Detector-Based Reference Calibrations for Electro-Optical Instruments

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By

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PREFACE

Improved detector technology in the past two decades opened a new era in the field of optical radiation measurements. An increased number of calibration and measurement facilities and procedures could be developed with lower measurement uncertainties using the newly developed detector/radiometer standards instead of traditionally applied source standards (blackbodies and lamps). Shrinking of the traditional source-based calibrations and the large increase of optical detector-based calibrations motivated the writing of this book series.

The book series is a comprehensive description of optical detector based radiometric practices. Instead of giving the traditional lexical-type tutorial information, a research-based material is systematically organized and described. The large number of examples cover modern detector applications in the field of radiometry, photometry, colorimetry, and radiation temperature measurements. All the discussed devices and applications have been implemented, realized, tested, verified, and evaluated. These applications are described to obtain uniform results with low measurement uncertainties. They are described with enough details to successfully repeat them by the readers/users. The applications and evaluations follow the recommendations of international standardization. The described subjects are detailed and distributed in five volumes.

Properties of radiometric quality detectors, their use and selection for optical radiometers, design considerations of radiometers and detector-based standards, description of spectral and broadband detector-based calibrations and measurements using modern setups based on the new radiometer standards are described for practicing scientists, engineers, and technicians.

The book series includes many hundreds of designs, drawings, measurement schemes, a large number of detector-based measurement and calibration setups, measurement equations and results, calibration-transfer and measurement methods/procedures all tested in practical applications.

In addition to reference level detector/radiometer calibrations, measurement of radiometric quantities used in practice (secondary laboratory and field applications), are discussed. Such quantities are radiant power, irradiance, and radiance. Measurement of spectral and broadband (integrated) quantities are discussed from 200 nm in the ultraviolet to 30 μm in the infrared.

All discussed calibrations and measurements are traceable to the System International (SI) units through National Measurement Institutes (NMIs) and/or the discussed intrinsic detector standards.

Linear and traceable measurement of detector output signals, including DC and AC photocurrent (sub-scale) and voltage measurements, detector-amplifier gain-calibrations, and gain-linearity tests are discussed in detail.

Uncertainty determination/calculation methods of detector-based measurements are described. It is a general rule for the discussed large number of design and application examples, to keep the calibration/measurement uncertainties low.

The author thanks all the colleagues listed in the references at the end of each volume for their help and contribution to perform the discussed large number of measurements and evaluations.

Dr. George P Eppeldauer, author

1. INTRODUCTION

In order to utilize the significant improvements obtained in detector performances during the past 20 years, user friendly responsivity standards and responsivity measurement techniques were developed. Spectral responsivity is one of the most important detector characteristics widely used to derive device and system calibrations from high level detector standards. The goal is to convert from the traditional source-based optical radiation measurements to the more efficient and higher accuracy detector-based applications and calibrations. In addition to the single element detectors that are discussed in this book, radiometers with multiple-reflection input geometries (trap, wedge, and sphere), filters, windows, diffusers, and apertures are used. Also, small field-of-view and/or narrow band-pass are frequently used in modern radiometers. In addition to radiant power (flux) responsivity calibrations, irradiance and radiance responsivity measurements are needed in many applications, especially in field measurements.

This book describes how to perform spectral radiant power, irradiance, and radiance responsivity measurements. Measurement methods are described for detectors, radiometers and photometers to determine the relative spatial, angular, and spectral variations of their responsivities. Determination of absolute responsivities are also discussed in detail. The book describes measurement geometry, measurement setups, typical types and properties of different detectors, radiometers, and photometers, and measurement methods. The measurement methods include procedures to obtain traceability to National Metrological Institutes (NMI) and guidance on selecting standards. Responsivity scale realizations and extensions are described from reference Si standards for the ultraviolet (UV) to infrared (IR) ranges. Directional errors when using the detector and radiometer standards are also discussed. The spectral responsivity calibrations are discussed for photometers and tristimulus colorimeters and also for electronic imaging devices. Evaluation of measurement uncertainty and state of the art measurement uncertainty values are discussed. Responsivity uncertainties are derived from principal measurement equations. Common problems in all of the above measurements, such as spectral issues, DC and AC measuring methods and instruments are also discussed. An extended list of references are given to find more details for the above discussed subjects.

The book is to guide the optical radiation measurement community, researchers, manufacturers, calibration laboratories, students, and practicing engineers to switch from the old and limited use measurement methods to the higher performance and wider use detector-based measurements.

Details of the primary standards and related procedures for the realization of the SI units (the tasks of NMIs) are not discussed in this book. More discussions about multi-element devices can be found in Technical Reports (TR) of the International Commission on Illumination (CIE) such as the TC2-51 TR.

2. SPECTRAL RESPONSIVITY BASED CALIBRATIONS

The responsivity *s* of an optical radiation detector (radiometer or photometer) is the ratio of its output electrical signal *Y* to its input radiometric quantity *Q.* In general, responsivity is the ratio of two integrals:

$$s = \frac{Y}{Q} = \frac{\int_{\lambda} R(\lambda) S_{\lambda} d\lambda}{\int_{\lambda} S_{\lambda} d\lambda} \tag{1}$$

where $R(\lambda)$ is the absolute spectral responsivity and S_{λ} is the spectral power distribution to be measured. The spectral responsivity $R(\lambda)$ is the responsivity at a specific wavelength λ. The spectral power distribution (e.g. spectral flux in radiant power measurement) is the input signal (density) at a wavelength λ.

