Aalto University

School of Electrical Engineering

Metrology Research Institute

Petri Kärhä

Jari Hovila

Maksim Shpak

Tuomas Poikonen

Hans Baumgartner

Iikka Huttu

Quality Manual of Spectral Irradiance Measurements

Version 2.6

14/1/2021

1. Table of contents

2.   Definition

2.1.   Scope

This quality manual describes the principle and operation of the equipment used for spectral irradiance measurements. Procedures are defined to calibrate primary standard lamps of spectral irradiance using a filter radiometer. Operation and calibration of secondary spectroradiometers are described in their own Instruction Manuals. Procedures are given to calculate colour coordinates (*x*,*y*) and correlated color temperature *Tc*. Calibrations can be performed on DXW and FEL lamps, and occasionally on Wi41/G lamps.

2.2.   Object and field of application

Filter radiometer: Primary standard for spectral irradiance measurements. Used for calibrating primary standard lamps.

Spectroradiometer: Secondary transfer standard calibrated with the primary standard lamps and thereafter used for calibrating light sources of customers.

2.3.   Features

a) Filter radiometer

The filter radiometer consists of a trap detector, a set of optical band-pass filters, a copper oven for temperature stabilisation of the filters, and a precision aperture. All of the components form a compact and robust filter radiometer. One filter at a time can be used. Change of the filter has been made straightforward and reliable. The filter radiometer can be used to calibrate a primary standard lamp of spectral irradiance in the wavelength region from 290 nm to 900 nm, with an uncertainty between 2.6 % and 0.7 %. Using the filters, 14 discrete spectral irradiance values may be obtained. These values may be interpolated to give a continuous spectrum throughout the region. Measurement of a lamp using all the filters takes approximately 2 hours, excluding the time needed for alignment.

b) The spectroradiometer

Six spectroradiometers are available for customer calibrations. All spectroradiometers are mostly automated, computer controlled, and convenient to use. They are calibrated with a primary standard lamp measured with the filter radiometer.

The BENTHAM DM150 spectroradiometer can be used in low-accuracy measurements between 200 nm and 845 nm wavelengths. A lamp measurement with 1 nm intervals takes about 15 minutes. The results need to be corrected for temperature. At present (Nov 2018) this device is inoperable.

The BENTHAM DTMc300 spectroradiometer can be used in higher-accuracy measurements over wide wavelength region between 250 nm and 2500 nm wavelengths. A typical lamp measurement over whole region takes about 30 minutes. The two detectors of the spectroradiometer are temperature stabilised.

Konica Minolta CS1000 and *CS2000* are imaging spectroradiometers capable of measuring luminance and spectral radiance. They can be equipped with a diffuser to facilitate spectral irradiance measurement. The wavelength regions are 380 – 780 nm. These devices are used for color temperature adjustments and radiance measurements.

Ocean Optics QE65 Pro is an array spectrograph capable for fast spectral irradiance measurements in the wavelength region 200 – 1100 nm. This device is not to be used in calibration work.

Instrument Systems Spectro320D is a scanning spectroradiometer operating over wavelength region 250 – 2300 nm. Scanning a lamp for the whole region takes approximately 20 min.

2.4. Principle of realisation

The principle of the realisation of the spectral irradiance scale has been explained thoroughly in Refs. [1, 2, 3]. Therefore, only a brief description is given here.

The realisation is based on a known detector instead of the traditional method of using a known source. A simplified measurement setup is shown in Figure 1. A detector with known spectral responsivity is equipped with a narrow band optical filter with measured spectral transmittance. The field of view is limited using a precision aperture with accurately known area at a measured distance *d* from the lamp. By using several interchangeable filters, the spectral irradiance of the lamp may be derived at several discrete wavelengths. These discrete values may be interpolated using suitable physical models.
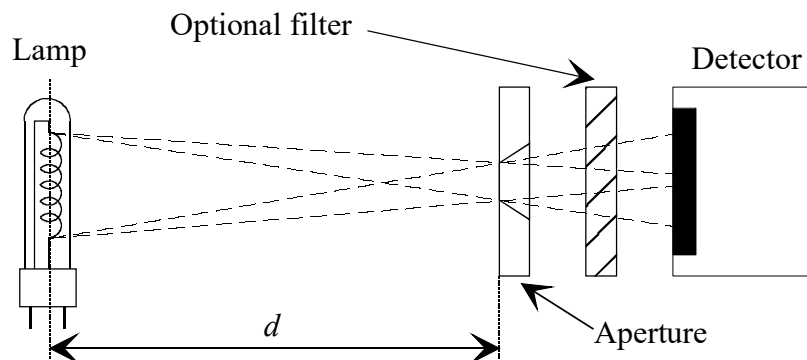
Figure 1. Principle of detector-based realisation of spectral irradiance.

In practice, the aperture, the detector and the interchangeable filters have been combined as a practical filter radiometer. The mechanical construction of the filter radiometer is presented in Figure 2. The temperature of the filters is stabilised using a copper oven whose temperature is measured by a temperature sensor and adjusted by a circular see-through Peltier element. Details about the construction and its' performance may be found in [4].

