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AUTOMATED SPECTRORADIOMETRIC SYSTEMS: COMPONENTS & APPLICATIONS

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Automated Spectroradiometric Systems: Components and Applications

Spectroradiometery — measuring optical power as a function of wavelength or frequency — is vital to the characterization of light sources, optical transmission media, reflectors and detectors. Heretofore, spectroradiometric system calibration, data collection and subsequent calculations have been tedious and time-consuming. Now spectroradiometers, fitted with specialized attachments that extend possible applications, can interface to desktop computers, alleviating the chores of measurement.

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Radiometry involves the measurement of ultraviolet (UV) radiation (wavelengths of 200 to 400 nm), visible light (VIS) (wavelengths of 400 to 700 nm) and infrared (IR) radiation (wavelengths from 700 nm to about 1 mm). Spectroradiometry presents the measurements in the form of spectra — functions of wavelength.

The essential components of a spectroradiometer include a tunable dispersive element (eg., a grating, that separates radiation into its spectral components) and a detector (eg., a photodiode, that generates an electrical signal when exposed to optical radiation) and an amplifier and detector signal read-out.

Spectroradiometric systems can also incorporate input optics such as cosine receptors, integrating spheres, imaging optics, telescopes, fiberoptic probes, microscopes and light-emitting-diode receptors. In addition, numerous detector modules covering various spectral regions and with different sensitivities are also available. In all cases, calibration standards needed depend on the application.

In the past, measuring a radiating

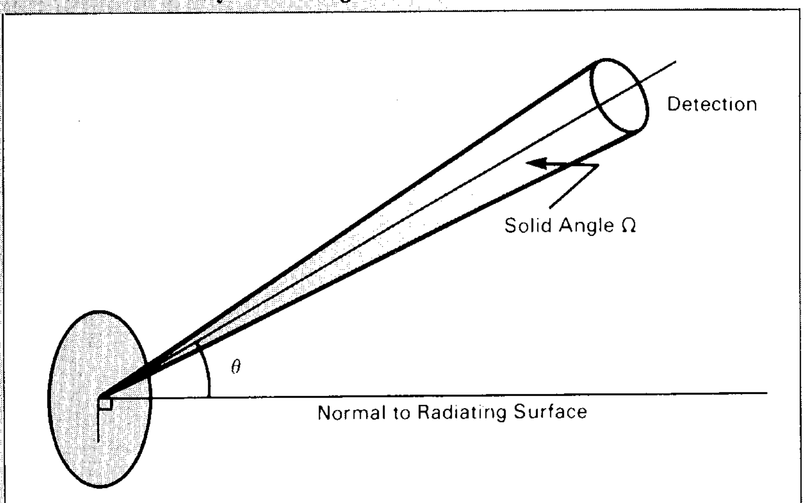
Of Units and Measurement

C.G. Masi Editor

Light is the flow of electromagnetic energy at frequencies between about 1.5×10^{12} Hz (far infrared) and about 3×10^{16}Hz (far ultraviolet). Directly measuring the frequency of such waves is impossible with current technology, but measuring their wavelengths is relatively easy. Therefore, we usually identify light by its wavelength (between 100 Angstroms and 2 million Angstroms). Alternatively, we can use *wavenumber* — the number of waves in one centimeter — which is the inverse of wavelength. So, 5,556 Angstrom green light has a wavenumber of about 18,000 cm^{-1} (1 cm = 10^8 Angstroms).

Photometric measurements measure the total amount of light — the rate of energy flow or power — by placing a detector so as to intercept part

FIGURE 1. Geometry for defining radiance.



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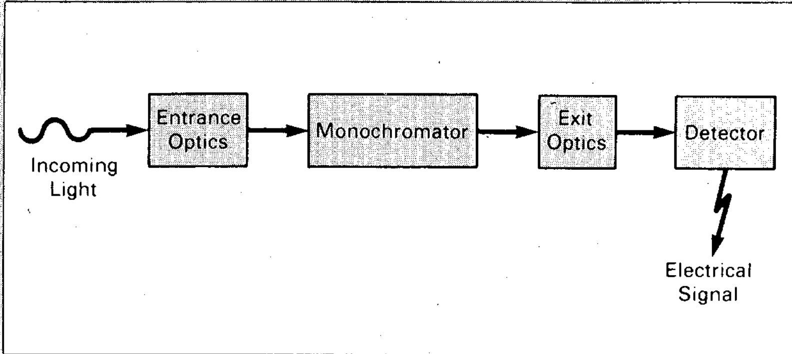


FIGURE 2. Block diagram of a spectroradiometer.

