Aalto University
School of Electrical Engineering
Metrology Research Institute

Farshid Manoocheri
Saulius Nevas

Quality Manual for
Spectral Responsivity Calibrations

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2. Definition

2.1. Scope

This quality manual describes the use of Reference spectrometer and of transfer standard detectors for absolute spectral responsivity calibrations of optical detectors. Transfer standard detectors are calibrated with (or traceable to) the cryogenic radiometer with lasers. Modelling or spectral flatness are used to extrapolate the wavelength regions in the ultraviolet (UV), visible (VIS), and near-infrared (NIR) from 220 nm to 1800 nm.

Spectral responsivity measurements using the laser light sources are described elsewhere.*

2.2. Object and field of application

Pyroelectric radiometer: Thermal, spectrally flat detector used in UV, VIS and NIR regions. The operational wavelength region is 200 nm – 16 µm and the highest measurable power is 1 W.

Broad band detectors: Silicon photodiodes and multi-element detectors (trap detectors) for both radiometric and photometric measurements of optical power at wavelengths between 220 nm and 1050 nm. Some traps have also been calibrated with the pyroelectric radiometer for the wavelength region 220 nm – 950 nm. The maximum measurable power level is ~10 µW.

Broad band NIR detectors: Indium Gallium Arsenide (InGaAs), Germanium (Ge) photodiodes and detectors (including a preamplifier) used for radiometric measurements of optical power at wavelengths between 820 nm and 1800 nm.

Narrow band filter radiometers: Detectors made of a combination of diffuser-aperture, a narrow or bandpass filter, and a photodiode are used in radiometry. Such filter radiometers are typically used to determine the irradiance of a light source with in a specific wavelength band.

2.3. Features

The configuration of the reference spectrometer for measurements of the spectral responsivity includes the following features:

a) Automated instrument allowing simultaneous measurement of the response of the reference detector and a test detector in a wide range of wavelength settings

b) Reflecting optics

* Quality Manual of Optical Power Laboratory, MRI Publication.

c) Collimated single-beam design allowing the determination of various uncertainty components

d) Trap detectors with low back reflection and predictable spectral responsivity are used as transfer standard and reference detectors

2.4. Spectral responsivity of transfer standard detectors

Spectral responsivity in UV and visible

Trap detectors are used as transfer standard and reference detectors built at MRI. The detectors consist of three windowless silicon photodiodes. In principle, photons that are absorbed in silicon each create one electron-hole pair that can be measured in the external circuit as a photocurrent. The spectral responsivity R(λ) of the trap detector is

$$R(\lambda) = [1-\rho(\lambda)]\,[1-\delta(\lambda)]\,\frac{e\,\lambda}{h\,c}, \qquad (1.10)$$

where e is the elementary charge, λ is the wavelength in vacuum, h is the Planck constant, c is the speed of light in vacuum, $\rho(\lambda)$ is the reflectance of the detector, and $\delta(\lambda)$ is the internal quantum deficiency of the photodiodes. This deficiency is caused mainly because of trapped charge under the silicon dioxide coating of the photodiodes [†].

The spectral responsivity scale in the visible region has been realised by characterisation of trap detectors. The method is based on the measurements of absolute responsivity and reflectance of the detectors at several discrete wavelengths. The cryogenic radiometer and an auxiliary trap detector are used for the absolute responsivity and reflectance measurements, respectively. The obtained internal quantum deficiency and reflectance values of the trap detectors are extrapolated to predict the absolute spectral responsivity in the range 380 - 920 nm by using mathematical models.

The responsivity of trap detectors can not be extrapolated to UV wavelengths with comparable uncertainty as described above. Therefore, the spectral responsivity scale at wavelengths between 240 nm and 380 nm is derived by employing a pyroelectric radiometer with spectrally flat responsivity over a wide wavelength range (0.25-16 µm, see Table 1). The scale is, however, transferred to trap detectors because of their compactness, higher sensitivity, uniform spatial responsivity, superior linearity, and ease of operation.

