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Quality Manual
of
Optical Power Measurements

Version 3.4

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1. Table of contents

2. Definition

2.1. Scope

This quality manual describes the use and maintenance of transfer standard detectors for calibrations of optical power meters. Transfer standard detectors are calibrated alternately with (or traceable to) a Predictable Quantum Efficient Detector (PQED) or a cryogenic radiometer using lasers. Modelling or spectral flatness are used to extrapolate the wavelength region.

Measurements with lasers are described in this manual. Spectral responsivity measurements using the reference spectrometer are described elsewhere [1].

2.2. Object and field of application

Trap detectors: Secondary transfer standards for both radiometric and photometric optical power measurements in visible region. Trap detectors can be modelled in the wavelength region 380 nm – 950 nm. Some traps have also been calibrated with the pyroelectric radiometer for the wavelength region 250 nm – 380 nm. The maximum measurable power level is ~1 mW.

Reference trap detector: A trap detector having direct or close calibration to cryogenic radiometer or PQED. Use is limited to checking working standard trap detectors only.

Working standard trap detector: A trap detector having calibration to transfer standard trap detectors. Working standards are calibrated for various purposes. Some are calibrated at fixed laser wavelengths only, some are modelled for spectral responsivity over UV-VIS-NIR regions.

Pyroelectric radiometer: Thermal spectrally flat detector used in UV, VIS and near-IR regions. Pyroelectric radiometer is also used for measurements in the region 1 mW – 10 W because trap detectors cannot be used to measure such high power levels. The measurable wavelength region is 250 nm – 16 µm and the highest measurable power is 10 W.

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[1] Quality Manual for Spectral Responsivity Calibrations, MRI Publication.

3. Equipment

3.1. Description of setups

Table 1. Equipment needed in measurements with the trap detectors.

Description

A. Trap detectors

1. Trap detector
2. Optical stand for trap detector
3. Cable for trap detector

B. Light sources

1. HeCd laser (325 nm, 442 nm) (2 available)
2. HeNe laser (543.5 nm)
3. HeNe laser (633 nm) (2 available)
4. HeNe laser (1523 nm)
5. AR+ laser with selectable wavelengths of 458.1, 488.1, 514.7 nm
6. KrAr laser (476.5, 482.6, 488.1, 496.7, 514.5, 520.9, 531, 568.4, 647.3, 676.6, 10 lines)
7. Diode laser (932 nm)
8. Diode laser (405 nm)
9. Ti:Sapphire laser (700 – 1000 nm) (in MIKES)

C. Measurement and data acquisition

1. Digital multimeter, HP3458A, HP/Agilent 34401A, HP/Agilent 34410A
2. Current to voltage converter (Vinculum, FEMTO, MRI-Vinculum, Stanford)

D. Miscellaneous

1. Ando spectrum analyser for wavelength measurement
2. Neutral density filters (1 %, 10 %)
3. Intensity stabilizer (3 different types available)

Operating instructions of the lasers and the pyroelectric radiometers are stored in the PQED/Laser laboratory.

There are various trap detectors for various purposes in the laboratory. All trap detectors are listed with their calibration and maintenance history in file

\\work.org.aalto.fi\MIKES-Aalto\Quality\radiom\trapdata.xls

The traps intended to be used as *Reference standards* have direct traceability to primary standards. Use of them should be limited to a minimum. Some of the traps intended to be used as *Working standards* have calibration to primary standard traps or cryogenic radiometer. They can be used more freely. Common calibration interval for traps is three years, so the status of calibrations needs to be checked before use.

The traps are stored in the dry cabin located in Irradiance laboratory.

Table 2. Equipment needed in measurements with the Rk-5700 pyroelectric radiometer.

	Item	Identification
1.	Pyroelectric detector RkP-575 (Detector 1)	9301-0327
2.	Pyroelectric detector RkP-575 (Detector 2)	066-105-001
3.	Chopper 1 (Broken, 7.12.2015)	9302-0322
4.	Chopper 2 (Broken, 30.11.2018)	110-087-001
5.	Readout electronics Rk-5700	9202-0055
6.	Cable between chopper and RkP-575	-
7.	Optical stand for RkP-575 (Thread in Inches!)	-
8.	Briefcase containing the above	-
9.	External chopper with own electronics	

The pyroelectric radiometer is stored in an aluminium briefcase located in the PQED/Laser laboratory. After use, all parts should be returned to the briefcase.

For more accurate calibrations, there is an RS-5900 series pyroelectric radiometer that can be used with power levels between 1 uW to 10 mW.

Table 3. Equipment needed in measurements with the RS-5900 pyroelectric radiometer.