When exposed to optical radiation, the filter radiometer will produce a photocurrent

$$i = A \int_\lambda E(\lambda)\tau(\lambda)R(\lambda)d\lambda , \qquad (1)$$

where A is the area of the aperture, λ is the wavelength, $E(\lambda)$ is the spectral irradiance to be determined at the aperture plane, $\tau(\lambda)$ is the known spectral transmittance of the filter and $R(\lambda)$ is the known spectral responsivity of the trap detector. The photocurrent is measured with a HP3458A digital voltmeter equipped with a sensitive VINCULUM current-to-voltage converter.
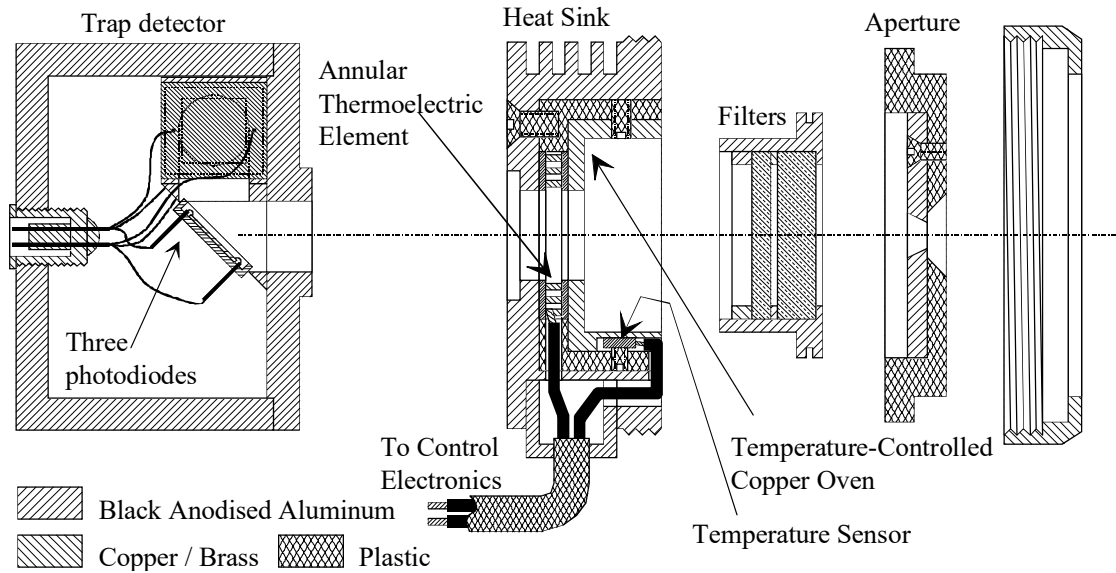
Figure 2. Construction of the filter radiometer.

The spectral irradiance of the tungsten filament lamps used can be modelled as

$$E(\lambda) = \frac{B\varepsilon'(\lambda)}{\lambda^5 \left[\exp(c_2/\lambda T) - 1\right]} \, , \tag{2}$$

where B is an auxiliary multiplication factor, $\varepsilon'(\lambda)$ represents the effective spectral emissivity of the lamp, $c_2 = 1.4388 \cdot 10^{-2}$ m·K is the second radiation constant, and T is the temperature of the lamp filament in kelvins. The effective emissivity $\varepsilon'(\lambda)$ is modelled with an Nth degree polynomial as

$$\varepsilon'(\lambda) = \sum_{i=0}^{N} b_i \lambda^i \, , \tag{3}$$

where b_i's are free parameters, and maximum N is 7.

Equations (1) and (2) are solved with a recursive iteration method so, that the spectral irradiance values at the effective wavelengths

$$\lambda_{eff} = \frac{\int_\lambda \lambda E_c(\lambda)\tau(\lambda)R(\lambda)d\lambda}{\int_\lambda E_c(\lambda)\tau(\lambda)R(\lambda)d\lambda} \tag{5}$$

of the filters match.

As the result, we obtain the discrete spectral irradiance values at the effective wavelengths and a function in the form of Eqs. (2) and (3) giving a continuous spectral irradiance curve.

Selecting the values for N and for the integration limits depend on the number of filters in use. N has to be approximately 2-3 lower than the number of filters in use, in order to prevent unexpected behaviour of the interpolation function between the fixed values. The obtained interpolation function is valid only between the effective wavelengths of the lowest and highest filters. In some cases, it may be advantageous to model the spectral irradiance separately in UV and visible/NIR.

The calibration is stored in the filter radiometer. For short periods, the calibration of the lamps may be used. The calibrated lamp is used to calibrate the spectroradiometer, which may then be used in customer calibrations.

3. Equipment

3.1. Description of setups

Table 1. Equipment needed when calibrating a primary standard lamp.

Description	Quantity*)	Remarks/Id
Filter radiometer 1997		
Trap detector	1(~10)	None, used in transmittance
Temperature controlled filter holder	1	(black with brass ring)
Temperature controller electronics	1 (5)	Thorlabs, Wavelength electronics
Precision aperture	1(2)	(A10, 3 mm)
Briefcase containing the items mentioned above	1	
Filter radiometer 2001 (FR Candela)		
Trap detector	1(~10)	UVFR-8
Temperature controlled filter holder	1	(black with aluminium ring)
Temperature controller electronics	1 (5)	Thorlabs, Wavelength electronics
Precision aperture	1(1)	NFRA1 (3 mm)
Optical stand for trap detector	1	
Filter radiometer 2007 (Spectral irradiance)		
Trap detector	1(~10)	MRI-9807 (blue with black front)
Temperature controlled filter holder	1	(blue with aluminium ring)
Temperature controller electronics	1 (5)	Thorlabs, Wavelength electronics
Precision aperture	1 (1)	NFRA2 (3 mm)
Optical stand for trap detector	1	
Filter radiometer accessories		

Filter set	1 (14)	290, 300, 312, 330, 350, 365, 380, 440, 500, $V(\lambda)$, 600, 700, 800, 850, 900
Current-to-voltage converter	1 (13)	Vinculum SP042, MRI-CVC
Digital voltmeter	1 (21)	HP / AGILENT 3458A / 34401A / 34410A