The responsivity of a detector is determined during a measurement (calibration) transfer. After calibration, the detector can be taken as a standard and can measure the same kind of radiometric quantity it was calibrated for. The magnitude of the radiometric quantity to be measured will be equal to the measured electrical signal of the device divided by the responsivity. The three basic radiometric quantities can be determined from three different measurement equations. The radiant power is

$$\phi = \frac{Y}{s_{\phi}} , \tag{2}$$

Where s_{ϕ} is the radiant power responsivity;

The irradiance (radiant power per area) is

$$E = \frac{Y}{s_E}\,, \tag{3}$$

where s_E is the irradiance responsivity;

The radiance (radiant power per solid angle per projected area) is

$$L = \frac{Y}{s_L}\,, \tag{4}$$

where s_L is the radiance responsivity.

For all three cases, Y is the result of an integration as shown above.

For a perfect radiometer that can measure radiant power, irradiance, and radiance, the responsivities may be interrelated:

$$s_P = \frac{s_E}{A} = \frac{s_L}{A\Omega} \tag{5}$$

where A is the detector active area and Ω is the viewing solid angle of the radiometer.

A test device can be calibrated against the detector standard if it can be substituted for the detector standard. The responsivity of the test device will be the ratio of its electrical output signal (current or voltage) to the magnitude of the measured radiometric quantity determined by the detector standard.

Responsivity measurements can be made broadband or spectrally (versus wavelength). This document is mainly focused on spectral responsivity measurements. In order to make uniform measurements, the bandwidth of the detector (radiometer) has to be designed according to the bandwidth of the source to be measured. E.g., a broad-band source can be measured with a broad-band detector only if the spectral responsivity of the detector is known. The relative standard measurement uncertainty of the test device will be always larger than that of the standard device because of the increased number of the calibration steps (during the measurement transfer).

Responsivity related calibrations are:

- Relative spectral responsivity (in power, irradiance, and radiance modes)
- Absolute spectral responsivity (in power, irradiance, and radiance modes)
  - Uniformity:
    - · relative variation within spatial responsivity (versus wavelength)
    - · relative variation within angular responsivity (versus wavelength)
  - Aperture effective area measurement
  - Linearity versus wavelength
  - Temporal characteristics
  - Temperature coefficient of detector responsivity

Responsivity measurements can be utilized in the field of:

- Optical radiometry
- Photometry
- Colorimetry
- Temperature measurements of blackbody radiators
- Optical pyrometry
- Solar photovoltaic quantum efficiency measurements

The optical radiation related quantities and units are defined in Section 845-01 and the radiometric, photometric, and colorimetric measurements, including physical detectors, are defined in Section 845-05 of the International Lighting Vocabulary (ILV) [1] . More definitions are given in the International Vocabulary of Basic and General Terms in Metrology (IVM) [2]. These definitions will be used in this work where applicable.

2.1 Calibration methods

The purpose of spectral responsivity calibrations is to transfer the spectral responsivity function from the selected reference standard to different test devices.

If low uncertainties are needed, a reference trap-detector can be used between 405 nm and 920 nm. The trap detector field-of-view has to be larger than the convergence angle of the beam to be measured.

If the spectral range of the Si trap detector is in not large enough for a given application, a spectrally flat transfer device can be used for extension of the wavelength range. In this case, the relative spectral responsivity of the wavelength extending transfer device can be determined first. As an example, the wavelength extending transfer standard can be a pyroelectric detector [3]. Its transmission for the incident beam is negligible. The front surface of the detector can be measured for spectral total reflectance to determine the spectral absorption (one minus reflectance). The spectral absorption is proportional to the relative spectral responsivity. As a second step, the absolute (tie) points can be determined against a reference standard detector, using the substitution method. E.g., the reference standard is a silicon tunnel-trap radiometer. The transfer standard pyroelectric detector is substituted for the reference standard and both are underfilled by the same laser beam [4]. In this example a 442 nm stabilized laser beam was used.

A secondary calibration laboratory can be prepared for spectral responsivity calibrations. Test detectors are always substituted for the standard detector of the calibration laboratory to further derive the spectral responsivity function.

2.1.1 Detector substitution method.

The substitution method transfers the radiant power responsivity of a standard detector to a test detector that has similar properties as the standard detector. When the standard detector measures the input (incident) beam, its output signal (e.g. photocurrent) is:

$$I_{\mathrm{S}} = s_{\mathrm{S}} \cdot \Phi \tag{6}$$

where s_{S} is the known responsivity of the standard detector and Φ is the constant (stabilized) incident radiant power that underfills the detector. In the following step, the test detector is substituted for the standard detector and measures the same power in the same arrangement:

$$I_{\mathrm{T}} = s_{\mathrm{T}} \cdot \Phi \tag{7}$$

where I_T is the output signal of the test detector and s_T is the unknown radiant power responsivity of the test detector that can be calculated from Eqs.(6) and (7):

$$s_T = s_S \frac{I_T}{I_S} \tag{8}$$

This is the principle measurement equation for the detector substitution method. Here it is assumed that any background contributions are negligible or have been corrected for.

