
SPECTRORADIOMETRY

Carolyn J. Sher DeCusatis

Pace University

White Plains, New York

38.1 INTRODUCTION

Spectroradiometry is the measurement of the spectral content of optical radiation. This has many important applications. The measure of terrestrial, direct, solar spectral irradiance between 295 and 305 nm can be used to calculate atmospheric ozone thickness.¹ More close to home, irradiance measurements are used to characterize light fixtures, and solar UV spectroradiometry methods also apply to the measurement of artificial sources that mimic the sun for applications like phototherapy to treat seasonal affective disorder (SAD) and tanning booths.² Transmission spectra are used to analyze the chemical composition of samples, such as the concentration of chlorophyll in a solution. Spectral reflectance quantifies the color of surfaces, with many practical applications to building, lighting, and design. Spectral responsivity is a necessary part of calibrating photodetectors.

38.2 DEFINITIONS, CALCULATIONS, AND FIGURES OF MERIT

Defining Quantities

There is a relationship between radiometric, photometric, and spectroradiometric quantities. Radiometric and photometric quantities, such as irradiance and luminous flux have been defined in other chapters of this book. Photometric quantities that are similar to radiometric quantities, such as radiant energy versus luminous energy, have the same symbol with a subscript of γ . In general, the spectroradiometric quantity that is defined by the similar radiometric quantity is preceded by the term “spectral,” and designated by the symbol λ , either in parenthesis or with a subscript.

Spectral Irradiance is the quantity most frequently measured in spectroradiometry.¹ Irradiance E is the total radiant flux incident on an element of surface divided by the surface area of that element

$d\Phi/dA$, in watts per meter squared. The average spectral irradiance \bar{E}_λ is the irradiance for a wavelength interval, or

$$\bar{E}_\lambda = \frac{\Delta\Phi}{\Delta\lambda \cdot \Delta A} \quad (1)$$

where $\Delta\Phi$ is the radiant flux within a wavelength interval $\Delta\lambda$ incident on a surface area ΔA . As the area and wavelength are made smaller, \bar{E}_λ becomes the spectral irradiance for that wavelength,

$$E_\lambda(\lambda, P) = \frac{d^2\Phi}{d\lambda \cdot dA} \quad (2)$$

where P is the position and λ is the wavelength. The SI unit for spectral irradiance is the watt per meter cube. However, more intuitive units, such as microwatt per square centimeter of area and per nanometer of wavelength ($\mu\text{W} \cdot \text{cm}^{-2} \cdot \text{nm}^{-1}$) are also used.

The spectral irradiance is dependant on the position, the size of the solid angle subtended, and the orientation of the surface. This leads to the cosine dependence, where the spectral irradiance of a point source is proportional to cosine θ , where θ is the angle between the normal to the surface and the direction of the source, and the inverse square law, relating to the distance between the point source and the detector.

When the radiation from a point source is emitted into a solid angle $d\Omega$, the *spectral radiance* L_λ is the flux per unit solid angle and per unit projected area perpendicular to the specified direction, per wavelength.

$$L_\lambda = \frac{d^3\Phi}{dA \cdot \cos\theta \cdot d\Omega \cdot d\lambda} \quad (3)$$

The unit for spectral radiance is watt \cdot centimeter $^{-2} \cdot$ steradian $^{-1} \cdot$ nanometer $^{-1}$.

Spectral radiance represents the flux density at a point for a particular direction through that point. While it is not usually the desired quantity an experiment is designed to measure, it is required for quantitatively analyzing data, and is also very useful for flux transfer calculations.

If you know the wavelength dependence of the radiant flux, you can also calculate *radiant flux* Φ , and *luminous flux* Φ_γ .

$$\phi = \int_\lambda \Phi(\lambda) d\lambda \quad \text{in watts} \quad (4)$$

$$\phi_\gamma = 683 \int_\lambda \Phi(\lambda) V(\lambda) d\lambda \quad \text{in lumens} \quad (5)$$

where $V(\lambda)$ is the relative photopic luminous efficiency curve (normalized at 555 nm). The absolute luminous efficacy at 555 nm is 683 lumens per watt.

Spectral transmittance $\tau(\lambda)$, which is widely measured during spectrometry, is

$$\tau(\lambda) = \phi^t(\lambda) / \phi^i(\lambda) \quad (6)$$

where t and i refer to transmitted and incident flux. The transmittance has two parts: the regular and diffuse transmittance. The regular transmittance follows Snell's law, while the diffuse transmittance is scattered by the roughness of the surface.

Similarly, *spectral reflectance* $\rho(\lambda)$ is also a flux ratio, but in this case, it is the ratio of the reflected radiant flux to the incident flux.

$$\rho(\lambda) = \phi^r(\lambda) / \phi^i(\lambda) \quad (7)$$

where r refers to reflected flux. The total reflectance is also composed of specular and diffuse components.

The *spectral responsivity* $R(\lambda)$ is the current from a detector divided by the incident flux for a specific wavelength.

$$R(\lambda) = r(\lambda) / \phi(\lambda) \quad (8)$$

where $r(\lambda)$ is the electric signal generated by the photodetector. The units of responsivity are amps per watt. Spectral responsivity is an important part of calibrating photodetectors. The spectroradiometer itself will be calibrated using a standard lamp.

Calculations

Since spectroradiometers provide the spectral content of light, it is natural to use their data to calculate color values. The *tristimulus values* for sources can be calculated,³

$$X = \sum_{\lambda=380}^{780} \bar{E}(\lambda) \bar{x}(\lambda) \Delta\lambda \quad (9)$$

$$Y = \sum_{\lambda=380}^{780} \bar{E}(\lambda) \bar{y}(\lambda) \Delta\lambda \quad (10)$$

$$Z = \sum_{\lambda=380}^{780} \bar{E}(\lambda) \bar{z}(\lambda) \Delta\lambda \quad (11)$$

where $E(\lambda)$ is the irradiance in watt · meters⁻¹, and \bar{x} , \bar{y} , and \bar{z} are the CIE 1931 spectral tristimulus values.

When analyzing the reflection off an object, the values assume the color as seen under a standard light source.

$$X = k \sum_{\lambda=380}^{780} \bar{E}(\lambda) \Gamma(\lambda) \bar{x}(\lambda) \Delta\lambda \quad (12)$$

$$Y = k \sum_{\lambda=380}^{780} \bar{E}(\lambda) \Gamma(\lambda) \bar{y}(\lambda) \Delta\lambda \quad (13)$$

$$Z = k \sum_{\lambda=380}^{780} \bar{E}(\lambda) \Gamma(\lambda) \bar{z}(\lambda) \Delta\lambda \quad (14)$$

where $\Gamma(\lambda)$ is the *spectral reflectance* or *transmittance data*, and

$$k = \frac{100}{\sum_{\lambda=380}^{780} \bar{E}(\lambda) \bar{y}(\lambda) \Delta\lambda} \quad (15)$$

Since $\bar{y}(\lambda)$ is the photopic curve, k is a constant that can be used to couple the colorimetric (photometric) quantities with the radiometric ones. This can be expressed in equation form as

$$E_v [\text{lm cm}^{-2}] = 683 Y [\text{W cm}^{-2}] \quad (16)$$

because absolute luminous efficacy of the photopic curve at 555 nm is 683 lumens per watt.