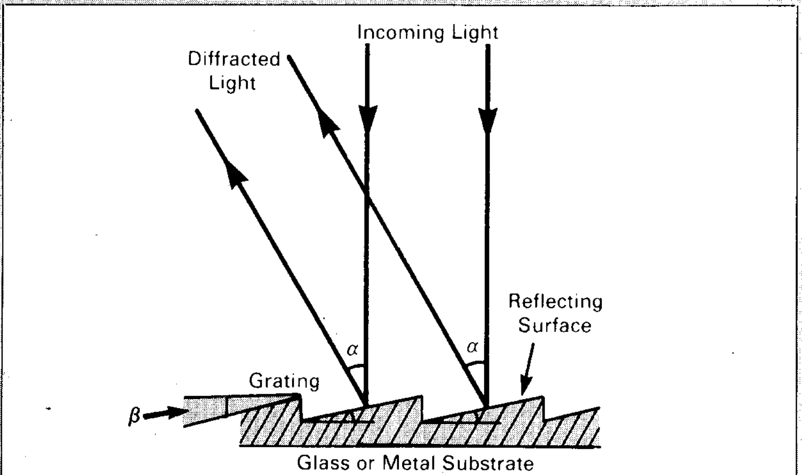


FIGURE 3. Cross-section of a diffraction grating.

of it. The larger the detector area, the more power the detector absorbs. Dividing by the detector's area to obtain a detector-independent measurement gives the *irradiance* (E): the power absorbed per unit area.

Sources do not send light out uniformly in all directions. Figure 1 shows the geometry used to define *radiance* (L) — the irradiance in a given direction per unit solid angle — which is equal to

$$L = \frac{E \cos \theta}{\Omega}$$

where Ω is the solid angle subtended by the detector and ϕ is the angle between the line-of-sight and the normal to the radiating surface.

Spectroradiometers determine how incoming light is distributed across the wavelength spectrum. Figure 2 is a block diagram of a typical spectroradiometer. The entrance optics define the spectroradiometer's field of view. The monochromator is a tunable narrowband wavelength filter. The exit optics collect light that passes through the monochromator onto the detector. The detector produces an electrical signal proportional (usually) to the power it absorbs.

Figure 3 shows the most common type of wavelength filter: a diffraction grating. Parallel grooves cover the grating surface, making it resemble a wide staircase. Incoming light bounces off each step's reflecting surface. Rays from adjoining steps arrive at the exit slit with different phases. Constructive interference occurs only for a narrow band of wavelengths centered around the wavelength given by the well known (first order) formula

$\lambda = d \sin \alpha$.

(continued)

source's spectral output or a photodetector's spectral response was time-consuming; it took many hours to calibrate the system, collect the data and calculate and graph results. Interfaced to desktop computers, automatically calibrated commercially available spectroradiometers can measure a variety of parameters such as spectral output of light sources, response of detectors and transmission and reflectance of materials. In addition, from the spectral data obtained, a variety of computer programs can determine parameters such as color temperature, chromaticity coordinates, photometric light output, dominant wavelength, spectral summation and peak wavelengths.

Basic Design Requirements

In selecting an automatic spectroradiometer, important factors to consider, in addition to cost, include:

- Wavelength range,
- System sensitivity,
- Wavelength accuracy,
- Wavelength repeatability,
- Available bandwidths,
- Stray light level,
- Availability of appropriate input optics
- Means of calibrating a system with the appropriate input optics,
- Interfacing to a computer for automatic operation,
- Availability of software for desired measurements,
- Ability to interchange detectors, gratings, blocking filters and input optics to expand the range or type of measurement.

Monochromators

The main component of a spectroradiometric system — the optical dispersive element — may be a diffraction grating, prism, interference filter or interferometer. The most common type of optical dispersive element, by far, is the grating; single monochromators contain one grating; double monochromators contain two. (Two single monochromators mounted back to back on a single, rigid frame comprise a double monochromator.) Figure 1 shows the construction of a single monochromator.

The diffraction grating and other design features determine the range of wavelengths over which the monochromator operates. Frequently the same instrument can operate in other wavelength bands with only a change

Of Units and Measurement *(continued)*

The quality and size of the grating and the width of the entrance slits govern the width of the monochromator's pass-band. Changing angle α tunes the monochromator to different wavelengths.

