Physikalisch-Technische Bundesanstalt
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Fundamentals of radiation thermometry

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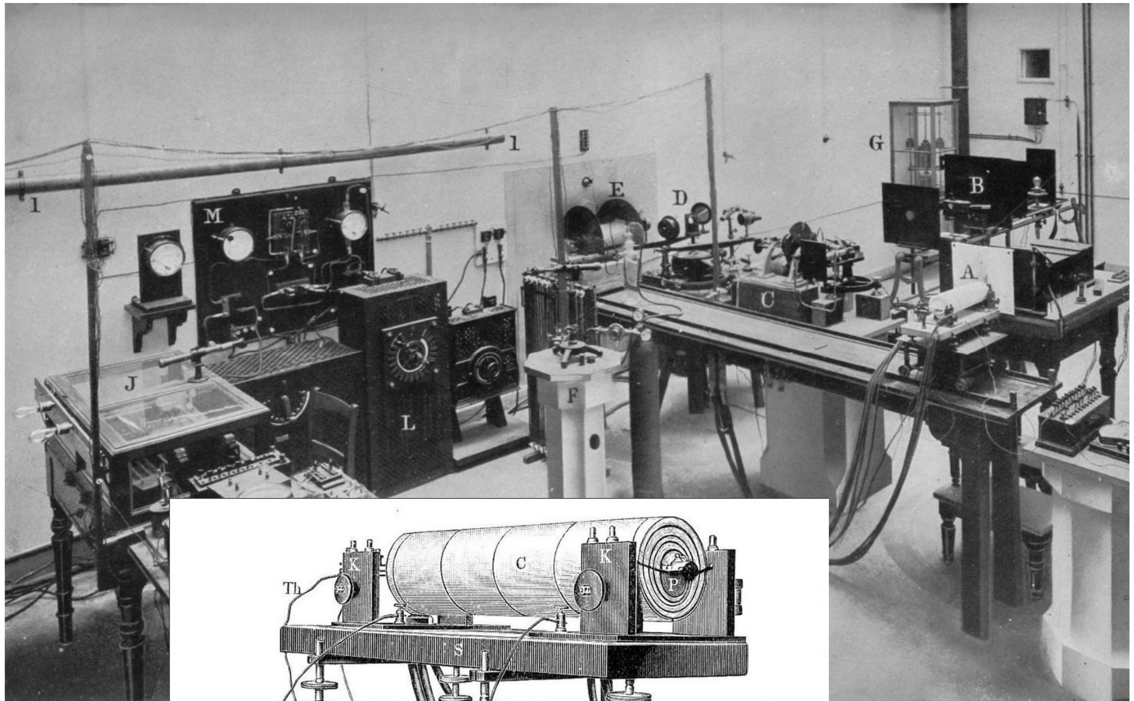
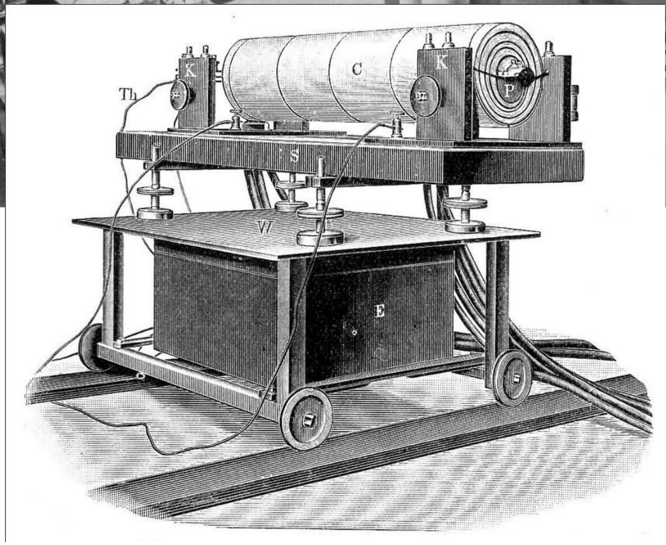
Outline

- Thermal radiation
- Detectors, Optical components
- Influencing factors on measurement
- Calibration, Measurement uncertainties
- Further reading

