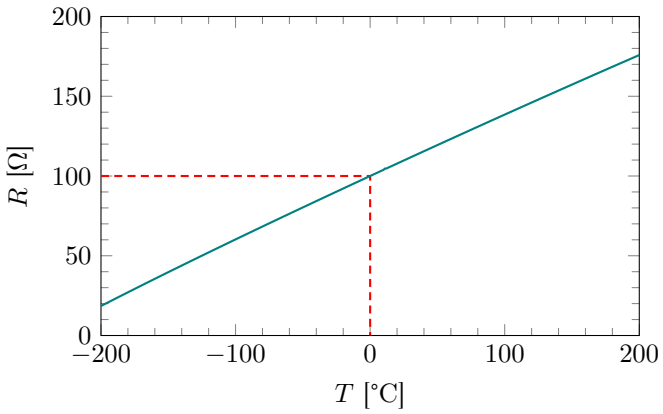


Figure 7: Representation of the tabulated $R(T)$ values of a Pt100 resistor. These can also be found as Table A1 in the instructions for Experiment 350.