The grating is most efficient near a *blaze wavelength* (λ_b) that depends on angle β. When the monochromator is tuned to this wavelength, the reflecting surfaces have just the right orientation to reflect light from the entrance slit out through the exit slit by simple specular reflection. For a grating with a step angle β, the blaze wavelength is

$$\lambda_b = d \sin 2\beta.$$

in the grating (and possibly detector). This feature is especially important in the infrared, where changing detectors and gratings extends the range markedly.

Wavelength Accuracy, Precision and Resolution

A high-quality spectroradiometer system provides wavelength accuracies of ±0.5 nm or better over the ultraviolet, visible and near infrared, corresponding to approximately ±0.1% of the wavelength. Because irradiance (radiant flux per unit area) distributions of many sources change rapidly in the UV as wavelength varies, UV measurements quite often require 0.5 nm accuracy (or better) and 0.1 nm precision. For example, tungsten-halogen lamp output changes about 7.5% per nm at 250 nm (UV), but less than 1% per nm for wavelengths greater than 500 nm (VIS).

The three principal factors that determine spectral resolution or bandwidth of a grating monochromator are:

- focal lengths of the collimating and imaging mirrors,
- grating groove density,
- entrance and exit slit widths.

Monochromators have either fixed non-removable slits, multiple sets of interchangeable slits or adjustable slits. Precision interchangeable fixed slits ensure repeatable performance. Adjustable slits allow slit width control to the micron level for the highest possible resolution. Double monochromators provide higher spectral resolutions.

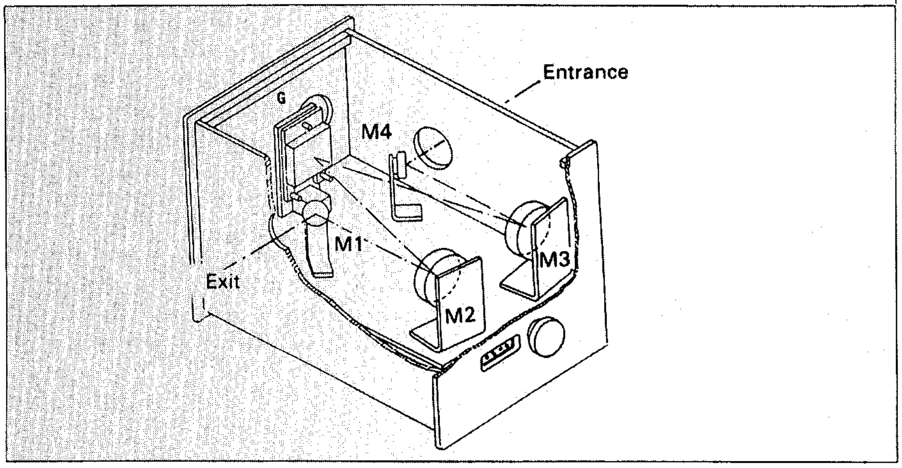
Stray Light or Spectral Purity

When operating in wavelength regions where an otherwise intense source is very weak, such as the UV from tungsten lamps or sunlight, spectroradiometers must have low stray-light levels. However, measuring or specifying stray light is difficult because the amount of unwanted radiation may vary widely depending on source distribution and wavelength.

The principal sources of stray light are room light leaks, second order (harmonic) spectra and scattering. Proper design can generally eliminate light leaks. Carefully designing single monochromators with blocking filters can eliminate most light due to second order spectra and scattering at unwanted wavelengths. A double monochromator can greatly reduce scattered light from wavelengths adjoining the passband. Stray light is often more significant in the UV because of the generally lower intensity levels (relative to the usual visible and near IR intensities). Use of solar-blind detectors that have virtually no response to visible sunlight or special UV filters helps significantly.

Stray light can also be tested by inserting a strong UV absorbing filter, such as plate glass or mylar, before an intense broadband source such as a xenon arc lamp. Any signal in the strongly absorbing (transmittance less than 0.01%) region must be due to stray light).

FIGURE 1. Optical layout of a single grating monochromator.



During the last decade, the area of optical radiation measurements has grown at a dynamic pace. Scientists and engineers in many unrelated fields have a need for making accurate measurements of optical radiation. The increased demand for instrumentation capable of performing many different kinds of measurements has led to the proliferation of optical accessories.