Spectral responsivity of reference detectors in NIR

Employing the pyroelectric radiometer in a similar manner as is done for the UV region allows us to derive the spectral responsivity scale at NIR wavelengths between 0.8 µm and 1.8 µm. In this case the measurements are made in conjunction with the reference

[†] P. Kärhä, Trap detectors and their applications in the realisation of spectral responsivity, luminous intensity, and spectral irradiance, Thesis for the degree of Doctor of Technology, (Helsinki University of Technology, Metrology Research Institute, Espoo, Finland 1997) 92 p.

spectrometer. The absolute responsivity of the pyroelectric radiometer is calibrated using a reference trap detector at wavelengths between 0.8 µm and 0.92 µm. The Ge and InGaAs detectors are then calibrated with the pyroelectric radiometer at wavelengths between 0.8 µm and 1.8 µm. The Ge and InGaAs detectors are also compared with each other to confirm the results.

Spectral responsivity of detectors to be measured

Usually the detector to be calibrated is also a silicon-photodiode based detector whose responsivity is different because of material of the window or coatings on the active area of the diode. Others may include electronic amplification and reading instruments so that the output voltage signal or display reading should be calibrated.

3. Equipment

3.1. Description of setups

The configuration of the reference spectrometer for spectral responsivity measurements is shown in Figure 1. Equipment needed for the calibrations is presented in Table 1. The equipment required for use and calibration of wavelength scale that is the same for all measurement set-ups of reference spectrometer is given in a separate document.[‡] For measurements in which movement of the detectors is not possible, the setup shown in Figure 2 is employed. We perform the measurements in two scans to cancel the effects of the beam splitter.

Table 1. Equipment for spectral responsivity calibrations.

Description	Quantity	Identification
A. Reference spectrometer		
B. Reference detector	1	
1. Trap detector	2	MRI-9911, MRI-9806
2. InGaAs photodiode	2	HUTIGA-1, -2
3. Pyroelectric detector	1	RS-5900
4. Pyroelectric radiometer		Rk-5720-RkP575
C. AR coated Achromatic lens		
1. UV, f=250 mm	1	
2. VIS, f=50 mm, f=250 mm	2	
3. NIR, f=50 mm, f=250 mm	2	
D. Linear translator stage		Physik-Instrumente
1. Rail components.	3	
E. Iris, limiting apertures, stands, and holders	1 x	(built at MRI)
F. Alignment system		
1. Alignment laser	1	OMTec
G. Control and data acquisition		
1. Computer	1	PC (Mxxx)
2. Current-to-voltage converter	2	Vinculum SP042 (SR570)