Optical Bench (Horizontal) for FEL lamps

Horizontal optical rail in light tight enclosure	1	1.5-m rail installed on the table in Irradiance laboratory
Baffle with shutter	1	
Mounting plate for rail	2	One with electronic distance measurement unit
Alignment laser	1	OMTec two-beam alignment laser
Digital distance measurement electronics	1	

Optical Bench (Vertical) for DXW lamps

Vertical optical rail	1	Installed on the table in Irradiance laboratory when needed
Baffle	1 (2)	Diameters 5 and 10 cm
Mounting plate for rail	3	Manual
Alignment laser[**]	1	OMTec two-beam alignment laser

Light Source

Lamp with corresponding lamp holder	1 (12)	*OSRAM FEL-S.T6:* Lamps and their nominated use are listed in a separate database SPIRR_Lamps.xlsx
Alignment jig	1	Lamp specific
Shunt resistor	1 (2)	Guildline 9230-15
Current source	1 (2)	Heinzinger PTN55 125-10
Digital voltmeter	2	As above. For measurement of lamp current and voltage

Light Source with spectral lines

PSU for WL-lamp	1	Oriel Lamp PSU, 6061	
Argon-mercury WL-lamp	1	Oriel Ar-Hg lamp, 6035	
Krypton WL-lamp	1	Oriel Kr lamp, 6031	
PSU for WL-lamp	1	UVP 0.21 A PSU for Neon lamps, 99-0057-02	
Neon WL-lamp	1	UVP Neon Pen Ray (10 mA), 90-0015-01	
Neon WL-lamp	1	UVP Neon-Hg (18 mA), 90-0016-01	
Mercury-lamp + external AC-adapter	1	Ocean Optics HG-1, add s/n	

Software

Excel model for analysing results	1	SPIRR_template_40.xlsx (August 2020)
Matlab model for analysing results	1	SPIRR_calculation_program_10.m (August 2020)
		Requires subprogram cprintf.m, input file Devos.xlsx, and input/output file SPIRR_template_40.xlsx
Program for interpolating average of emissivities for group fitting of lamps	1	SPIRR_interpolation_10.m
		Requires input file Average_em.xlsx

*) The number in parentheses indicates the number of optional items available. The number not in parentheses indicates the minimum amount of the concerned item needed.

3.1.1. Pin configurations of the filter radiometers

Table 2. Pin configurations of the temperature controllers.

	Filter Radiometer	Thorlabs, TED200	Thorlabs, TED200C	Wavelength Electronics, LFI-3551
Connector type:	Six-pole	D9	D15	D9
TEC (+)	1	4	5, 6, 7	1

TEC (-)	2	5	13, 14, 15	2
AD 590 (-)	4	7	10	5
AD 590 (+)	5	9	11	6

3.2. Calibration requirements

3.2.1. Filter radiometer

- The multimeters used are auto-calibrated every day before the start of the calibration measurements. Before autocalibration, the temperature of the DVM has to be allowed to stabilise for at least 1 h (longer time recommended). Calibration of the multimeters is done according to the MRI calibration schedule.

- The current to voltage converter is calibrated according to the MRI calibration schedule.

- The trap detector is calibrated according to MRI calibration schedule and modelled to to cover UV-VIS-NIR ranges. The methods used are described in [5].

- Filter transmittances are calibrated once a year prior to irradiance measurements using methods described in [6]. Alternately, a well known lamp is measured to identify filters whise transmittances have changed, and they are re-calibrated. Before calibration / measurement, the filters are inspected visually for dust or degradation. The filters that degrade appear "foggy" may need to be replaced. They may also be cleaned by agreement with the Branch manager of Spectrophotometry. Transmittance data is analysed for Centroid wavelength, Bandwidth, Integrated transmittance and Maximum transmittance. These values are compared with earlier results to monitor stability. The data is stored in

  \\work.org.aalto.fi\T405\MIKES-Aalto\Maintenance\irradiance\filters

- Filter transmittances are calibrated in the wavelength region $\lambda_0 \pm 50$ nm, where λ_0 is the peak wavelength of the filter. Out-of-band leakage's are studied in the wavelength region $[\lambda_0 + 50$ nm…1 100 nm] once for each new filter.

- If Deuterium lamps are to be measured, also possible leakage's below λ_0 need to be considered.

- Reflectances of the filters have to be measured once for each filter when taking into use. These reflectances are needed to take into account the interreflections between the filter and the trap detector. If reflectances are not measured, a value (10±10) % is used. The uncertainty is taken into account in calculations.

- The trap detectors are stored with the protective cap closed whenever they are not in use. This is to keep dust away from the surfaces of the photodiodes. Before measurements, it is visually checked that there is no dust inside the detector. If there is visible dust, it may be carefully cleaned from the first photodiode with Kodak lens cleaning tissue. If other tissues are used, make sure that there is no silicon in the tissue. The two inner diodes can be cleaned with pressurized nitrogen with permission from branch manager. Note that this is a major operation and may lead to recalibration of the trap.

- The areas of the precision apertures are measured according to MRI calibration schedule by VTT-MIKES length section. Alternately, they may also be calibrated using the direct optical method, DOM [7,8].

- The shunt resistor is calibrated according to the MRI calibration schedule in VTT MIKES.

3.2.2. Spectroradiometers

- The spectroradiometers are calibrated for spectral irradiance responsivity before calibration measurements if the previous calibration is more than six months old.

- The wavelength scales of the spectroradiometers are checked once a year.