For example, spectroradiometer systems can be furnished with such input optics as cosine receptors, integrating spheres, imaging optics, telescopes, fiberoptic probes, microscopes and LED receptors. In addition, numerous detector modules that operate over various spectral regions and have different sensitivities are also available. In all cases, the type of standard used to calibrate the measurement system depends on the application.

The following simple guidelines should be especially considered when calibrating spectroradiometer instruments.

- Use a standard source to calibrate the system when measuring sources.
- Use a standard detector to calibrate the system when measuring detectors.
- Use a standard of spectral irradiance to calibrate the system when measuring spectral irradiances.
- Use a standard of spectral radiance to calibrate the system when measuring spectral radiances.
- Whenever possible select a calibration source similar to the test source in intensity and optical characteristics.

Spectral power measurements use irradiance standards along with an appropriate area factor. Keeping these simple guidelines in mind simplifies selecting the appropriate standards and instruments.

Detector Selection

In general for a 300 to 1,000 nm range instrument, a silicon photodetector is the best choice for many optical measurements. Silicon's high stability and uniformity are ideal properties for radiometry. When higher sensitivities are needed a photomultiplier tube can be used. The PMT's approximately 1,000 times increase in response is needed for low-level-light measurements or measurements which require the use of high resolution microscopes or telescopes. Unfortunately, for many measurements, the typical PMT has considerable non-uniformity in angular and spatial response and is generally used with diffusing optics. Unfortunately, good diffusers frequently reduce the available light to be measured by 100 to 1,000 times so there may be little or no advantage over the basic silicon detector. However, some measurements require the use of high-accuracy input optics diffusers such as integrating spheres to accurately characterize the source and in this case the high sensitivity of the PMT is a clear benefit. The PMT is also subject to unpredictable changes in sensitivity and therefore requires frequent recalibration. Ultra-high sensitivities can be obtained by cooling the PMT and by using photon-counting methods.

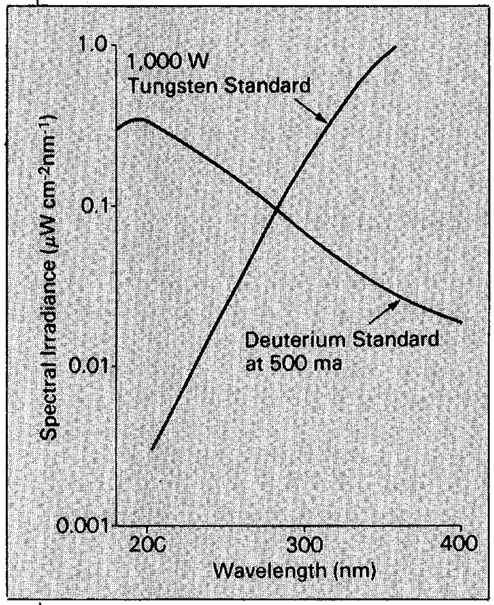


FIGURE 2. UV spectral irradiance of 50 W deuterium lamp and 1,000W quartz-halogen lamp.

Germanium detectors are available for use in the infrared over wavelengths of 800 to 1,800 nm. However, to obtain sensitivities and repeatabilities approaching those of silicon detectors, germanium detectors must be cooled. Thermoelectric cooling down to -25° C can reduce germanium detector dark current (the current when no illumination is present) by a factor of more than 100. Other infrared detectors are generally less satisfactory than visible light detectors because of drift and noise. Using optical choppers along with lock-in amplifiers reduces these effects. Thermal detectors such as thermopiles, thermistors and pyroelectrics all have limited sensitivity because of random thermal fluctuations. High-quality thermal detectors have noise levels of approximately 10^{-9}W, while silicon detectors are sensitive to about 10^{-13}W and lead sulphide detectors may reach 10^{-12}W at peak sensitivity (2,500 nm). All infrared photovoltaic and photoconductive detectors are limited by their own internal thermal noise levels. Cooling, either by thermoelectric coolers (useful for PbS and InAs detectors) or by dry ice, liquid nitrogen or liquid helium (useful for highly sensitive IR detectors, such as InSb and HgCdTe) can reduce these noise levels. IR detectors are generally quite small physically (2-3 mm or less) and non-uniform in response.

In the UV region (200-400 nm) the principal problem is stray light. A good detector in this range is the solar-blind PMT — which has practically no response beyond 400 nm and therefore greatly reduces stray light errors. A quartz window PMT with S-20 response is ideal for the region from 200 to 800 nm and possibly out to 900 nm (S-20 refers to a standard PMT spectral response curve).