History of Radiation Thermometry

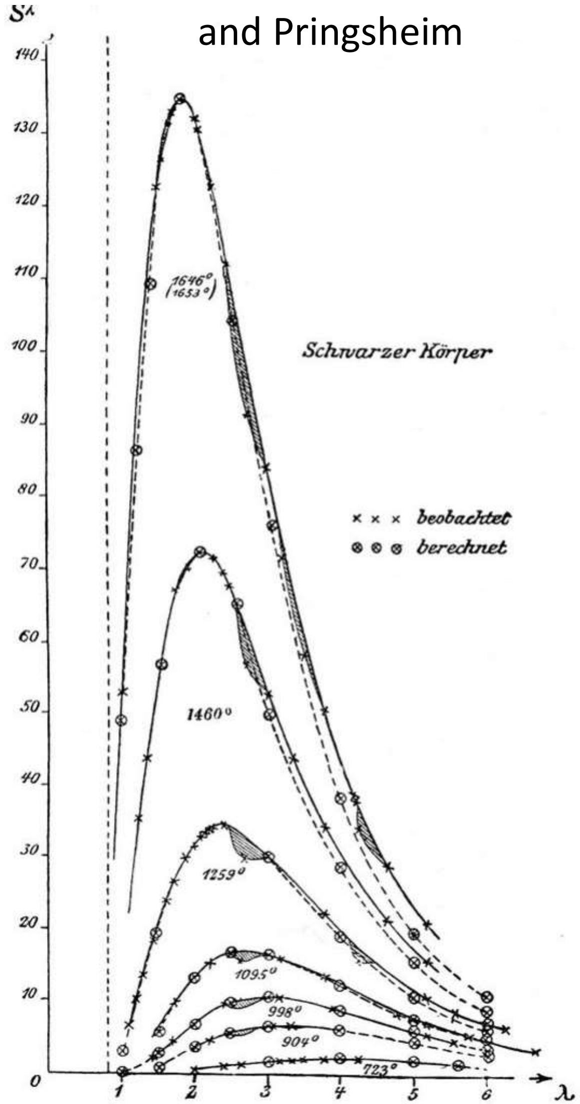
Laboratory for Radiative Physics of PTR around 1900





Blackbody radiator used by Lummer and Kurlbaum

Results of Lummer and Pringsheim



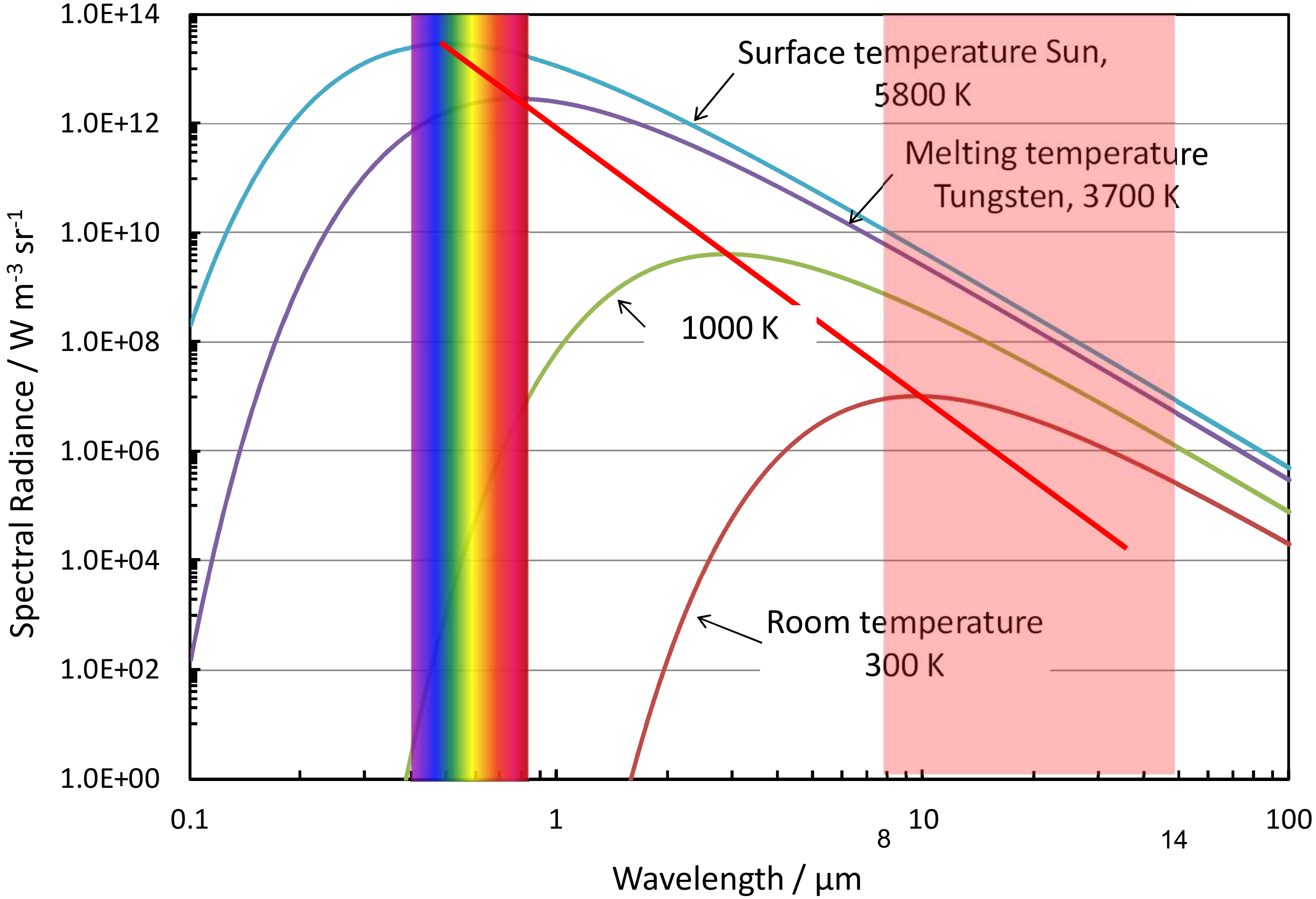
Planck's Law of Radiation

Planck: $L_{\lambda,b}(\lambda,T) = \frac{c_1}{\lambda^5} \cdot \frac{1}{e^{\frac{c_2}{\lambda \cdot T}} - 1}$