When detectors are substituted for each other in power measurement mode the distance of the detectors relative to the origin of the source is not critical.

A monitor detector can be used to continuously measure the time dependent changes of the incident beam. Simultaneous ratio of the detector signal (both standard and test) to the monitor signal will reduce contributions to the combined uncertainty of the responsivity due to power fluctuations in the incident beam [5], provided the monitor detector and its preamplifier have characteristics similar to the test detector as well as to the standard detector and their preamplifiers.

2.1.2 Measurement transfer to test devices

The calibration transfer starts with the spectral responsivity measurement of the transfer standard against the realized spectral responsivity function at an NMI and ends in a secondary or field calibration laboratory where the responsivity of test detectors is measured. Low uncertainty of the responsivity value of a realization always needs sophisticated measurement setups and selected and well characterized detector standards. In applications where the relative measurement uncertainty requirement is 1 % or larger, the substitution method gives satisfactory results to transfer the spectral responsivity. The substitution can be made at all wavelengths where the detector responsivities overlap. Often, chopping or stability corrections with a monitor radiometer are not needed and lower power throughput is sufficient for the spectral instrument and the related optics. In this case, the simplified version of the measurement setup (as shown below in Fig. 2) can be used.

When signal modulation (chopping) is needed, such as in case of pyroelectric detectors or other infrared measurements (where separation of the useful signal from the DC background signal is needed), the responsivity transfer can be more complicated. In this case, during calibration, the responsivity versus frequency function should be measured (using the chopper and lock-in amplifier of the calibration laboratory) and the equivalent (or virtual) DC responsivity should be determined by fitting a curve to the measured data points. Frequently, this DC responsivity is reported by calibration laboratories even if the calibrated detector can be used only in AC measurement mode. When the calibrated detector is used in an application where different instruments (chopper, lock-in amplifier etc) are applied, the DC responsivity (reported by the calibration laboratory) can be derived (extended) to any other frequencies if the responsivity versus frequency curve is measured again with the different instruments of a given application. This method is very convenient and can result in very small increase in the measurement uncertainty during a calibration transfer.

Photometers used for luminous intensity lamp calibrations, usually have an aperture and a filter combination in front of the Si photodiode. Sometimes, the filters are temperature controlled. If the separation between the aperture and the detector is large, the photometer FOV can be small. Care should be taken that the FOV is large enough for the detectors when they measure the total beam power during a calibration procedure. Similarly, the beam convergence angle of the monochromator in the calibration setup should be made small enough to reach the detectors even in applications where the detector FOV is small. This way, beam clipping can be avoided.

Photometers usually measure illuminance or luminance. In field applications, diffusers or cosine corrections are used between the aperture and the filter combination to achieve compliance with the cosine law of illuminance measurement. In these applications, the cosine response is important because the radiation reaches the photometer (illuminance meter) from the hemisphere above the aperture. The side effect of a diffuser (cosine corrector) application can be poor uniformity in the spatial responsivity.

Illuminance meters can be calibrated in radiant power measurement mode. The photopic filter inside the photometer modifies the spectral power responsivity of the photodiode such that it will be similar to the standard photometric observer (the CIE V(λ) function) [6]. As a result, the radiant power will be converted into luminous flux, the photometric equivalent of radiant power. Both the filter package and the detector can have significant spatial non-uniformity. In order to decrease uncertainty contributions, the radiant power responsivity of an illuminance meter has to be mapped out and the average power responsivity should be used. Averaging the spatial non-uniformities of the photometer is important to make the measurement geometry at calibration equal to that at applications. The calibration geometry should be similar to that of a luminous intensity lamp measurement, where the lamp produces a uniform field of radiation in the aperture plane and the filter and detector spatial non-uniformities are averaged out. In radiant power mode calibrations, the calibration and measurement geometry will not be equal because the beam shapes at calibration (converging beam from the monochromator) and application (collimated within the aperture) will be different resulting in different reflection patterns for the two cases.

Radiometers with filters and/or apertures can be calibrated similarly to photometers. The important requirement for keeping the measurement uncertainty low is to use equal calibration and application beam-geometry to obtain the same reflection pattern inside the test radiometer for both cases. The similar rule applies for a detector standard used in a substitution type calibration unless the standard is invariant for the changes in the beam geometry between its own calibration and the application.

The equal calibration and application geometry requirement for illuminance meters can be achieved perfectly in irradiance calibration mode using a spectral irradiance responsivity standard where the uniform monochromatic radiation overfills the apertures of both the test photometer and the irradiance responsivity standard.