- Incandescent lamps may be used for storing the spectral irradiance calibrations for short periods. Calibration interval for OSRAM FEL T6 lamps is 2 years or 15 hours of burning time, whichever exceeds first. Change in lamp voltage (by more than 0.3 V) indicates need for recalibration.
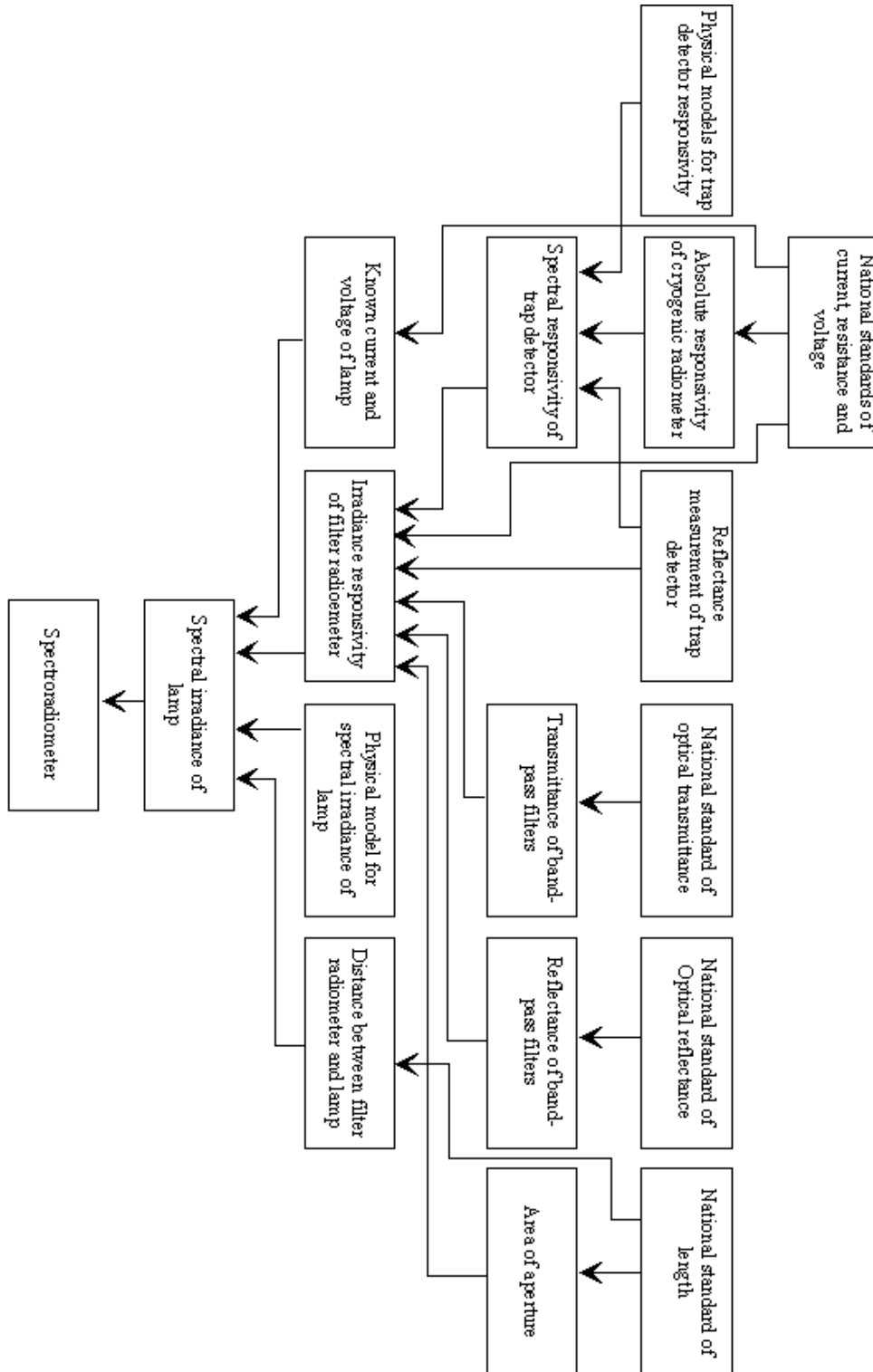
4. Measurement traceability

Figure 3. Traceability scheme of the spectral irradiance measurements.

5. Calibration and measurement procedures including validation methods

5.1. Measurement ranges

5.1.1. Measurement range using the filter radiometer

Lowest current that can be measured reliably with the trap detector is 1 nA. The highest measurable current is 1 mA due to nonlinearity [9]. The lowest and highest measurable spectral irradiance values resulting in these limiting current values are presented in **Table 3** for all filters presently in use. The values have been calculated assuming a light source of T_c = 3130 K, and an aperture area of 7.2036 mm² (3 mm diameter) for high end and diameter of 4 mm for low end.

Table 3. Minimum and maximum allowed spectral irradiance values for the filters in use with the filter radiometer.

Filter	E_{min} [pW mm^{-2} nm^{-1}]	E_{max} [μW mm^{-2} nm^{-1}]
290	498.6	886.5
302	281.7	500.8
315	267.4	475.4
333	103.6	184.1
352	163.8	291.3
382	38.4	68.3
440	22.9	40.6
501	17.3	30.7
572	3.2	5.7
600	10.8	19.3
698	7.4	13.1
801	10.9	19.3
902	10.0	17.9

Based on the values, we can define our typical measurement range as 10 pW mm^{-2} nm^{-1} - 500 μW mm^{-2} nm^{-1} using 3-mm and 4-mm apertures.

5.2.   Measuring a primary standard lamp

- Build the setup as described in [10]. The reference also gives instructions on operating the lamps. The lamps to be used as spectral irradiance standards typically include 1 kW FEL and DXW type lamps. It is also possible to calibrate 200W lamps, but the uncertainties are slightly higher, and results in the UV region end up out of the CMC scope.