Integration over hemisphere and λ yields
Stephan Boltzmann law $M = \varepsilon\, \sigma \cdot T^4$

$c_1 = hc^2$

$c_2 = hc/k$

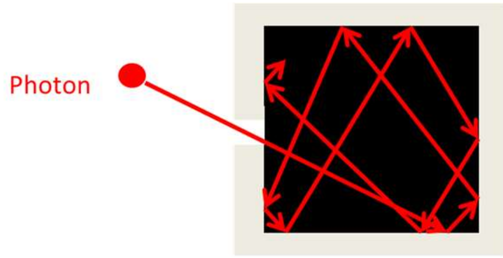


Wien´s displacement law $\lambda_{\max} T = 2898 \ \mu m K$

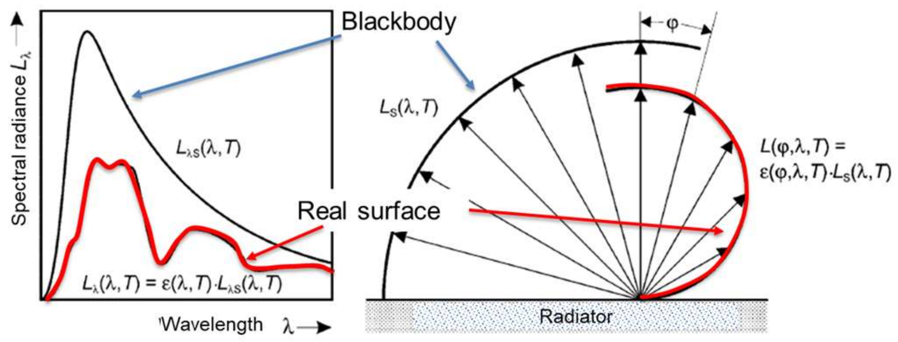
Blackbody radiation and emissivity

- Cavity with small opening
- Isothermal, opaque walls
- Ideally high emissivity of the wall material, walls are opaque

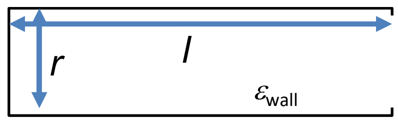
  ➔ Emissivity $\varepsilon \approx 1$



$$\text{Emissivity of a surface} = \frac{\text{radiation emitted by the surface}}{\text{radiation emitted by a perfect blackbody}}$$

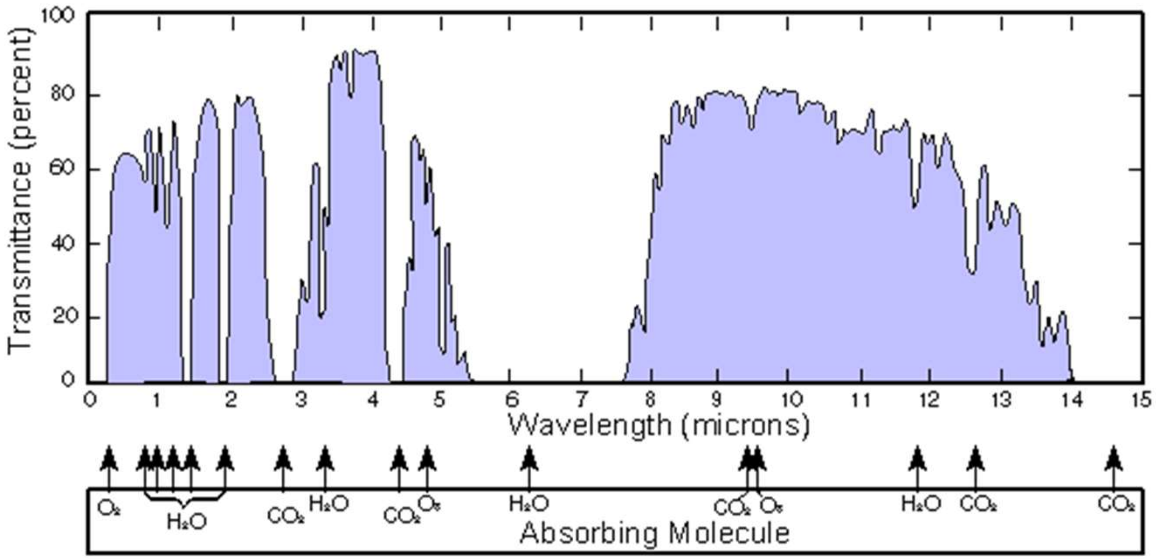


Approximation:



$$\varepsilon_{BB} = 1 - (1 - \varepsilon_{wall})\left(\frac{r}{l}\right)^2$$

Transmission / Absorption of the atmosphere and media



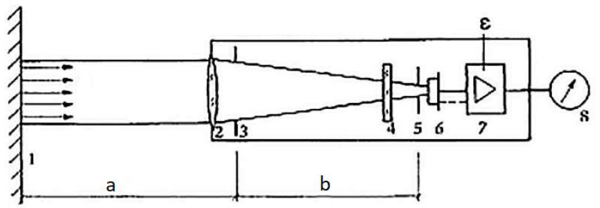
Source: wikipedia.org/wiki/Infrared_window

A comparison of a thermal image (left) and an ordinary photograph (right). The plastic bag is mostly transparent to long-wavelength infrared, but the man's glasses are opaque.