2.1.3 Pyroelectric spectral-reflectance based responsivities

Pyroelectric detectors have a renaissance for use in radiometric standardization. Their noise-equivalent power (NEP) has been improved [7] by orders of magnitude in the last several years. The improved NEP pyroelectric detectors can exhibit excellent radiometric characteristics as well [8]. The NEP is low enough to obtain high signal-to-noise ratios at the output of monochromators which was impossible or difficult before the NEP improvement. Fast, monochromator-based measurement of the spectral reflectance of their black coating with couple of percent uncertainty, made it possible to determine the spectral responsivity of these pyroelectric detectors from UV to IR with close to 0.1 % (*k*=2) uncertainty [9]. This is a significant improvement in calibration time and measurement simplicity compared to tunable laser applied detector-substitution type responsivity calibrations.

In a few previously discussed examples, the spectral response of the pyroelectric detector was not “flat”. It changed several percent in the VIS-IR. The flat response from a reference pyroelectric detector for spectral (responsivity) calibrations is not needed. The obtained uncertainties when the above described traditional spectral-responsivity calibration methods were applied (the test detector was substituted for the standard detector of known spectral responsivity and the responsivity from the standard detector was transferred to the test detector while measuring the output signal from both detectors for the same incident radiation) were in the percent level.

The monochromator applied spectral reflectance measurements of the black-coatings can produce the frequently required close to 0.1 % (*k*=2) uncertainty in the relative spectral responsivity of the herein discussed pyroelectric hybrid detectors even if the uncertainty of the spectral reflectance measurements is a few or several percent. Utilizing the relative spectral response of a pyroelectric hybrid detector determined from its spectral reflectance measurements, reference responsivity scales can be realized from the UV to the IR even at high-accuracy (e.g. tunable laser applied) detector calibration facilities. The conversion of the relative response into absolute can also be performed with low responsivity uncertainty, by substituting the pyroelectric detector against a transfer standard detector (e.g. Si trap detector) traceable to a primary standard cryogenic radiometer. This monochromator-used pyroelectric-based responsivity scale realization can be much faster and less expensive than calibrations performed at tunable-laser applied responsivity calibration facilities.

The spectral reflectance characteristics and measurements of selected pyroelectric detectors were discussed in Section 5 of Volume 1: The Properties of Optical Radiation Detectors and

Radiometers. The design issues of pyroelectric transfer standard radiometers were discussed in Section 3.2.1 of Volume 3: Optical Detector and Radiometer Standards.

Typically, the spectral responsivity calibration problems are different in the UV and IR ranges compared to the VIS and near-IR ranges.

Usually, power- and irradiance-responsivity scales are traceable to power measuring primary-standard cryogenic radiometers. Most frequently, Si trap-detector transfer standards are used for the VIS and silicon wavelength ranges [10], and sphere-input InGaAs [11] and sphere-input extended-InGaAs [12] detectors are used for the near-IR and short-wave IR ranges. Usually, these transfer standards are not used to hold the scales because of instability (response degradation) problems. Si trap detectors may exhibit UV-damage-caused responsivity degradation for wavelengths shorter than 450 nm. In spite of this degradation problem, sometimes they are calibrated down to 365 nm. In this case, the responsivity degradation can be avoided if an input shutter is used to minimize the UV exposure-time for the trap-detector. Also, the power-level of the incident radiation within the UV range should be low to avoid the response damage. The Spectralon [13] coated sphere, mounted at the input of the InGaAs or extended-InGaAs transfer standard detector, is exposed to the ambient and the degradation of the coating may cause long-term stability problems for these detector standards. Accordingly, these transfer standards should be used only for short-term responsivity transfer. Both the trap detectors and the input spheres have precision apertures (of known area) at their (front) inputs and they can be used as power-to-irradiance responsivity converters.

Typically, the responsivity scales are held by sealed single-element detectors. For radiant power measurement, large-area single-element detectors with small spatial nonuniformity of response are selected. These detectors are not used for power-to-irradiance responsivity conversion, primarily because their spatial uniformity is not good enough (it is close to 1 % peak-to-peak response variation) and their active area is not known. An added front-aperture may cause inter-reflections increasing the irradiance responsivity uncertainty. The detectors that hold the irradiance responsivity scale, might have significant spatial response non-uniformities if the measured (incident) radiation is spatially uniform.

Based on the above considerations, pyroelectric UV and IR responsivity scales have been developed at NIST [8]. The applied organic-black coated pyroelectric hybrid detectors with low NEP are excellent candidates to realize accurate and stable UV and IR responsivity scales with low uncertainties when they are calibrated based on spectral reflectance measurement of their black coating.

In early NIST performed scale realizations, sphere-input extended-InGaAs transfer standards gave the SI traceability of the responsivity function to the cryogenic radiometer. They produced the absolute responsivity tie points for conversion of the reflectance-based relative response function of the pyroelectric detector into an absolute function. Later, Si trap detectors were used to produce the tie points with significantly lower responsivity uncertainty. Using this method, the wavelength coverage of the NIST IR-SCF was extended from 0.6 μm to 24 μm in radiant power measurement mode and from 0.6 μm to 12.5 μm for irradiance responsivity calibrations. The responsivity uncertainties in both modes were between 2 % and 3 % (k=2) [14].