- With FEL lamps: 1) Measurement distance is 500 mm measured from the outermost surface of the lamp base 2) Operating current is 8.1000 A, unless otherwise stated. 3) Lamp is aligned using the targets in the briefcase of the lamps. The grooved surface of the alignment jig must be pointed away from the lamp (towards the filter radiometer). Lamp numbers have been written in the jigs.

- With DXW lamps typically: 1) Measurement distance is 500 mm or 700 mm measured from the outermost surface of the alignment jig. 2) Operating current is 8.0000 A 3) Lamp is aligned using the target provided by the customer.

- Operating procedures of customer lamps must be agreed with the customer because the alignment procedures vary.

- Alignment with all lamps is done using the 900c filter in the filter radiometer.

- OMTec alignment laser between the lamp and the filter radiometer is to be used in the alignment unless there is special need for other methods.

- If calibrating customer lamps in the field, measure the distances to the appropriate reference planes using the equipment of customers.

- Measure the lamp using each filter. Before measurement, record the dark current, and subtract it from the measured signal. With each measurement, check/adjust the lamp current, and record the lamp voltage. Start with 900 nm filter and measure it in the beginning and at the end of the measurement sequence.

- When changing the filters, allow the temperature of the new filter to stabilise for 5 minutes before measuring. During this time, light must be blocked. The time may be shortened if the temperature of the laboratory is close to 25 °C.

- Record the temperature and humidity of the laboratory to be later added to the calibration certificate.

5.3.   Analysing the results

The theoretical background for analysing the results is given in [1, 3]. Measured photocurrents of lamps are converted to irradiance values at effective wavelengths 290 – 900 nm, and an interpolation/extrapolation program giving a smooth interpolation function for irradiances in the wavelength region 250 – 1000 nm. Regions 250 – 290 nm, and 900 – 1000 nm are not traceable.

Data-analysis can either be carried out using Excel or Matlab. In both cases, all raw data are entered into an Excel file SPIRR_template, where the final results are written as well. The models are based on Planck's law and effective emissivity. In Excel, the emissivity is interpolated with a polynomial with maximum degree of 7. The Matlab model can interpolate the emissivity with polyfit function with an unlimited degree or c-spline.

5.3.1. Excel program SPIRR_template

The template is located in

\\work.org.aalto.fi\T405\MIKES-Aalto\Quality\Radiom\Spirr_calculation_program\SPIRR_template.The template spreadsheet for spectral irradiance calibration is used and saved as a copy for analysis of each lamp. Excel should have solver add-in installed.

SPIRR_template contains the following sheets:

- Multiplication. The sheet is used for numerical integration, no data entered here.

- Filters Fig. The sheet plots the transmittances of the filters used.

- Filters. The sheet contains transmittances of the filters in wavelength region 260 – 940nm. The latest values must be updated here.

- Detector. The sheet contains responsivities and reflectances of detectors. The detector used must be written in cell C3. The latest detector data must be updated here.

- Lamp data. The measurement results are entered here.

- Emissivity. The user can choose what emissivity to use by writing the option to cell D4. The options are linear/matlab/devos. If interpolation is done with Excel-only, then linear option must be used. If interpolation is done by Matlab, then matlab option must be used.

- Emissivity Fig. The sheet plots the chosen emissivity and measured emissivities at effective wavelengths.

- Irradiance Fig. The sheet plots measured and interpolated irradiance.

- Lightsource. The sheet calculates spectral irradiance and black-body values in wavelength region 250 – 1000nm. No data entered here

- Difference. The sheet plots the differences of calculated irradiance and measured irradiance in percent.

- CVC. The user must enter CVC's name and newest calibration certificate and number in cells A2, B2, C2. Calibration data of the CVC must be pasted onto a table on the sheet.

- Measurements. This sheet collects all the calculation. Including polynomial fitting parameters, color temperature and geometrical constant. The diameters of

the apertures are listed in cells E4 and E5. Latest data of aperture diameters must be there. in cell B7 is the area of the aperture and the user must edit the cell's equation to match the aperture used. The minimization of square sum of error is done here.

- Intercomparisons. Here the user can compare the results with older calibration data. The older data can be found from older calibration certificates. The user must also calculate the percentual difference with older data.

- Intercomparisons figure. Here the user can plot the percentual difference with older data with Excel's select data tool.

Measurement results are entered into the Lamp Data-sheet. This data includes

- dark signal [mV], signal [V], and gain-value of CVC for each filter,

- (filter at 900 nm is measured twice, in the start and at the end),

- lamp name and the date of measurement.

For calibration, the goal is to get the modelling of spectral irradiance fitted as accurately as possible to the measurements. Figures from sheet Emissivity Fig, Irradiance Fig and Difference can be used to analyse the fit of the interpolation.

5.3.2. Analysis using Excel

First step of the interpolation is to go to the Emissivity-sheet write to cell C3 'devos'. In Measurements-sheet, the raw data can be seen from the differences between the measured values and fitted values there.

In the Measurements-sheet, one can see the square sum of the errors. To minimize the square sum, user must choose the cell (B27), choose "Data" from the toolbar and choose solver and choose minimizing option. This process gives polynomial fitting parameters in lines 55-56 of the Measurements-sheet, also it produces new values for colour temperature and geometrical constant in cells E27 and E28.

Second step of the interpolation is to copy lines 55-56, go to the Emissivity-sheet, and highlight cells F2:G14. Right-click and choose paste-special: <values> and <transpose> to update emissivity. Then write linear in cell C3. For the following iterations, option linear must be on.