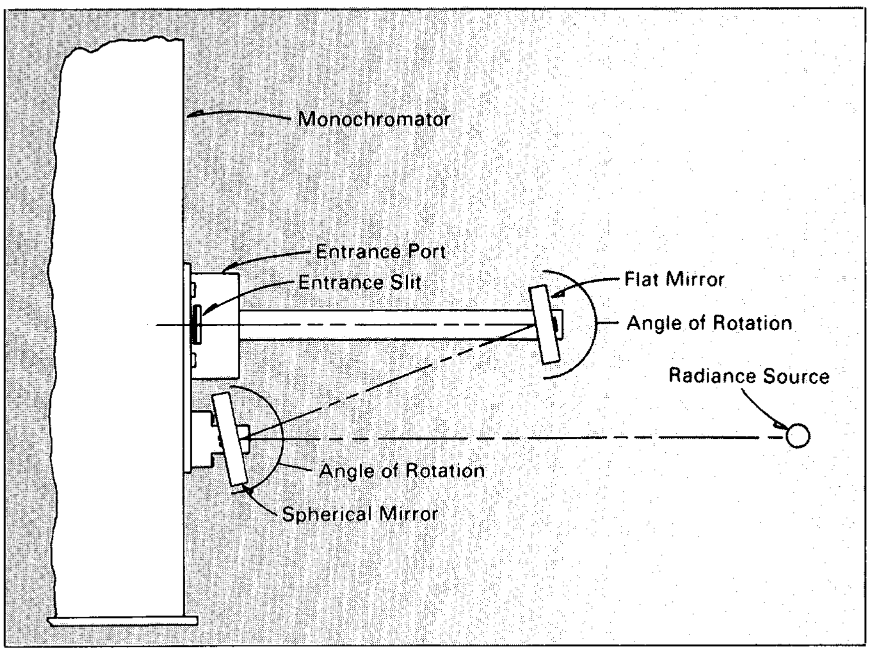
Input Optics and Calibration Standards

A well designed spectroradiometric system capable of performing a variety of optical radiation measurements will have a wide selection of input optic modules along with the appropriate standards for calibrating the system as an integral unit. A versatile system will have the capability of measuring spectral output of light sources over selected wavelength regions. This includes measurements of spectral irradiance, spectral radiance and spectral power. In addition, with the appropriate input optics and standards, such a system will also be capable of accurately measuring spectral response of detectors, spectral transmittance of optical components and spectral reflectance of diffuse or specular materials.

Spectral Radiance

To measure spectral radiance of a uniformly emitting source, such as a ribbon-filament lamp or a plasma, relay-optics (such as the mirror set shown in Figure 3) can form an image of the source at the entrance slit of the monochromator. The technique uses low distortion mirrors from UV to IR with no chromatic aberration while good quality achromatic lenses operate over the visible range. Ribbon-filament lamps (Figure 4)

FIGURE 3. Mirror input optics.



with sapphire windows are commercially available as spectral radiance standards calibrated for wavelengths between 0.25 microns and 6.0 microns. For wavelengths beyond 6.0 microns, calibrated blackbody sources are preferable.

Measuring the spectral radiance of small area radiating sources requires a microscope input adapter (Figure 5), a reflex viewer (for alignment and focusing the source on the target aperture) and a selection of objective lenses and field-of-view apertures. In addition, a fiber optic cable to transfer radiant flux from the microscope to the monochromator is desirable. Ideally, the fiber optic cable should have a circular opening at the microscope end and, to conform to the entrance slit, a rectangular opening at the monochromator end. Microspectroradiometer calibration requires a uniform, diffuse source. In the region from 350 to 1,100 nm, lamp-transmitting diffuser combination sources are sufficient for most spectroradiometer applications. Integrating sphere calibration sources are available for calibrations above 1,100 nm and below 350 nm.

Automatically calibrating commercially available spectroradiometers can measure a variety of parameters.

Measuring spectral radiance of a distant object requires a telescopic input module. Here again, a reflex viewer and a selection of FOV apertures are essential. A telescope employing an achromatic lens is desirable when measurements are confined to the visible range. For measurements in the UV and near IR, a lens of high-quality fused silica is usable, but it will be subject to chromatic aberration. Measurements over an extended wavelength region, especially in the IR beyond 2,500 nm, require a mirror system.

Calibration of tele-spectroradiometer systems may use either a point source at some distance from the telescope or a large-area, diffusely emitting source that fills the telescope field. The point source should be calibrated for spectral irradiance and the large-area source for spectral radiance.