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

3.	Digital voltmeter	2	HP 3458A (34410A)
4.	Computer programme	1	metrolog.pas (exe)

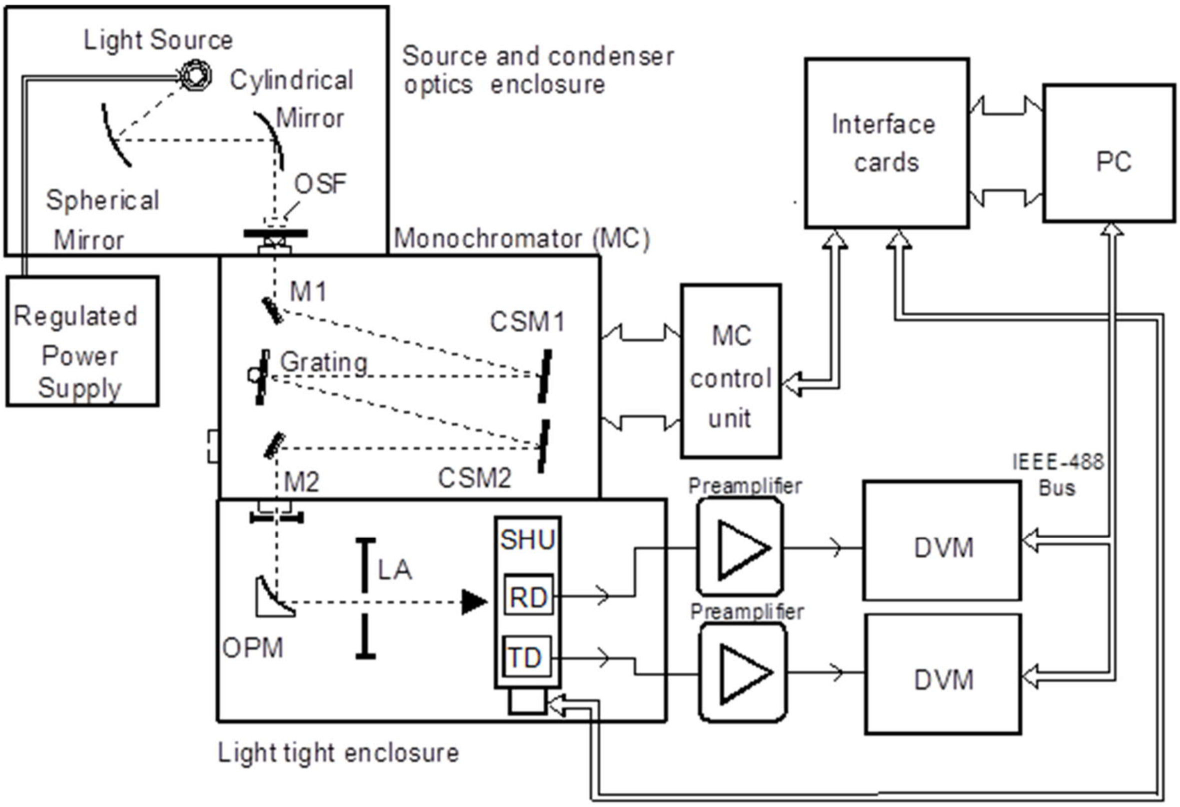

Figure 1. Schematic for the spectrometer configuration in spectral responsivity measurements. OSF, order-sorting filter; CSM1, CSM2, collimating spherical mirrors; M1, M2, flat mirrors; LA, limiting aperture; OPM, off-axis parabolic mirror; SHU, detector-holder unit; RD and TD, reference and test detectors; DVM, digital multimeters.

3.2. Calibration requirements

3.2.1. Maintenance of the equipment

- The multimeters are "Autocalibrated" every time before the start of the calibration measurements. Calibration of the multimeters is performed according to the calibration schedule of Calsched.
- The current to voltage converters are calibrated according to the calibration schedule of Calsched.

- The time since last calibration for reference (trap) detectors used for calibrations should not exceed two years. This applies also to absolute responsivity measurements with cryogenic radiometer, reflectance measurements, and responsivity extrapolations.§
- The pyroelectric radiometer is calibrated once a year. Due to its spectral flatness, the calibration only needs to be done at one visible wavelength.
- Before calibration it is visually checked that there is no dust inside the trap detector. If there is visible dust, it may be carefully cleaned from the first photodiode with Kodak lens cleaning tissue. The two inner diodes cannot be cleaned. Air should not be used for cleaning, because the dust may end up on the inner diodes.
- Other equipment is calibrated according to the Calsched calibration schedule.