The CIE 1931 chromaticity x , y , z coordinates are

$$x = \frac{X}{X + Y + Z} \quad (17)$$

$$y = \frac{Y}{X + Y + Z} \quad (18)$$

$$z = \frac{Z}{X + Y + Z} \quad (19)$$

Similarly, the R, G, B tristimulus values are⁴

$$R = k \sum_{\lambda=380}^{780} P(\lambda) \bar{r}(\lambda) \Delta\lambda \quad (20)$$

$$G = k \sum_{\lambda=380}^{780} P(\lambda) \bar{g}(\lambda) \Delta\lambda \quad (21)$$

$$B = k \sum_{\lambda=380}^{780} P(\lambda) \bar{b}(\lambda) \Delta\lambda \quad (22)$$

where $P(\lambda)$ is the spectral power distribution in watts, and \bar{r} , \bar{g} , and \bar{b} are the color-matching functions of the CIE 1931 Colorimetric Observer.

The UCS 1960 u and v coordinates, and the UCS 1976 u' and v' coordinates are³

$$v = \frac{6y}{12y - 12x + 3} = \frac{2}{3} v' \quad (23)$$

$$u = \frac{4x}{12y - 12x + 3} = u' \quad (24)$$

The CIE LAB/LUV color space calculations (1976) are calculated using the tristimulus values normalized equally to $Y = 100$. X_n , Y_n , and Z_n are the tristimulus values of the reference white. The coordinates can be defined in either the $L^*a^*b^*$ color space, or the $L^*u^*v^*$ color space. When X/X_n , Y/Y_n , and Z/Z_n are all greater than 0.01,

$$L^* = 116 \left(\frac{Y}{Y_n} \right)^{1/3} - 16 \quad (25)$$

$$a^* = 500 \left[\left(\frac{X}{X_n} \right)^{1/3} - \left(\frac{Y}{Y_n} \right)^{1/3} \right] \quad (26)$$

$$b^* = 200 \left[\left(\frac{Y}{Y_n} \right)^{1/3} - \left(\frac{Z}{Z_n} \right)^{1/3} \right] \quad (27)$$

Otherwise

$$L^* = 116 \left[f \left(\frac{Y}{Y_n} \right) - \left(\frac{16}{116} \right) \right] \quad (28)$$

$$a^* = 500 \left[f \left(\frac{X}{X_n} \right)^{1/3} - f \left(\frac{Y}{Y_n} \right)^{1/3} \right] \quad (29)$$

$$b^* = 200 \left[f \left(\frac{Y}{Y_n} \right)^{1/3} - f \left(\frac{Z}{Z_n} \right)^{1/3} \right] \quad (30)$$

where

$$f(Y/Y_n) = \left(\frac{Y}{Y_n} \right)^{1/3} \quad \text{for } Y/Y_n > 0.008856 \quad (31)$$

$$f(Y/Y_n) = 7.787 \left(\frac{Y}{Y_n} \right) + 16/116 \quad \text{for } Y/Y_n \leq 0.008856$$

and $f(X/X_n)$ and $f(Z/Z_n)$ are defined in the same way, and

$$u^* = 13L^*(u' - u'_n) \quad (32)$$

$$v^* = 13L^*(v' - v'_n) \quad (33)$$

These values represent a comparison to a standard illuminant for sources and an ideal white object illuminated by a standard illuminant for objects.³

The *correlated color temperature* is calculated using interpolation from a table of 30 isothermperature lines. Robertson's method, which uses successive approximation, should be accurate to within 0.1 μrad , with a maximum error from 1600 to 3000 K of less than 0.2 K plus the measurement uncertainty. This technique should only be used for sources with chromaticities farther than 0.01 from the Planckian locus.³

When using a spectroradiometer or spectrophotometer to measure transmission through a sample, the *Beer-Lambert law*, also known as *Beer's law* is used to calculate the *concentration* of a sample solution. The absorbance A is defines as

$$A = -\log_{10}(\tau) \quad (34)$$

where τ is the transmittance. The Beer-Lambert Law states:

$$A = cl\alpha \quad (35)$$

where c is the concentration, l is the path length, and α is the absorption coefficient.

The absorption coefficient is related to the wavelength by

$$\alpha = \frac{4\pi k}{\lambda} \quad (36)$$

where k is the extinction coefficient.

Figures of Merit

Spectroradiometry measurements have large errors compared to other physical measurements. During an intercomparison of solar ultraviolet monitoring between 14 instruments the measured solar irradiances agreed to within 3 percent when the instruments remained outdoors, but the spectral irradiance responsivities changed upon moving the instruments.⁵ In a 2002 intercomparison study by the project Quality Assurance of Ultraviolet Measurements in Europe (QASUME), the spread of absolute irradiance between spectroradiometers was 12 percent(± 6 percent).⁶ There are two major reasons for the large uncertainties:

- The measurement has many dimensions—it is dependent on the magnitude of the flux, its position on the entrance aperture, its direction, its wavelength distribution, and its polarization.
- The instability of measuring instruments and standards, which are very dependent on room conditions such as temperature, and are frequently off by 1 percent or more.

Potential errors in spectroradiometer measurements include measurement noise, detector instability, wavelength instability, nonlinearity, directional and positional effects, spectral scattering, spectral distortion, polarization effects, and size of source effect.¹

These errors can be characterized as³

- Random noise from the detector, electronics, and light source
- Systematic errors from
 - The measurement of the geometry
 - The calibration, including uncertainty from the calibration standard

Noncosine collection of light
 Stray light
 Nonlinearity of the detector and its electronics
 Dark noise subtraction errors

- Periodic errors from drifts due to temperature, humidity, air movement, electronics, beating of AC sources, and changes in stray light

The way of calculating uncertainty was standardized in 1992 by the International Committee for Weights and Measures (CIPM), and the *Guide to the Expression of Uncertainty in Measurement* was published in 1993.⁷ There are two ways to determine the uncertainty of a component: A. statistically or B. “usually based on scientific judgment using all the relevant information available.”⁸

In spectroradiometry, Type B evaluation finds the upper and lower limits of the value (or correction), and then assumes a probability distribution between these values to obtain the standard uncertainty. If you have nothing to base the probability distribution on, you are instructed to assume that it is rectangular (uniform).

For example, for value a where $a = (a_+ - a_-)/2$, where a_+ is the upper limit and a_- is the lower limit, the standard uncertainty is $a/\sqrt{3}$, but assuming a triangular distribution makes it $a/\sqrt{6}$, and a Gaussian distribution makes it $a/3$.

The collected uncertainties for each identified potential error combines as the square root of the sum of the squares, called the *suggested* or *overall uncertainty*. Often this value is multiplied by a constant, under current international practice of value 2, to form the expanded uncertainty.

CIPM requires that all the standard uncertainties and their derivation are included in the uncertainty report.^{7,8}

If your value for spectral irradiance can be expressed of the form

$$E_{\lambda}^{\text{report}} = E_{\lambda}^{\text{observed}} + c_1 + c_2 + c_3 + \cdots + c_n \quad (37)$$

where $E_{\lambda}^{\text{report}}$ is the reported spectral irradiance, $E_{\lambda}^{\text{observed}}$ is the measured value of the spectral irradiance, and the c_i 's are the corrections mentioned earlier in this section, then by the CIPM method, the uncertainty U is calculated from the uncertainties u of the parts as follows

$$U = 2\sqrt{u^2(E_{\lambda}^{\text{observed}}) + u^2(c_1) + u^2(c_2) + u^2(c_3) + \cdots + u^2(c_n)} \quad (38)$$

Spectroradiometers are calibrated by use of a standard, which has a known value with a reported error. Assuming your system is linear,

$$E_{\lambda}^{\text{obs}} = \frac{S}{S^s} E_{\lambda}^s \quad (39)$$

where S is the measurement and the superscript s refers to the standard.