	Item	Identification
1.	Pyroelectric detector RSP-590	9903-019
2.	Readout electronics RJI-700	9903-018
3.	Chopper CTX-515	9903-020
4.	Power supply for chopper (18V AC)	

The device is stored in Transmittance laboratory.

3.2. Calibration requirements

- Calibration of all devices is performed according to the calibration schedule of MRI and recorded in Calsched.xls (\\work.org.aalto.fi\T405\MIKES-Aalto\Quality):
  - Multimeters, Current to voltage converters
  - Trap detector absolute responsivity measurements with cryogenic radiometer every three years at RI.SE (Technical Research Institute of Sweden) or with PQED.

  - Trap reflectance measurements and spectral responsivity extrapolations [2] every three years
  - The pyroelectric radiometer Rk-5700 is calibrated once a year. Due to its spectral flatness, the calibration only needs to be done at one visible wavelength
  - The pyroelectric radiometer RS-5900 is calibrated after three years. Due to its spectral flatness, the calibration only needs to be done at one visible wavelength
- The multimeters are auto-calibrated every day before the start of the calibration measurements.
- Trap detectors are visually checked before calibration to confirm that there is no dust on the photodiodes. If there is visible dust on the first photodiode, this can be cleaned with lens cleaning paper and a cotton swab. If there is dust on the inner diodes, the trap should be disassembled and photodiodes should be carefully cleaned using dry nitrogen flow. Nitrogen flow must be directed to the photodiodes in the direction so that dust particles cannot land on other photodiodes. Dry air can also be used for cleaning. Cleaning should be carried out only by the person responsible for trap maintenance.

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[2] Instruction Manual for the Spectral Modelling of Three-Element Silicon Trap Detectors, MRI Publication.

4. Measurement traceability

The spectral responsivity of the trap detectors at the laser wavelengths is traceable to P-type predictable quantum efficient detectors (PQED) of Aalto, predictable in the wavelength range from 400 nm to 800 nm. In addition, the scale is periodically compared with the cryogenic radiometer of RI.SE, Sweden. Minimum of three traps are used as reference traps.

PQEDs [3] are traceable to natural constants. They consist of high quality photodiodes with minimal losses for internal quantum deficiency and reflectance. P-type PQEDs used are modelable in the wavelength range from 400 nm to 800 nm, as they have shown excellent stability and repeatability of up to 80 ppm.

The trap detectors used for spectral responsivity measurements, are modelled in the wavelength region 250 nm – 950 nm. Modeling takes into account the ideal responsivity, the reflectance, and the internal quantum efficiency of the traps.

In the wavelength regions 250 nm – 380 nm, and 900 – 950 nm, the traps are calibrated with a pyroelectric radiometer to assist modeling. Measurements are traceable to the spectral flatness of the pyroelectric radiometer specified by the manufacturer and to the trap responsivities in the visible wavelength range. Results are interpolated using methods described in [2].

The wavelengths of the gas-lasers used are fundamental and therefore traceable to tabulated generally accepted physical constants. Gas lasers are used to calibrate the Ando spectrum analyser. The analyser is used to calibrate the wavelengths of the diode lasers.

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[3] M. Sildoja, F. Manoocheri, M. Merimaa, E. Ikonen, I. Müller, L. Werner, J. Gran, T. Kübarsepp, M. Smîd, and M. L. Rastello, “Predictable quantum efficient detector: I. Photodiodes and predicted responsivity,” Metrologia 50, 385–394 (2013).

5. Calibration and measurement procedures including validation methods

5.1. Use of trap detectors

Trap detectors [4, 5] are widely used as secondary transfer standards of optical power measurements. They only need to be calibrated at discrete wavelengths. At MRI multiple laser wavelengths between 325 nm and 933 nm are available. The spectral response at other wavelengths can be extrapolated by using models for the reflectance and the internal quantum deficiency of the detector. This is described more detailed in [2].

The responsivity $R(\lambda)$ of a trap detector in [A/W] can be expressed as

$$R(\lambda) = [1-\rho(\lambda)][1-\delta(\lambda)]\frac{e\cdot\lambda}{h\cdot c} \qquad (1)$$

where λ is the vacuum wavelength, $\rho(\lambda)$ is the reflectance of the detector, $\delta(\lambda)$ is the internal quantum deficiency of the photodiodes, *e* is the elementary charge, *h* is Planck's constant and *c* is the speed of light in vacuum.