After one cycle, it is good to look at the earlier mentioned figures to determine if the interpolating process should be repeated. In a good interpolation the absolute error between the measurements and the model should be under 1%.

If single measured values do not fit in the interpolated curve after multiple iterations, there is a high probability measurement errors in transmittances, or fauty operation of filters. If possible, the transmittances should be remeasured. If not, individual measurements can also be corrected mathematically. In the Measurement-sheet, one can find

lines Trap correction, Dust correction and Distance correction, where the user can estimate how much these irregularities have affected the measured value in percent, and the software makes a correction.

If older calibration data exists, the data can be added to Intercomparisons-sheet.

After the data analysis name your spreadsheet in the format of <lamp name><date><possible extra information> without the angle brackets and quotation marks. The model must be saved for calibration certificate.

5.3.3. Analysis using Matlab

The program is located in

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The folder contains

- SPIRR_calculation_program.m. This is the main program. It interpolates the spectral irradiance from the Excel file SPIRR_template and writes it there.

- cprintf.m. This is a subprogram for SPIRR_calculation_program.

- Devos.xlsx. This is file contains De Vos emissivity for the program.

- SPIRR_template.xlsx. The data is inserted here.

- SPIRR_interpolation.m. This program is for group fitting.

- Average_em.xlsx. This xlsx-file is for group fitting.

The program reads data from SPIRR_template and the user must insert previously mentioned data and save and close the file.

The user must open a Matlab-file called "SPIRR_calculation_program.m".

SPIRR_calculation_program has 7 variables that user can manipulate

- filename. The user must type the path and the name of the Excel file in quotation marks. If the Excel file is in the same folder as the program, then the name in quotation marks is enough.

- mode_choice. The user can choose the wanted interpolation method. The range of mode choice is from 0 to 3. The interpolation methods are briefly explained in the comments of the program.

- wanted_step. The program produces 2 emissivities, one for the excel model (one step) and the other is for the calibration certificate. The size of the step is the value of wanted_step.

- csapi_smoothness. If the user chooses mode 3 (smoothing cubic spline), then this variable determines the smoothness of interpolation curve. It has a range from 0 to 1, where 0 is a straight line and 1 is the smoothest possible.

- Fitdegree. If the user chooses modes 0 or 1, then the program uses polynomial fit. Fitdegree determines the degree of the polynomial fit.
- guess_250 and guess_1000 are guesses for emissivity for 250 nm and 1000 nm so that the interpolation stays stable.

After the variables are set. Then the user can press the run-button to start the interpolation.

After the program has done its interpolation, the program's command line will guide the user if he/she wants to change the filter correction values for a specific filter.

The program fill produce a plot of the interpolated emissivity and spectral irradiance and they will update if the user chooses to change filter correction values. The program is also able to interpolate the emissivity even if the measurement was missing several filters.

The results that the program writes in the Excel-file is colour temperature, geometric constant, filter correction values, emissivity in 1 nm step and emissivity in step size determined by variable wanted_step.

After the user is satisfied with the results, the program will automatically write the results in the excel-file and print out "END", after that user may close the program.

In the excel file where the program writes the values, one can examine the emissivity figure in excel by going to "emissivity"-sheet write matlab to cell C3.

5.3.4. Group fitting of lamps

The lamps of the same type are very similar in their properties. This offers a way to identify outliers in the measurement data using group fitting.

In group fitting, the emissivities at effective wavelengths for each lamp is taken and averaged. The averaged values are then interpolated and used for modelling the spectral irradiance.

In \\work.org.aalto.fi\T405\MIKES-Aalto\Quality\Radiom\Spirr_calculation_program

are 2 files for group fitting

- Average_em.xlsx.
- SPIRR_interpolation.m

The user must insert the effective emissivities from each lamp's Excel model in Emissivities-sheet of Average_em. It calculates the averages of effective emissivities on row A of Averages-sheet.

The user can insert also the effective wavelengths from each lamp's Excel model in Wavelengths. Usually the effective wavelength values do not change too much. The averages are on row B of Averages-sheet.

When all needed data is entered to Average_em, file is saved and closed.

The user must open SPIRR_interpolation and press run. The program prints polynomial fitting coefficients automatically to Average_em.

The polynomial fit coefficients are then copied and pasted to each lamp's Excel models Emissivity sheet to get the group fitting for emissivity.

Now every lamp has the same emissivity curve, but different colour temperature and geometrical constant.

If the original emissivity for single lamp drastically differs from the average, then it can be taken away from the final results.

5.4. Calculating colour co-ordinates and colour temperature

Colour co-ordinates and colour temperature are calculated using the interpolated spectrum (1 nm interval) of the lamp with equations and colour-matching functions defined in [11].

Spectral irradiance values are multiplied with colour-matching functions $\bar{x}, \bar{y}, \bar{z}$ and the products are summed to obtain tristimulus values *X, Y, Z*. Chromaticity co-ordinates *x, y* are calculated as *x = X/(X+Y+Z) and y = Y/(X+Y+Z)*.

Colour co-ordinates *u, v* (1960 UCS diagram) are calculated as *u = 4X/(X+15Y+3Z), v = 6Y/(X+15Y+3Z)*. Correlated colour temperature T_c is obtained as the temperature of a black body radiator, whose colour difference in 1960 UCS diagram is minimised with respect to the colour co-ordinates *u, v* of the lamp.