Source:
wikipedia.org/wiki/Thermal_radiation

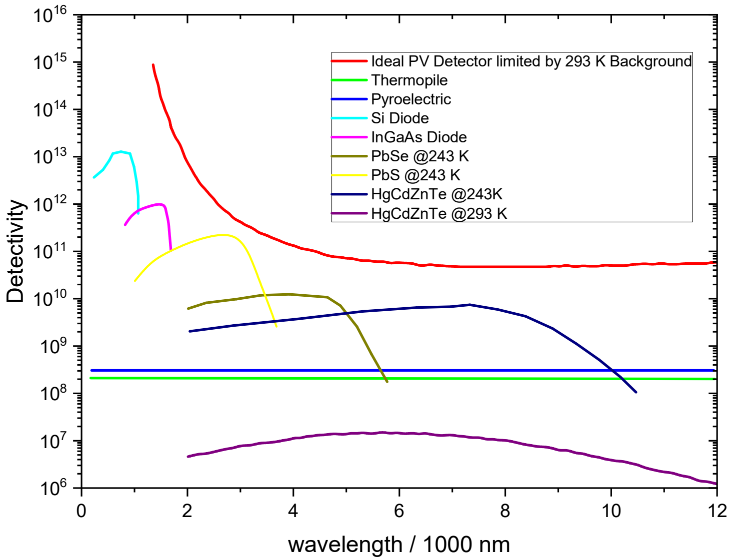
Components of a radiation thermometer

1. A lens which collects the emitted thermal radiation from a defined surface.
2. A detector which converts this energy into an electronic signal.
3. An emissivity correction feature, so that the instrument can be adjusted according to properties of the target material.
4. A compensation feature for ambient temperature which prevents the detector from factoring the instrument's own temperature into the output signal.



Schematics of a radiation thermometer
a measuring distance, **b** focal length , ε emissivity correction, **1** measuring object, **2** lens, **3** aperture diaphragm, **4** spectral filter, **5** detector aperture, **6** detector, **7** evaluation electronics, **8** display

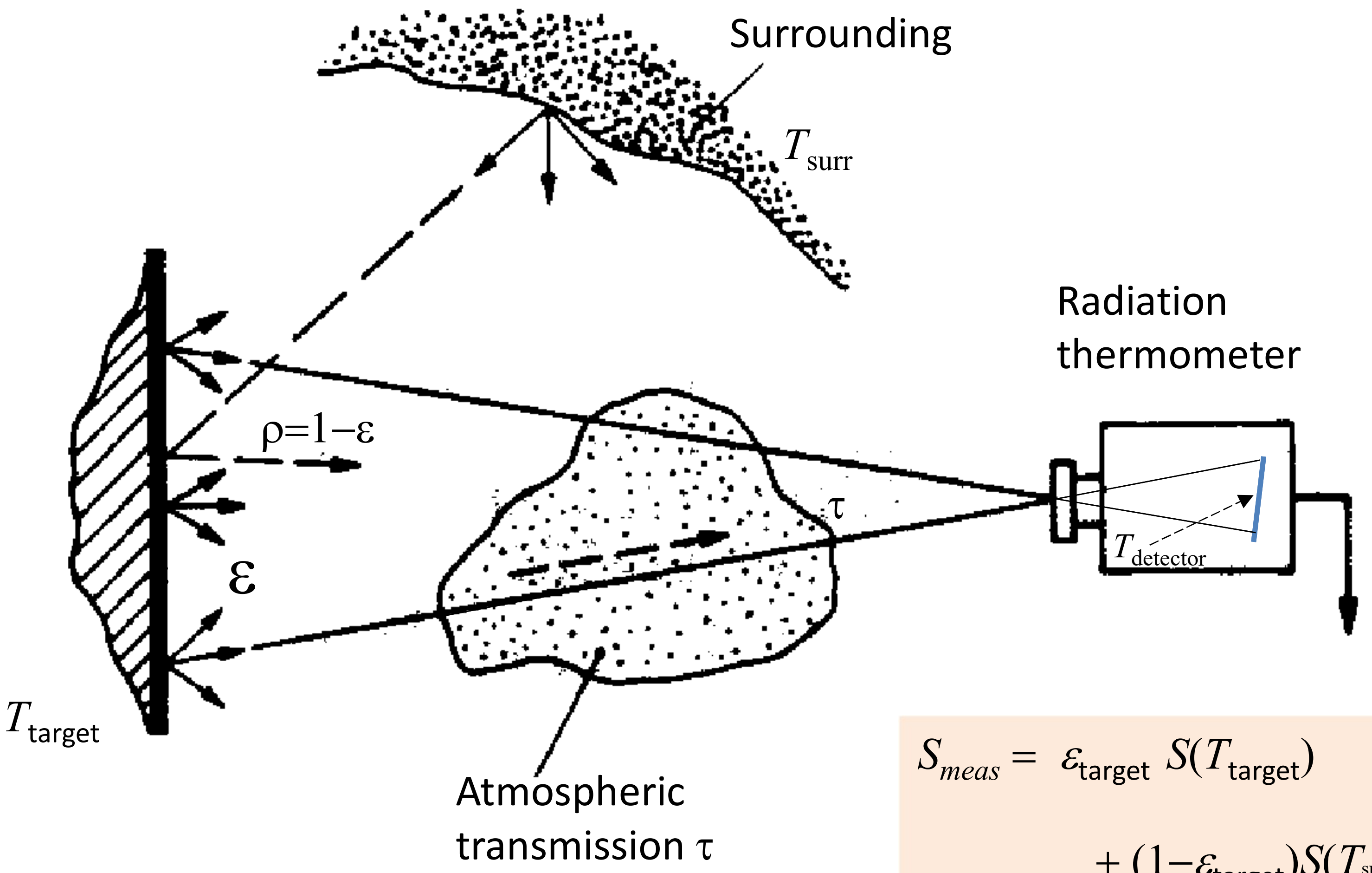
Spectral sensitivy of radiation detectors