Both the monochromator used and the tunable laser applied calibration facilities require UV responsivity scales with low responsivity uncertainty. For the 200 nm to 600 nm range, UV trap detectors were used at NIST as transfer and working standards. These trap detectors were built using UV damage-resistant Si photodiodes. These are nitride-passivated or thin oxide nitrided-Si photodiodes with 1 cm^2 active areas [15]. These UV trap detectors can be calibrated against the cryogenic radiometer in power measurement mode. Since they are equipped with a front aperture, they can be used as irradiance responsivity standards as well. The organic-black coated pyroelectric detectors with the low-NEP were first-time used as reference irradiance measuring detectors at high accuracy UV and IR responsivity calibration facilities.

2.2 Calibration/measurement setups

2.2.1 Monochromator based setups

Most commonly, monochromator based measurement setups are used for spectral responsivity measurements. The complexity of a spectral responsivity measurement setup depends on the measurement uncertainty level and the wavelength range needed for the test detector. For instance, if the spectral responsivity function has to be extended from a high accuracy Si trap detector to a pyroelectric detector (where the noise floor is high), the setup has to be more versatile than for similar type test and working standard detectors especially when both have high sensitivity.

2.2.1.1 Filter monochromator.

One or more (narrow) bandpass filters can be used in place of a monochromator for spectral responsivity determinations at one or several wavelengths or when the budget is severely constrained. For successful results, the filters chosen must be of high quality and meet demanding specifications. Typically bandpass filters are used with a continuous source such as a tungsten-halogen incandescent lamp. Sometimes satisfactory results may be obtained by using a filter to isolate a single line from a source that contains many lines (e.g., Hg) or to reduce the background from wavelengths other than those from a selected source (e.g., a laser). The following definitions and discussion is limited to bandpass interference filters, the only ones suitable for passbands between 5 and 20 nm.

- Center Wavelength - the wavelength of peak transmission for a symmetrical filter, or the wavelength midway between the 50 % points for an asymmetrical filter.
- Percent Transmission - The transmission at the peak wavelength.
- Bandpass - Conventionally, the wavelength difference between the 50 % transmission points. The moments normalization method generally gives somewhat wider effective passbands.
- Bandpass Shape - Typically like a Gaussian or Lorentzian curve. Because many filters have several stacks in series (like 4th order), the Gaussian or Lorentzian may be raised to an arbitrary power for optimal curve fit.
- Out-of-Band Rejection - The transmission at wavelengths beyond the limits of the bandpass. Usually given as 10^{-4}, for example.
- Clear area and uniformity over clear area - The clear area is the area where the filter action takes place. For a 25mm diameter circular filter, it is typically 21mm diameter. The margin should be masked to prevent light from traversing that portion of the filter.
- Variation of Characteristics with Incident Angle - All of the

following filter characteristics change with incidence angle

a. The peak transmission decreases.
b. The center wavelength shifts to shorter wavelengths.
c. The bandwidth increases.
d. The transmission characteristics become different for s and p polarization.
e. The transmission characteristics become far more complex in a converging beam as many incidence angles are simultaneously present.

- Environmental Considerations - Filters are subject to reversible change of transmission with temperature, and irreversible degradation with exposure to humid atmospheres. In addition, the transmission changes slightly with atmospheric pressure.
- Stability over time with frequent exposure to source - Intense sources, particularly UV, may cause permanent degradation in the filter transmission. They should be characterized regularly to establish the time over which they can be reliably used.
- Fluorescence in filters - Some materials of construction may have fluorescence, emitting visible radiation when excited with ultraviolet. All filters should be inspected before use.
- Cleaning Method - Manufacturers specify the way a filter should be cleaned. Keeping the instrument closed when not in use is recommended. Avoid getting liquids on the edges to prevent seepage and subsequent filter delamination.

As for determination of the wavelength setting of a monochromator, the wavelength should be determined as the centroid of the radiation passed by the combination of the source and filter.

In spectral radiant power responsivity measurements, where broadband-sources are used with either narrow-band filters or monochromators, the incident beam is usually convergent onto the detectors. Figure 1 shows a typical arrangement for this type of measurement using a lamp-source and a series of interference filters. The field stop restricts the viewing area of the source to obtain a uniform source image. The radiation emerging from the field stop is collimated by a plano-convex lens with the flat side facing the source. The interference filters are mounted in a filter wheel and each of them converts the broadband parallel radiation into a quasi-monochromatic beam. This beam is then re-focused on the detectors.

The optimal position of the lenses depends on the wavelength. The detectors are single element detectors and the beam spot on the detector has to be smaller than the sensitive area of the detector. Test detectors can be calibrated against a standard detector of known spectral power responsivity. When filters are used, their temperature should be controlled. They can be recalibrated to minimize ageing effects, using the same geometry. Usually, the effective bandpass and centre wavelength of the individual filters are different, depending in part on the spectral responsivities of the test and standard detectors.

