Accurate stand-off temperature measurement using cost-efficient MEMS-based NIR spectrometer technology

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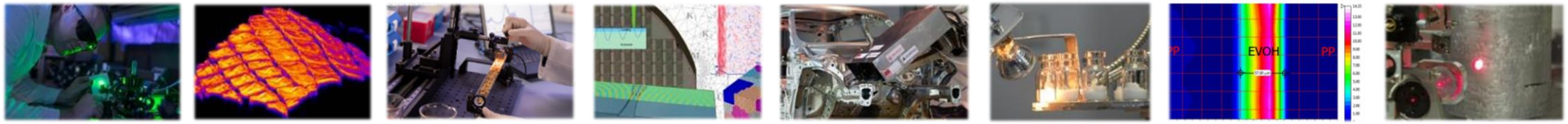
RECENDT
RESEARCH CENTER NON DESTRUCTIVE TESTING

NDT4Industry

Member of UAR INNOVATION NETWORK

upper austria



Temperature – what is it and why measure it ?

- **Temperature** (unit K or °C) describes the **average kinetic energy** per molecule/atom in a substance (different from heat which is the amount of energy transferred between objects of different temperature)

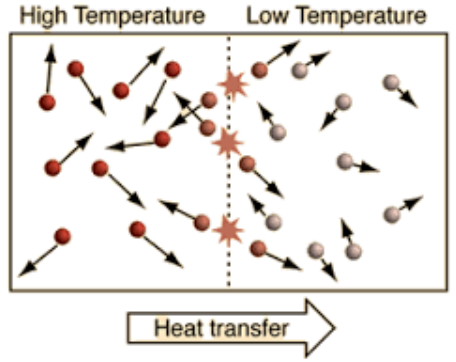
thermodynamic definition of temperature:

$$T = \left(\frac{\partial U}{\partial S}\right)_{V,N}$$

second law of thermodynamics:

$$dS \geq \frac{\delta Q}{T}$$

„Heat can never pass from a colder to a warmer body without some other change, connected therewith, occurring at the same time."



- **Temperature and heating/cooling rates can have very strong influences** on many parameters/properties in a system, such as:
  - Rate/speed of **chemical reactions**
  - Rate/speed of **physical reactions** (e.g. drying rate, mixing rate)
  - **Material properties** (e.g. aggregation state, oxidation state, microstructure, viscosity, …)

→ **Accurate temperature measuement and control can significantly improve product quality and process efficiency**

Image source: http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/temper.html

S = Entropy, U = internal Energy, V = Volume, N = Number of Particles

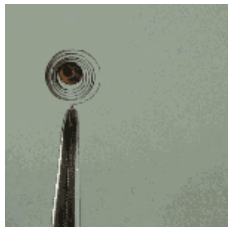
How to Measure Temperature

- **Many different methods** have been developed to measure temperature

- These methods usually rely on **changes in material properties** to measure temperature such as:
  - Volume/length (glass thermometer, gas thermometer, bi-metal mechanical thermometer,…)
  - Electrical potential/resistance (thermocouples, resistance thermometer, PTC/NTC thermistors,…)
  - Pressure (vapour pressure thermometer, gas pressure thermometer,…)
  - …

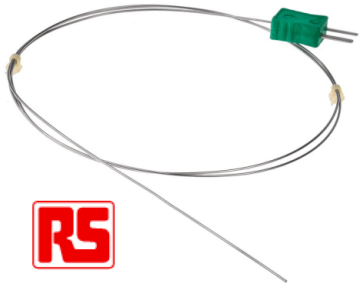
- for above mentioned methods, the **sensing element must be in direct contact with the sample**

→ often not possible or desirable

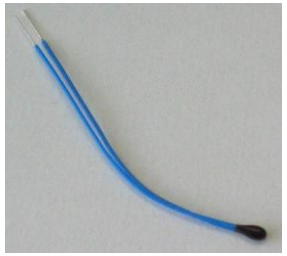


Bi-metal coil from a thermometer reacting to heat*

Mercury-in-glass Thermometer*



Type-K thermocouple



NTC thermistor*

*images taken from www.wikipedia.com

Contactless Temperature Measurement

- Another possibility to measure temperature is to **detect thermal radiation emitted from the sample surface** (blackbody-radiation)

- Every object with a temperature >0 Kelvin, emits electromagnetic radiation from its surface, which is (in the idealized case) given by **Planck's law of blackbody radiation**

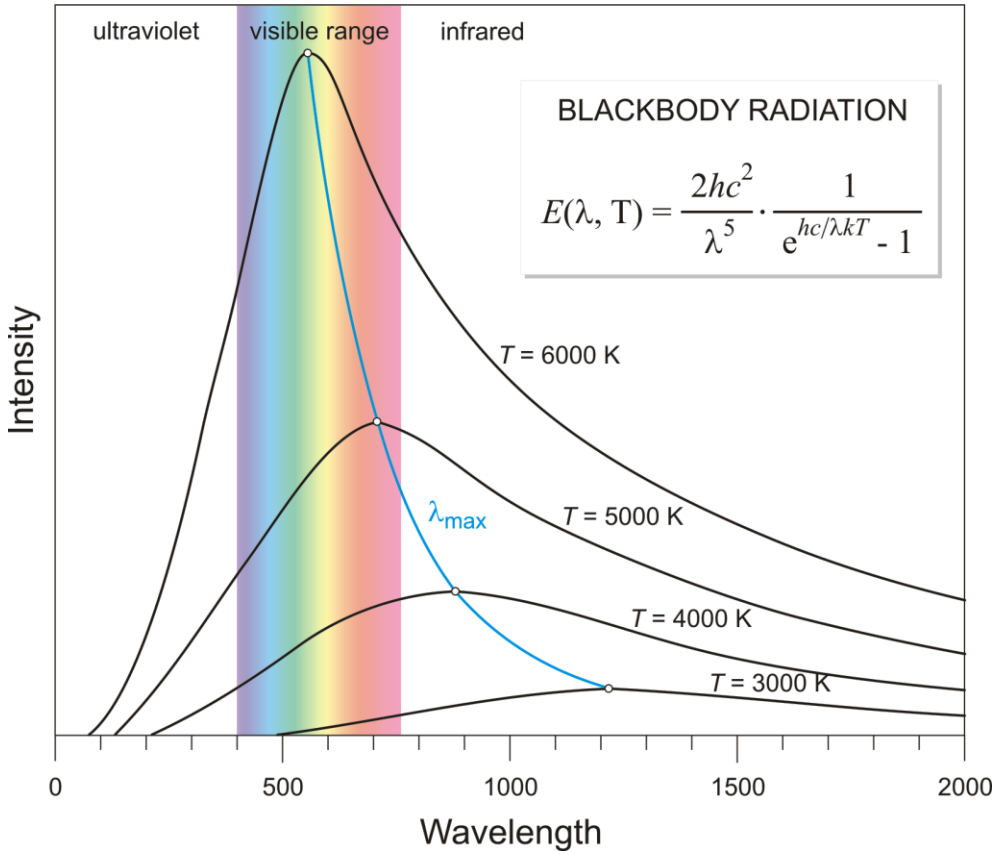
Wien's displacement law:

$$\lambda_{max} = \frac{2898\,\frac{\mu m}{K}}{T}$$

Stefan-Boltzmann law:

$$j = \sigma \cdot T^4$$

E. Generalic, https://glossary.periodni.com/glossary.php?en=blackbody+radiation



→ **Power and wavelengths of radiation emitted from an object is very strongly influenced by its (surface) temperature**

h = Planck's constant ($\approx 6.6261 \cdot 10^{-34} J \cdot s$), j = black-body radiance emittance, σ = Stefan-Boltzmann constant ($\approx 5.6704 \cdot 10^{-3} \frac{W}{m^2 K^4}$)

Contactless Temperature Measurement

- A blackbody is an **idealized theoretical object, absorbing all incoming radiation** and allowing **no reflection or transmission** of electromagnetic radiation:

$$\varepsilon = \alpha = 1$$

ε = emissivity
α = absorption

- **A better approximation** for real-life objects **is the grey body** for which

$$\varepsilon + \rho + \tau = 1 \longrightarrow \varepsilon + \rho = 1$$

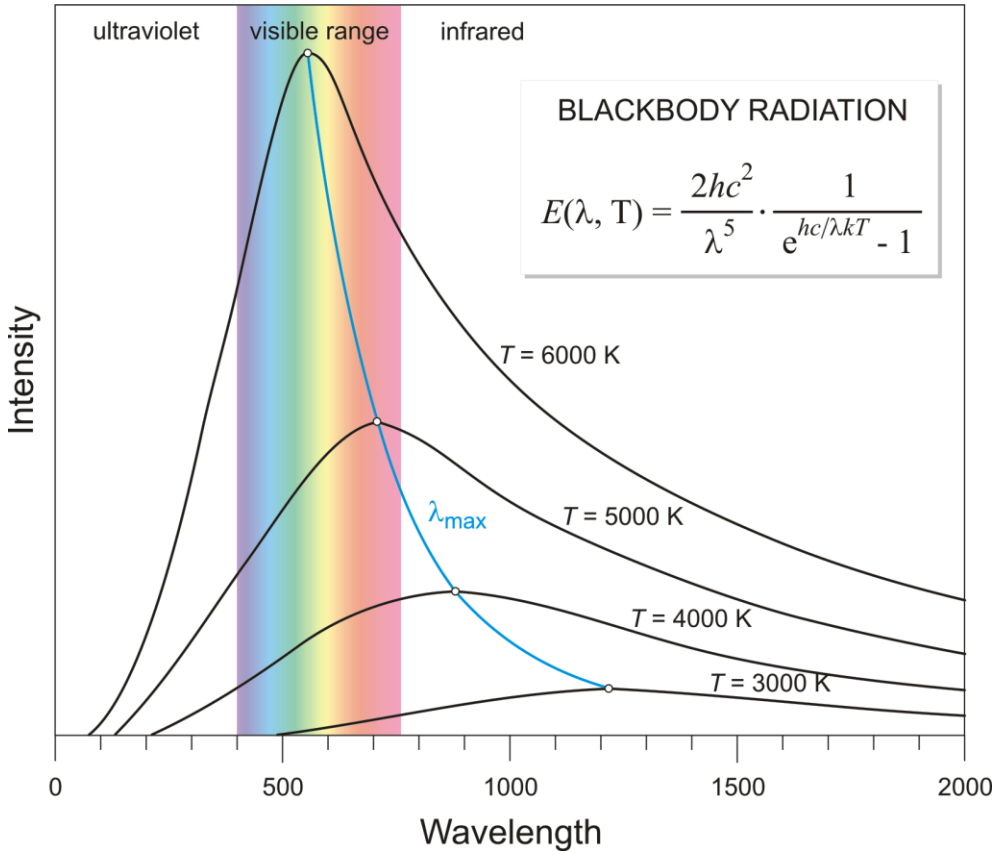
transmission in the infrared can mostly be neglected

ρ =reflection
τ= transmission

- The **emitted thermal radiation for a grey body** is therefore given by:

$$E(\lambda, T) = \varepsilon \cdot \frac{2hc^2}{\lambda^5} \cdot \frac{1}{e^{hc/\lambda k_B T} - 1} \quad \text{with} \quad 0 < \varepsilon < 1 \longrightarrow \text{Stefan-Boltzmann law:} \quad j = \varepsilon \cdot \sigma \cdot \mathrm{T}^4$$

E. Generalic, https://glossary.periodni.com/glossary.php?en=blackbody+radiation



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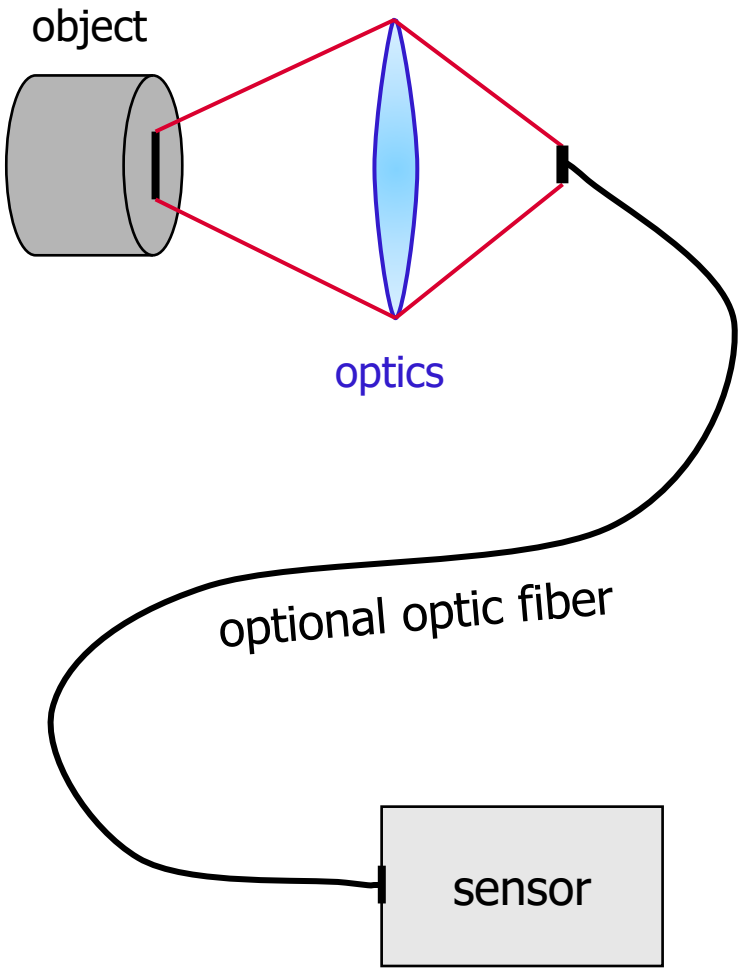
Contactless Temperature Measurement – Instrumentation