Spectral Irradiance

Measuring the spectral irradiance of a point source or a source similar in size to the calibration standard used requires no input optics, provided the monochromator transmittance is fairly uniform over its field of view and the detector has uniform response over its receiving surface. However, measuring the irradiance from large-area sources or sources appreciably different in size from the calibration standard requires a diffuser input with cosine response (one whose response varies as the cosine of the angle of incidence). Integrating spheres provide accurate cosine response together with wide spectral range (250 to 2,500 nm). Unfortunately, they are fragile, easily contaminated by dust and smoke, and rather difficult to fabricate. Transmitting diffusers are more convenient and offer good performance over limited wavelength regions. For example, teflon-dome diffusers are efficient from 250 to 400 nm and opal glass from 380 to 1,100 nm. Barium sulphate and teflon powder also make good reflecting diffuser materials. Tungsten-halogen lamps calibrated for spectral irradiance in W/cm^2 per nm wavelength over all or part of the spectrum from 250 nm to 4,500 nm are good standards for visible and infrared spectrometer calibrations.

Special light sources with integrating spheres are available for calibrating extremely high-sensitivity systems. Most of these sources have

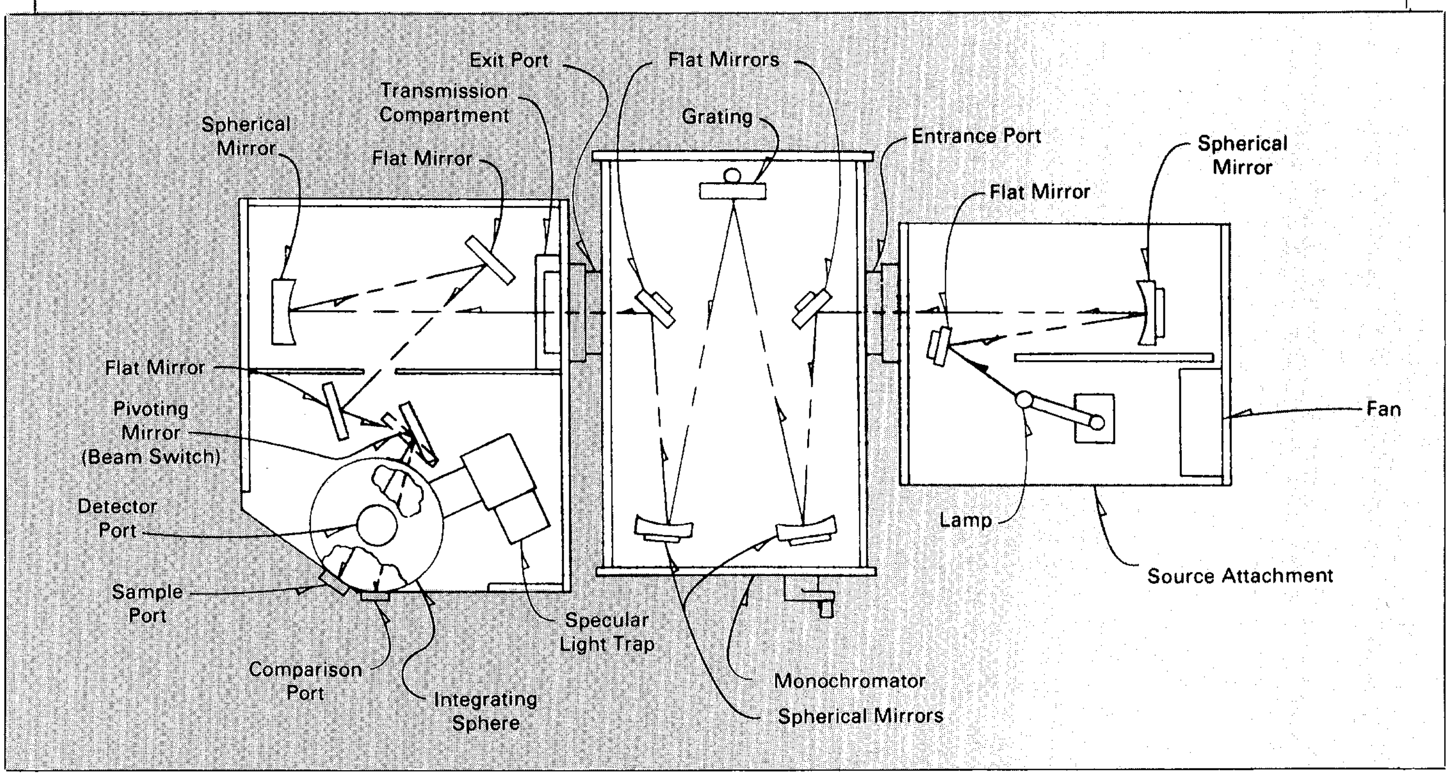


FIGURE 6. Optical layout of diffuse and specular spectral reflectance and spectral transmittance measurement system.