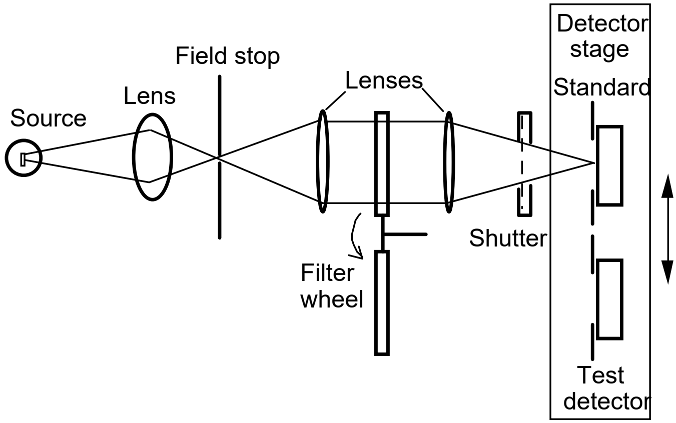

Fig. 1. Converging beam geometry for spectral radiant power responsivity measurement using a broadband-source with interference filters.

2.2.1.2 Monochromators

A typical monochromator-based responsivity measurement setup is shown in Fig. 2. A broadband lamp is imaged onto the input slit of the monochromator using lens or mirror imaging systems. Mirrors have no internal reflections, unlike lenses and are preferable for wide spectral range applications because they show no chromatic aberrations. Spherical mirrors are most commonly used for imaging, operated at near-normal angles of incidence to reduce off-axis aberrations. Spherical aberration is usually negligible for slow (i.e., F/8 or greater) mirrors. Double monochromators are used in high accuracy applications where high stray light rejection is needed. Single monochromators have higher throughput but lower performance in terms of spectral stray light.

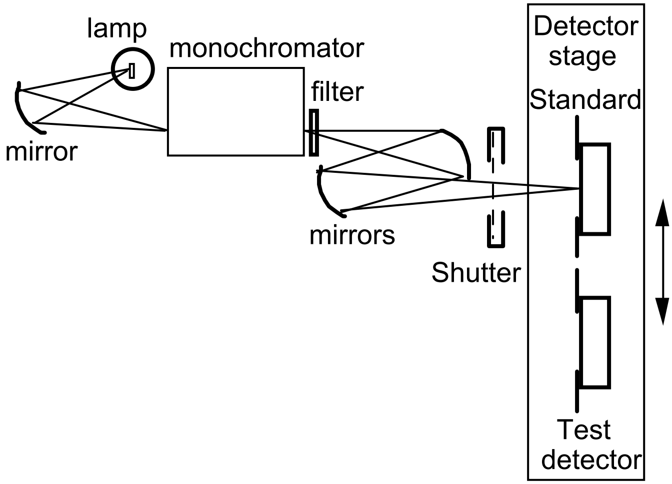

Fig. 2. Spectral responsivity measurement setup using a monochromator.

The dispersing elements are either prisms or gratings. The dispersion of prisms is highly non-linear. Therefore, when constant spectral bandpass is needed, elaborate cams have to be used for both the wavelength and the slit-width drives. It is difficult to find prism materials that have high enough transmission and dispersion in a wide wavelength range. Prism monochromators are more complex, hence, more expensive than grating versions. Gratings have anomalies that render their spectral efficiency highly irregular and they need order sorting (cut-on) filters. The output slit is imaged at the surface of the detectors. A light shutter can be used to subtract both the background radiation and the output offset voltage of the detector-amplifier from the output signal.

A versatile monochromator-based measurement setup is shown in Fig. 3. This setup has a computer controlled detector stage where test detectors can be calibrated against the standard detector. All detectors are operated in underfilled mode and measure the same total power of the monochromatic beam leaving the output imaging optics of the monochromator. Different broad-band sources can be imaged to the input slit of the monochromator through the input imaging optics. The power level and the spectral purity of the monochromatic beam (imaged on a detector) depend on the properties of the monochromator, the related optical system, and the type of the illuminating source. Usually, a combination of tungsten halogen lamps, Xenon lamps, and/or Argon arc sources is used to cover a wavelength range from 200 nm to 2.5 μm. The detector stage is optically shielded from the source related components of the setup using a baffle inside the light-tight box. The baffle can minimize the stray radiation seen by the detectors. A shutter can also reduce the contribution to the combined measurement uncertainty of the spectral radiant power responsivity by further decreasing stray and background radiation.