When using the trap detector for measuring laser sources, the following instructions apply:

- The responsivity is a strong function of wavelength. The trap detector used must have calibration or modelling at the wavelength being measured.
- Trap detectors are used unbiased in short-circuit mode. This requires use of a current to voltage converter. If measuring the current with an ordinary current meter, the signal becomes non-linear as described e.g. in [5].
- The trap detectors are stored in the dry cabinet with the protective cap closed whenever they are not in use. This is to keep low moisture level and dust away from the surfaces of the photodiodes.
- Some protecting caps of the traps have glued windows. These detectors should be aligned with their caps attached to the trap. The caps are only removed for the actual measurement.
- Trap detectors are used perpendicular to the measured beam. The perpendicularity is adjusted by directing the weak reflected beam almost back to the laser. (A little tilt is required not to influence intensity stabilizer functionality and/or because certain lasers do not stay locked).

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[4] N. P. Fox, "Trap Detectors and their Properties," *Metrologia* **28**, 197-202 (1991).

[5] P. Kärhä, Detector-based scales for spectral responsivity and spectral irradiance, Licentiate thesis, HUT, 1995.

5.2. Use of predictable quantum efficient detector

The responsivity $R(\lambda)$ of a PQED in [A/W] can be expressed as Eq. 1. Using the responsivity and measured current signal, the optical power of a PQED can be calculated as

$$P = \frac{I\,h\,c}{e\,\lambda\,[1-\rho(\lambda)]\,[1-\delta(\lambda)]}, \qquad (2)$$

where I is the measured current of the PQED, λ is the vacuum wavelength of the laser used, $\rho(\lambda)$ is the reflectance of the detector, $\delta(\lambda)$ is the internal quantum deficiency of the photodiodes, assumed to be approximately 8 ppm, e is the elementary charge, h is Planck's constant and c is the speed of light in vacuum. [3]

The reflectance of the PQED for the available wavelengths is presented in Table 4 and in Fig. 1. The values stated in the table are modelled reflectances of PQED N8 at room temperature. The measured reflectances are used to build a model for the reflectance of PQED over a spectral range of 400 nm to 800 nm. The complete reflectance model file, including original measurement results and reflectances interpolated at 0.5 nm interval, can be found in the file ..\..\..\Quality\Radiom\P_type_PQED_reflectance.xlsx.

Table 4: Reflectance of a predictable quantum efficient detector (PQED-N8) at the laser lines available [3, 11].

Wavelength [nm]	Reflectance	Internal Quantum Efficiency	External Quantum Deficiency
405	9.98E-05	0.9915	0.008
442	4.38E-05	0.9916	0.008
476	3.24E-05	0.9919	0.008
488	2.74E-05	0.9920	0.008
515	1.65E-05	0.9922	0.008
543	8.61E-06	0.9924	0.008
633	1.11E-05	0.9920	0.008
647	1.4E-05	0.9912	0.008

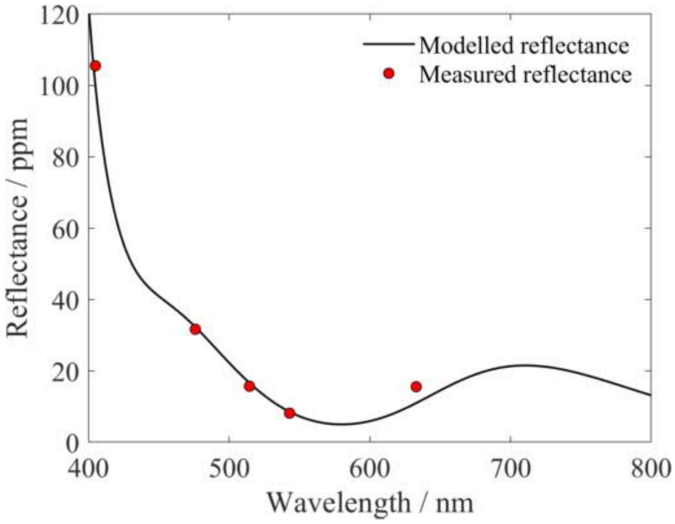

Figure 1: Modelled reflectance of PQED over the spectral range of 400 nm to 800 nm.

5.3. Use of pyroelectric radiometer

Operation of the Rk-5700 pyroelectric radiometer is described in [6]. Operation of the RS-5900 pyroelectric radiometer is described in [7].

Due to its wide spectral range, pyroelectric radiometer is very sensitive to changes in the environment, e.g. far-IR radiation from the surrounding walls etc. Detaching the chopper from the detector part and moving it as close to the measured light source as possible may reduce this.

5.4. Comparison of two detectors

Two trap detectors can be compared with each other by using the lasers and computer controlled translators and data acquisition system installed in the Laser laboratory [8, 9].

Customer meters are calibrated using the same measurements system as for trap detectors. Following principles apply:

- One or several lasers listed in Chapter 3.1 are used during the calibration. Operating instructions for the lasers are stored on the bookshelf of the laboratory.

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[6] RK-5700 Series Operating Instructions, August 1, 1989, 12655 REV. C

[7] RS-5900 Electrically Calibrated Pyroelectric Radiometer –Instruction Manual -, Rev B, January 1991.