Then, the uncertainty of the observed spectral irradiance can be calculated using

$$u(E_{\lambda}^{\text{obs}}) = E_{\lambda}^{\text{obs}} \sqrt{\left(\frac{u(S)}{S}\right)^2 + \left(\frac{u(S^s)}{S^s}\right)^2 + \left(\frac{u(E_{\lambda}^s)}{E_{\lambda}^s}\right)^2} \quad (40)$$

The values for $u(S)$ and $u(S^s)$ are typically calculated by a Type B evaluation, while the standard lamp's uncertainty $u(E_{\lambda}^s)$ is calculated from the uncertainty U reported by the standard lamp's supplier.¹

38.3 GENERAL FEATURES OF SPECTRORADIOMETRY SYSTEMS

There are four parts in every spectroradiometer system

- Input or fore-optics
- A monochromator
- A detector
- Electronics and software to analyze data

There is a fifth aspect to every spectroradiometer system, although it is not usually included on these types of lists, because it is not a “part” of the spectroradiometer. However, I believe it is important to consider it while considering other fundamental parts of the system, because it is essential for the accurate measurement of optical radiation:

- Calibration, usually using standard lamps, reflectance standards, or a standard detector

The Input or Fore-Optics

The input optics gathers light from a specified field of view. The layout determines the quantity which is being measured. For example, when measuring spectral irradiance, the light must be diffused, so an integrating sphere or diffusing plate is used, but when measuring spectral radiance, imaging optics control the solid angle and source area, so a focusing mirror is typically used. Transmittance can be measured by placing a light source at the entrance of the system, and measuring the signal twice: with and without the object to be measured. However, an instrument dedicated to measuring transmittance may have a double beam optical design where the light source is split and recombines at the photodetector.

For measurements in the ultraviolet, or light below 190 nm, the radiation is absorbed by the oxygen in the air, so the whole system will be designed to be enclosed and under vacuum.

Telescoping input optics are used when the sources are large distances from the measurement system, turning a spectroradiometer into a telespectroradiometer. Mounting a microscope to the entrance port of the monochromator can make it possible to measure small radiating sources. Fiber-optic probes can be coupled directly to the monochromator, or in combination with any of the previously mentioned input optical devices.³

The Monochromator

The monochromator is the heart of the spectroradiometric system, because separating the radiation into its component wavelengths is the fundamental aspect of the system. While monochromators used to be made with prisms, they are now always made with diffraction gratings. Monochromators come in different sizes; a large monochromator will be more accurate, but a smaller monochromator can be easier to evacuate to measure the ultraviolet, or place in a dry carbondioxide-free enclosure to measure the infrared.

The monochromator is designed to collimate and focus light. After the entrance slit, light hits a collimating element. Since light is often diverging when it reaches the slit, a concave mirror can form it into a collimated beam directed at the grating.

Generally, the grating will rotate so this beam hits it at different angles. There are also monochromators with curved gratings, but they are limited in wavelength range.

The grating equation, which defines the wavelength of the diffracted flux to the angle of diffraction, is

$$m\lambda = d(\sin\theta \pm \sin\beta) \quad (41)$$

where m is an integer known as the *order of diffraction*, λ is the wavelength, d is the distance between grooves, θ is the angle of incidence, and β is the angle of diffraction. To remove higher orders ($m > 1$), *blocking filters* that absorb short wavelengths while transmitting long wavelengths are used.

The maximum theoretical groove density is $2/\lambda$, although a practical limit is usually 0.85 of the maximum.

The efficiency of a monochromator is directly proportional to large grating area, short focal length, high groove density, long slit length, and high transmittance.¹ However, there is a trade-off between this efficiency and accuracy, which requires large focal lengths. The f -number is the focal distance divided by the entrance slit. Large f -numbers (>3 or 4) are required because the mirrors are spherical, not parabolic, and introduce errors.³

The *dispersion* is the width of the band of wavelengths per unit of slit width, in nm/mm. The *band pass* is the spectral interval that may be isolated. If the dispersion at a groove density k is known, then the band pass can be calculated

$$B = (n_k D(n_k) S) / n \quad (42)$$

where B is the bandpass (in nm), n_k (in grooves/mm) is the known groove density where $D(n_k)$ is its dispersion (in nm/mm), S is the slit width (in mm), and n (in grooves/mm) is the groove density of the grating used.

Bandpass should be small for the best precision. However, there is a trade-off between bandpass and *geometrical etendue* G the light gathering power of an optical system.

$$G = \frac{h n m G_A B}{F 10^6} \quad (43)$$

where h is the slit height (mm), n groove density (groove/mm), m is order of the grating, G_A area of the grating (mm²), B is the bandpass (nm), and F is the focal length (mm). The ratio h/F implies that the etendue may be increased by making the height of the entrance slit larger. However, this does not work as well in practice; increasing the height of the slit will increase stray light and may also increase the system aberrations, reducing the bandpass.

Geometrical etendue is a limiting function of system *throughput*.⁹

High signal, for which high throughput is necessary, is limited by bandpass. Sometimes the slit size is determined by other factors, like the field of view. But the slit size might be chosen to optimize other factors. In this case, monochromatic sources behave differently from broadband sources, and mixed sources are a combination of the two. For a fluorescent lamp, which is a mixed source, as you decrease the bandpass, the peaks due to the monochromatic lines become much higher in proportion to the broad emission spectra of the phosphors.³

In night vision systems, stray light becomes an important factor which affects system design. To limit stray light, a double monochromator system is used, where the output of the first monochromator is the input of the second one. This can reduce typical stray light levels from 10^{-4} to 10^{-8} .³

Some spectroradiometers are designed with multichannel detectors within the monochromator, or so multichannel detectors can be easily installed. Multichannel detectors can also eliminate the need to scan, reducing moving parts and allowing for longer integration times or quick measurements of unstable or short-lived sources. However, they are not suitable for all types of spectral irradiance and radiance measurements, and spectral transmission, reflection and responsivity require the monochromatic light to exit the monochromator and interact with samples.

The Detector

The desired wavelength range will strongly influence the type of detector used. In Table 1 the approximate wavelength ranges of different spectroradiometry detectors are shown. Other important factors in choosing a detector include the dynamic range, sensitivity, and response time required for the data, as well as environmental factors determining how rugged a detector is needed.

TABLE 1 Approximate Wavelength Ranges of Different Spectroradiometry Detector Types

Detector	Wavelength Range
PMT	200–850 nm
Si photodiode	200–1100 nm
Ge photodiode	1100–1800 nm
InGaAs photodiode	850–1700 nm
PbS photoconductor	1–4.5 μm
PbSe photodiode	1–4.5 μm
InSb photodiode	1.5–5 μm
Pyroelectric	500 nm–50 μm
CCD	200–1100 nm
InGas PDA	800–1700 nm

The two types of detectors most commonly used in spectroradiometry are photomultiplier tubes and semiconductor devices, although thermal detectors have some very limited applications. Detector sensitivity is measured in noise equivalent power (NEP) or equivalent noise input (ENI), which basically mean the same thing, the minimum detectable signal, whose units can be taken in watts.¹ The detectivity is the inverse of the NEP.