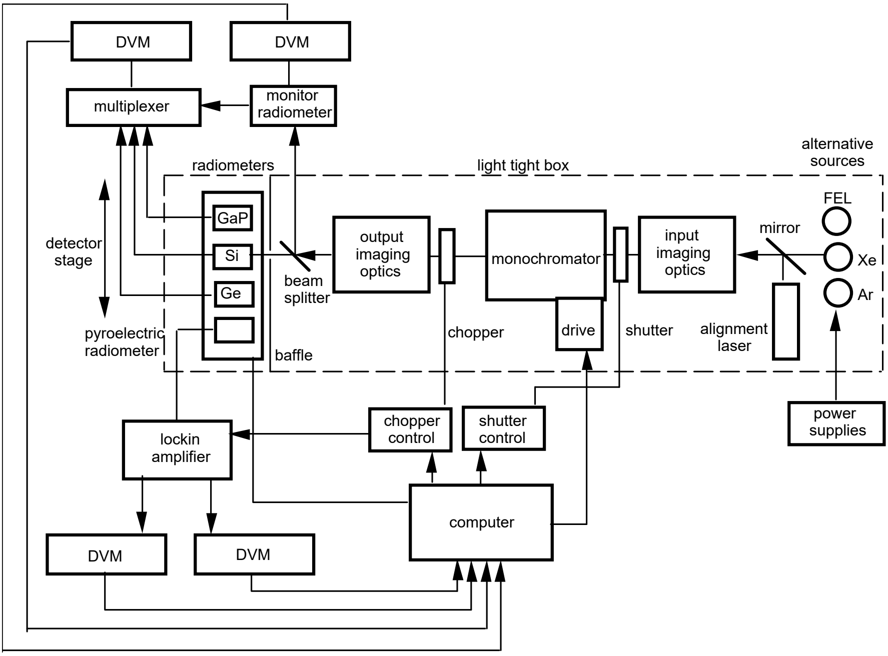

Fig. 3. A versatile monochromator setup to measure spectral responsivity.

In order to subtract the same dark signal as the one superimposed on the signal (for the shutter off and on), the shutter should be positioned far from the detectors. If a monitor detector measures a (constant) part of the monochromatic beam simultaneously with the signal of the measured detector, the ratio of the two output signals (signal to monitor) can decrease the source fluctuations in the measured data. The ratio method will be efficient only if both the spatial and the temporal changes are equal (or very similar) in both channels. All detectors, the monitor, the test, and the standard detector need short-circuit current-to-voltage converters to obtain linear operation. The output voltages of the converters are measured by digital voltmeters (DVMs), usually under computer control as is the data acquisition.

2.2.1.3 Monochromator characteristics

A monochromator is an optical instrument which is capable of isolating a narrow range of wavelengths. It is a tunable optical bandpass filter where both the wavelength and the width of the passband may be varied. Monochromators are the key spectral component in spectroradiometers, spectrophotometers, and spectroreflectometers, and are also used as tunable sources or detectors. For this document, a monochromator is combined with a source of optical radiant energy to form a narrow-band source for use in a spectral responsivity measuring setup (spectral comparator). (Characteristics of monochromators are briefly discussed in CIE Publication 63 [16]).

In order to perform this task, a monochromator must meet certain minimum requirements regarding the following characteristics:

- Spectral range
- Resolution, passband (slit function)
- Throughput (speed, F/#)
- Spectral purity (stray light)
- Wavelength uncertainty (calibration and reproducability)

Optical schematic diagrams of basic monochromators are shown in Figures 4 and 5.

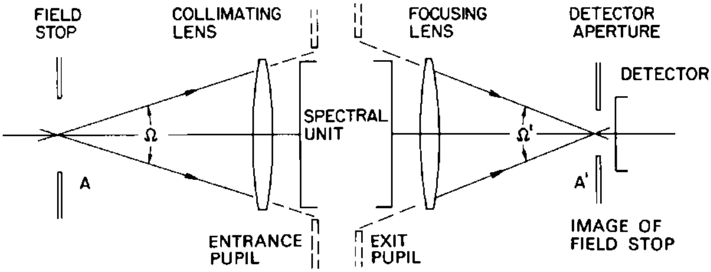

Fig. 4. Basic monochromator schematic of Goodman [17].

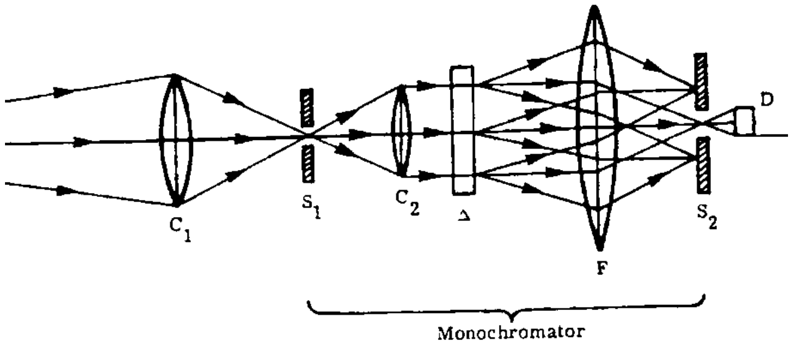

Fig. 5. Basic monochromator schematic of Zissis [18]. C_1 and C_2 are collimating lenses, S_1 is the input slit, S_2 is the output slit, Δ is the disperser, F is the focusing lens, and D is the detector.

2.2.1.3.1. Basic operation

Optical radiation entering the entrance aperture (circular or slit), is collected and collimated by the collimator lens or mirror. In Figs. 4 and 5, lenses are shown for clarity, but mirrors are normally used as they are achromatic. Collimated radiation is presented to the disperser that can be prism or grating. The disperser angularly separates the radiation as a function of wavelength. The focusing optic, which can be lens or mirror, collects the dispersed radiation and forms a series of overlapping images of the entrance aperture. The linear dispersion at the exit aperture is the angular dispersion multiplied by the focusing optic focal length. In most instances, unit magnification is used (collimator focal length equals focal length of focusing optic). The exit aperture, that can be circular or slit, selects a narrow range of wavelengths to transmit.