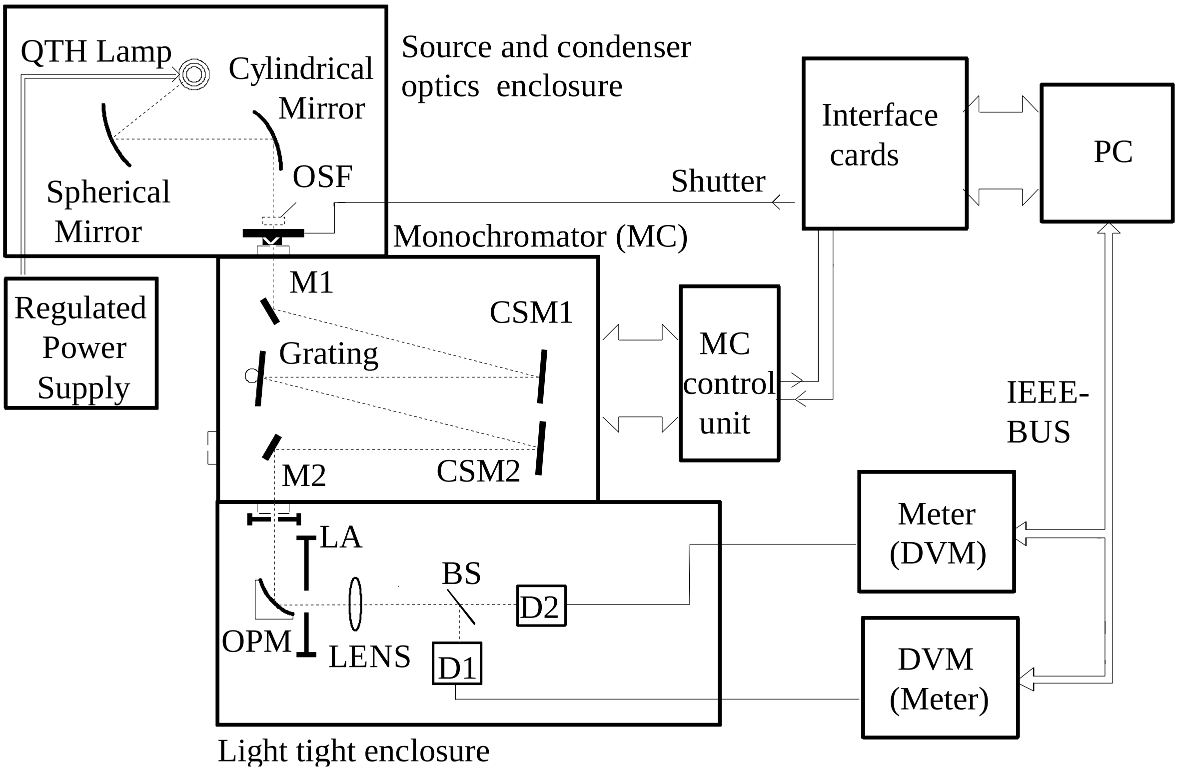

Figure 2. Schematic of the spectrometer configuration for spectral responsivity measurements when movements of detectors are difficult. OSF, order-sorting filter; CSM1, CSM2, collimating spherical mirrors; M1, M2, flat mirrors; LA, limiting apertures; OPM, off-axis parabolic mirror; BS, beam splitter; D1 and D2, reference and sample detectors at measurement positions 1 and 2; DVM, digital multimeter.

§ Instruction Manual for Cryogenic Radiometer, MRI Publication.

3.2.2. Responsible Persons

Branch manager and deputy are defined in the Quality Management System. Persons authorised to do calibrations are defined in Annex A.

4. Measurement traceability

Traceability of responsivity measurements

The calibration of a detector measured for spectral responsivity is traceable to the absolute cryogenic radiometer using calibrated reference detectors as secondary transfer standards.* Figure 3 shows the traceability chain for calibration measurements of spectral responsivity.

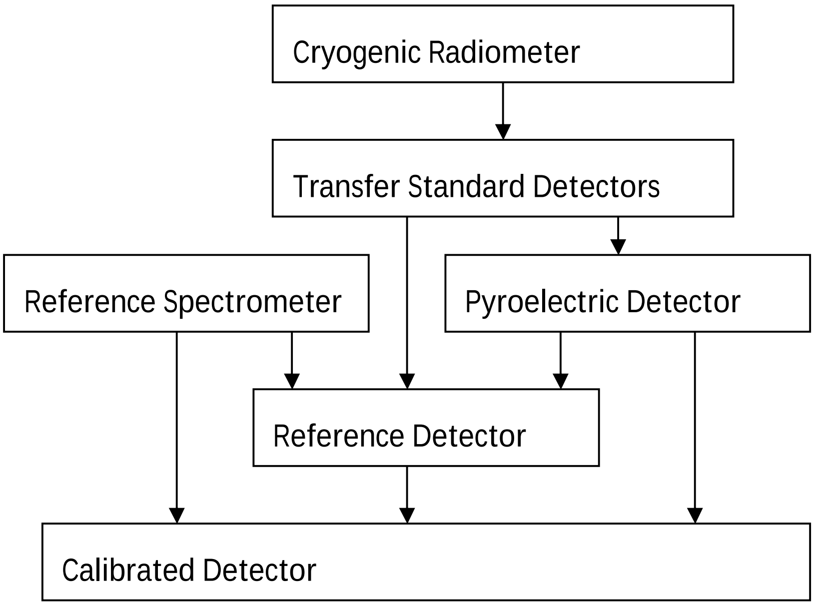

Figure 3. Traceability chain of detector calibrations for spectral responsivity.