Photomultiplier tubes are the most sensitive detectors when used in their wavelength region, with ENIs ranging from 10^{-15} W at 1100 nm to 10^{-17} W from 850 nm to 200 nm and 5×10^{-16} W at 110 nm. They are usually used from 200–850 nm, their range of greatest sensitivity. Silicon photodiodes have NEPs reported of 2×10^{-14} W at 1100 nm, 10^{-15} W at 850 nm, 5×10^{-15} W at 350 nm, and 10^{-14} W between 300 and 200 nm. Silicon photodiodes are used in these wavelength ranges when the signal is sufficiently large, because they are more temperature stable and more rugged.¹

From 1100 to 1800 nm, germanium photodiodes are the most sensitive, with NEPs in the 10^{-13} W range, and lead sulfide photoconductors the most sensitive from 1800–3800 nm, with NEPs ranging from 4×10^{-13} W to 4×10^{-12} W, although InAs may also be used in this range.¹

Photomultipliers, germanium photodiodes, and PbS photoconductors would be cooled, but silicon photodiodes can operate at room temperature (25°C).

Thermal detectors are less sensitive, having NEPs of about 6×10^{-10} W, and have a flat response.¹

When comparing detectors, it is also common to compare the normalized detectivity. There is some confusion in the nomenclature, in that sometimes this is D^* , and sometimes D^* refers to the specific detectivity, which has a different definition. Therefore, I will refer to the normalized detectivity as D_N .

$$D_N = D \sqrt{AB_w} \quad (44)$$

where D is the detectivity, A is the detector area, and B_w is the detector bandwidth.

For example, the D_N of an InAs photodiode is roughly the same as that of a PbS photoconductor at 3000 nm, and the rise time for InAs is one thousandth of PbS. At that specific wavelength, the two detector types have equivalent sensitivity, but InAs has a faster response. However, the D_N drops off more rapidly for InAs at longer and shorter wavelengths than for PbS.¹

Multichannel detectors are sometimes used for spectroradiometry. They have the advantage in spectral irradiance and radiance measurements that they can eliminate the need to scan, reducing moving parts and allowing for longer integration times, as well as making measurements of nonstable sources or short-lived, such as flashbulbs, explosions, and solar measurements during changing weather conditions, possible. Silicon photodiode linear arrays (PDAs) and charge-coupled detectors (CCDs) both singly and with microchannel plates (intensified arrays) are used, as well as a combination of microchannel plates with resistive film called resistive anode (MCP-RA's).¹ These detectors are temperature dependent and therefore require cooling. Noise is also a factor.

The NEP of array detectors is measured with respect to integration time. This is because array detectors operate in the capacitive-discharge mode, which collects charge for a period of time before

TABLE 2 A Comparison of the NEP in Watts of Five Different Multichannel Detector Types with 5-Second Integration Times.

Detector Type	250 nm	550 nm	850 nm	1100 nm
Si PDA at -40°C	$1.4 \cdot 10^{-15}$	$2.7 \cdot 10^{-16}$	$2.2 \cdot 10^{-16}$	$1.3 \cdot 10^{-15}$
CCD at -110°C	$6.0 \cdot 10^{-18}$	$1.6 \cdot 10^{-18}$	$1.0 \cdot 10^{-18}$	$2.5 \cdot 10^{-17}$
Intensified Si PDA at -40°C	$1.3 \cdot 10^{-18}$	$8.2 \cdot 10^{-19}$	$1.1 \cdot 10^{-17}$	
Intensified CCD at -110°C	$1.3 \cdot 10^{-18}$	$8.3 \cdot 10^{-19}$	$1.1 \cdot 10^{-17}$	
MCP-RA at -30°C	$2.0 \cdot 10^{-18}$	$1.3 \cdot 10^{-18}$	$7.3 \cdot 10^{-18}$	

This data is compiled from Tables 15.4, 15.6, 15.7, 15.9, and 15.11 of Ref. 1.

discharging, which will be discussed in more detail in the next section on electronics and software. However, in Table 2 you can see a comparison of the NEP of the five different types of detectors at integration times of 5 seconds. It can be noted that CCD detectors have NEPs comparable with photomultiplier tubes, even without the advantage of multichannel detection.

While the detectors compared above were all cooled, there exist many commercial spectroradiometers with multichannel detectors which are not cooled for applications where sensitivity is less important, such as projector calibration and film and video post production.

Signal to noise ratio is also a major concern when comparing detector types, but that is also dependent on the integration time. As a general rule, the signal to noise ratio is much lower for PDAs than other multichannel detectors, but at 0.5 second integration times, CCDs are superior.¹

Spectral scattering is a more important concern with multichannel detectors than with single detectors. Interference filters are used to block the short wavelength scattered flux.

The Electronics and Software

In “The Detectors” section we have discussed photomultiplier tubes, semiconductor detectors (photodiodes and photoconductors), PDA-based detectors, and CCD-based detectors.

Photomultiplier tubes use a 250- to 2500-V power supply, and the gain of the detector is adjusted by changing the voltage of the power supply. The signal is the anode current, and the simplest way of measuring it is measuring the voltage drop over a load resistor. However, many problems can be eliminated by using an operational amplifier with a feedback resistor instead, creating a transimpedance current to voltage converter. For even lower signal to noise ratios, integrated current is used as the signal, and the amplifier is chosen to have a short enough time constant that the entire anode current is integrated during the entire sampling time. It is important to make sure that the integrating time is properly matched with the scanning time.

Photodiodes are usually used in the photovoltaic or unbiased mode to minimize noise. In this mode a voltage amplifier with a high-input impedance measures the voltage generated across the photodiode.

Photoconductors decrease in resistance when absorbing radiant flux. The detector is placed in series with a load resistor and a bias voltage. As the resistance of the detector decreases there is an increase in the voltage over the load resistor.

Lock-in amplifiers are often used with semiconductor detectors to decrease 1/f noise.

PDA-based detectors operate in the capacitive-discharge mode where the photodiodes store charge as well as sense light. The diodes are reverse biased for 5 V and then electrically isolated while being exposed to light. After an integration time, the charge required to bring the diode back to 5 V is measured.

CCD-based detectors have arrays of pixels that convert radiation to charge. Parallel gates between the pixels can release the charge at will. The charge is then moved along the channels of the arrays by changing the voltage at the gates, until it reaches an output shift register at the end of the channel. The charge is then amplified and measured. Sometimes neighboring pixel's values are intentionally combined, which is known as *binning* or *pixel summation*.

While the readout of a single detector's signal can be as simple as a digital voltmeter, in most cases spectroradiometric data will be recorded by a computer. Often it will be part of an automated system that also controls the drive mechanism. After the information is recorded by the computer, it is analyzed by the computer software. Examples of typical calculations performed on spectroradiometric data are in Sec. 38.2 "Definitions, Calculations, and Figures of Merit" under Calculations.