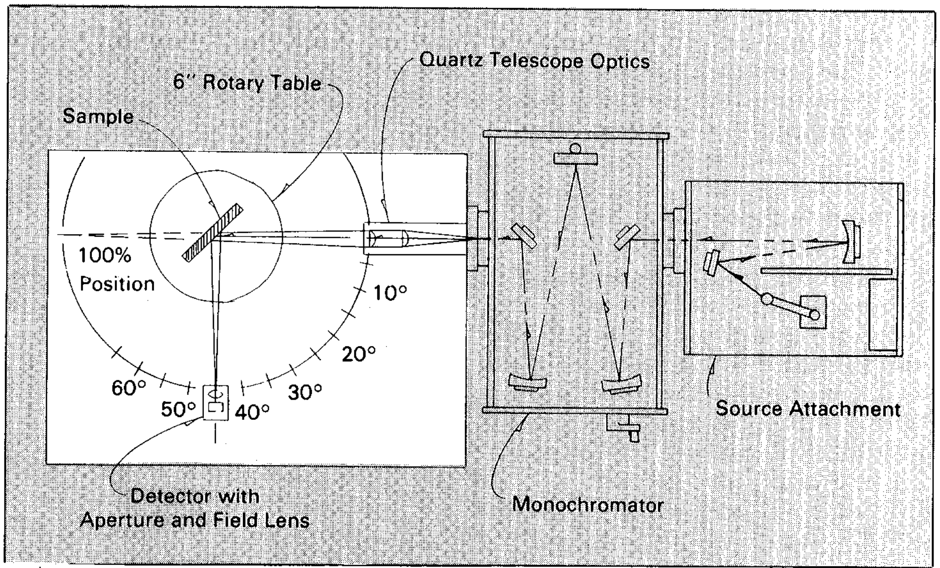


FIGURE 7. Specular reflectance attachment.

adjustable irradiance levels that span several decades. They are useful when making measurements at starlight levels.

Deuterium arc lamps are useful for UV spectral irradiance calibrations. Unlike tungsten lamps, the spectral distribution of deuterium lamps peaks in the ultraviolet at about 200 nm (Figure 2).

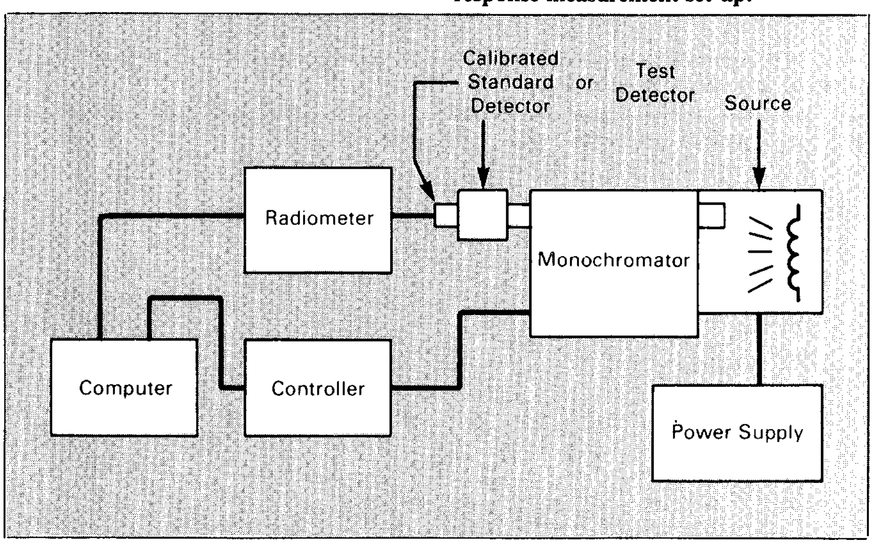
A very common requirement is the measurement of the spectral power output of LEDs. In this case an integrating sphere input optics module is recommended. The system is calibrated using a standard of spectral irradiance. The spectral power input to the integrating sphere is determined by multiplying the spectral irradiance of the standard by the area of the entrance port of the sphere. Once the system is calibrated, the LED is placed directly in front of the entrance port such that all of the flux emitted by the LED is collected by the integrating sphere. An integrating sphere input optics module is not required if only the peak wavelength or beam irradiance is desired.