[8] Anna Vaskuri, Multi-wavelength setup based on laser for characterizing optical detectors and materials, Diploma work, MRI, 8+57 p., 2014.

[10] A. Vaskuri, P. Kärhä, A. Heikkilä, and E. Ikonen, “High-resolution setup for measuring wavelength sensitivity of photoyellowing of translucent materials,” Review of Scientific Instruments 86, 103103-1–8 (2015).

- Spatial filter and external power stabiliser installed in the measurement system should be used. In less demanding calibrations or using custom built setups requiring maximum power from the laser, only iris diaphragms can be used to limit the size of the beam and to clean the satellite beams off.
- Standard detector and the meter under calibration are placed to the same location in the beam using linear translator to alternate the detectors. The reading of the calibrated meter is compared to the average of measurements with the standard detector before and after the measurement.
- If necessary, the power is attenuated with the neutral density filters.
- Measurement is repeated as many times as necessary (usually five times), to reduce uncertainty caused by repeatability. The noted value for repeatability is used in the uncertainty estimation.
- Uncertainty component caused by non-uniformity of the calibrated meter may be evaluated by moving the detector spatially, and recording the noted change. This can be done using the scanning function of the translator software.

6. Handling of calibration items

Optical surfaces of detectors should not be touched. Detector surfaces are not to be cleaned without agreeing with the customer.

7. Uncertainty budgets

Uncertainty calculations can be found in directory \\work.org.aalto.fi\T405\MIKES-Aalto\Quality\radiom\ in file uncert_trap_2019.xls.

7.1. Uncertainty of trap calibration with predictable quantum efficient detector

The uncertainty budget of the spectral responsivity of a P-type PQED is presented in Table 5. Uncertainty of a trap detector calibrated against a PQED is presented in Table 6. Explanation of various uncertainty components can be found in [3, 10]. When the calibrated trap detector is used in further measurements, the spatial uniformity needs to be accounted.

Table 5. Uncertainty budget [ppm] of a PQED responsivity.

Source \ Wavalength / nm	**405**	**476.4**	**514.5**	**543.7**	**632.8**	**633 - 800.0**
Reflectance	10	6.3	4.6	2.0	7.7	
Reflectance model	1.74					10
Non uniformity of PQED	82					
Internal quantum efficiency	70					
Stability and repeatability	16					
Temperature dependence	2					
Alignment	1					
Combined standard uncertainty	109.5	109.2	109.1	109.1	109.3	109.5
Expanded uncertainty (*k* = 2)	219.0	218.4	218.3	218.1	218.6	219.0

It should be noted that the uncertainty for the non-uniformity is much larger than anticipated. The PQED was for some reason noisy in the measurements. This issue will be studied further for the next scale realisation.

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[10] T. Dönsberg, M. Sildoja, F. Manoocheri, M. Merimaa, L. Petroff, and E. Ikonen, ``A primary standard of optical power based on induced-junction silicon photodiodes operated at room temperature'', Metrologia 51, 197-202, 2014.

Table 6. Uncertainty budget [%] of trap calibration against PQED.

Source \ Wavelength / nm	**476.4**	**514.5**	**543.7**	**632.8**
PQED uncertainty (Table 5)	0.011	0.011	0.011	0.011
Repeatability	0.010	0.003	0.003	0.008
Current to voltage converter	0.003			
DVM	0.001			
Alignment	0.0001			
Combined standard uncertainty	0.015	0.012	0.012	0.014
Expanded uncertainty (*k* = 2)	0.030	0.024	0.024	0.028

7.2. Uncertainty in measurements with trap detectors

The uncertainty components in measurements with the trap detectors are summarised in Table 7.

Table 7. Typical uncertainty budget [%] of a detector calibration against a trap detector as a function of wavelength [nm].

Source \ Wavelength	290	300	315	330	350	380	440	500	570	600	700	800	900
Trap calibration with PQED or Cryo	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015
Trap reflectance modelling	0.00	0.00	0.00	0.00	0.00	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Trap IQE modelling	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Trap nonlinearity	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Trap spatial uniformity	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01
Spectral flatness of pyro	0.50	0.50	0.30	0.30	0.30	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Repeatability of pyro measurements	0.4	0.4	0.4	0.4	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Photocurrent measurement	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Sum of squares	0.64	0.64	0.50	0.50	0.50	0.27	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Expanded uncertainty (*k*=2)	1.3	1.3	1.0	1.0	1.0	0.5	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Uncertainty in customer measurement with a trap detector (typical values)													
Source \ Wavelength	290	300	315	330	350	380	440	500	570	600	700	800	900
Trap model	0.64	0.64	0.50	0.50	0.50	0.27	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Ageing of trap	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Resolution of customer meter	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Spatial uniformity of customer meter	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Repeatabilityof calibration	0.2	0.2	0.2	0.2	0.2	0.1	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Sum of squares	0.71	0.71	0.59	0.59	0.59	0.37	0.26	0.26	0.26	0.26	0.26	0.26	0.26
Expanded uncertainty (*k*=2)	1.4	1.4	1.2	1.2	1.2	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Explanation of the various components may be found in [11].