5. Calibration and measurement procedures including validation methods

5.1. Calibration methods and procedures for spectral responsivity

The spectral responsivity measurements for the wavelengths from 240 to 1700 nm are performed using the single-beam reference spectrometer. A three-element reflection trap detector a temperature-stabilised 5-mm diameter InGaAs-photodiode and a Ge detector (serve as the reference detectors for measurements within the spectral range of 240-950 nm, 940-1600 nm and 800-1800 nm wavelengths, respectively.

The reference detector and the test detector are interchangeably placed in the beam and the responses are measured at each wavelength. After subtraction of the dark signal from reading, the ratio of the test detector response to that of the reference detector is calculated. The known spectral responsivity of the reference detector is finally used to determine the spectral responsivity of the test detector. A detailed description of the measurements and uncertainty analysis is given in the publication [6] listed at the end of this document.

5.2. Automation software

In order to control the related operations of the instruments a computer program package has been developed (see also publication [**]). The program, "RefSpecV3", is a menu-driven PC program written in LabView. The program controls the operation of each automated device of the spectrometer not only during the transmittance measurement procedures but also whenever their action is required. The DVMs are controlled via a GPIB-488 controller card. The monochromator, and the filter wheel unit are automated with separate interface cards via a parallel printer port. The linear translator stage used as the detector-holder is automated via a controller-driver card.

The main command menu of the program offers choices of measurement procedures. The program allows a choice of the position of detectors and wavelength scans at equally spaced intervals or arbitrary specific wavelengths. The results of the responsivity measurements are saved in a file that can be monitored by a program menu command after the measurements are done. Detailed information on the instrument automation is available in [**].

[**] F. Manoocheri, Operating Instructions for Reference Spectrometer, ''a short note on steps to be taken for spectral transmittance measurements'', Quality Manual of Metrology Research Institute, (1994).

6. Handling of calibration items

All items are handled with care and stored in locked rooms/laboratories.

Upon arrival, items are checked visually to note possible damage in the transport. Before calibration, operation of the items is tested.

If a defect in an item is noted, the item is not repaired without notifying the customer. This applies to cleaning or service of items as well.

Some calibration items, e.g. delicate optics such as diffuse reflectance standards, may require special handling procedures. If such requirements exist, they should be defined in the Quality or Instruction manuals.

7. Uncertainty budgets

7.1. Uncertainty components of responsivity measurements

The uncertainty budget for the spectral responsivity measurements is presented in Table 2 for UV, visible and NIR at wavelength of 300 nm, 600 nm, and 1500 nm, respectively. The wavelength-dependent expanded uncertainty is presented graphically in Figure 4. The uncertainty components induced by the detector to be calibrated are included in the budget for a typical high quality photodiode. Other detector related uncertainty components should be taken into account separately. The uncertainty in responsivity of the reference detectors is due to the procedure used in transferring the scales from the primary detectors. The component due to temperature is caused by a maximum variation of 1°C in the temperature of the output optics compartment of the spectrometer and the temperature coefficient of the detector.

The linearity of the detectors has been measured to be satisfactory within the working power range (0.01-20 µW) with the given standard uncertainty [††]. The component due to the spatial nonuniformity of the detector responsivity is based on the results of relevant measurements of beam nonuniformity and for an uncertainty of 1 mm in centring of the detector in the measurement beam [‡‡,§§]. At NIR wavelengths, the InGaAs reference detector is usually used in with an antireflection coated acromatic lens or in combination with an averaging sphere with a nonuniformity of 0.04% mm^{-1}. The effect is taken into account when bare Ge or InGaAs detectors must be used. The components induced by the reference spectrometer are obtained from the characterisation measurements of the instrument and are given elsewhere.‡

Table 2. Relative Uncertainty Components of Spectral Responsivity Measurements.

		Standard uncertainty (%)		
	Component \ Wavelength	UV	Visible	NIR
	Transfer standard detector	Pyroelectric	Si trap	Pyroelectric
1.	Primary reference	---	0.03	---
2.	Reflectance modeling	---	0.04	
3.	IQE modelling		0.05	
4.	Spectral flatness of Pyro	0.5	---	0.5

[††] T. Kübarsepp, A. Haapalinna, P. Kärhä, and E. Ikonen, "Nonlinearity measurements of silicon photodetectors," Appl. Opt. 37, 2716-2722 (1998).