Calibration

To calibrate a spectroradiometer for irradiance and radiance, standard lamps are usually used, although standard detectors are available. While spectroradiometric standards available for use over the visible are based on the spectral radiance of a blackbody as defined by Planck's radiation law, most commercially available blackbodies are used primarily in the infrared at wavelengths above 1000 nm. Blackbodies suitable for the visible are very expensive because they must operate at temperatures of 2500 K or higher, and are not practical for normal laboratory calibrations.³

Standard lamps introduce a certain degree of error; in the ultraviolet intercomparison in 2002 where the error was 12 percent (± 6 percent), 6 percent of that error was attributed to the calibration lamps.⁶ In earlier intercomparisons, it was more like 1.4 percent from 250 to 2400 nm, but 3 to 4 percent in the infrared.¹

Different lamps are used to calibrate over different wavelength regions. From wavelengths of 250 to 2400 nm, tungsten lamps are used; below 250 nm, a deuterium lamp, argon miniarc, or synchrotron radiation are used.¹

In Table 3 the wavelength range of frequently used spectral irradiance and spectral radiance source standards is listed.

For a discussion of the history of calibration standards, and some additional standards see reference.³

The FEL 1000-W tungsten lamp is the most widely used source standard for spectral irradiance. It is a commercially available 1000-W clear quartz envelope tungsten-halogen, coiled coil filament lamp that is modified to a medium bipost base with 1/4-inch diameter stainless steel posts. It is 5 inches high with a filament about 1 inch long and 1/4 inch in diameter. It is operated at 8-A DC and about 120 V. It is mounted base down with the steel post vertical and the optic axis of the spectroradiometer is horizontal. For more details of the calibration procedure, see reference.¹

It is important to recognize that any individual standard lamp may develop problems. It is recommended to have three standard lamps, so if one changes significantly, you still will have two that agree. It is also standard procedure to transfer the calibration of your newly acquired standards to working standards, lamps that you calibrate using your detector and the NIST traceable standards that have been shipped to you. These lamps can be commercially acquired, but then you must age them for 40 hours at 120-V DV and check them for stability; they must have a drift of less than 0.5 percent at 650 nm in 24 hours. The working standard should be compared to your three purchased standards after 50 to 100 hours of use.

The responsivity of the spectroradiometer can be modeled from a measurement equation, although it is necessary to actually calibrate any system.

TABLE 3 The Wavelength Range of Frequently Used Spectral Irradiance and Spectral Radiance Source Standards

Irradiance	
Tungsten FEL lamp	250–2400 nm
Deuterium lamp	165–350 nm
Argon mini-arc	90–350 nm
Radiance	
Tungsten strip lamp	225–2400 nm
Blackbody below 1000 K	1000–4000 nm
Argon miniarc	90–350 nm

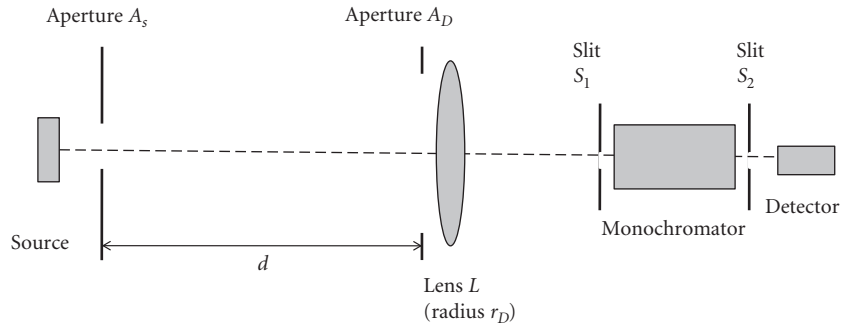


FIGURE 1 A schematic of the experimental setup to measure the spectroradiometer's responsivity.

If the monochromator is set to a wavelength λ_0 , the spectral responsivity $R(\lambda_0, \lambda)$ can be separated into two parts: the slit scattering function $\rho(\lambda_0, \lambda)$ which is an envelope around wavelength λ_0 and the overall responsivity as a function of wavelength $R^f(\lambda)$

$$R(\lambda_0, \lambda) = \rho(\lambda_0, \lambda) R^f(\lambda) \quad (45)$$

When put in an experimental setup shown in Fig. 1, the signal response for a monochromator, ignoring small corrections, is

$$r(\lambda_0) = \frac{A_s A_D}{(r_s^2 + r_D^2 + d^2)} \int_{\lambda} L_{\lambda}(\lambda) \rho(\lambda_0, \lambda) R^f(\lambda) d\lambda \quad (46)$$

where A_s is a circular aperture in front of a standard radiometric source of radius r_s , A_D is an aperture a distance d away from the source in front of a focusing lens L of radius r_D , and $L_{\lambda}(\lambda)$ is of the Lambertian calibration source.¹⁰

If the constants are collected in a term C , and a suitably averaged luminance is used, the signal response can be calculated by

$$r(\lambda_0) = CL_{\lambda}(\lambda_0) \int_{\lambda} \rho(\lambda_0, \lambda) R^f(\lambda) d\lambda \quad (47)$$

Detector standards are also available. In this case, the assumption is that any drift is not very wavelength specific. It is possible to interpolate between calibration laser wavelengths using a blackbody,¹⁰ but that is not usually done, because it is very time consuming and probably an insignificant difference within the larger sources of error.¹ Detectors that presently are suitable for use in transfer standards include silicon, germanium, and InGas photodiodes, and certain types of thermal detectors. The basic approach is to have the two detectors measure the same sources. A typical source is a continuous wave (CW) laser directed at the entrance aperture of an integrating sphere. Types of lasers which can be used are helium-neon, argon, krypton, helium-cadmium, Nd:Yag, and Ti:sapphire.¹¹ When using a detector standard to calibrate a spectroradiometer's spectral irradiance, the area of the entrance aperture and spectral slit width become important and must be taken into account, so it is not a simple measurement.¹

Spectroradiometers are used for reflectance measurements as well as irradiance and radiance measurements. For these purposes, reflectance standards are used for calibration. A number of reflectance standards are available which have been developed for spectroscopy applications, as well as to calibrate colorimeters and spectrophotometers. Specular reflectance standards are calibrated mirrors, and diffuse reflectance standards are made of material similar to the inside of integrating spheres.

Labsphere makes Spectralon into a diffuse white standard and a selection of diffuse gray and color standards, which are calibrated and NIST traceable. Halon, a trade name for polytetrafluoroethylene

(PTFE) powder (which is also used to coat integrating spheres) is also used to make NIST traceable reflectance standards. In a round-robin intercomparison of bidirection diffuse reflectance (BRDR) four types of diffuse reflectors (spectralon, halon, sintered halon, and vacuum deposited aluminum on a ground aluminum surface) were measured at five laboratories. These four types of standards were chosen because of their different scattering mechanisms; Spectralon and pressed PTFE scatter from the bulk, aluminum scatters from the surface, and sintered PTFE scatters from both the bulk and the surface. The purpose of this experiment was to test the laboratories, not the standards, but there was general agreement with the NIST specifications to 2 percent.¹²

38.4 TYPICAL SPECTRORADIOMETRY SYSTEM DESIGNS

Spectral Irradiance and Radiance

The input optics for spectral irradiance measurements require a diffuser in order to eliminate or reduce directional, positional, and polarization effects. This diffuser can be an integrating sphere coated with Halon, which is the best choice for sunlight and large or irregularly shaped sources, a plane reflector diffuser coated with BaSO_4 , or a transmitting diffuser made of teflon.

