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STANDARDS FOR CALIBRATION OF OPTICAL RADIATION MEASUREMENT SYSTEMS

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STANDARDS FOR CALIBRATION OF OPTICAL RADIATION MEASUREMENT SYSTEMS

Recent growth in the area of optical radiation measurements has required development of secondary standards. These are referenced to established standards of total irradiance, spectral radiance, and spectral irradiance. Absolute radiometers, such as electrically calibrated radiometers and self-calibrating silicon diode radiometers, show great promise.

By William E. Schneider and David G. Goebel

The accurate measurement of optical radiation involves not only the use of a stable, well-characterized photometer, radiometer or spectroradiometer, but also, somewhere along the line, the use of a standard. This standard can be in the form of a radiating source whose radiant output and geometrical properties are accurately known or a detector whose response is accurately known. For most spectroradiometric applications, a standard source should be used to calibrate the system if the system will be used to measure the spectral output of sources. A standard or calibrated detector should be used if the system will be used to measure the spectral response of detectors. This article will concentrate on the more widely used standard sources with emphasis on special purpose calibration standards, and standard detectors. Only incoherent optical radiation from about 200 to 6000 nm will be covered.

The first section will cover some of the more widely used "basic radiometric standards," which have been established by the various national standards laboratories, and which are available through commercial calibration laboratories. These "basic radiometric standards" include:

- Standards of total irradiance
- Standards of spectral radiance
- Standards of spectral irradiance
- Absolute or self-calibrated detectors.

The second section covers "special purpose calibration standards," which can be defined as a source other than the "basic standard," but whose calibration is based on one of the basic standards.

The need for these special purpose calibration standards is exemplified by users of high sensitivity photometers, radiometers and spectroradiometers who are measuring radiating sources that are three to ten decades less intense than the available basic standards. One cannot hope to use a 1000-W lamp standard whose spectral irradiance is in the 10^{-5}W/cm^2 per nm range to calibrate a spectroradiometer, which will be used to measure fluorescence light levels ten decades lower, and expect to obtain meaningful results. This also applies to a photometer. One cannot expect good measurements when using a 100 footcandle basic standard to calibrate a photometer that will be used to measure star light levels in the 10^{-8} footcandle range.

Standards of total irradiance

Until about 68 years ago, the only radiometric standards in existence were crude oil lamps or candles. It was in 1913 that W.W. Coblentz recognized the importance of a convenient standard of thermal radiation,[1] and accordingly set up the carbon-filament lamp as a practical working standard of total irradiance.

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The carbon-filament lamps were calibrated relative to the emittance of a blackbody radiator as given by the Stefan-Boltzmann law. The Stefan-Boltzmann law relates the emittance or total radiant flux from a unit area of a blackbody (M) to the absolute temperature (T) by the relationship.

$$M = \sigma T^4. \qquad (1)$$

The precise value of the Stefan-Boltzmann constant, σ can be derived from other physical constants from the relationship

$$\sigma = \frac{2\pi^5 k^4}{15c^2 h^3} \qquad (2)$$

where: k = Boltzmann constant, c = speed of light, and h = Planck's constant.

It is interesting to note that the value of σ employed by Coblentz in 1913, namely 5.70, differs very little from the present value of 5.67.

The total irradiance of the lamps was on the order of 100 μW/cm^2. In addition to the relatively low irradiance, these lamps operated at relatively low color temperatures of about 1900 K. Thus, most of the emitted radiant flux was in the infrared spectral region. The carbon-filament lamps received wide acceptance in scientific research throughout the world, and were used quite extensively until the establishment of tungsten filament lamps as standards of total irradiance.

Calibration of the tungsten lamps for total irradiance was based on the spectral radiance, L_λ, of a blackbody as defined by Planck's radiation law

$$L_\lambda = \frac{c_2}{\lambda^5[e^{c_1/\lambda T} - 1]} \qquad (3)$$

λ = wavelength in cm, c_1 & c_2 are constants.

In 1965 new tungsten standards were established at NBS.[2] These lamps operated at color temperatures of 2800 to 2850 K. Three different size lamps (100, 500 and 1000 W) were set up as standards, and had total irradiance levels ranging from 0.5 to 7.5 mW/cm^2.

Shortly after these lamps were set up as standards of total irradiance, the calibrations were transferred to compact 1000-W tungsten-halogen lamps. These lamps could be operated at color temperatures of about 3000 K, and the compactness of the lamp enabled calibrations to be made at a relatively small distance of 50 cm. The total irradiance of these lamps is on the order of 30 mW/cm^2.

In order to obtain even higher levels of total irradiance, the 1000-W lamps were cemented into specially designed slip-cast fused silica reflectors.[3] These standards, designated as Solar Constant Irradiance Standards, have a total irradiance of about 136 mW/cm^2.