This example shows the various components that need to be taken into account in measurements at different wavelengths. If measurements are made with lasers that have also been used in the calibration of the trap detector, then components related with modelling are not taken into account. Components "Repeatability of calibration," "Spatial uniformity," and "Resolution" depend on the meter to be calibrated.

7.3. Uncertainty in measurements with pyroelectric radiometer

The uncertainty components in measurements with the RK-5700 pyroelectric radiometer are summarised in Table 8. The uncertainty has been calculated for calibration of a power meter using a 10 mW laser at 932 nm wavelength.

Table 8. Typical uncertainty budget of a calibration with the pyroelectric radiometer Rk-5700.

Source	**Uncertainty**
Calibration of the pyroelectric radiometer	0.5 %
Linearity	0.6 %
Spectral flatnes	0.3 %
Resolution	0.2 %
Repeatability	0.2 %
Alignment	1.5 %
Combined standard uncertainty	1.7 %
Expanded uncertainty (*k*=2)	3.5 %

Value for the uncertainty component due to the calibration of the pyroelectric radiometer is obtained from the calibration certificate. Linearity and spectral flatness come from the specifications of the manufacturer.

Alignment has been obtained by checking the effect of the misalignment. It may also be calculated by using the measured spatial uniformity of the pyroelectric detector.

7.4. Measurement ranges and best measurement capabilities

The expanded uncertainty of a trap detector calibrated with the cryogenic radiometer or PQED is 0.025 - 0.05 %. This uncertainty may be obtained in calibrations of perfect power meters with the gas lasers listed in Chapter 3.1 with power levels of 0.1 – 0.5 mW.

If calibrations of power meters or lasers are done at different wavelengths, then best measurement capabilities given in Table 9 apply. The upper limit for measured power is 1 mW. Above this level, trap detectors turn non-linear. The minimum measurable power is approximately 1 nW. Below this level, the uncertainty in the current measurement is

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[11] T. Kübarsepp, P. Kärhä, F. Manoochehri, S. Nevas, L. Ylianttila, and E. Ikonen, "Spectral irradiance measurements of tungsten lamps with filter radiometers in the spectral range 290 nm to 900 nm," Metrologia 37, 305-312 (2000).

too large. When measuring low power levels, the uncertainty of current measurement in the given table should be increased.

Table 9. Best measurement capabilities with the trap detectors [%]. Values have been calculated for 3 different wavelength regions. At short wavelengths the uncertainty is dominated by the reference pyroelectric radiometer. It is assumed that pyroelectric radiometer Rk-5900 is used as reference.

Source \ Wavelength	**250 - 300 nm**	**300 - 380 nm**	**380 - 900 nm**
Calibration with PQED or Cryo	0.015	0.015	0.015
Reflectance modelling	0.00	0.00	0.02
IQE modelling	0.0	0.0	0.1
Spectral flatness of pyro	0.50	0.30	0.00
Repeatability of pyro measurements	0.1	0.1	0.0
Interpolation	0.3	0.3	0.0
Current measurement	0.01	0.01	0.01
Nonlinearity	0.01	0.01	0.01
Combined standard uncertainty	0.59	0.44	0.06
Expanded uncertainty (*k*=2)	1.18	0.87	0.12

Best measurement capabilities for the pyroelectric radiometers are given in Table 10 and Table 11. The uncertainty estimation has been divided into several power and wavelength regions because of variations in linearity and spectral flatness.

Table 10. Best measurement capabilities with the Rk-5700 pyroelectric radiometer.