In Fig. 2 we see a block diagram of a spectroradiometer designed to measure spectral irradiance. The basic steps that have to be taken are the signal must be diffused (cosine corrected), then wavelength selected by the monochromator, after which it is detected by the detector, amplified and analyzed.

In certain special cases, such as when measuring the spectral irradiance of point sources or collimated sources, and if the spectroradiometer responds uniformly over the angular field viewed, no input optics are necessary. However, most of the time input optics are necessary. In Fig. 3 we see a typical setup of the input optics for measuring the irradiance of a large source using a small integrating sphere and a spherical mirror. A typical small sphere may have a 2.5-cm outer diameter with a 3-mm-thick PTFE coating (or BaSO_4 in the 310 to 350 nm wavelength region, where PTFE fluoresces weakly), and a circular entrance port of 1 cm² and a rectangular exit port with dimensions

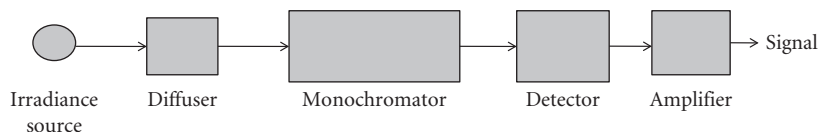


FIGURE 2 Block Diagram to measure spectral irradiance.

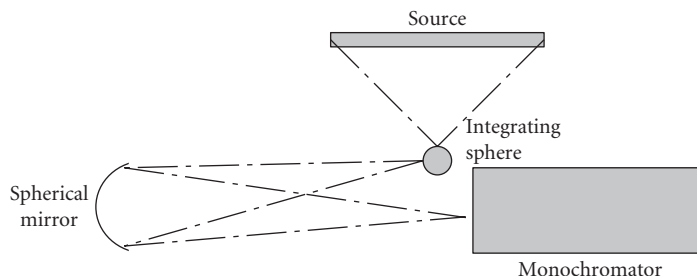


FIGURE 3 Typical setup of the input optics for measuring the irradiance of a large source using a small integrating sphere and a spherical mirror.

3 mm \times 12 mm. The radiation which has one reflection does not get into the monochromator because it is reflected away from the spherical mirror. The radiation that does reach the monochromator is independent of the direction and position of the incident flux. However, it is worth noting that the attenuation of a system of this type is large.

In Fig. 4 we see more compact input optics to measure irradiance. The disadvantages are that the sphere is harder to reach, position, and orient, and more stray flux reaches the monochromator.

In Fig. 5 we see typical input optics using a plane diffuser instead of an integrating sphere. In Fig. 6 we see typical input optics using a transmitting diffuser.

In Fig. 7 we see the schematic of a single monochromator and Fig. 8 we see the schematic of a double monochromator. Both of these designs assume an external detector outside the exit slit. In Fig. 9 we see the layout of a single grating monochromator with a built-in multichannel detector.

The input optics for measuring spectral radiance form an image of the source on the entrance port of the monochromator. Possible geometries include a plane and spherical mirror which focus

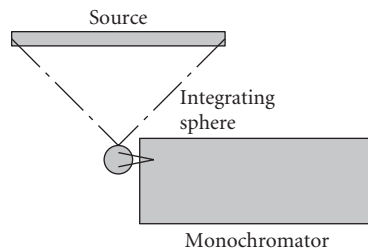


FIGURE 4 Measuring irradiance directly using an integrating sphere.

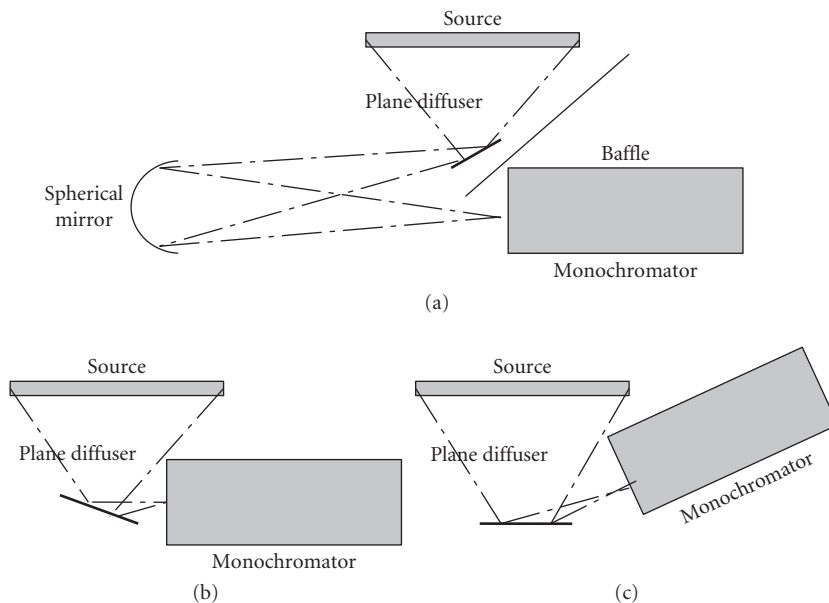


FIGURE 5 Typical setups using a plane diffuser to measure irradiance: (a) with a spherical mirror, (b) and (c) directly reflected off the diffuser into the sphere.

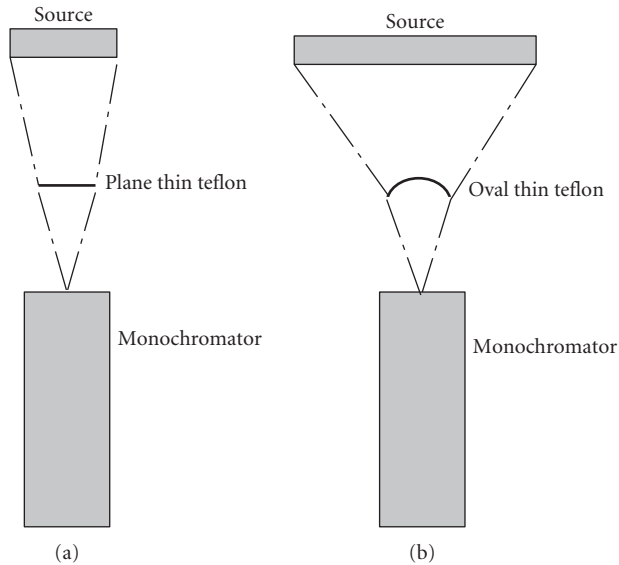


FIGURE 6 Typical input optics for irradiance measurements using a (a) plane thin teflon diffuser and (b) oval shaped thin teflon diffuser.

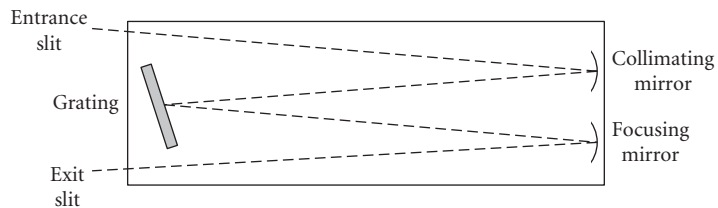


FIGURE 7 Schematic of a single monochromator.