Thermal detector
detected temperature change is a measure of radiant energy
Bolometer, Thermopile

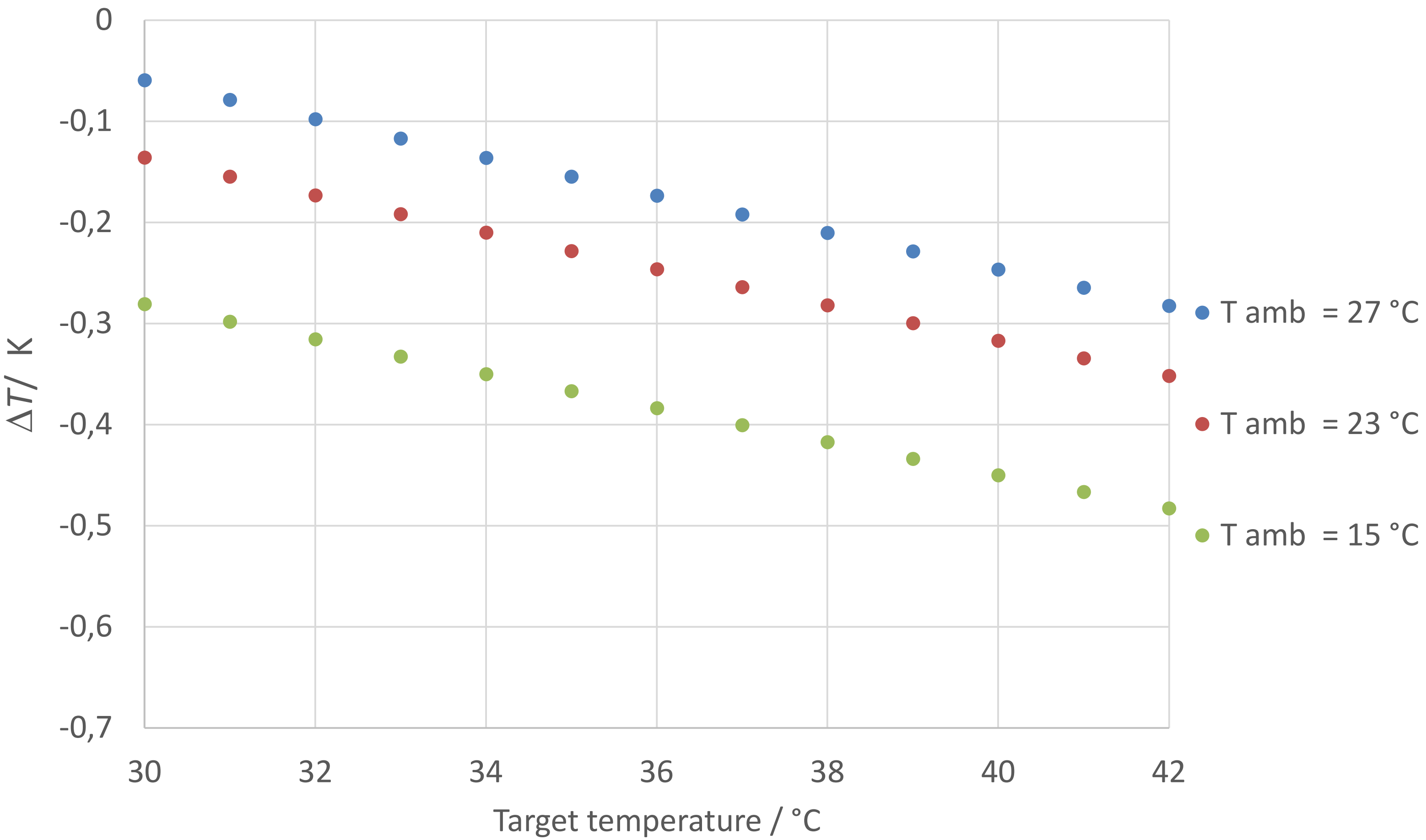
Quantum detector:
photons generate charge carriers
Photocathode, Photodiode