Pyroelectric radiometer Rk-5700 with detector RkP-575					
Source \ Wavelength	250 - 300 nm	300 - 400 nm	400 - 900 nm	900 - 1000 nm	900 - 1700 nm
Calibration of pyro	0.50%	0.50%	0.50%	0.50%	0.50%
Spectral flatnes	0.58%	0.58%	0.29%	0.29%	0.29%
Spatial uniformity	2.00%	1.50%	1.50%	1.50%	1.50%
Power level 10 uW - 100 uW					
Linearity and noise	1.00%	1.00%	1.00%	1.00%	1.00%
Combined standard uncertainty	2.36%	1.96%	1.89%	1.89%	1.89%
Expanded uncertainty (*k*=2)	4.73%	3.92%	3.79%	3.79%	3.79%
Power level 100 uW - 1 mW					
Linearity	0.29%	0.29%	0.29%	0.29%	0.29%
Combined standard uncertainty	2.16%	1.71%	1.63%	1.63%	1.63%
Expanded uncertainty (*k*=2)	4.32%	3.42%	3.27%	3.27%	3.27%
Power level 1 mW - 2 W					
Linearity	0.58%	0.58%	0.58%	0.58%	0.58%
Combined standard uncertainty	2.22%	1.78%	1.71%	1.71%	1.71%
Expanded uncertainty (*k*=2)	4.43%	3.56%	3.42%	3.42%	3.42%
Power level 2 W - 10 W					
Linearity	1.44%	1.44%	1.44%	1.44%	1.44%
Combined standard uncertainty	2.58%	2.22%	2.16%	2.16%	2.16%
Expanded uncertainty (*k*=2)	5.16%	4.43%	4.32%	4.32%	4.32%
Evidence	(none)	CCPR-K2.b	CCPR-K2.b	CCPR-K2.b	CCPR-K2.a
Level of equivalence	-	1.70%	0.50%	0.70%	3.50%
CMC uncertainty (100 mW - 1 W)	-	4.00%	4.00%	4.00%	4.00%

Table 11. Best measurement capabilities with the RS-5900 pyroelectric radiometer.

Pyroelectric radiometer RS-5900					
Source \ Wavelength	250 - 300 nm	300 - 400 nm	400 - 900 nm	900 - 1000 nm	900 - 1700 nm
Calibration of pyro	0.40%	0.40%	0.40%	0.40%	0.40%
Spectral flatnes	0.50%	0.50%	0.50%	0.50%	0.50%
Spatial uniformity	0.58%	0.58%	0.58%	0.58%	0.58%
Power level 10 uW - 100 uW					
Linearity and noise	1.00%	1.00%	1.00%	1.00%	1.00%
Combined standard uncertainty	1.32%	1.32%	1.32%	1.32%	1.32%
Expanded uncertainty (*k*=2)	2.64%	2.64%	2.64%	2.64%	2.64%
Power level 100 uW - 1 mW					
Linearity	0.10%	0.10%	0.10%	0.10%	0.10%
Combined standard uncertainty	0.87%	0.87%	0.87%	0.87%	0.87%
Expanded uncertainty (*k*=2)	1.74%	1.74%	1.74%	1.74%	1.74%
Power level 1 mW - 100 mW					
Linearity	0.10%	0.10%	0.10%	0.10%	0.10%
Combined standard uncertainty	0.87%	0.87%	0.87%	0.87%	0.87%
Expanded uncertainty (*k*=2)	1.74%	1.74%	1.74%	1.74%	1.74%
Evidence	(none)	CCPR-K2.b	CCPR-K2.b	CCPR-K2.b	CCPR-K2.a
Level of equivalence	-	1.70%	0.50%	0.70%	3.50%
CMC uncertainty (10 uW - 100 uW)	-	3.00%	3.00%	3.00%	3.00%
CMC uncertainty (100 uW - 100 mW)	-	2.00%	2.00%	2.00%	2.00%

8. Accommodation and environmental conditions

Measurements are usually done in the Laser laboratory that is located in room 1569 in the basement of the School of Electrical Engineering (TUAS). This laboratory is kept as clean as possible.

During optical power calibrations:

- The Clean Zone -aggregate should be on to prevent dust contamination.
- Temperature should be monitored (/controlled).
- Humidity should be monitored (/controlled).

Humidity and temperature values during the calibrations are written to calibration certificates.

9. Field calibrations

Measurements can be done in the customer laboratories. This typically concerns calibration of the customers’ power meter using customer’s laser which is impractical to transfer. Equipment described in Table 1 (suitable parts) is carried to the customer laboratory.

It should be ensured that the cleanliness of the customer laboratory is sufficient for the calibrations. Suitability of the customer equipment for the calibration required (e.g. stability and wavelength of the laser) should be verified.

Customer equipment may be used to monitor the environmental conditions during the calibration.

Care should be taken when preparing the calibration certificate. It should be clearly identified which of the devices used were customers devices. Methods used should be written down clearly so that the same measurements can be repeated in future.

10. Control data

The measurement data of calibrations, analysis of results, and development of equipment are archived.

Electrical data of all personnel are stored in:

\\work.org.aalto.fi\T405\MIKES-Aalto\Users\##Name##\Calibrations\

This directory is backed up by Aalto IT, is accessible to whole laboratory personnel, and remains after the person leaves the institute. Directories of people who left are stored in:

\\work.org.aalto.fi\T405\MIKES-Aalto\Users\Z Old personnel\

Measurements done by Petri Kärhä are written in a chronological order to a black notebook labelled *Detector calibrations and measurements*.