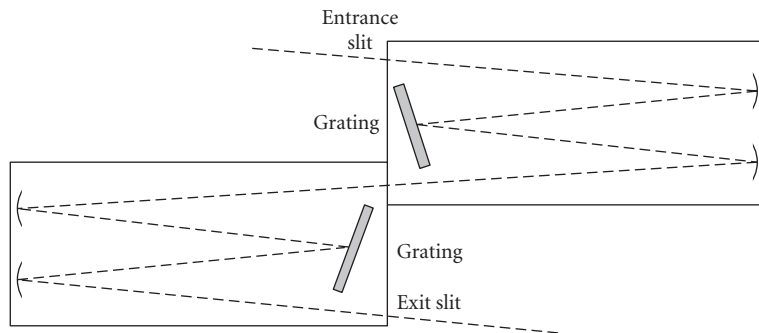


FIGURE 8 Schematic of a double monochromator.

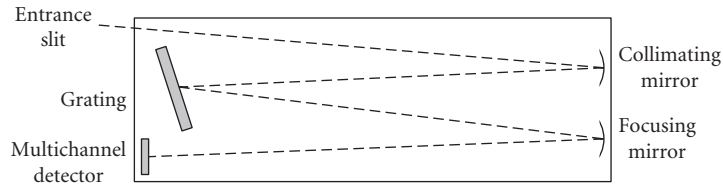


FIGURE 9 Schematic of a single monochromator with a built-in multichannel detector.

the radiation on the entrance slit, and a field of view baffle attachment to limit the acceptance angle of the monochromator.

In Fig. 10 we see the simplest input optics for measuring spectral radiance. However, it is much more likely you are using a system that measures both irradiance and radiance. In that case, your input optics are more likely to look like Fig. 11, where a mirror will reflect the light away from the integrating sphere, and toward the spherical mirror.

The same monochromator and detection electronics would be used for irradiance and radiance measurements.

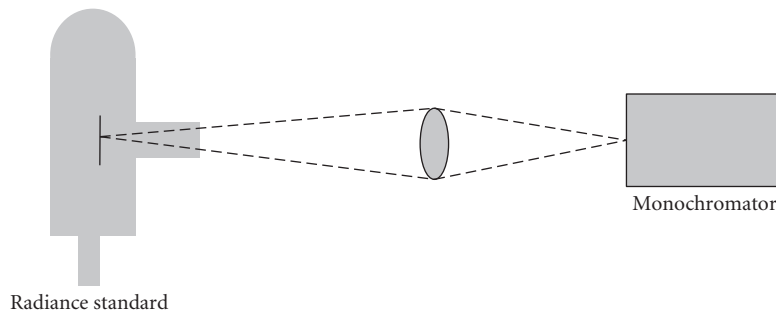


FIGURE 10 Measuring spectral radiance.

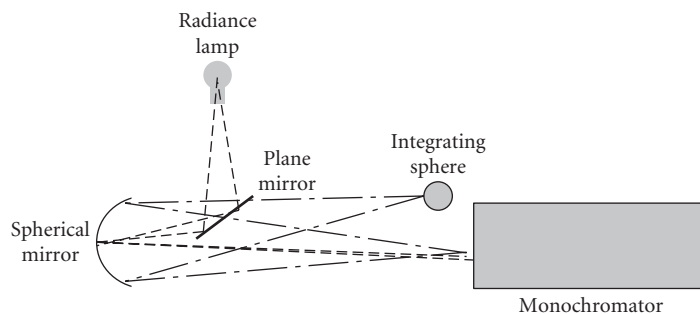


FIGURE 11 System for measuring both irradiance and radiance. The radiance setup adds a plane mirror and measures the radiance lamp. The irradiance setup removes the plane mirror and measures light after it passes the integrating sphere.

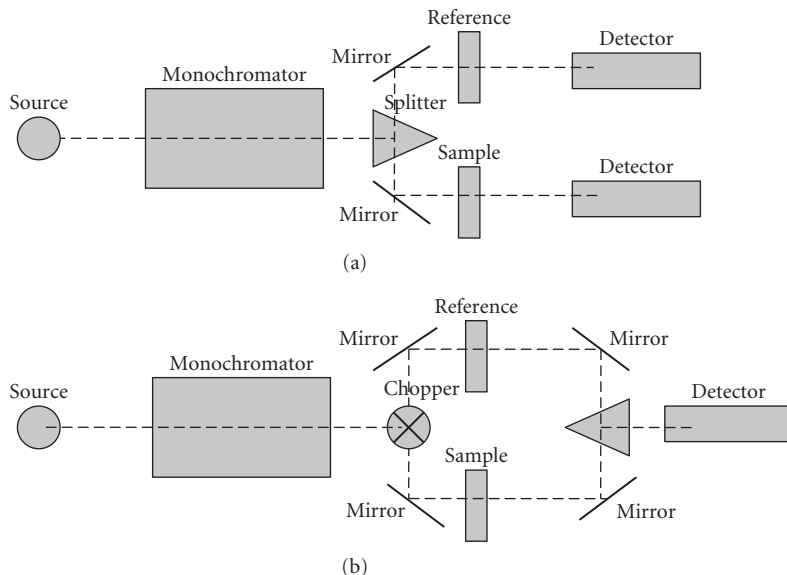


FIGURE 12 Spectrophotometer measuring spectral transmission: (a) dual-beam design and (b) double beam design.

Spectral Transmittance

Spectral transmittance measurements use the source and monochromator to create monochromatic radiation, rather than to measure it. The goal is to pass the radiation through a sample, to measure the sample's properties. This application is of vast importance to biology and chemistry, and there are many commercially available spectroradiometers dedicated to measuring transmittance and reflectance, known as *spectrophotometers*.

Chemists use absorbance spectroscopy to obtain qualitative and quantitative information about samples, using the Beer-Lambert law, also known as Beer's law, as was discussed in Sec. 38.2. Most spectrophotometers use a dual or double beam configuration, as is shown in Fig. 12. This experimental design measures regular transmittance, the signal that passes directly through the sample without being scattered and follows Snell's law. The output is the ratio of the signal in the sample beam to the signal in the reference beam with respect to wavelength. It is necessary to ensure that the only difference between the sample beam and the reference beam is the quantity to be measured, which implies that liquid cells with equal amounts of solute, or gas cells with equal amount of carrier gas, should be placed in the reference beam.¹³

Because of fluorescence, broadband illumination may have different results than monochromatic illumination. This should be considered when measuring transmittance and the setup should approximate the same manner in which the material will be used. Total spectral transmission, which is a combination of regular and diffuse transmission requires the addition of an integrating sphere after the beam transmits through the sample.³

Spectral Reflectance

Manufacturers use spectral reflectance information to provide color information about inks and textiles. There exist several spectral libraries (USGS,¹⁴ Johns Hopkins,¹⁵ JPL¹⁶) which contain almost 2000 spectra of powdered materials for use in spectroscopy, measured by using spectrophotometers and spectrometers in the diffuse reflectance mode.