[‡‡] K. D. Stock, R. Heine, and H. Hofer "Influence of inhomogeneity of NIR-photodiodes on calibrations at 1047 nm," Metrologia 28, 207-210 (1991)

[§§] F. Manoochehri, "High-Accuracy Spectrometer for Applications in Photometry and Radiometry", Doctors thesis, Helsinki University of Technology, 115 p. (1998).

5.	Spatial nonuniformity	0.4	0.01	0.5
6.	Range correction	0.4	---	0.3
7.	AC to DC conversion	0.3		0.3
8.	(a) Root of sum of squares	0.81	0.07	0.82
	Reference detector	Si trap	Si trap	InGaAs
9.	Repeatability	0.2	0.05	0.23
10.	Temperature	0.1	0.01	0.12
11.	Linearity	0.05	0.02	0.05
12.	Spatial nonuniformity	0.04	0.01	0.14
	Reference spectrometer			
13.	Stray light	0.08	0.02	0.03
14.	Beam displacement	0.09	0.04	0.04
15.	Wavelength scale	0.03	0.02	0.05
16.	Interreflections	0.04	0.01	0.15
17.	Current-to-voltage-conversion	0.08	0.04	0.04
18.	Polarisation	0.02	0.01	0.05
19.	(b) Root of sum of squares	0.28	0.09	0.35
	Calibration of single photodiodes	Silicon	Silicon	Germanium
20.	Repeatability	0.2	0.08	0.09
21.	Temperature	0.05	0.01	0.12
22.	Linearity	0.04	0.02	0.05
23.	Beam displacement	0.09	0.09	0.09
24.	Interreflections	0.08	0.01	0.15
25.	Current-to-voltage-conversion	0.08	0.04	0.04
26.	(c) Root of sum of squares	0.25	0.13	0.24
27.	Expanded uncertainty (k=2)	1.79	0.35	1.85

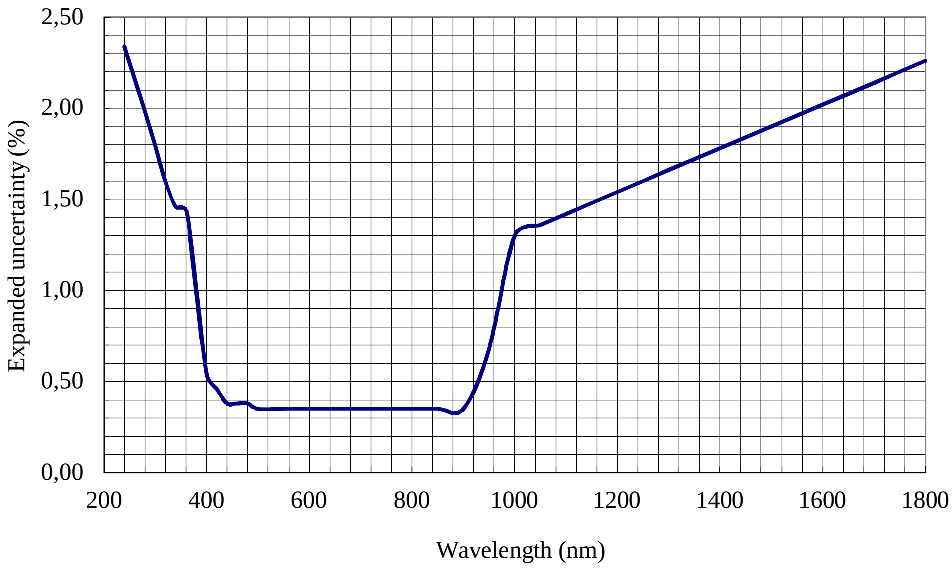

Figure 4. Expanded uncertainty in calibration of a high quality photodiode in UV, visible and NIR wavelength regions.

7.2. Measurement ranges and best measurement capabilities

The best measurement capability of the reference spectrometer for spectral responsivity has been calculated in Table 2. The expanded uncertainty of a reference trap detector calibrated with the reference spectrometer is 0.22 %. This uncertainty may be obtained in calibrations of detectors with dynamic impedance of greater than 10kΩ. This is due to the use of amplifier gain of greater than 10^6 for a beam size of 3 mm.