Sensor and optics are not in contact with the measured object, but collects **emitted radiation** via suitable optics

This brings **several advantages** compared to contact-measurements:

→ **Allows temperature measurement of samples that are moving, hard-to-reach and/or very hot**

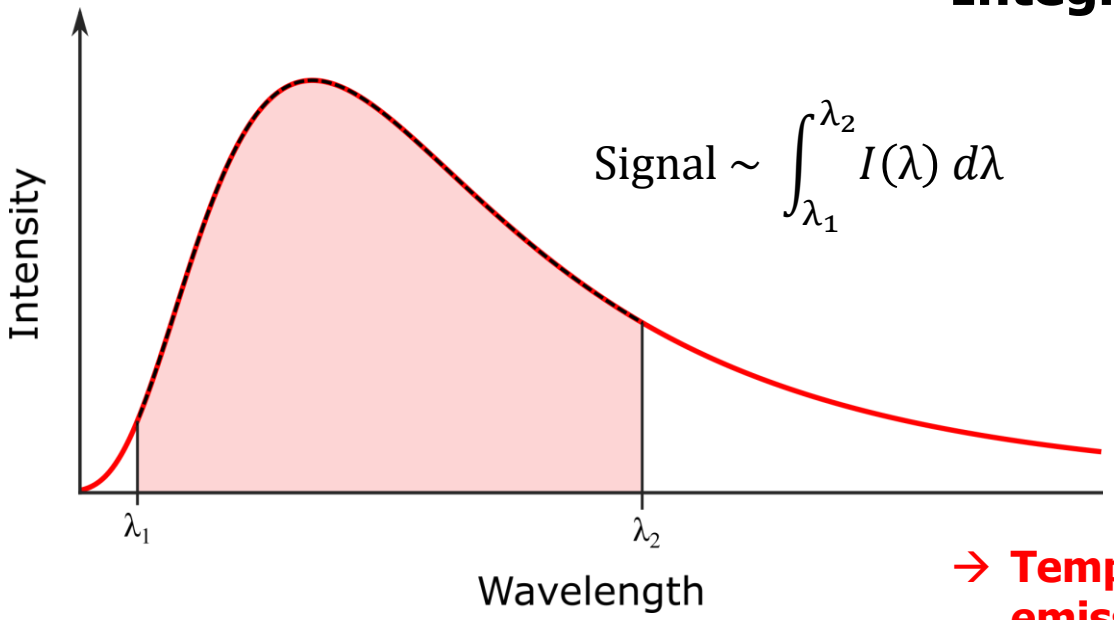
→ **Fast measurement and response times**

→ **Measurement does not influence the measured object**

→ **Measurement is completely non-destructive**

→ **No wear and tear leading to increased longevity**

- Different sensor options can be used for the measurement of electromagnetic radiation emitted from the sample



→ **Low cost hardware**

→ **Sensor can be very compact**

Integrative measurement („1-color"-pyrometers):

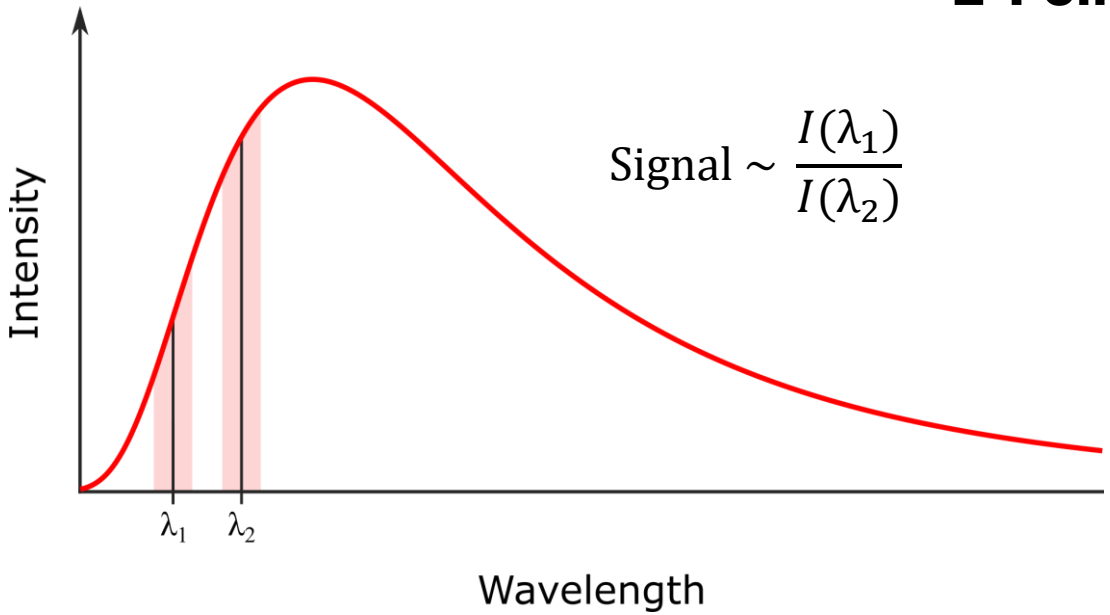
- Radiation emitted from the sample is measured in a certain wavelength window, typically somewhere between 1µm and 14µm
- Sensor signal is proportional to the temperature of the sample surface

→ **Temperature reading is strongly influenced by changes of emissivity ε**

→ **Changes in absolute intensity directly change measured temperature**

→ **Detected temperature is influenced by surroundings (e.g. dust, outside radiation sources etc.)**

- Different sensor options can be used for the measurement of the electromagnetic radiation emitted from the sample



$$\text{Signal} \sim \frac{I(\lambda_1)}{I(\lambda_2)}$$

2-Point measurement (2-color pyrometers):

- Radiation emitted from the sample is measured in two wavelength windows
- Temperature is calculated via the ratio of the intensities at both wavelengths

→ **Absolute intensity does not have direct influence on measured temperature**

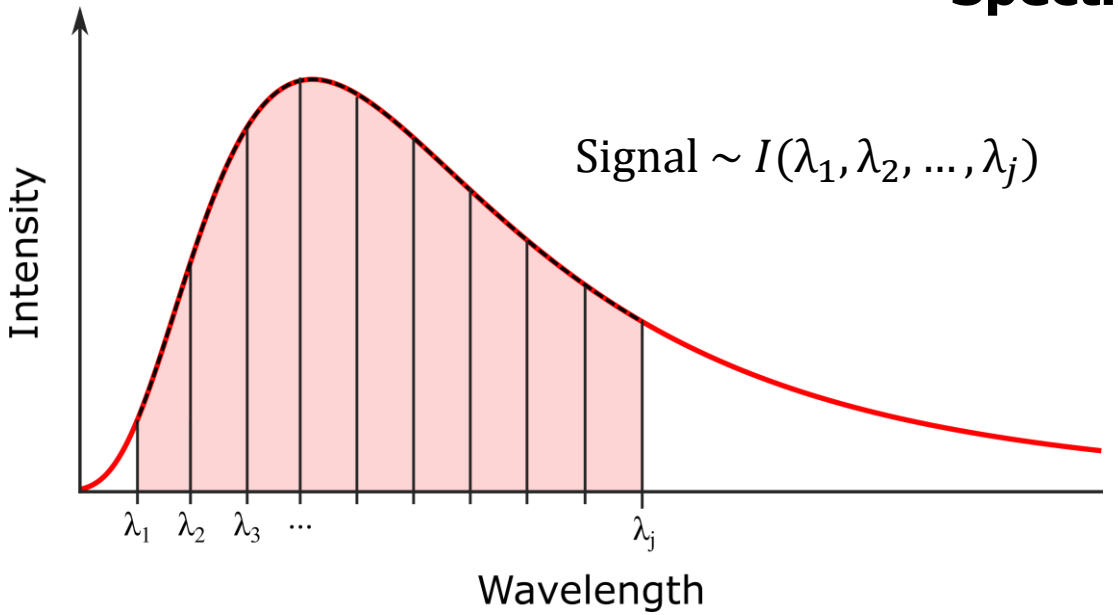
→ **Influence of emissivity ε can be significantly reduced**

→ **Wavelength dependent changes in emissivity e.g. due to changes in surface structure can give false readings**

→ **Heat radiation from the sourroundings can lead to wrong temperature measurement**

→ **Measured wavelengths are fixed and usually only suitable for a limited temperature range**

- Different sensor options can be used for the measurement of the electromagnetic radiation emitted from the sample



→ **Depending on the hardware, measurement times can be a bit longer (second range)**

→ **Higher hardware price**

Spectral measurement (with spectrometer):

- Radiation emitted from the sample is measured at multiple (up to several hundred) different wavelengths
- Temperature can be calculated in different ways from the measured intensities

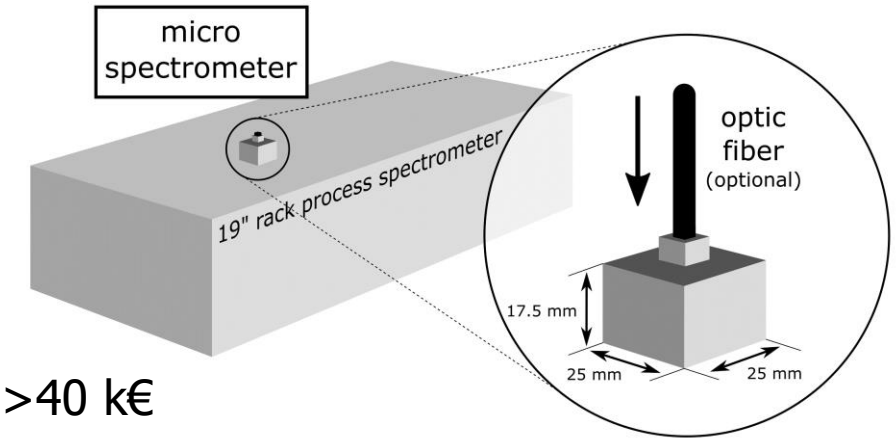
→ **Influence of emissivity changes can be further reduced due to more available data**

→ **Large number of measured wavelengths allows to measure a broad temperature range**

→ **Gives information on measurement quality**

→ **Allows to gain further knowledge about the sample (e.g. oxide layer growth or other chemical changes)**

One major downside are the relatively high costs of conventional NIR-spectrometers



>40 k€

<3 k€

MEMS-based infrared spectrometers

Low Cost - Rugged - Compact

MEMS … Micro-Electro-Mechanical Systems

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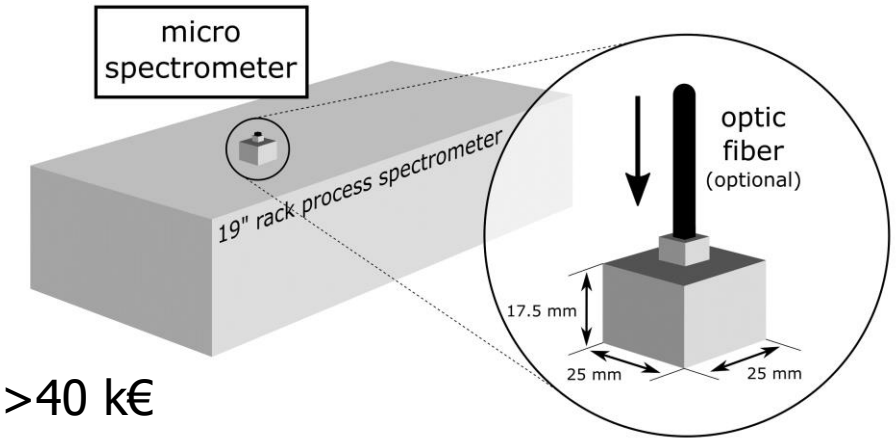

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MEMS-based infrared spectrometers