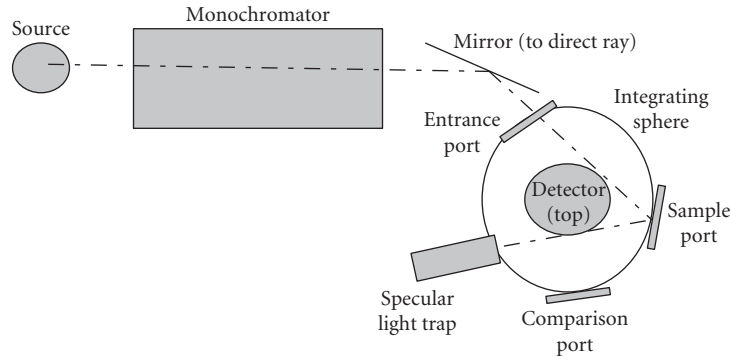


FIGURE 13 Schematic of a spectroradiometer measuring diffuse spectral reflectance.

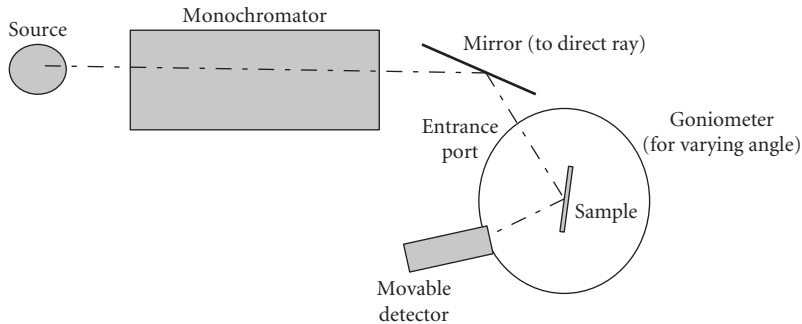


FIGURE 14 A schematic of a spectroradiometer measuring specular spectral reflectance.

Figure 13 is a spectroradiometer configured for measuring diffuse spectral reflectance. There is a double beam design, allowing for the comparison method of using a diffuse reflectance standard. An integrating sphere collects the diffuse radiation, with a removable light trap allows the user to block spectral reflectance. If the light trap is not in place, total reflectance, rather than diffuse reflectance, is measured. The sample to be measured is placed in the sample port, and the standard is placed in the comparison port. The detector is perpendicular to the samples and the incident radiation.

Figure 14 is a spectroradiometer configured for measuring specular spectral reflectance. Specular reflectance can be measured at various angles of incidence, including 0° for a 100 percent reading. A calibrated mirror (specular reflectance standard) is not necessary in this design.

Spectral Responsivity

In 38.3 General Features of Spectroradiometer Systems under “Calibration” we discussed how to calculate the spectral responsivity (see Fig. 1) of the spectroradiometer. Once that is known, spectroradiometers can be used to find the spectral responsivity of other detectors.

A spectroradiometer can be configured to measure detector spectral responsivity. The first step uses the spectroradiometer’s standard detector to measure the monochromatic flux or irradiance of the source, generating a function $r^s(\lambda)$ for the standard detector, which has a known responsivity of $R^s(\lambda)$.

These values should not be confused with the responsivity of the total spectroradiometer system. This responsivity of the spectroradiometer system includes both the scatter from the slits and the detector responsivity. In this case we are singling out the detector responsivity. A NIST traceable standard silicon detector is usually used for measurements over the visible spectrum.³

Then the detector is replaced with the detector to be tested, and a signal response of $r'(\lambda)$ is generated. The responsivity of the test detector $R'(\lambda)$ will be

$$R'(\lambda) = r'(\lambda) / \Phi(\lambda) = r'(\lambda) R^s(\lambda) / r^s(\lambda) \quad (48)$$

38.5 REFERENCES

1. H. J. Kostkowski (1997) *Reliable Spectroradiometry*, La Plata, MD: Spectroradiometry Consulting.
2. *A Guide to Spectroradiometry: Instruments & Applications for the Ultraviolet*, Reading: Bentham Instruments (1997) (p. 24—tanning booth reference).
3. W. E. Schneider and R. Young (1997) "Spectroradiometry Methods," *Handbook of Applied Photometry*, Casimer DeCusatis (ed.), Chap. 8, pp. 239–287. New York: AIP Press.
4. J. D. Schanda (1997) "Colorimetry," *Handbook of Applied Photometry*, C. DeCusatis (ed.), Chap. 10, p. 347. New York: AIP Press.
5. E. Early, A. Thompson, C. Johnson, J. DeLuisi, P. Disterhoft, D. Wardle, and E. Wu, et al., "The 1995 North American Interagency Intercomparison of Ultraviolet Monitoring Spectroradiometers," *Journal of Research of the National Institute of Standards and Technology* **103**: 15 (1997).
6. A. R. Webb and D. Cotton (2002) "Report of Ispra Intercomparison, May 2002" *Assurance of Ultraviolet Measurements in Europe (QASUME)*. lap.physics.auth.gr/qasume/Files/EvalPdfs/QASUMEREPORT.pdf. Accessed May 19, 2009.
7. ISO (1993) *Guide to the Expression of Uncertainty in Measurement*, International Organization for Standardization, 1, rue de Varembe, Case postale 56, CH-1211 Geneve 20, Switzerland.
8. B. N. Taylor and C. E. Kuyatt (1993) *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, NIST Technical note 1297, Washington, D.C.: U.S. Government Printing Office.
9. J. M. Lerner and A. Thevenon (1988) *The Optics of Spectroscopy: A Tutorial*, vol. 2.0, pp. 1–56. Jobin-Yvon: Instruments SA Inc.
10. R. U. Datla and A. C. Parr (2005) "Introduction to Optical Radiometry," *Optical Radiometry*, A. C. Parr and R. U. Datla (eds.), Chap. 3, pp. 97–154. New York: Elsevier/AIP Press.
11. L. P. Boivin (2005) "Realization of Spectral Responsivity Scales," *Optical Radiometry*, A. C. Parr and R. U. Datla (eds.), Chap. 3, pp. 97–154. New York: Elsevier/AIP Press.
12. E. A. Early, P. Y. Barnes, B. C. Johnson, J. J. Butler, C. J. Bruegge, S. F. Biggar, P. R. Spyak, and M. M. Pavlov, "Bidirectional Reflectance Round-Robin in Support of the Earth Observing System Program," *Journal of Atmospheric and Oceanic Technology* **17**: 1077 (2000).
13. J. M. Palmer (2001) "The Measurement of Transmission, Absorption, Emission and Reflection," *Handbook of Optics*, M. Bass (ed.), I.25.5. New York: McGraw Hill.
14. R. N. Clark, G. A. Swayze, A. J. Gallagher, T. V. V. King, and W. M. Calvin (1993) "The U. S. Geological Survey, Digital Spectral Library: Version 1: 0.2 to 3.0 microns," *U.S. Geological Survey Open File Report 93–592*, 1340 pages, <http://speclab.cr.usgs.gov>. Accessed May 19, 2009.
15. J. W. Salisbury, L. S. Walter, N. Vergo, and D. M. D'Aria (1992) *Infrared (2.1–25 μm) Spectra of Minerals*, Baltimore, MD: The Johns Hopkins University Press.
16. C. I. Grove, S. J. Hook, and E. D. Paylor (1992) *Laboratory Reflectance Spectra of 160 Minerals, 0.4 to 2.5 Micrometers*. JPL-Publication 92-2. Pilot Land Data System. Pasadena, California: Jet Propulsion Laboratory.