Detector Spectral Response

Adding source imaging optics mounted at the entrance slit of the monochromator, exit optics that produce a uniform, collimated monochromatic beam at the exit slit and a standard calibrated detector converts a suitably designed spectroradiometric system to a measurement system for detector spectral response.

NBS provides calibrated silicon photodiode detectors based on the Detector Response Transfer Intercomparison Package (DRTIP). They consist of a carefully designed silicon detector radiometer calibrated to the NBS absolute radiant power scale, providing spectral response at selected wavelengths over the range from 250 to 1,064 nm. Commercial laboratories are now issuing calibrated silicon detectors based on the NBS DRTIP.

FIGURE 8. Automated detector spectral response measurement set-up.



Thermoelectrically cooled germanium detectors are useful in the range from 800 to 1,800 nm. The calibration procedure for these detectors consists of comparing their response to that of a thermal detector (nearly flat over the wavelength band) using a stable source to obtain a relative spectral response pattern, then performing an absolute calibration at a wavelength of about 1,000 nm using the NBS DRTIP and finally, normalizing the relative spectral response pattern produced from comparison to the thermal detector to obtain an absolute spectral response pattern.

Diffuse Spectral Reflectance

The use of an integrating sphere reflectance attachment further enhances the versatility of the basic spectroradiometric measurement system. Figure 6 shows the optical layout of a system capable of making both diffuse and specular spectral reflectance measurements and of measuring spectral transmittance. The integrating sphere attachment uses a true double beam optical design with comparison and sample ports and a manual beam switch. A light trap can be inserted at the specular position at the sphere wall to provide a measurement of diffuse component reflectance (specular excluded).

The reflectance standards consist of powder samples such as $BaSo_4$, MgO, Halon, etc., which are pressed into sample holders. The pressed powder standards are generally stable over several months if handled with care.

Specular Spectral Reflectance

Figure 7 shows an attachment for measuring specular reflectance of polished surfaces as a function of angle of incidence. It is a simple, single beam design, but, because it can measure the incident beam power, it can produce absolute calibrations.

Automatic Control of Spectroradiometers

Basic requirements for automated spectroradiographic systems include:

- Accurate wavelength data available in a digital form.
- A precise drive motor to position gratings within 0.1 nm.
- A digital motor control interface with remote START, STOP,

FORWARD and REVERSE capability.

- An electronic limit circuit to prevent damage to drive gears by accidentally hitting mechanical limits.
- A motorized filter wheel mechanism to insert the proper second order blocking filters in the optical path automatically.
- An autoranging amplifier system for the detector signal.
- Digital detector signal and amplifier range signals.

Figure 8 shows a block diagram of an automated system. Most automated systems use stepping motor drives because they provide precise wavelength positioning, stopping with no overshooting, a wide range of speeds and directional change with virtually no hesitation. Less expensive designs have the motor rigidly connected to the wavelength drive shaft with a fixed step-per-nanometer ratio. The motor step size determines the wavelength precision.

A bidirectional optical shaft encoder provides wavelength feedback. An encoder also allows the user to disengage the motor and select wavelengths manually without losing digital wavelength readout.

The filter wheel — to reduce second order harmonics and stray light — must be motorized to insert the correct filters automatically. A random-access drive that works even when wavelengths are selected manually is preferred for measurement flexibility.

Since spectral irradiance distributions commonly vary several decades of intensity over the UV to near IR spectrum, amplifier gain must adjust automatically for accurate data collection. Computer control inputs should be "active-low" logic and momentary to allow the user to retain active front panel controls.

Under computer control, the drive motor steps through a series of wavelengths, allowing collection of data over a specific range. For most accurate results the system should pause at each measurement wavelength to allow the detector amplifier time to select the proper range and settle before recording data. Some systems sample several times and calculate the average. More elaborate systems may control even more functions, such as amplifier gain, range setting, filter wheel position, motor speed, system shutter for dark current tests, detector temperature and optical input. Remotely triggering a pulsed source or synchronizing the radiometer's integrator to the flash allows automatic measurements of a pulsed source.

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