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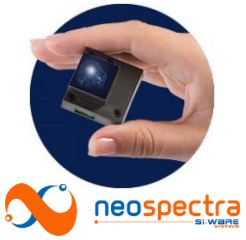
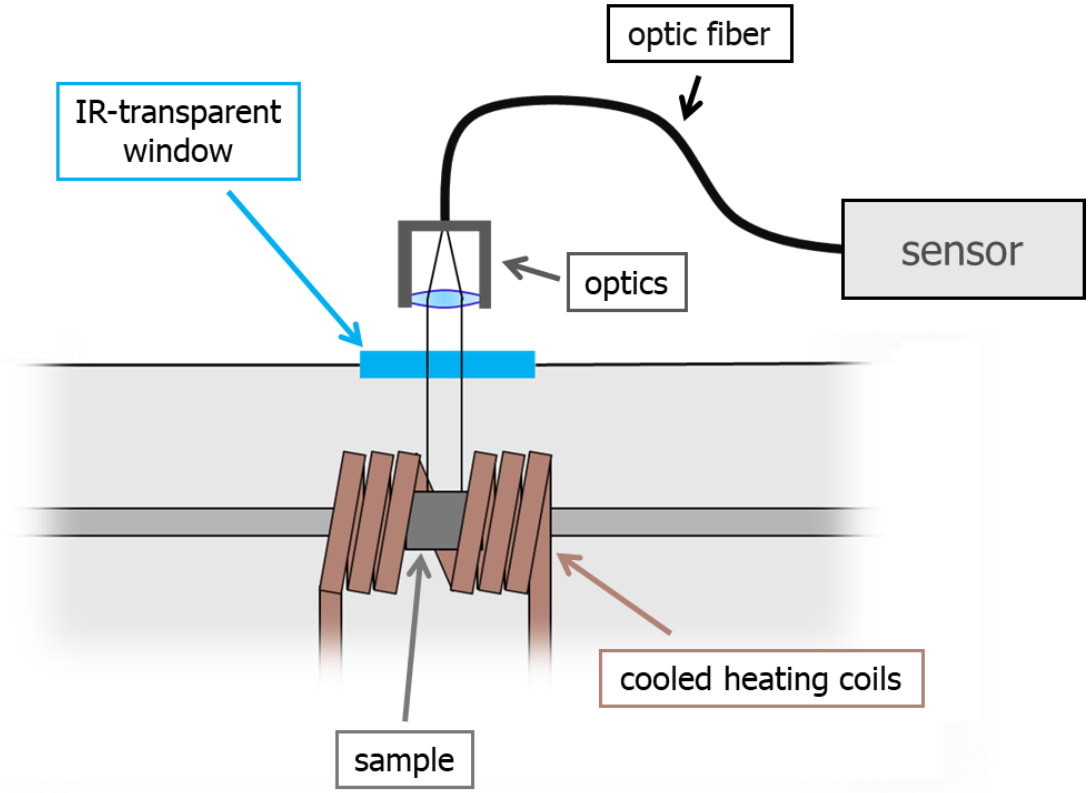


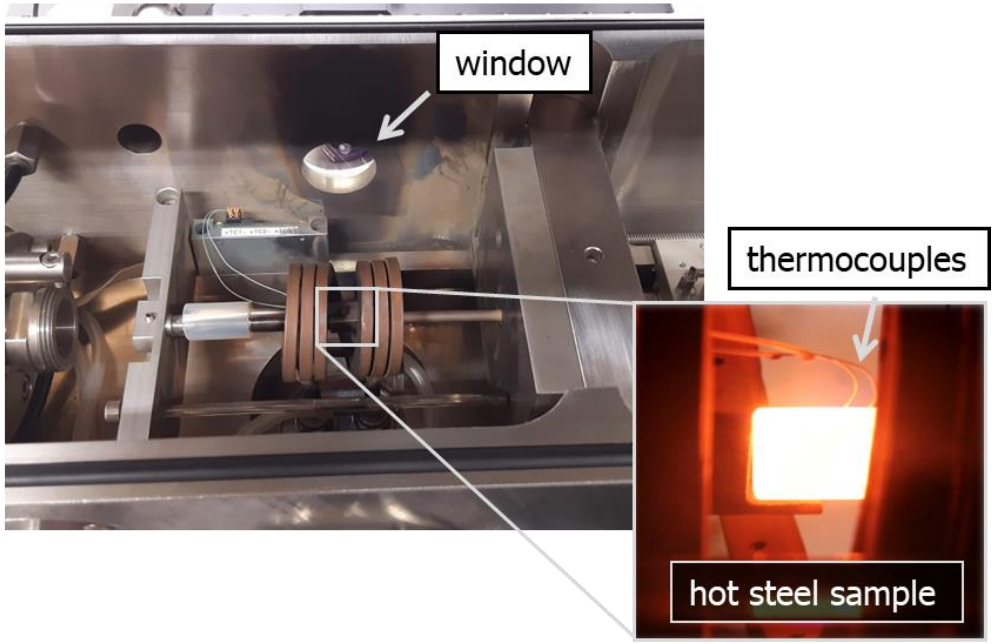
MEMS … Micro-Electro-Mechanical Systems

Measurement Example

- Measurement was carried out in a dilatometer on a steel sample in vaccum
- Reference measurement and temperature control was carried out using a thermocouple welded to the sample
- Near-infrared radiation emitted from the sample was collected using suitable optics and delivered to the sensor via an optic fiber

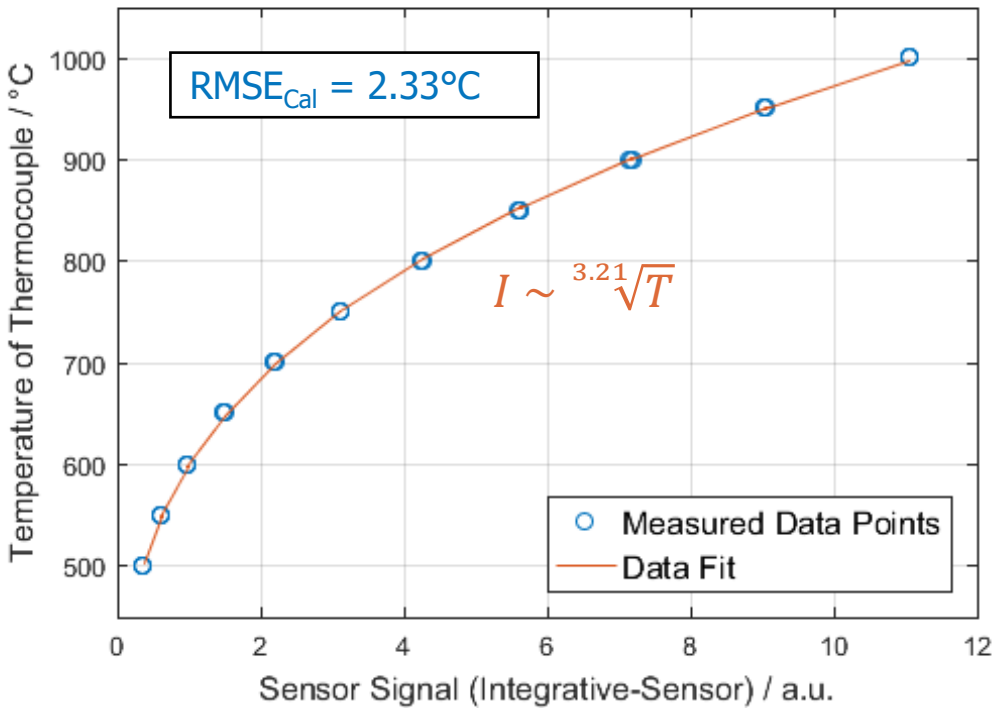


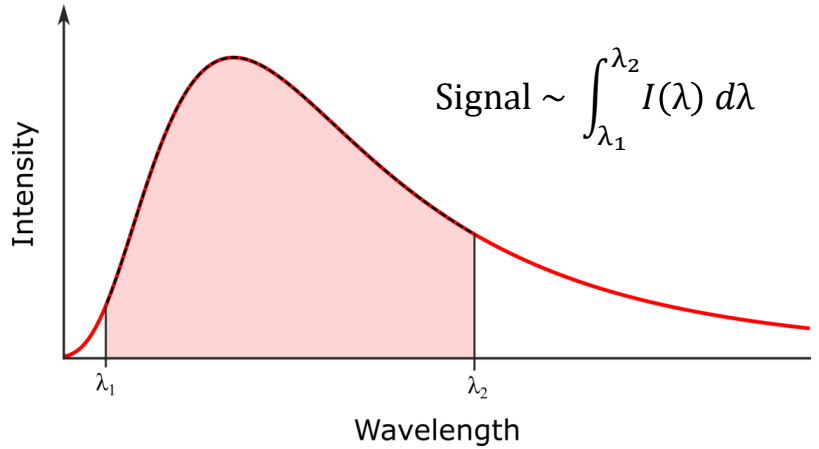
photograph of dilatometer with open lid



Measurement Example – Integrative Measurement

Experimental data

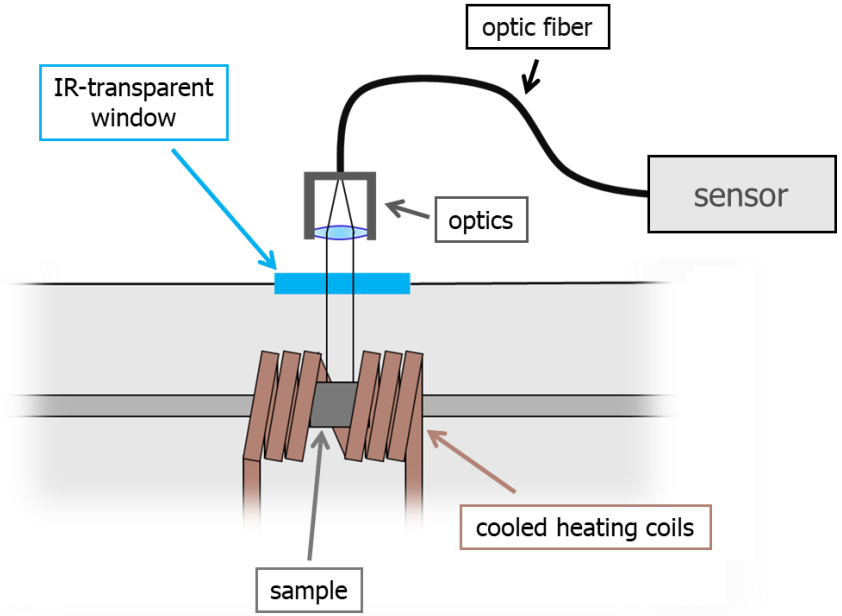




Stefan-Boltzmann law:

$$j = \varepsilon \cdot \sigma \cdot \mathrm{T}^4 \longrightarrow I \sim \sqrt[4]{T}$$

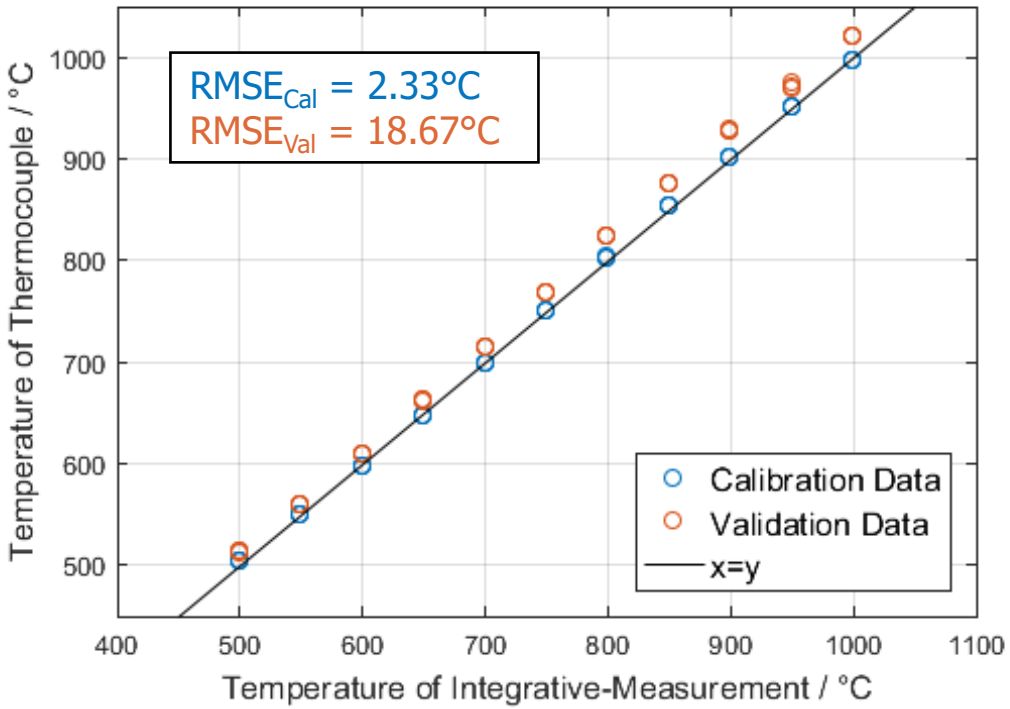
but not all wavelengths are measured (limited detector range)