Influences on measurement with a radition thermometer



$$S_{meas} = \varepsilon_{target}\, S(T_{target}) + (1-\varepsilon_{target}) S(T_{surr})) - S(T_{detector})$$

Effect of changing ambient temperature
λ=8…14 μm, ε = 0.98 compared to ε =1



To compute this yourself e.g. for radiation thermometer with fixed ε :
MSL provides excellent Technical Guide 22 incl. MSExcel spreadsheet

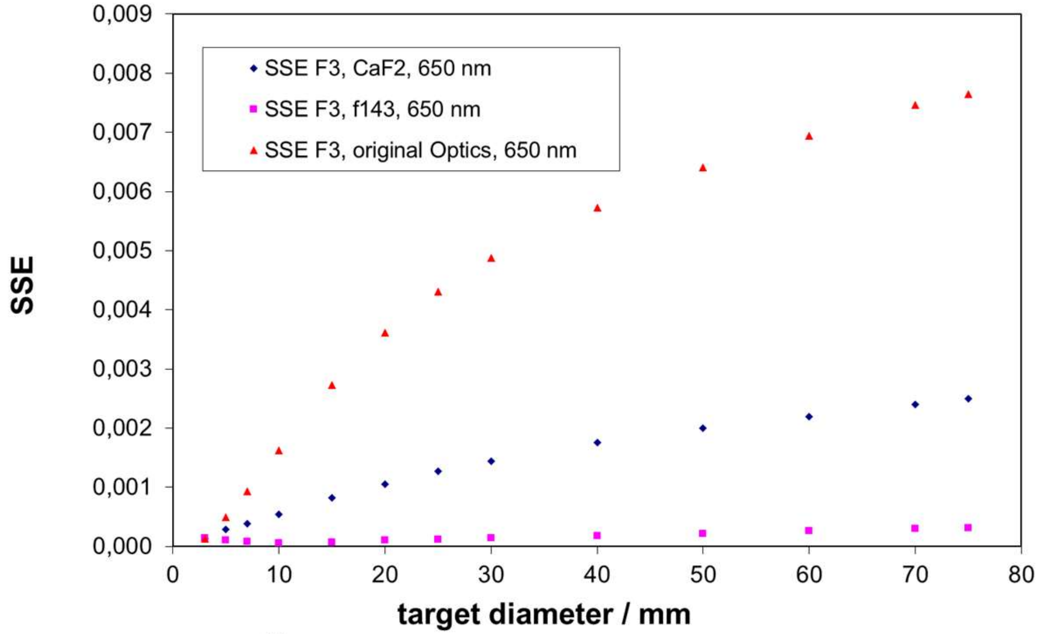
https://measurement.govt.nz/download/28 https://measurement.govt.nz/download/45

Size of Source Effect

= Sources of equal temperature but different size give rise to different apparent temperatures

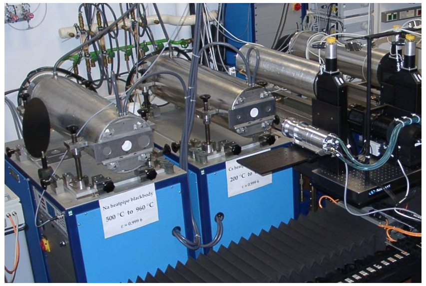
Origins:
Scattering at imperfections of optical components
Optical aberrations
Reflections at surfaces of lenses
Diffraction inside the pyrometer (at the aperture stop)

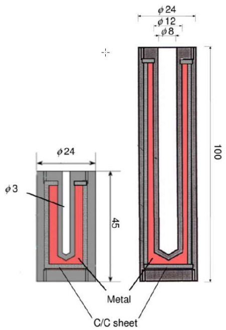
Quality RT
with low SSE



Calibration sources

NMI level





Variable temperature heatpipe BB
Traceable with SPRT,
and fixed-point BB radiators,
High emissivity ,
High temperature uniformity,
and temporal temperature stability,
small uncertainties,
often slow heating rates