The translation stages and the size of the enclosure of reference spectrometer limit the weight and physical size of detectors to be calibrated. Detector packages are limited with size and weight of 150 mm by 150 mm and 5 kg.

8. Accommodation and environmental conditions

The conditions of the environment are explained in the Quality Manual of Reference Spectrometer Laboratory.

9. Field calibrations

Not applicable.

10. Control data

The measurement data coming from calibrations or development of equipment is archived. The measurement notes (date, set up, raw data) are written down and the analysed measurement data is stored in chronological order. The related computer data files are also stored in the shelves of the responsible persons. The records are arranged in the following manner:

- Regular measurement records are kept in folders under the title of the spectral region (UV, VIS, NIR) in which the measurements are done. International comparison records are kept in files and disks.
- Calibration records are kept in files and disks under the title of ''Spectral responsivity calibrations and certificates''.

Maintenance records of the equipment are written in a chronological order to a notebook labelled "Calibrations and measurements with reference spectrometer" and it is kept in the Reference spectrometer laboratory.

11. Certificates

Calibration certificates are handled according to publication in Annex C of quality system.*** In brief, each calibration has a certificate with a unique running number as in the following pattern; T-R 1, T-R 2, T-R 3, etc. It includes the method of calibration, traceability, uncertainty, measurements, and results. The calibration certificates are stored at the archive of the Metrology Research Institute.

*** Instructions on writing calibration certificates, MRI document.

12. Intercomparisons

CCPR-K2.a International comparison of spectral responsivity in the wavelength region 900 nm to 1600 nm

The measurements for this key comparison were carried out by HUT in 1999. The results indicate a good agreement for HUT within uncertainties.

CCPR-K2.b International comparison of spectral responsivity in the visible region

The key comparison is on spectral responsivity measurements of trap detectors and photodiodes in the wavelength region from 300 nm to 1000 nm. The measurements for this comparison were carried out by HUT in 2000. The results indicate a good agreement for HUT within uncertainties [†††].

CCPR K2.c key comparison of spectral power responsivity of detectors in the ultraviolet spectral range from 200 nm to 400 nm

The measurements for this comparison were carried out by HUT in 2005 [Certificate of Calibration T-R 383]. The results indicate a good agreement for HUT within uncertainties [7].

[†††] R Goebel and M Stock, “Report on the comparison CCPR-K2.b of spectral responsivity measurements in the range 300 nm to 1000 nm,” Metrologia 41 (2004).

13. Publications

1. P. Kärhä, Trap detectors and their applications in the realisation of spectral responsivity, luminous intensity, and spectral irradiance, Thesis for the degree of Doctor of Technology, (Helsinki University of Technology, Metrology Research Institute, Espoo, Finland 1997) 92 p.
2. F. Manoocheri, Operating Instructions for Reference Spectrometer, ''a short note on steps to be taken for spectral transmittance measurements'', Quality Manual of Metrology Research Institute, (1994).
3. T. Kübarsepp, A. Haapalinna, P. Kärhä, and E. Ikonen, "Nonlinearity measurements of silicon photodetectors," Appl. Opt. 37, 2716-2722 (1998).
4. K. D. Stock, R. Heine, and H. Hofer "Influence of inhomogeneity of NIR-photodiodes on calibrations at 1047 nm," Metrologia 28, 207-210 (1991)
5. F. Manoochehri, "High-Accuracy Spectrometer for Applications in Photometry and Radiometry", Doctors thesis, Helsinki University of Technology, 115 p. (1998).
6. R Goebel and M Stock, "Report on the comparison CCPR-K2.b of spectral responsivity measurements in the range 300 nm to 1000 nm," Metrologia 41 (2004)
7. Lutz Werner, "Final report on the key comparison CCPR-K2.c-2003: Spectral responsivity in the range of 200 nm to 400 nm," Metrologia, 51 (2014)

Other related publications

8. F. Manoocheri, P. Kärhä, L. Palva, P. Toivanen, A. Haapalinna and E. Ikonen, "Characterization of optical detectors using high-accuracy instruments", Analytica Chimica Acta 380, pp. 327-337(1999).
9. Instruction Manual for Modelling Trap Detectors, MRI Publication.