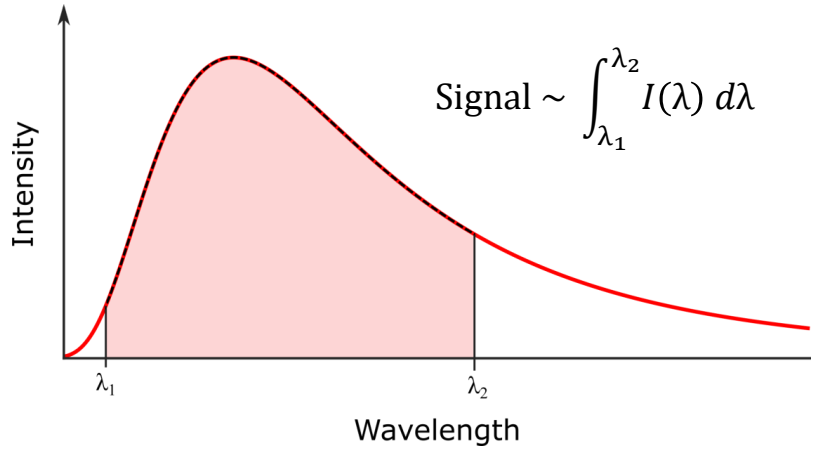


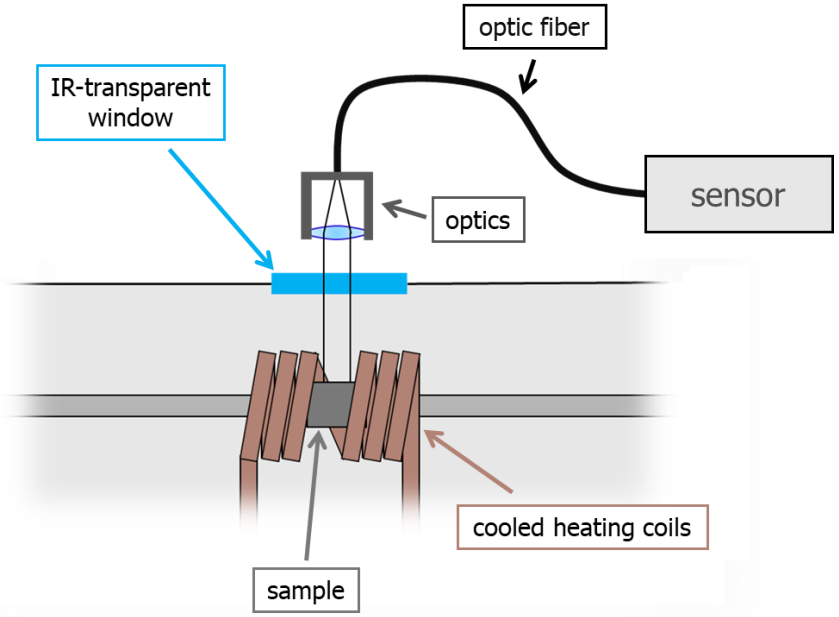
RMSE = Root Mean Squared Error

Measurement Example – Integrative Measurement

Experimental data







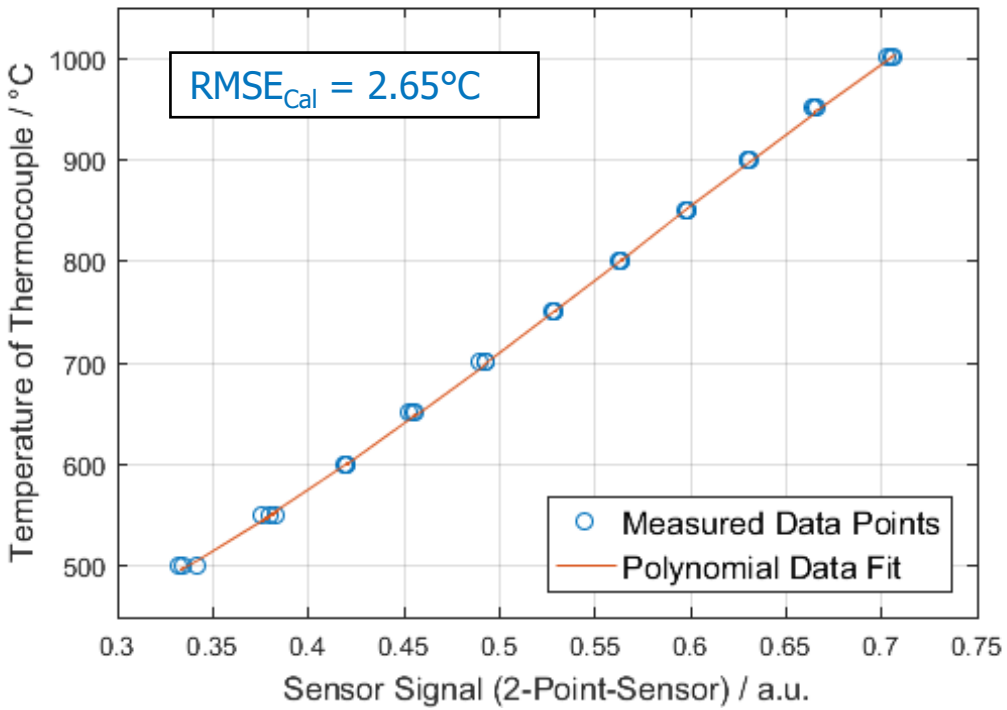
→ Validation measurement shows **rather large error**

- Emissivity ε might be slighty different (surface structure)
- Changes in orientation between optics and sample (intensity that reaches sensor changes slightly)

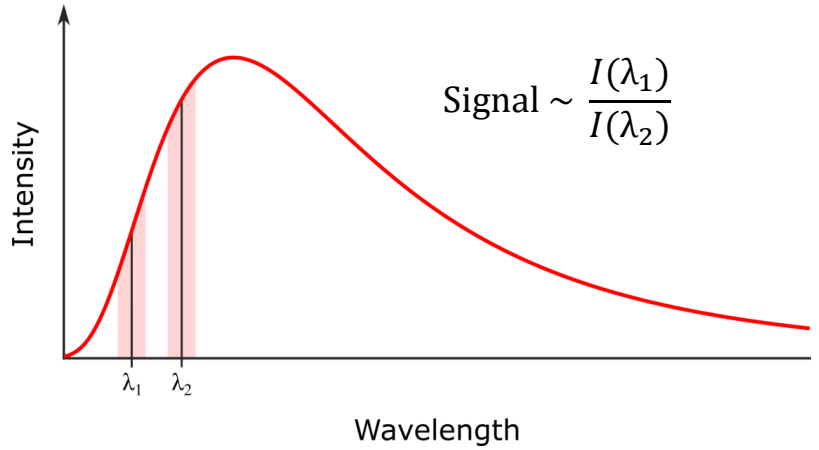
RMSE = Root Mean Squared Error

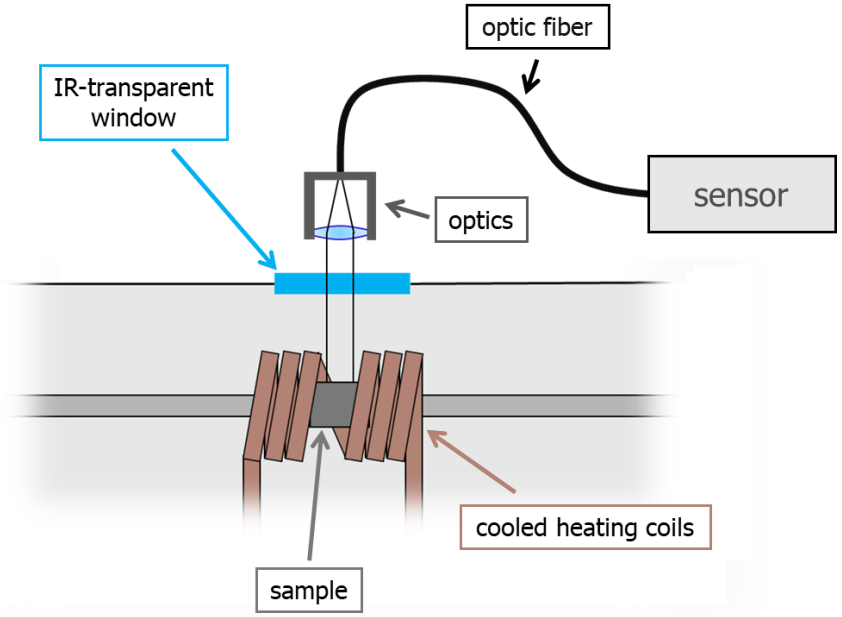
Measurement Example – 2-point Measurement

Experimental data



→ Only slight non-linearity

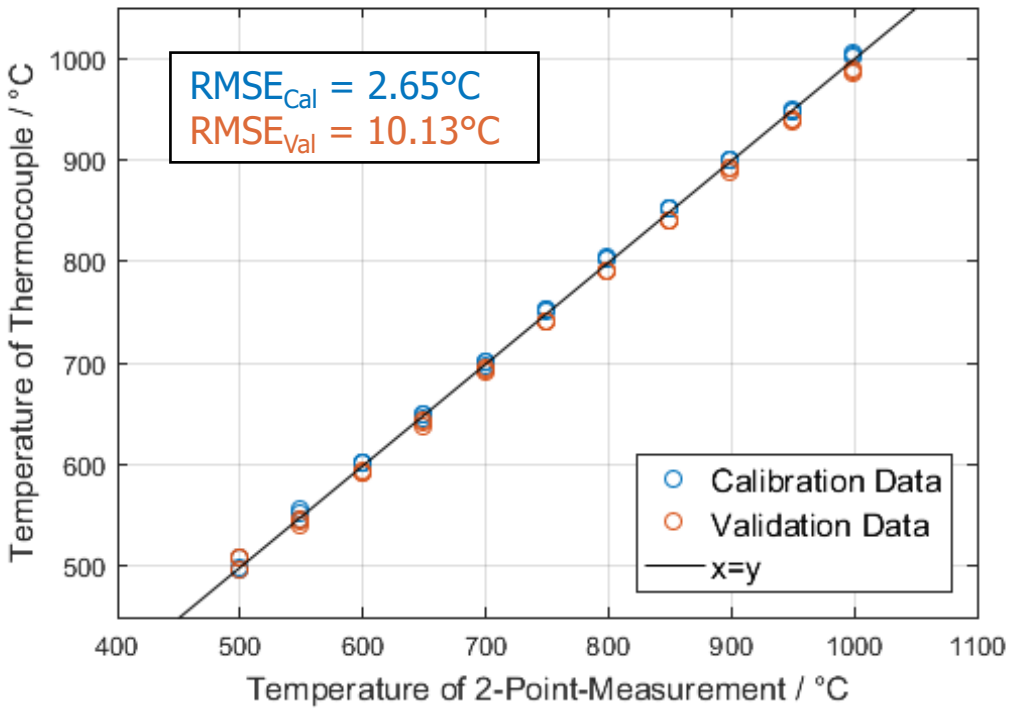


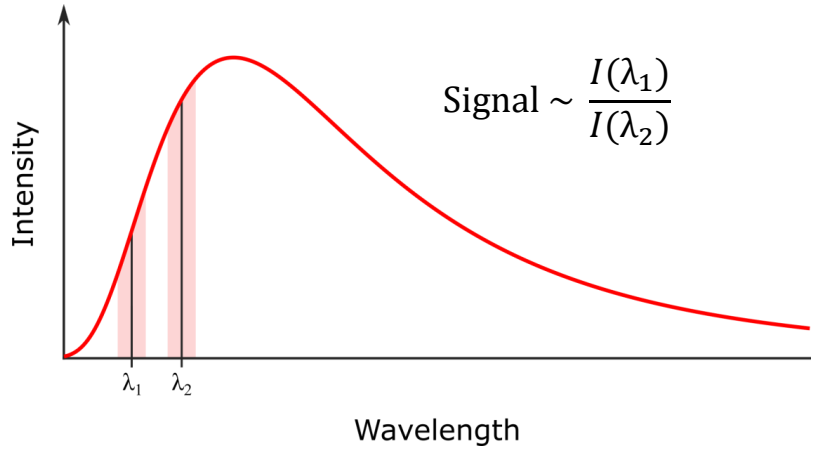


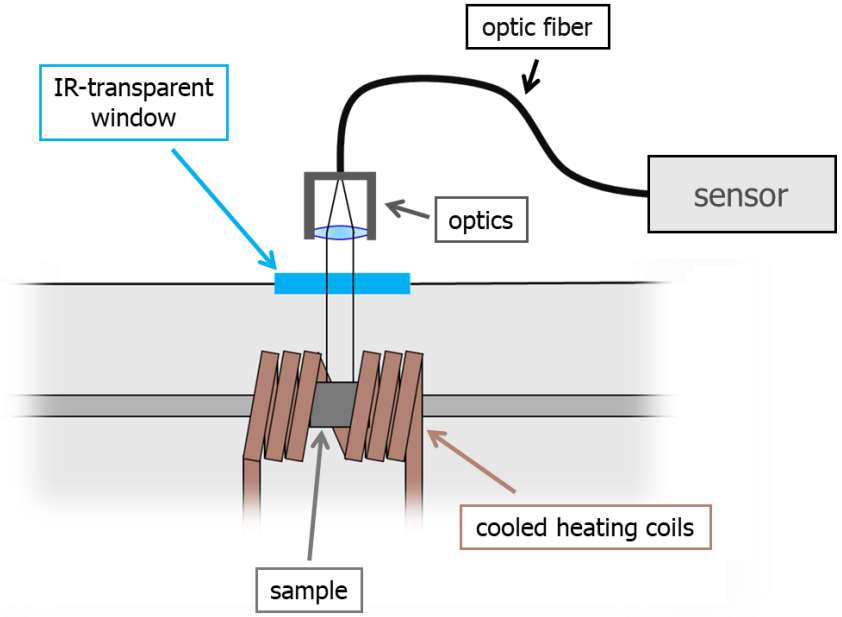
RMSE = Root Mean Squared Error

Measurement Example – 2-point Measurement

Experimental data





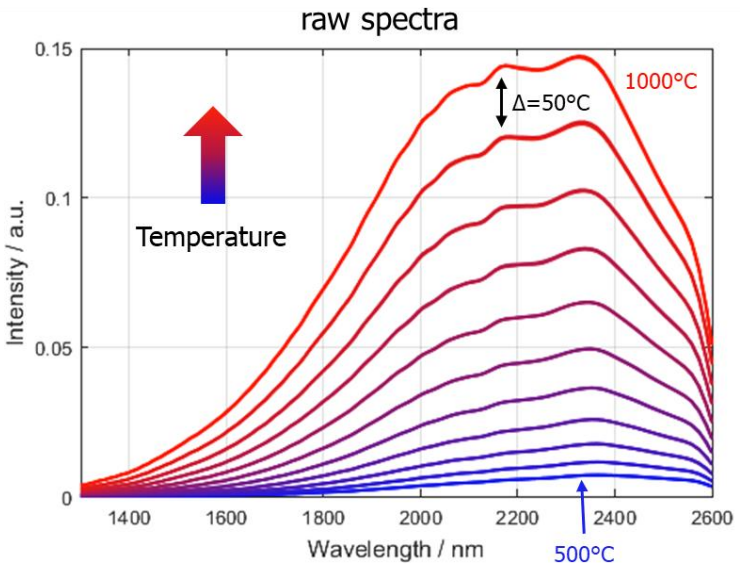


→ Validation measurement **error is significantly reduced**

- Influences of changing emissivity ε are strongly reduced
- Elimination of influences of absolute intensity