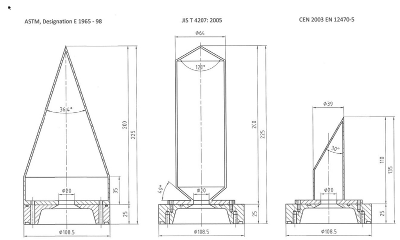
Industry / Calibration lab

Photo: fluke.com

Photo: isotech.co.uk

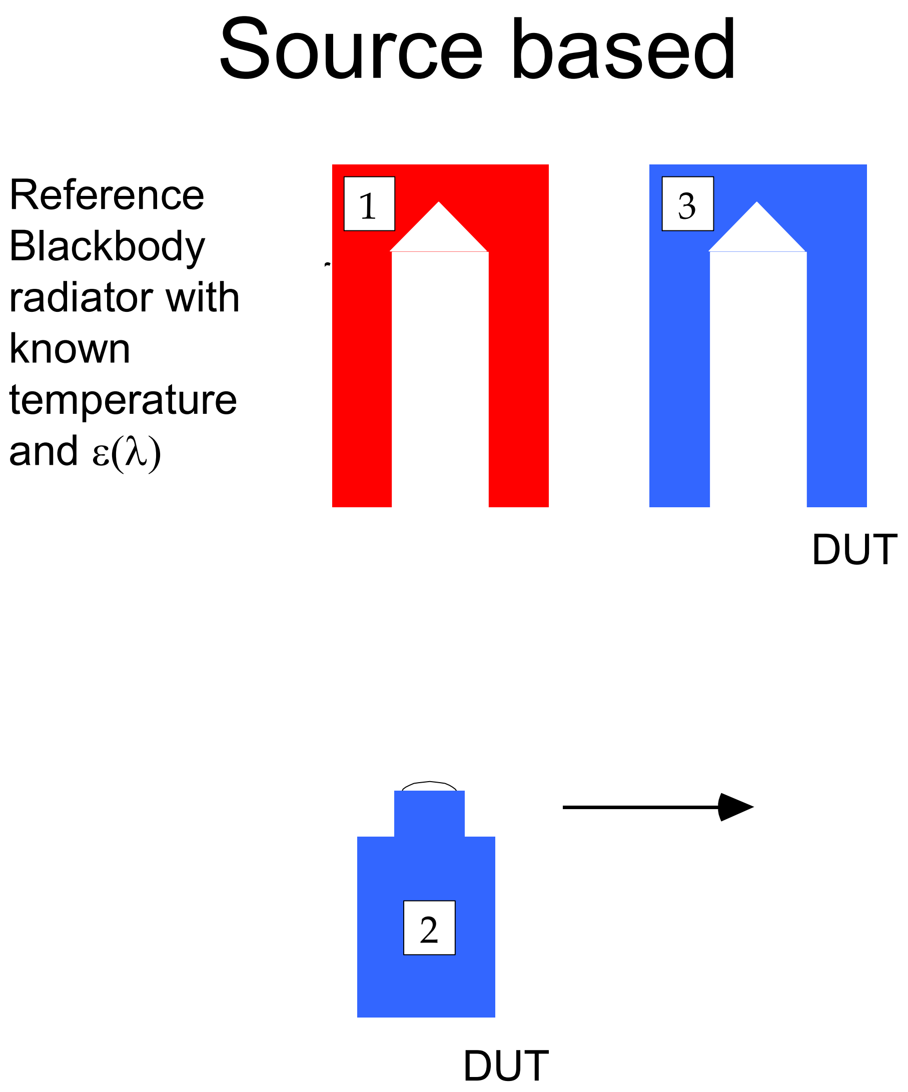
Commercial BB radiator
or flat plate radiator,
$\varepsilon(\lambda) < 1$,
RT with large field of view,
Transportable
Temperature uniformity and
temporal stability reaonable
fast heating rates

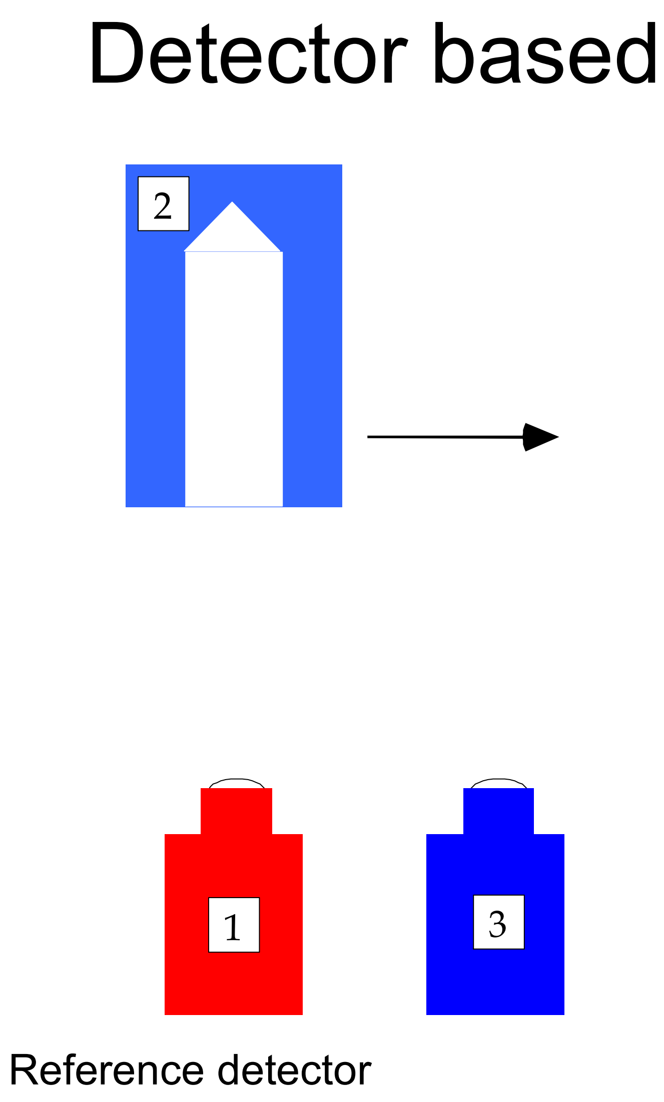
For specific application



Calibration BB for IR ear thermometers
Calibration devices regulated in normative
Documents with low unc. requirements
Realised as copper BB inlays installed
into stirred water bath
Traceability through PRT