Stability of the calibrated trap detectors is monitored. This data is stored in calibration certificates, which are archived. Summary of the calibrations is maintained as described in Chapter 3.1.

11. Certificates

Calibration certificates are handled according to [12]. Include the following information to the calibration certificate:

- Equipment used and their traceability
- Description of the measurement setup and method
- Ambient temperature and relative humidity
- Spectral responsivity values [A/W] and/or correction factors at the measured wavelengths
- Diameter of the beam
- Beam alignment
- Power level
- Wavelength

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[12] Instructions on writing calibration certificates, MRI document.

12. Intercomparisons

Comparison measurements performed with the cryogenic absolute radiometer are reported in References [13] and [14].

Spectral responsivity measurements have been compared in CCPR-k1.a [15] and CCPR-k2.b [16]. Additional comparison evidence for UV region was obtained in the EU-project SMT4-CT98-2242 “Improving the Accuracy of Ultraviolet Radiation Measurement.” Comparison of filter radiometer characterisations with measurements of NPL are in good agreement. Results have been reported in [17].

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[13] T. Varpula, L. Liedquist, H. Ludvigsen, H. Reyn and J. de Vreede, “Comparison of Quantum-efficient Silicon Photodetectors with a Cryogenic Absolute Radiometer at a Laser Wavelength of 543,5 nm,” *Metrologia* **28**, 349-352 (1991).

[14] A. Lassila, P. Kärhä and E. Ikonen, “Comparison of Silicon Trap Detectors with Cryogenic Absolute Radiometer,” Metrology Research Institute Report **5/94**, (1994).

[15] CCPR-K2.a Spectral responsivity (Wavelength 900 nm to 1600 nm). Draft A.

[16] CCPR-K2.b Spectral responsivity (Wavelength 300 nm to 1000 nm). Draft A.

[17] P. Kärhä, N. J. Harrison, S. Nevas, W. S. Hartree and I. Abu-Kassem, “Intercomparison of characterisation techniques of filter radiometers in the ultraviolet region,” *Metrologia* **40**, S50-S54 (2003).

13. References

This list compiles all the references in the manual.

[1] Quality Manual of Reference Spectrometer Laboratory, MRI Publication.

[2] Instruction Manual for Cryogenic Radiometer, MRI Publication.

[3] Instruction Manual for Modeling Trap Detectors, MRI Publication.

[4] N. P. Fox, "Trap Detectors and their Properties," *Metrologia* **28**, 197-202 (1991).

[5] P. Kärhä, Detector-based scales for spectral responsivity and spectral irradiance, Licentiate thesis, HUT, 1995.

[6] M. Sildoja, F. Manoocheri, M. Merimaa, E. Ikonen, I. Müller, L. Werner, J. Gran, T. Kübarsepp, M. Smîd, and M. L. Rastello, "Predictable quantum efficient detector: I. Photodiodes and predicted responsivity," Metrologia 50, 385–394 (2013).

[7] RK-5700 Series Operating Instructions, August 1, 1989, 12655 REV. C.

[8] RS-5900 Electrically Calibrated Pyroelectric Radiometer –Instruction Manual -, Rev B, January 1991.

[9] Anna Vaskuri, *Multi-wavelength setup based on laser for characterizing optical detectors and materials*, Diploma work, MRI, 8+57 p., 2014.

[10] A. Vaskuri, P. Kärhä, A. Heikkilä, and E. Ikonen, "High-resolution setup for measuring wavelength sensitivity of photoyellowing of translucent materials," *Review of Scientific Instruments* **86**, 103103-1–8 (2015).

[11] T. Kübarsepp, P. Kärhä, F. Manoochehri, S. Nevas, L. Ylianttila, and E. Ikonen, "Spectral irradiance measurements of tungsten lamps with filter radiometers in the spectral range 290 nm to 900 nm," *Metrologia* **37**, 305-312 (2000).

[12] T. Dönsberg, M. Sildoja, F. Manoocheri, M. Merimaa, L. Peteroff, and E. Ikonen, ``A primary standard of optical power based on induced-junction silicon photodiodes operated at room temperature'', *Metrologia* **51**, 197-202, 2014.

[13] Clean room instructions / Puhdastilaohjeet, MRI publication.

[14] Instructions on writing calibration certificates, MRI document.

[15] T. Varpula, L. Liedquist, H. Ludvigsen, H. Reyn and J. de Vreede, "Comparison of Quantum-efficient Silicon Photodetectors with a Cryogenic Absolute Radiometer at a Laser Wavelength of 543,5 nm," *Metrologia* **28**, 349-352 (1991).