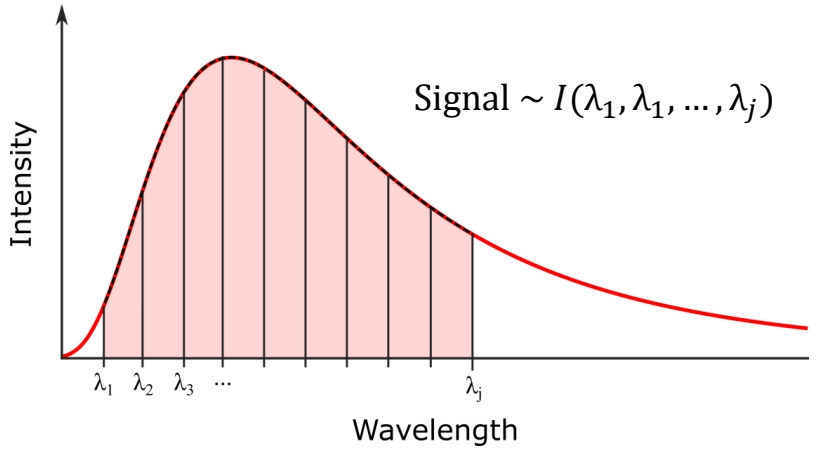
RMSE = Root Mean Squared Error

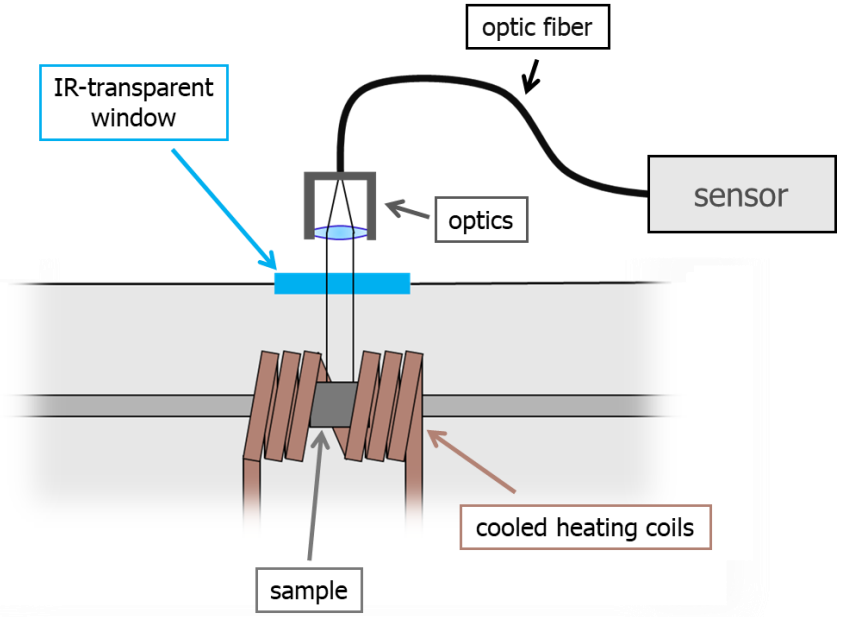
Measurement Example – Spectral Measurement



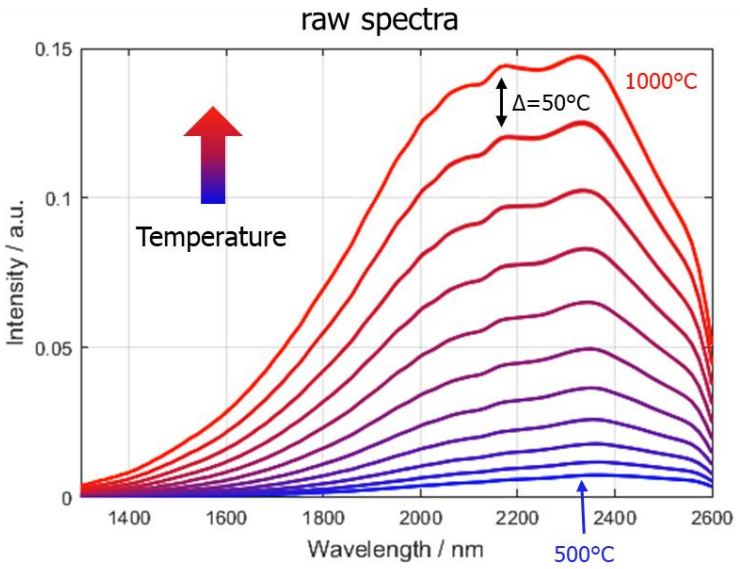
Stefan-Boltzmann law:

$$j = \sigma \cdot T^4$$





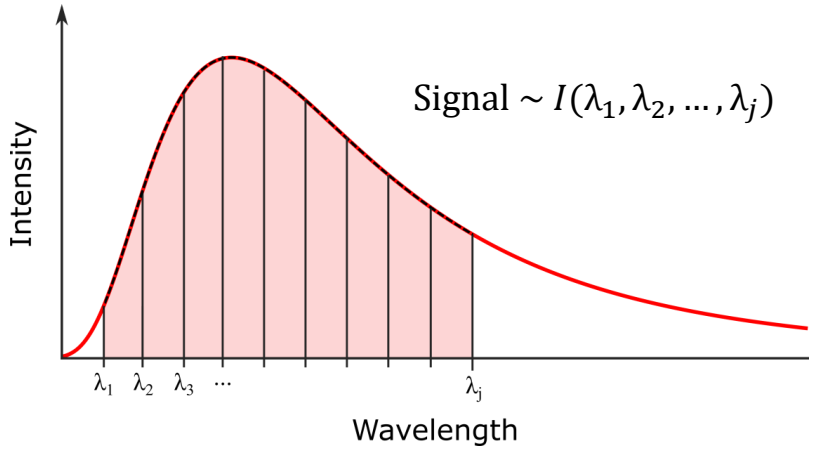
Measurement Example – Spectral Measurement

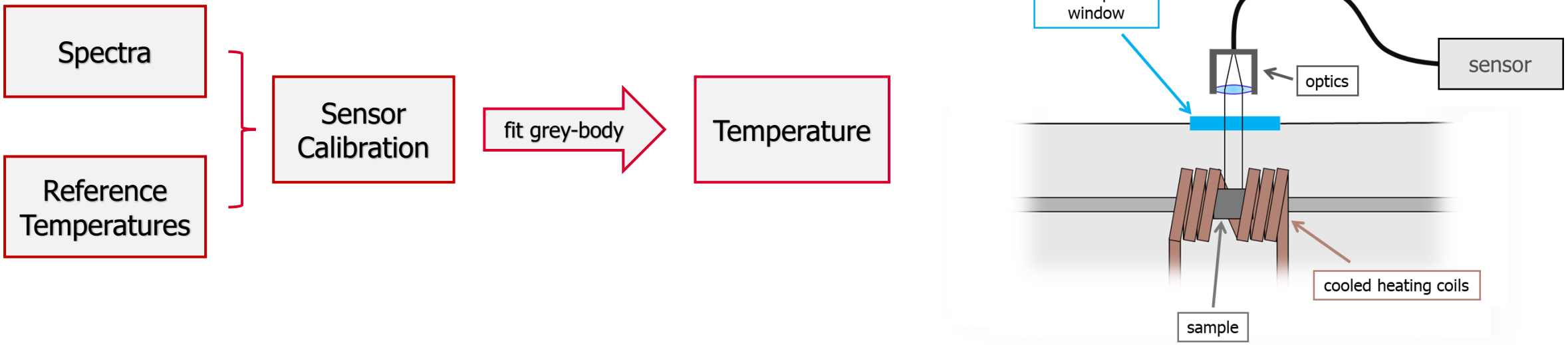


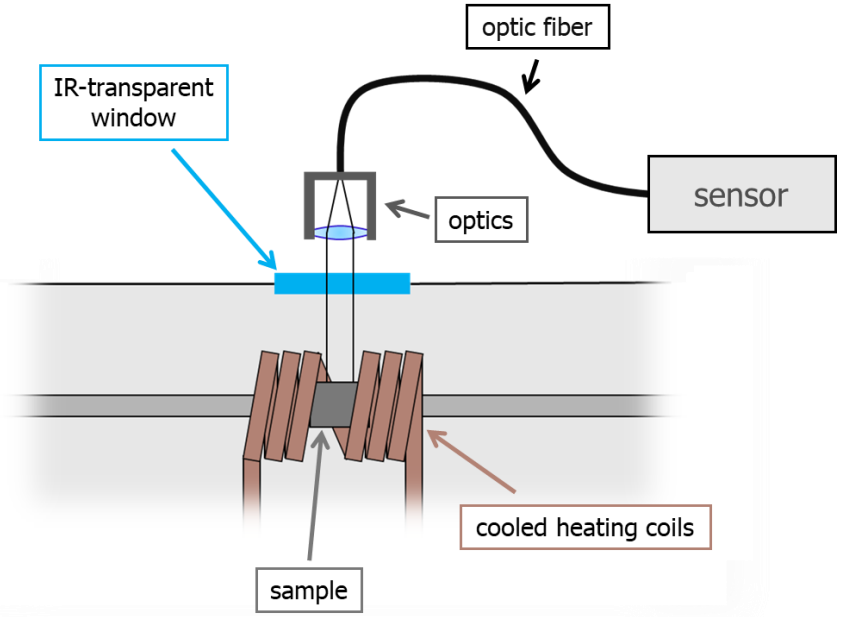
Two different ways to get the temperature:

1. Fit grey-body spectrum to the acquired NIR-spectra

$$E(\lambda, T) = \varepsilon \cdot \frac{2hc^2}{\lambda^5} \cdot \frac{1}{e^{hc/\lambda k_B T} - 1}$$