For analysing the T_c of a measured spectrum, an excel file MRI_CCT_Calc_2014.xlsm can be used. The latest version is stored in folder "T405/MIKES-Aalto/Quality/radiom/". The file has three calculation sheets for 1 nm, 2 nm and 5 nm spectral data between 360 nm and 830 nm. Copy the measured spectral data and paste it to the corresponding column in the file and then use the built-in iterative function "Excel solver" to calculate the CCT of the measured spectrum. The solver can be used with the pre-defined settings of the file that automatically refer to the correct cells. In the analysis, the Euclidean distance $\Delta(u,v)$ between the chromaticity coordinates of the measured source and a Planckian radiator is minimized by changing the temperature of the Planckian radiator.

5.5. Adjusting colour temperature

Colour temperatures of lamps are adjusted to certain values (e.g. 2856 K for CIE standard illuminant A) using a spectroradiometer. It is preferred to use the Konica Minolta CS2000A spectroradiometer with the dedicated diffuser head for adjusting the T_c of lamps. The CS2000A allows quick and repeatable measurement of the spectrum of the source and reduces the total burn time of the lamp significantly compared to using a scanning spectroradiometer for adjustment of the lamp T_c.

The CS2000A calculates the T_c of the lamp using an approximative method that results in a T_c value 1.5 K higher than analysed using the iterative method, when targeting at T_c

of 2856 K. This should be taken into account when adjusting the CCT of a lamp. In practice, adjusting a lamp to T_c of 2856 K requires the CS2000A to display 2857.5 K. The final adjusted T_c of a lamp should be verified with the MRI_CCT_Calc2014.xlsm file using the iterative method. In addition, it must be noted that the difference between the approximate method and the iterative method is nonlinear in nature and the difference of 1.5 K applies only for T_c of 2856 K. Adjusting the lamp to any other T_c than 2856 K needs to be checked with the iterative calculation method.

Procedure for adjusting the T_c of a lamp:

1. Measure the spectrum of the lamp within WL range of 380 – 780 nm (CS2000A).

2. Adjust the lamp current, wait for 1 minute and make a new measurement.

3. Repeat steps 1 and 2 until the colour temperature is within the specifications given by the customer, typically within 0.5 K from the target T_c.

4. Repeat the measurement a few times within a period of 10-15 min to verify that the adjusted T_c is stable and within the specifications. Adjust current, if necessary.

5. Verify the final T_c of the lamp with the iterative calculation method using the file MRI_CCT_Calc2014.xlsm

6. Handling of calibration items

- 1 kW lamps produce lots of UV. Avoid staring to the lamps. Use protective clothing and limit staying in the vicinity of the lamp to minimum.

- Never move hot lamps. They may explode or the filaments may damage! Allow lamp to cool down for min. 2 hours before disassembling the setup.

- Do not touch the envelopes. If there are fingerprints, do not try to clean them. Before operating, the dust should be removed with soft brush or by blowing clean air.

- Do not touch surfaces of the filters or edges of the apertures.

- If, by accident, any of the optical components get dirty or damaged, notify all colleagues who might be using the equipment. In case of damage to the lamps, record the incidence to the logbook.

- For more details, see [10].

7. Uncertainty budgets

7.1. Uncertainty of the filter radiometer

Table 4. Uncertainty budget of the spectral irradiance measurements of a 1-kW tungsten-halogen lamp by using the filter radiometer [3].

Source of Uncertainty	Standard Uncertainty [%]												
	291	302	315	333	352	382	441	501	572	599	698	801	902
Detector responsivity	0.67	0.67	0.54	0.51	0.51	0.28	0.08	0.07	0.07	0.07	0.07	0.07	0.06
Cryogenic radiometer	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
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	0.02
IQE modelling	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
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 meas.	0.40	0.40	0.40	0.40	0.40	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Current measurement	0.20	0.20	0.20	0.10	0.10	0.10	0.03	0.02	0.02	0.02	0.02	0.02	0.02
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
Filter transmittance	0.97	0.46	0.37	0.31	0.31	0.55	0.18	0.14	0.09	0.11	0.11	0.16	0.15
Peak transmittance	0.89	0.32	0.13	0.19	0.21	0.51	0.12	0.10	0.07	0.07	0.08	0.10	0.09
Wavelength uncertainty	0.24	0.21	0.19	0.17	0.14	0.11	0.08	0.05	0.03	0.03	0.01	0.01	0.01
Wavelength repeatability	0.08	0.12	0.12	0.15	0.14	0.15	0.11	0.08	0.01	0.07	0.07	0.11	0.11
Temperature	0.03	0.03	0.03	0.03	0.03	0.00	0.03	0.01	0.02	0.01	0.01	0.02	0.02
OOB leakage	0.30	0.22	0.26	0.10	0.11	0.08	0.03	0.04	0.03	0.03	0.04	0.05	0.05
Irradiance measurement	0.22	0.22	0.22	0.27	0.27	0.22	0.21	0.21	0.21	0.21	0.21	0.21	0.21
Lamp current	0.08	0.08	0.07	0.07	0.07	0.06	0.06	0.05	0.04	0.04	0.04	0.02	0.02
Distance measurement	0.14	0.14	0.14	0.21	0.21	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Alignment	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Diffraction	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Aperture area	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
Interreflections	0.05	0.14	0.10	0.10	0.11	0.11	0.03	0.02	0.02	0.02	0.01	0.01	0.01
Interpolation	0.50	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Combined standard uncertainty	1.30	0.91	0.76	0.73	0.73	0.73	0.42	0.40	0.38	0.39	0.39	0.40	0.40
Expanded uncertainty ($k = 2$)	2.6	1.8	1.5	1.5	1.5	1.5	0.84	0.80	0.8	0.8	0.8	0.81	0.80

The best measurement capability obtainable in irradiance measurements with the filter radiometer is shown in Table 4. Detailed description on the components may be found in [1. 3].