The spectral range is governed by the disperser. In prisms, it corresponds with the wavelength range over which the material is transmissive. In gratings it is related to grating line spacing, grating efficiency and provisions for order-blocking filters.

The resolution depends on the aperture width and the disperser resolving power.

The throughput (etendue) of a monochromator is the product of the aperture area A_{ap} and the solid angle subtended by the collimator.

$$T = \frac{\pi A_{ap}}{4\left(F/\#\right)^2} \quad \left(\mathrm{m}^{-2}\mathrm{sr}^{-1}\right) \tag{9}$$

where (*F*/#) is the focal ratio of the collimator. (It is assumed that the entrance aperture and the collimator are the limiting components.) The *F*/# is one of the important parameters for a monochromator.

The spectral purity is defined by the transmission of the monochromator outside the passband.

The wavelength uncertainty relates to the mechanical construction and to the procedure used to calibrate the wavelength scale.

2.2.1.3.2. Spectral purity

Typical stray light specification for single monochromators is 10^{-4}, the effective transmission for wavelengths outside the passband. This relatively high stray light specification causes trouble particularly at shorter wavelengths where both the source and the detector response may be low.

A single monochromator is unsatisfactory as a low-uncertainty spectral comparator. Placing two monochromators in series can improve the stray light specification to 10^{-8}, which is more than sufficient. Most double monochromators consist of two identical Czerny-Turner grating monochromators arranged such that the exit slit of the first monochromator also functions as the entrance slit of the second monochromator. The two are mounted on a common base-plate and the wavelength drives may be coupled via a timing belt. More sophisticated designs may employ the first monochromator mounted over the second monochromator such that both gratings (matched) are driven by a common shaft.

A double monochromator may be constructed on one of two ways. For additive dispersion, the gratings are arranged such that the dispersions are in the same direction, increasing the dispersion over a single monochromator. The resolution is primarily determined by the exit slit. For subtractive dispersion, as shown in Fig. 6, the mounting of the second grating reverses the dispersion of the first, and the output at the exit slit is homogenous, having all wavelengths uniformly mixed across the slit. The dispersion is that solely of the first monochromator, and the intermediate slit governs the resolution.

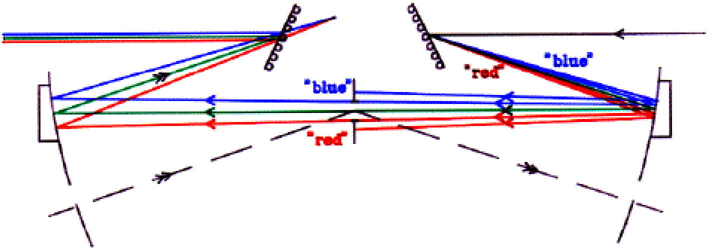

Fig. 6. Subtractive dispersion in a double-grating monochromator.

A satisfactory arrangement uses a low-dispersion prism monochromator to function as a pre-disperser (order-sorter) for a high-resolution grating monochromator. Among the most popular is the venerable Cary 14. This instrument uses a 30 degree fused silica prism and a single 600 line-per-mm echelette grating to cover the wavelength range from 185 nm to 2750 nm with few grating anomalies. The focal length of the prism monochromator is 300mm and the focal length of the grating monochromator is 400mm. The dispersion (in nm, FWHM per mm of slit width) is fairly constant at 3.5±0.2 nm/mm from 400 nm to 1700 nm, dropping to 2 nm/mm at 260 nm and at 2750nm. The arrangement of the Cary 14 prism-grating monochromator is shown in Fig. 7.

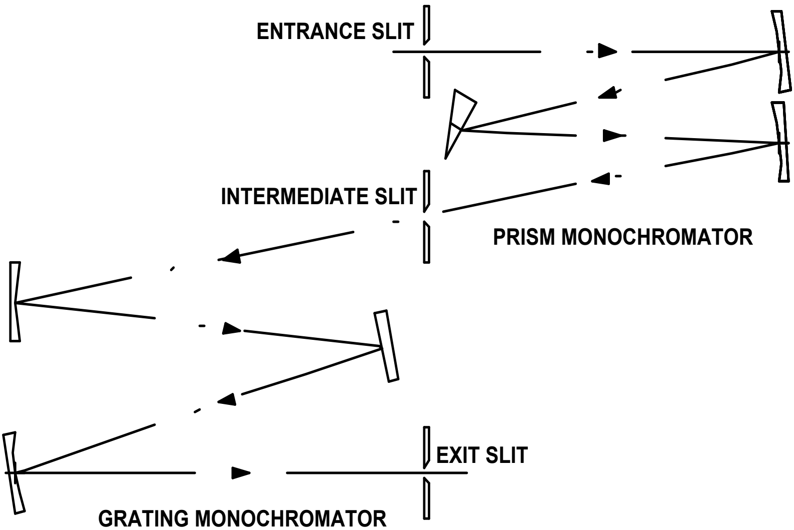

Figure 7. Scheme of the Cary 14 prism-grating double monochromator.