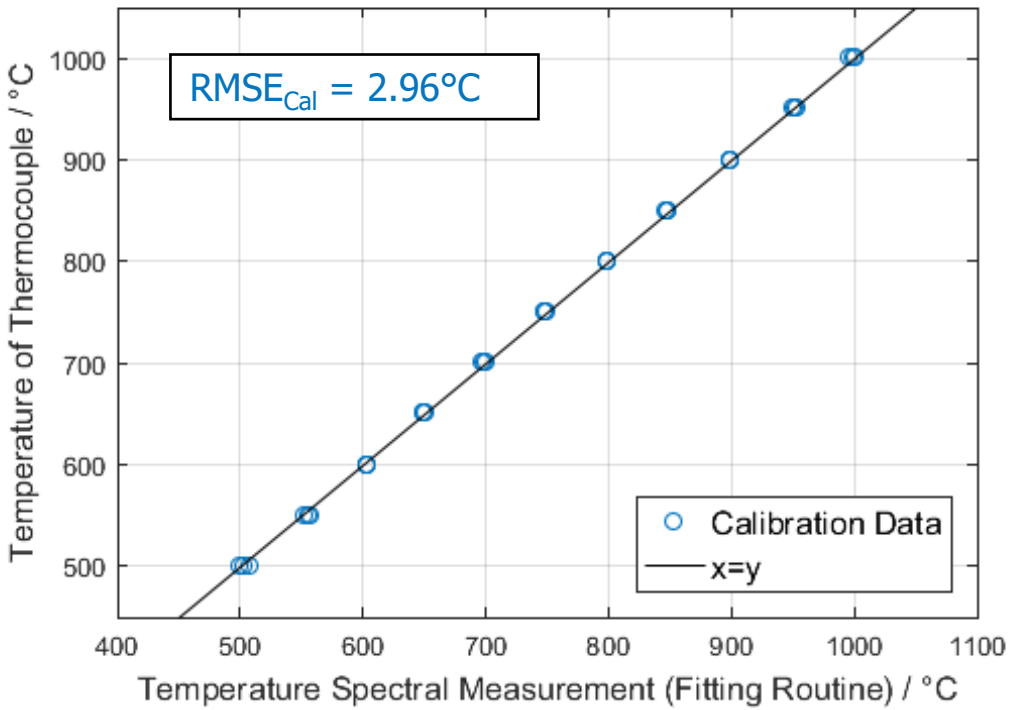


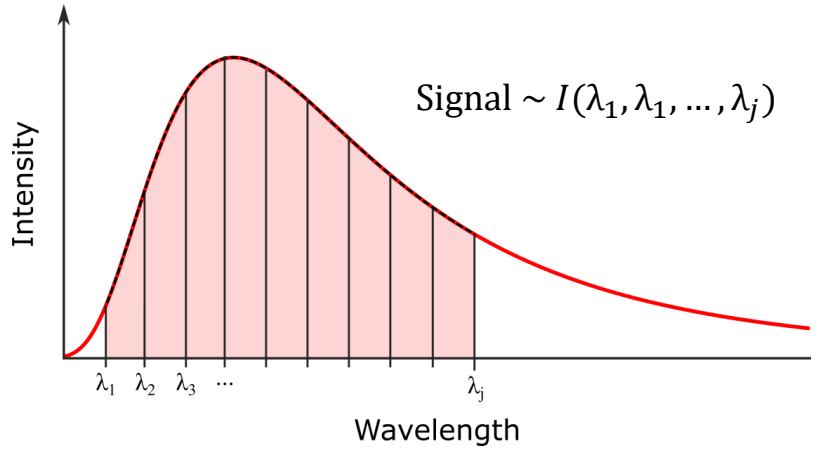


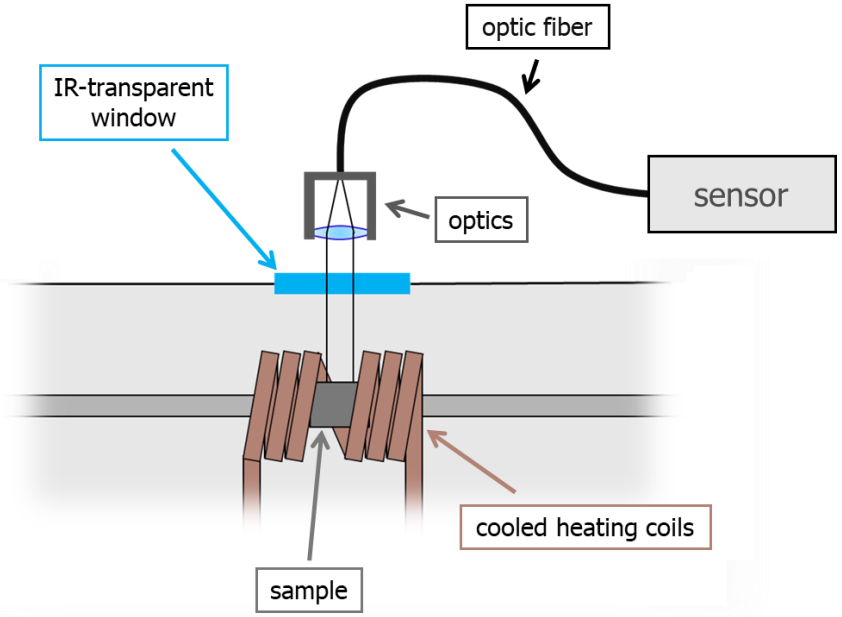


Measurement Example – Spectral Measurement

Experimental data







Spectra

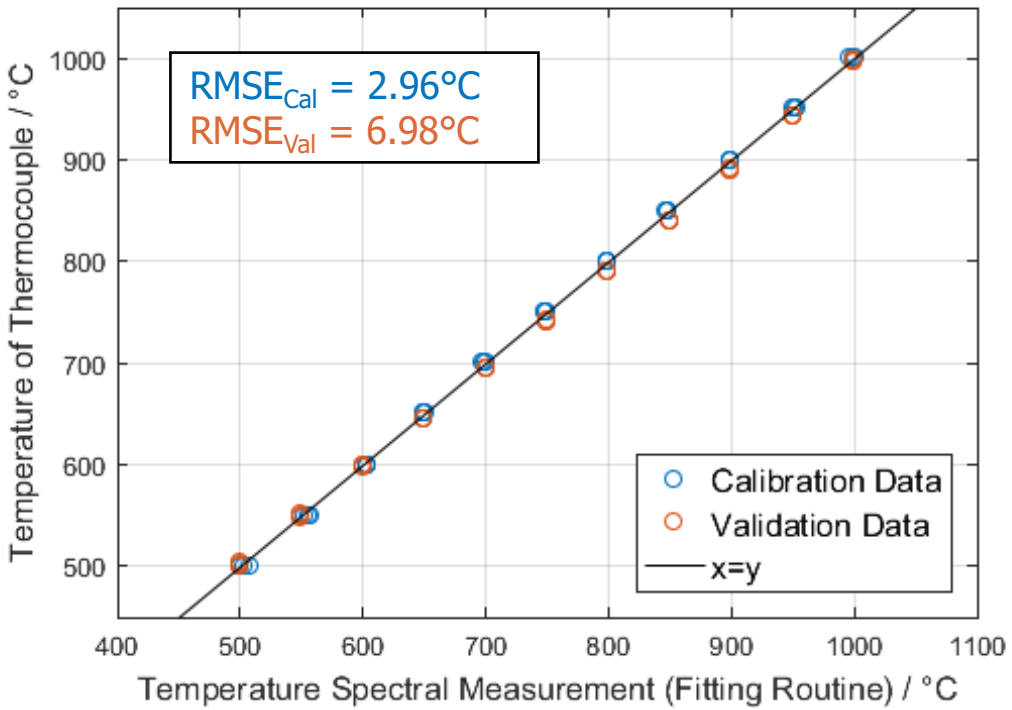
Reference Temperatures

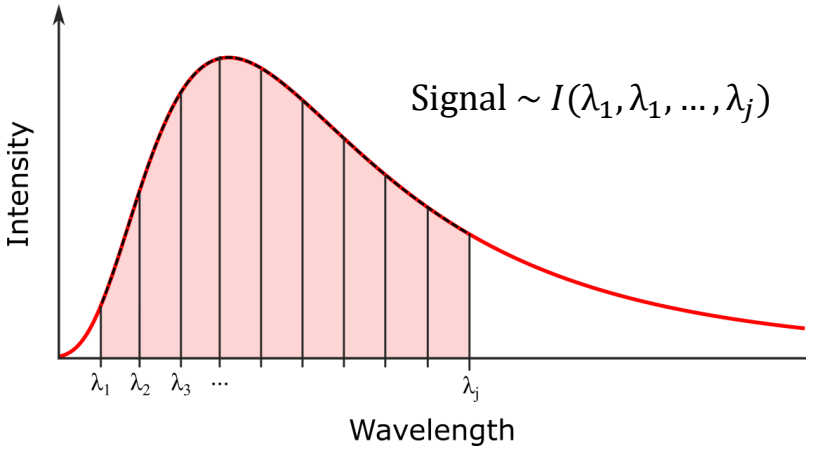
Sensor Calibration

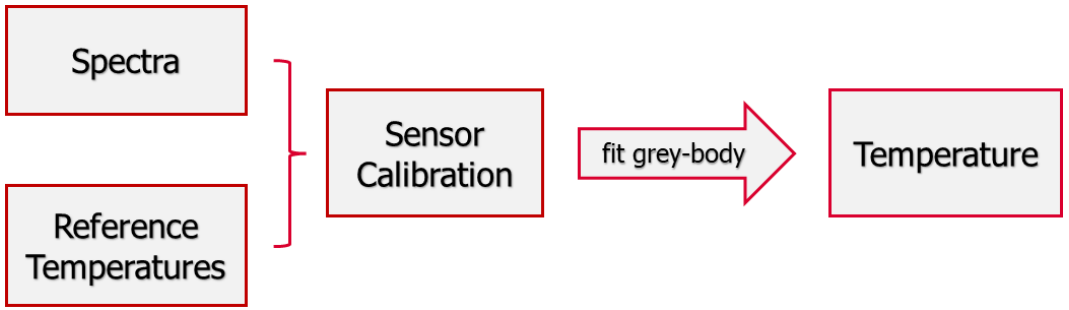
RMSE = Root Mean Squared Error

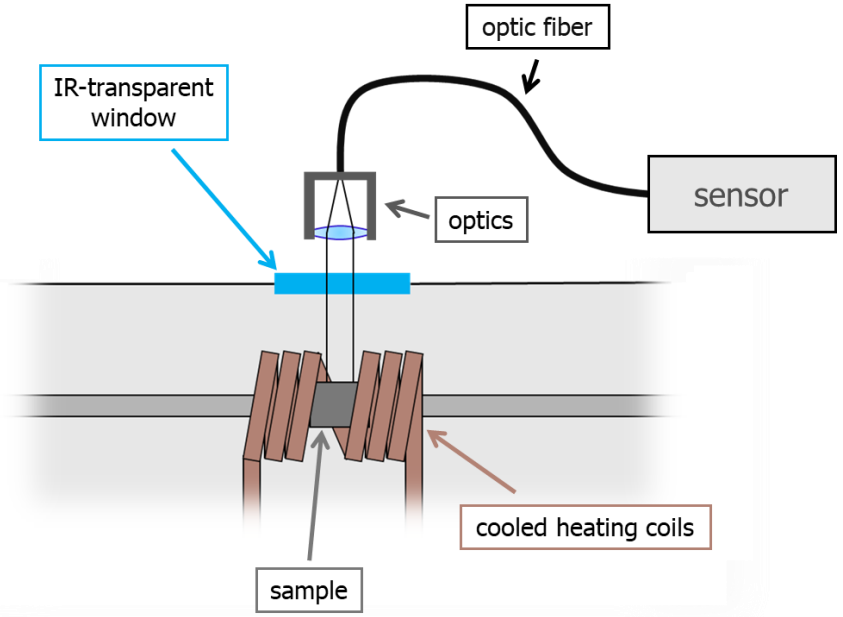
Measurement Example – Spectral Measurement