Different calibration schemes





Typical Calibration steps

Calibration using the blackbody reference sources at several temperatures over the calibration range

Radiation thermometer should be calibrated with a measurement geometry similar to its use
– furnace aperture ideally to be the same size as the measurement object
– same working distance

Variation of alignment and calibration distance
Repeat measurements allow to evaluate the short term stability
Different temperature stabilised apertures allow to evaluate size-of-source effect (SSE)

Measurement signal can then be fitted to Sakuma-Hattori equation

$$I_{Photo} = C \Big/ \left[\exp\left(\frac{c_2}{A \cdot T - B} \right) - 1 \right] = C \cdot \exp\left(\frac{-c_2}{A \cdot T - B} \right)$$

Measurement uncertainties to be considered

	Description	Quantity	FPBB Scheme	VTBB Scheme
Blackbody	Calibration temperature	$u_1(T_i)$		
	Impurities	$u_2(T_i)$		
	Plateau identification	$u_3(T_i)$		
	Blackbody emissivity, isothermal	$\frac{u_4(S_i)}{S_i}$		
	Blackbody emissivity, non-isothermal	$u_5(T_i)$		
	Reflected ambient radiation	$u_6(T_i)$		
	Cavity bottom heat exchange	$u_7(T_i)$		
	Convection	$u_8(T_i)$		
	Cavity bottom uniformity	$u_9(T_i)$		
	Ambient conditions	$u_{10}(T_i)$		
Radiation Thermometer	Size-of-source effect	$\frac{u_{11}(S_i)}{S_i}$		
	Non-linearity	$\frac{u_{12}(S_i)}{S_i}$		
	Reference temperature	$u_{13}(T_i)$		
	Ambient temperature	$\frac{u_{14}(S_i)}{S_i}$		
	Atmospheric absorption	$\frac{u_{15}(S_i)}{S_i}$		
	Gain ratios	$\frac{u_{16}(S_i)}{S_i}$		
	Noise	$u_{17}(T_i)$		
Calibration Equation	Interpolation error	u_{18}		
Use	Drift	$u_{19}(T)$		
	Unknown temperature	$u_{20}(T)$		

https://www.bipm.org/wg/CCT/CCT-WG-NCTh/Allowed/References/Low_T_Uncertainty_Paper_Version_1.71.pdf

Calibration of thermal imagers

Similar to radiation thermometers

- Calibration of a <u>specified region</u> of the image using variable temperature blackbody sources

- Evaluation of the size-of-source effect (SSE)
- Check effect of alignment/ calibration distance
- Evaluation of the short term stability by performing repeat measurements

Evaluation of image non-uniformity (if possible)
Consider distance effect if the imager is to be used at different distance compared to calibration
Field of view can be larger (large aperture source necessary, e.g. flat plate radiator)
Some of the uncertainties (e.g. SSE) can be larger than for radiation thermometers

Further reading

Normative documents
VDI/VDE 3511 Part 4, 4.1, 4.2, 4.3, 4.4, 4.5, 4.6 and 4.7 Temperature measurement in industry - Radiation thermometry
VDI/VDE 5585 Part 1, Part 2 – thermographic imagers
IEC/TS 62492-1 and 2
Industrial process control devices - Radiation thermometers - Part 1: Technical data for radiation thermometers, Part 2: Determination of the technical data for radiation thermometers

Monographs
D. Dewitt/G. Nutter: Theory and Practice of Radiation Thermometry, 1988, John Wiley & Sons Inc.
Zhuomin M. Zhang, Benjamin K. Tsai, Graham Machin Radiometric Temperature Measurements: Applications. II and Radiometric Temperature Measurements: I. Fundamentals , Academic Press
Peter Coates, David Lowe The Fundamentals of Radiation Thermometers, Taylor & Francis Ltd., 2016

Online (free of charge)
Technical guides published by MSL (New Zealand)
TG 22 https://measurement.govt.nz/download/28 and https://measurement.govt.nz/download/45
TG 26 https://measurement.govt.nz/download/31

Uncertainty budgets for calibration of radiation thermometers is discussed in this CCT document
https://www.bipm.org/wg/CCT/CCT-WG5/Allowed/Miscellaneous/Low_T_Uncertainty_Paper_Version_1.71.pdf

Short introduction to the calibration of radiation thermometers with additional links
https://www.covid19.ptb.de/calibration-of-infrared-thermometers

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