7.2. Uncertainty of colorimetric quantities

The principles for calculating the uncertainties for the correlated colour temperature and colour co-ordinates (x, y) of a lamp have been presented in [1]. The uncertainty of the colour temperature was calculated by assuming a scenario, where all measurement error accumulates as a function of wavelength. i.e., the other end of the spectrum was

raised and lowered by its uncertainty. The standard uncertainty of the correlated colour temperature obtained was 2 K, thus resulting in expanded uncertainty of 4 K (k = 2). Expanded uncertainty of 5 K has been accepted into the BIPM CMC database. Obtaining this low value requires use of the primary standard filter radiometer freshly calibrated. In most customer calibrations, U = 15 K (k = 2) is assumed.

Uncertainties of the colour co-ordinates (x, y) may be calculated using the uncertainty of the correlated colour temperature. These uncertainties depend heavily on the colour temperature of the source. Colour co-ordinates are calculated separately for a Planckian radiator at three temperatures: the nominal colour temperature and temperatures 2 K lower and higher. The average of the colour differences from the nominal colour co-ordinates can be used as the standard uncertainty component for the colour co-ordinate. Standard uncertainties calculated this way are given in Table 5 for several colour temperatures in the measurement range.

Table 5. Uncertainties of colour co-ordinates as function of correlated colour temperature. Uncertainties are given separately for x and y co-ordinates, both as absolute and relative uncertainties. Values are valid for black (grey) body sources only.

T_c	u_x	u_x/x	u_y	u_y/y
1000	0.00028	0.043 %	0.00025	0.073 %
1500	0.00025	0.043 %	0.00013	0.034 %
2000	0.00022	0.041 %	0.00003	0.008 %
2500	0.00018	0.038 %	0.00002	0.006 %
2856	0.00015	0.034 %	0.00004	0.011 %
3000	0.00014	0.033 %	0.00005	0.012 %
3200	0.00013	0.031 %	0.00005	0.013 %
3500	0.00011	0.028 %	0.00006	0.014 %

The best measurement capability may be estimated to be 0.1 % (k = 2).

8.   Accommodation and environmental conditions

The spectral irradiance measurements are carried out mainly in the Irradiance laboratory (1567) of the TUAS building, on two optical benches, vertical and horizontal.

During calibrations:

- The Clean Zone -aggregate should be on to prevent dust.

- Temperature should be controlled to 23 ^{o}C with the two heat pumps on the laboratory wall.

- In winter time when air is dry, humidity should be controlled to at least 30% using the humidifier on the laboratory wall.

- Temperature and humidity are monitored during calibrations, and their values are stated in the calibration certificate.

Measurements with the filter radiometer may also be done outside the university. These field measurements should be done in corresponding laboratory conditions.

9. Field calibrations

Field calibrations may be done for certain customers.

Quality assurance routines and operating instructions of the customers are to be followed. This concerns e.g.

- Operation of the customer lamps, including current and voltage monitoring.
- Control and monitoring of environmental conditions.
- Alignment and distance measuring.

The procedures used should be recorded to the calibration setups with care, and the effect of deviations should be estimated and added to the uncertainty budgets.

10.   Control data

The measurement data coming from calibrations and development of equipment are archived. The Excel or Matlab programs used for analysing the filter radiometer measurements are archived with the raw data. If Matlab programs are used to control the measurements, these programs are stored as well.

Raw measurement data from filter radiometer measurements are archived by Petri Kärhä. All data is written in a chronological order to a black notebook labelled "Detector calibrations and measurements." If the data are in a computer-file, file name and location with description about the measurement are written to the book. By default, all files are stored in \\work.org.aalto.fi\T405\MIKES-Aalto\users\pete\Calibrations\ which contains folder for each customer. Stability of the components, especially the filters, is monitored. This data is stored in calibration certificates, which are archived.

Lamp FEL-460 is used as a control lamp to monitor the history of the scale. Earlier this was carried out using FEL-245. This data can still be used, if longer history of the scale is studied.

11. Certificates

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

- Optical axis used, vertical / horizontal

- Distance and reference plane used

- Lamp current and voltage before and after the measurements

- Burning time of the lamp during the measurements

- Ambient temperature and relative humidity

- Accurate spectral irradiance values at the effective wavelengths of the filter radiometers

- Values of the parameters for the interpolation function

- Interpolated spectral irradiance values with e.g. 1 nm or 0.5 nm interval as agreed with the customer (in an attachment file).

- If required: Chromaticity co-ordinates x, y and correlated colour temperature T_c.

- Condition of the lamp:
    - Filament sag
    - Dust and stains on the envelope
    - Electrical stability

12. Intercomparisons

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13. Publications / References

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[3]   T. Kübarsepp, P. Kärhä, F. Manoocheri, 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).

[4]   P. Kärhä, A. Haapalinna, P. Toivanen, F. Manoochehri, and E. Ikonen, "Filter radiometry based on direct utilisation of trap detectors," *Metrologia* **35**, 255-259 (1999).

[5]   Quality manual of optical power laboratory.

[6]   Quality manual of reference spectrometer laboratory.

[7]   A. Lassila, P. Toivanen, and E. Ikonen, "An optical method for direct determination of the radiometric aperture area at high accuracy, *Meas. Sci. Technol.* **8**, 973-977 (1997).

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

[10]   Instruction manual for operating standard lamps.

[11]   Commission Internationale de l'Éclairage (CIE), *Technical Report, Colorimetry*, Second Edition, CIE 15.2 – 1986.

[12]   Instructions for writing calibration certificates.