Experimental data





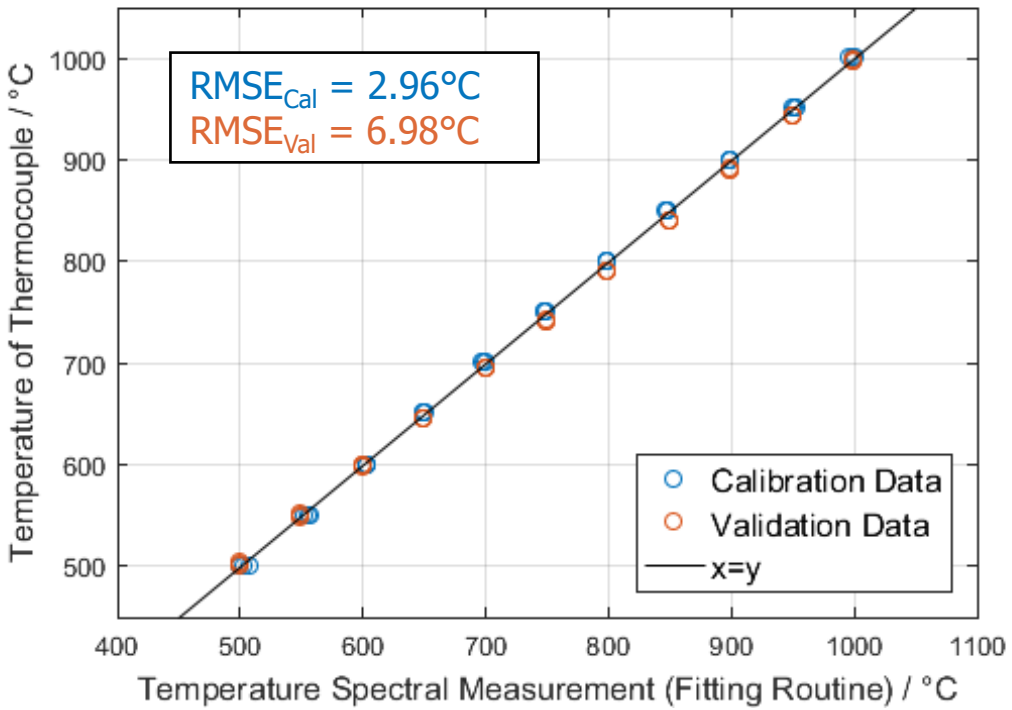


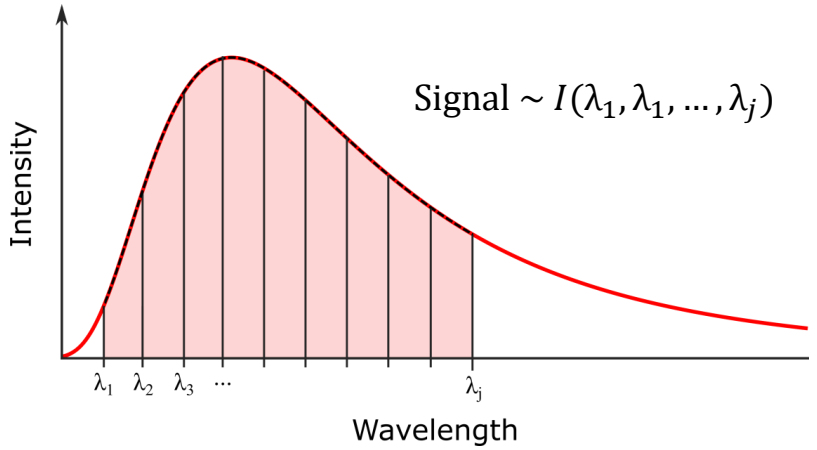


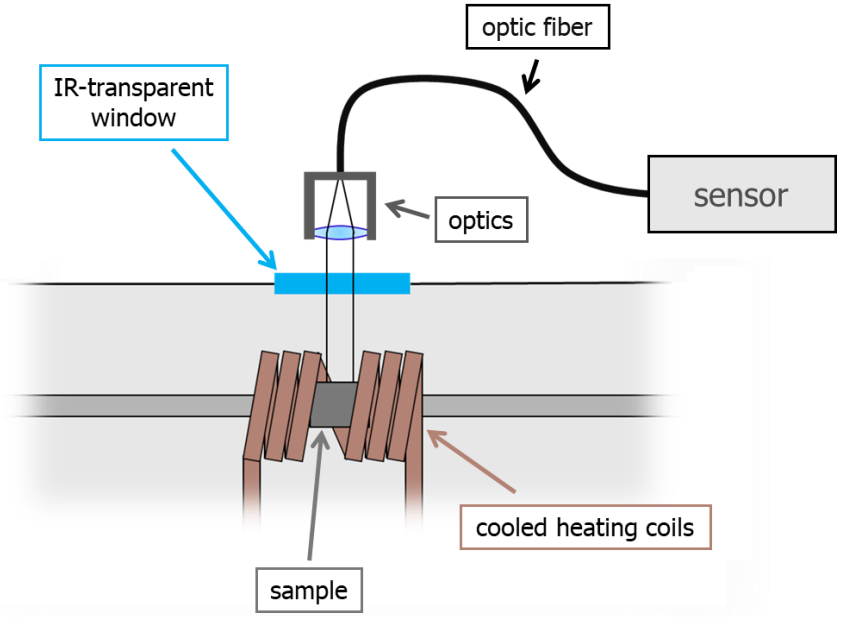
RMSE = Root Mean Squared Error

Measurement Example – Spectral Measurement

Experimental data





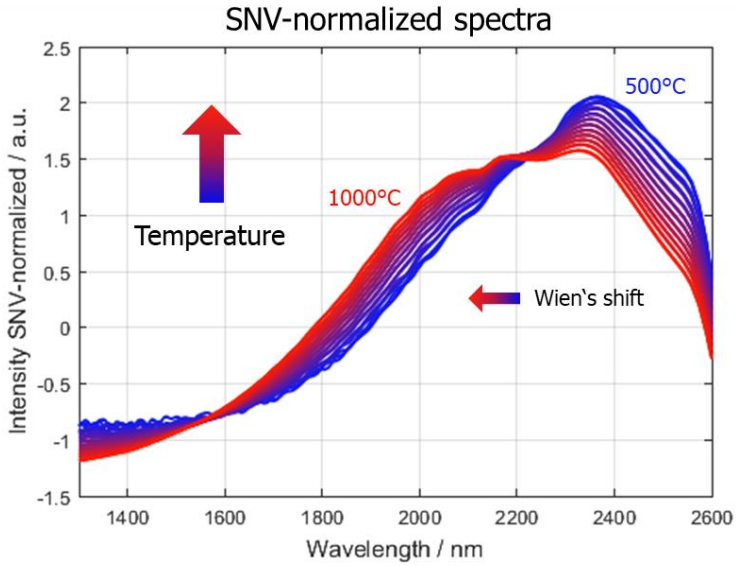


→ Validation measurement **error is further reduced** compared to 2-point-measurement

- Influences of emissivity and absolute intensity can be further reduced
- **Quality of the fit gives an estimation of the precision of each measured temperature**

RMSE = Root Mean Squared Error

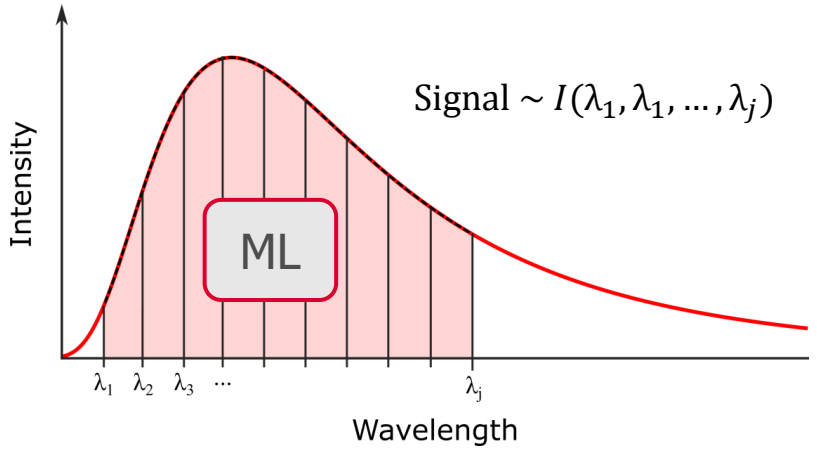
Measurement Example – Spectral Measurement

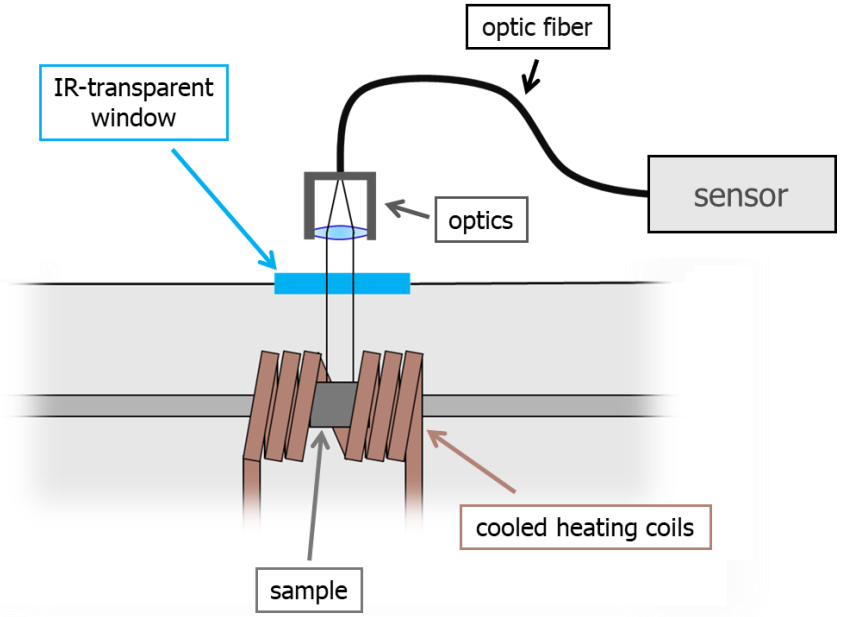


Two different ways to get the temperature:

1. Fit grey-body spectrum to the acquired NIR-spectra

2. Calibrate model to calculate the temperature from NIR-spectra using Machine Learning (ML) algorithms

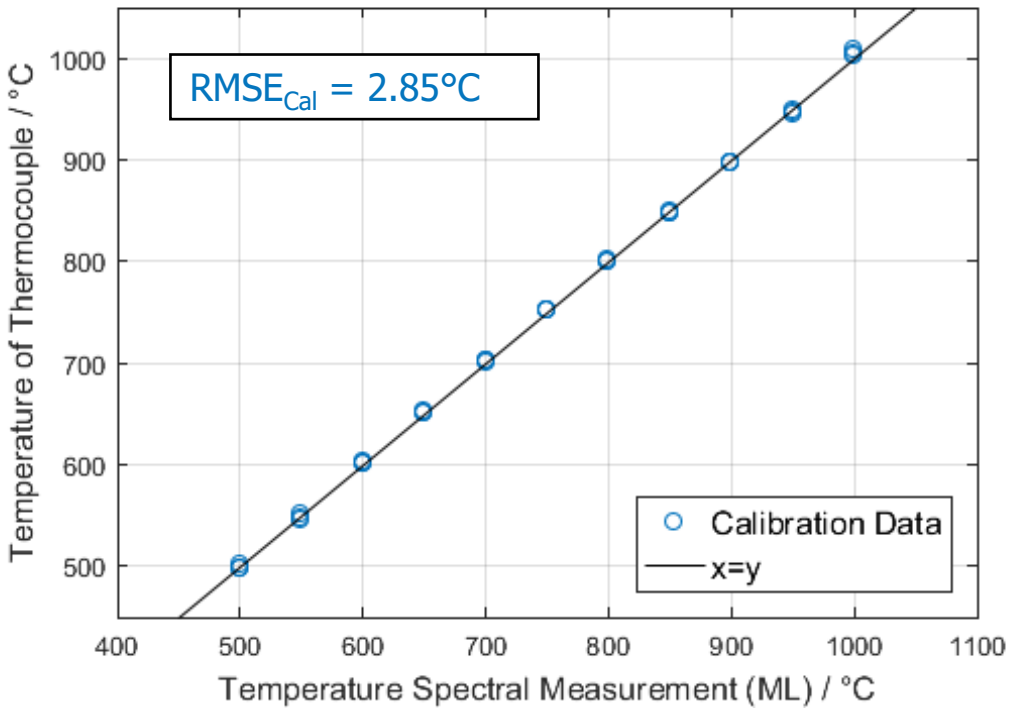


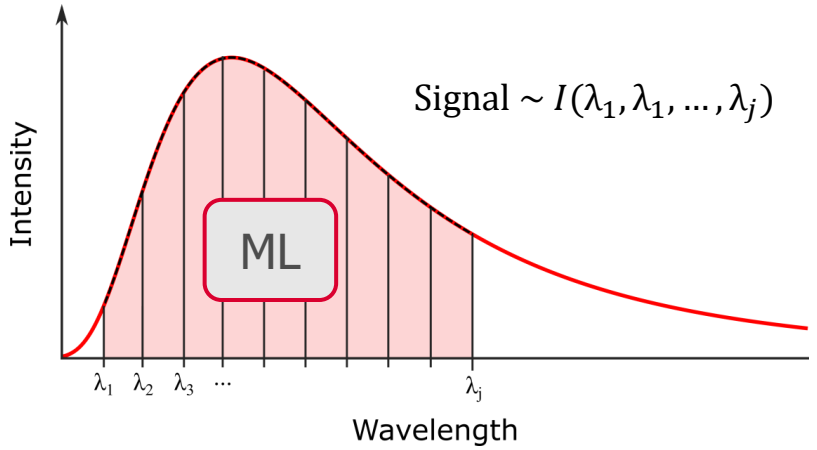


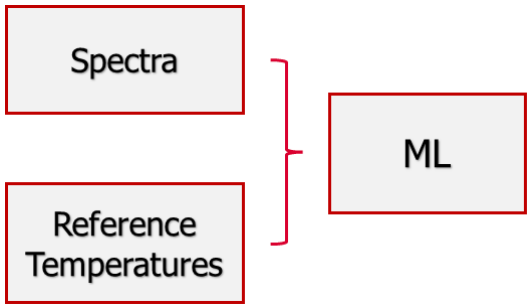
SNV = Standard Normal Variate

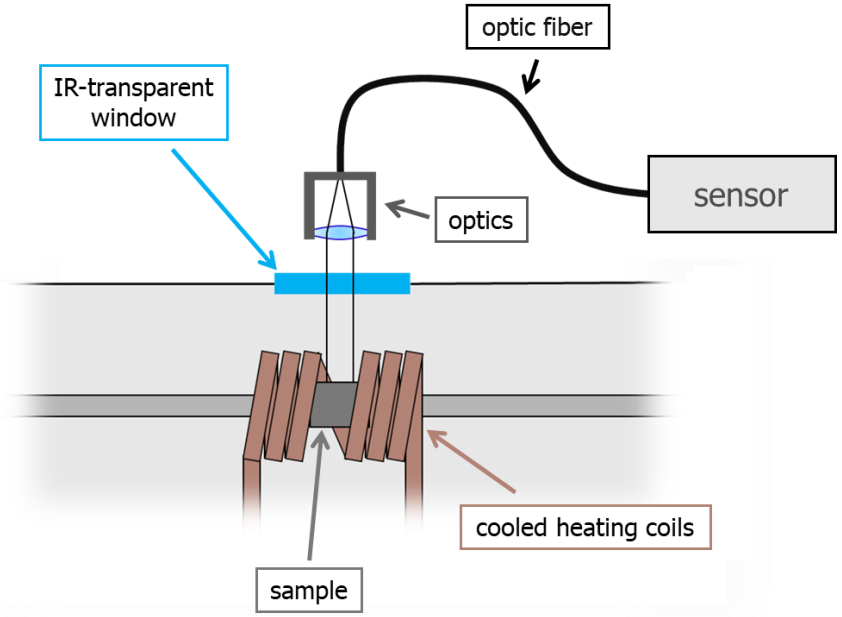
Measurement Example – Spectral Measurement