[16] Lassila, P. Kärhä and E. Ikonen, "Comparison of Silicon Trap Detectors with Cryogenic Absolute Radiometer," Metrology Research Institute Report **5/94**, (1994).

[17] CCPR-K2.a Spectral responsivity (Wavelength 900 nm to 1600 nm). Draft A.

[18] CCPR-K2.b Spectral responsivity (Wavelength 300 nm to 1000 nm). Draft A.

[19] P. Kärhä, N. J. Harrison, S. Nevas, W. S. Hartree and I. Abu-Kassem, “Intercomparison of characterisation techniques of filter radiometers in the ultraviolet region,” *Metrologia* **40**, S50-S54 (2003).

14. Publications

Publications relevant to performing calibrations are filed with the paper copy of the Quality/Instruction Manual. This includes e.g. publications and intercomparison results.

1. T. Varpula, H. Seppä and J.-M. Saari, “Optical Power Calibrator Based on a Stabilized Green He-Ne Laser and a Cryogenic Absolute Radiometer,” *IEEE Transactions on Instrumentation and Measurements* **38,** 558-564 (1989).
2. T. Varpula, L. Liedquist, H. Ludvigsen, H. Reyn and J. de Vreede, “Comparison of Quantum-efficient Silicon Photodetectors with a Cryogenic Absolute Radiometer at a Laser Wavelength of 543,5 nm”, *Metrologia* **28**, 349-352 (1991).
3. A. Lassila, P. Kärhä and E. Ikonen, “Comparison of Silicon Trap Detectors with Cryogenic Absolute Radiometer,” *Metrology Research Institute Report* **5/94**, (1994).
4. P. Kärhä, A. Lassila, H. Ludvigsen, F. Manoochehri, H. Fagerlund and E. Ikonen, “Optical Power and Transmittance Measurements and Their Use in Realization of the Luminous Intensity Scale,” *Optical Engineering*, **34**, 2611-2618 (1995).
5. T. Kübarsepp, P. Kärhä, and E. Ikonen, “Characterization of a polarization-independent transmission trap detector,” *Appl. Opt.* **36**, 2807-2812 (1997).
6. P. Kärhä, P. Toivanen, F. Manoochehri, A. Haapalinna, and E. Ikonen, “A detector-based absolute spectral irradiance scale in the 380-900-nm spectral range,” *Appl. Opt.* **36**, 8909 - 8918 (1997).
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9. P. Toivanen, F. Manoochehri, P. Kärhä, and E. Ikonen, “Method for characterization of filter radiometers,” *Appl. Opt.* **38**, 1709-1713 (1999).
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12. T. Kübarsepp, P. Kärhä, F. Manoochehri, S. Nevas, L. Ylianttila, and E. Ikonen, “Spectral irradiance measurements of tungsten lamps with filter radiometers in the spectral range 290 nm to 900 nm,” *Metrologia* **37**, 305-312 (2000).
13. P. Kärhä, Detector-based scales for spectral responsivity and spectral irradiance, Lisentiate thesis, HUT, Espoo, 1995, 80 p.

14. P. Kärhä, Trap detectors and their applications in the realisation of spectral responsivity, luminous intensity and spectral irradiance scales, Thesis for the degree of Doctor of Technology, HUT, Espoo, 1997, 92 p.
15. T. Kübarsepp, *Optical radiometry using silicon photodetectors*, Thesis for the degree of Doctor of Technology, HUT, Espoo, 1999, 37 p.
16. P. Toivanen, *Detector based realisation of units of photometric and radiometric quantities*, Thesis for the degree of Doctor of Technology, HUT, Espoo, 2000, 39 p.
17. A. Lassila, *National standards for dimensional and optical quantities*, Thesis for the degree of Doctor of Technology, J10/1997, MIKES, Helsinki, 1997, 36 p.
18. P. Kärhä, N. Harrison, S. Nevas and I. Abu-Kassem, Report on the filter radiometer measurements in Work Package 1, Report to EU Commission, February 2001.
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20. CCPR-K2.a Spectral responsivity (Wavelength 900 nm to 1600 nm). Draft A.
21. CCPR-K2.b Spectral responsivity (Wavelength 300 nm to 1000 nm). Draft A.
22. M. Sildoja, *Predictable Quantum Efficient Detector*, Thesis for the degree of Doctor of Technology, Aalto 199/2013, Helsinki, 2013, 47 p.
23. Hans Baumgartner, Metrology for III-V Optosemiconductors, Thesis for the degree of Doctor of Technology, Aalto University School of Electrical Engineering, Espoo, 2017, 90 p.
24. Anna Vaskuri, Spectral Modelling of Light-Emitting Diodes and Atmospheric Ozone Absorption, Thesis for the degree of Doctor of Technology, Aalto University, Espoo, 2018, 158 p.