Experimental data





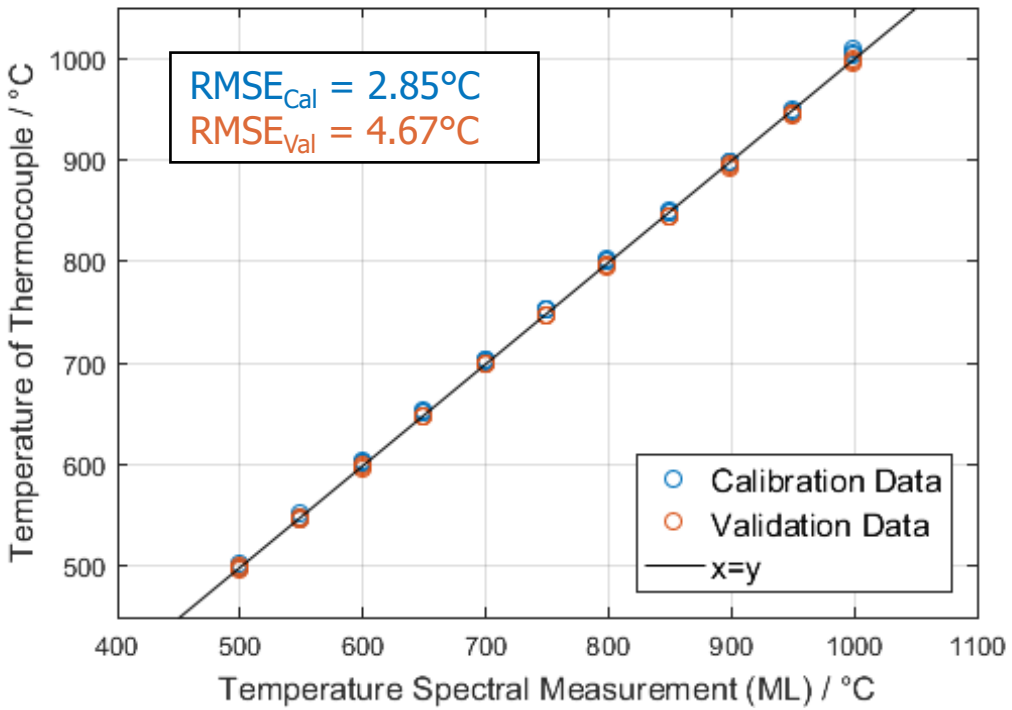


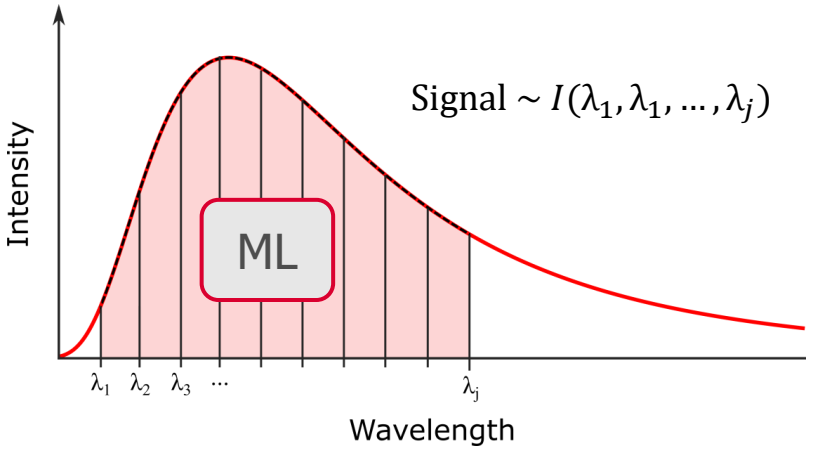


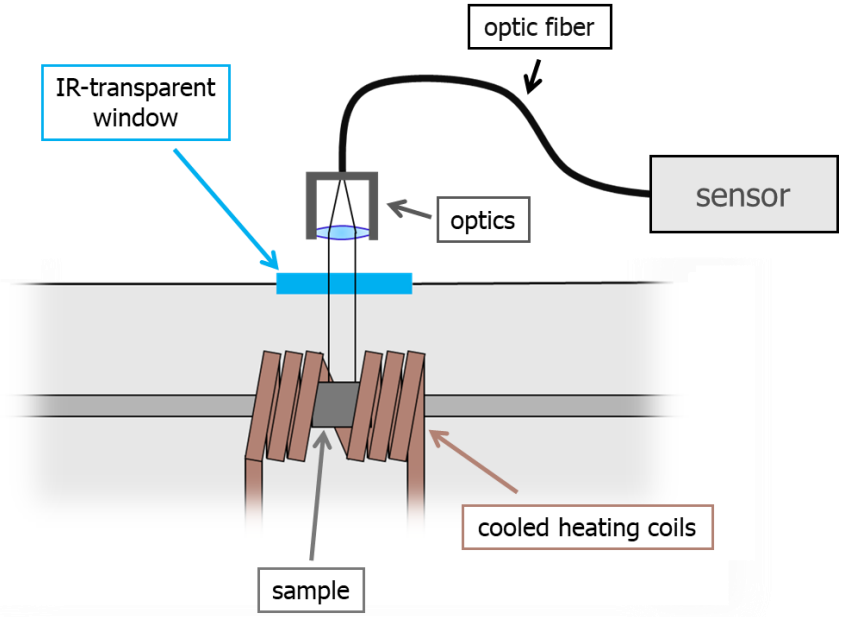
RMSE = Root Mean Squared Error

Measurement Example – Spectral Measurement

Experimental data



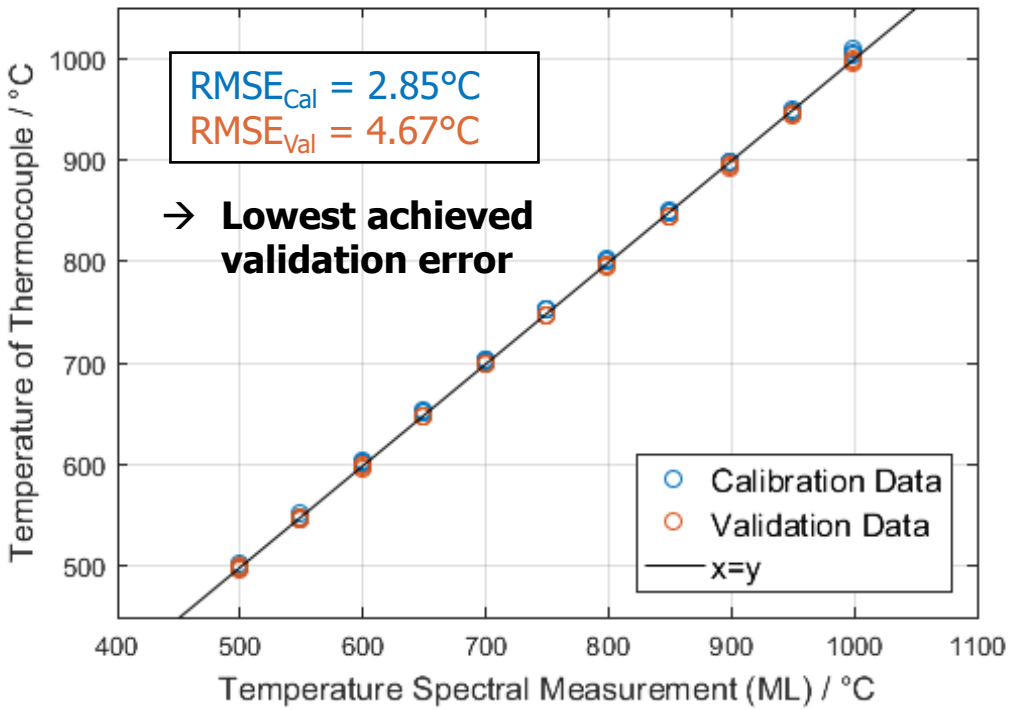


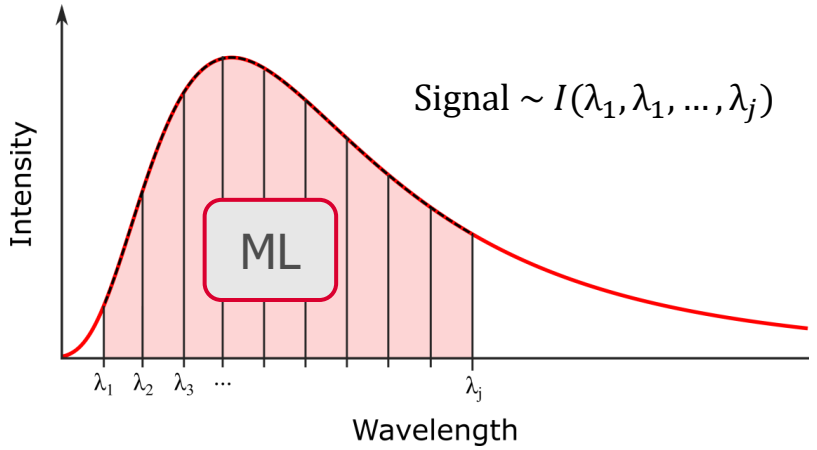


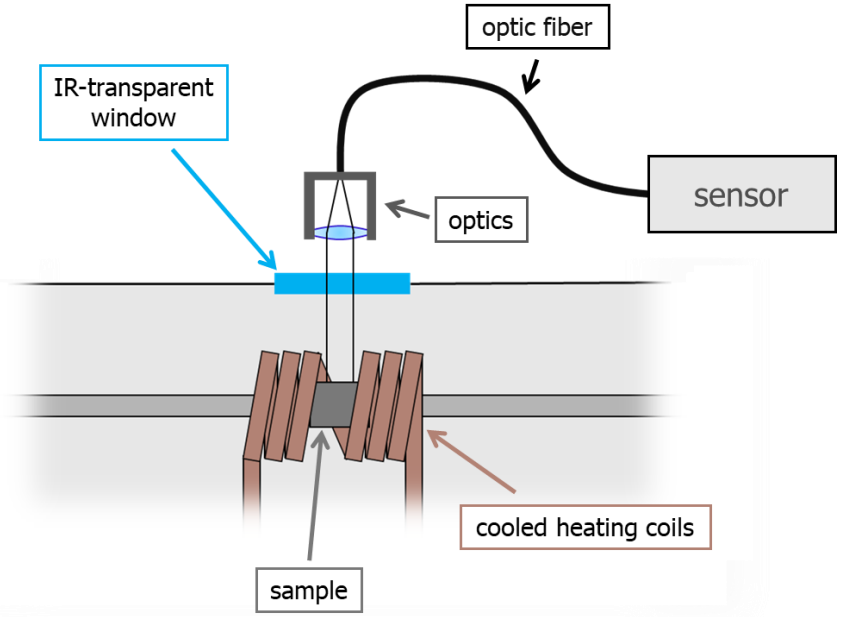
RMSE = Root Mean Squared Error

Measurement Example – Spectral Measurement

Experimental data





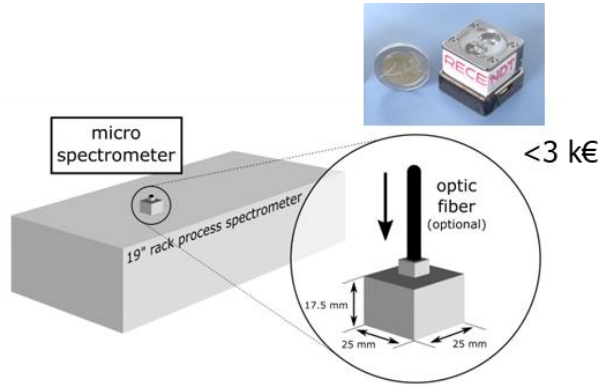


- ML-algorithm relates signal changes to temperature changes and allows to **minimize the measurement error**
- Spectral preprocessing methods (such as SNV-normalization) eliminate unwanted influences such as absolute intensity
- **ML-learning algorithm allows estimation of the precision of each measured temperature**

RMSE = Root Mean Squared Error, SNV = Standard Normal Variate

Comparison of Results / Summary

	integrative measurement	2-point measurement	spectral measurement (fitting)	spectral measurement (ML)
$RMSE_{Cal}$ / °C	2.33	2.65	2.96	2.85
$RMSE_{Val}$ / °C	18.67	10.13	6.98	4.67



- **NIR-spectroscopy is a powerful tool for stand-off temperature measurement** and offers some advantages compared to 2-color pyrometers

→ **Larger temperature range can be covered when broadband spectrometers are used**

→ **Additional information can be extracted from the collected NIR-spectra**

→ **Measured spectra give information about how trustworthy the measured value is**

→ **High flexibility regarding which and how many wavelengths are considered for the measurement**

- **Modern MEMS-based NIR-spectrometers** allow to measure **full NIR-spectra,** at a **comparable price** as with 2-color pyrometers

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Infrared & Raman group at RECENDT and external partners

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upper austria

Das Land Steiermark
Wirtschaft und Innovation

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