Standards of spectral radiance

With the exception of a blackbody radiator, there were no convenient spectroradiometric standards prior to about 1960.[4] Although the blackbody was and still is the primary standard used for most infrared calibrations, its use in the UV, visible and near IR is very limited.

In many laboratories the spectral distribution from a tungsten filament lamp was determined by using the published values of the emissivity of tungsten, and the observed color temperature or brightness temperature of the filament.[5-6] The calibration of the spectral emission was based upon a doubtful assumption that all samples of tungsten are identical in emissivity. No account was taken of the effects of impurities present, or of the size or shape of the filament or of its mechanical or crystalline structure. All these properties affect the true spectral and total emissivity. Furthermore, inter-reflections within the lamp envelope affect the total spectral radiation from a particular tungsten filament. Thus, in order to obtain the correct spectral radiance or irradiance of a lamp, it is necessary to calibrate the particular lamp against a blackbody.

The lamp chosen by NBS researchers for use as the standard of spectral radiance was the GE30A/T24/3. It has a mogul bipost base, and a nominal rating of 30 A at 6 V. Radiant energy is emitted from the flat strip filament through a 1 and ¼ in-fused-silica window located in the lamp envelope. The window is parallel to, and at a distance of about 3 to 4 in from the plane of the filament.

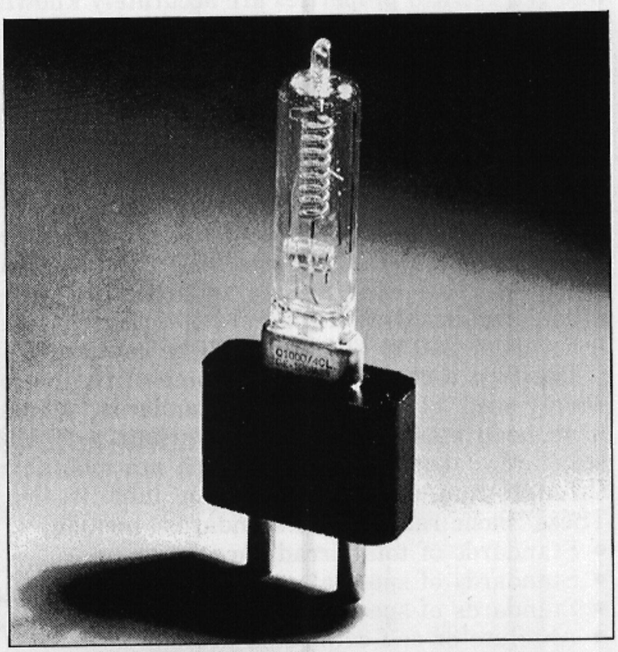

FIGURE 1. The FEL 1000-W lamp, the standard of spectral irradiance.

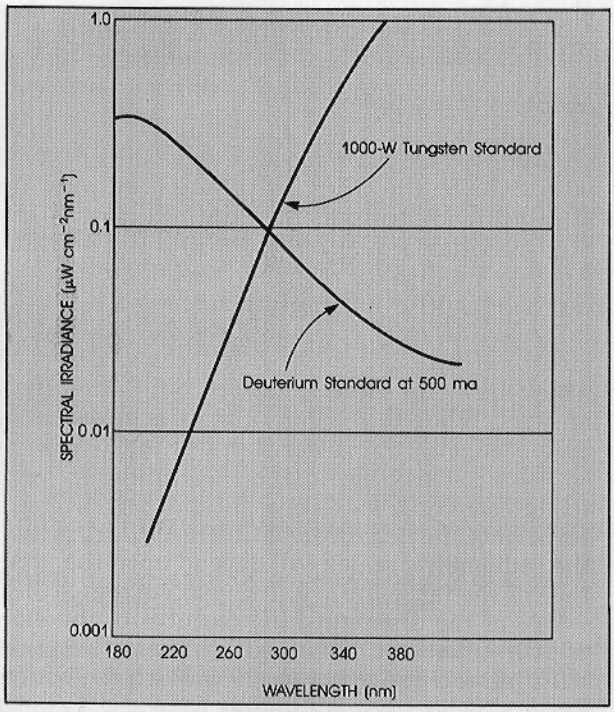

FIGURE 2. The spectral distribution of the deuterium standard lamp compared with the calibrated 1000-W tungsten quartz-halogen lamp.

Standards of spectral radiance were set up by NBS in 1960 covering the spectral regions of 0.25 to 0.75 μm, 0.5 to 2.6 μm, and 0.25 to 2.6 μm. Lamps calibrated over the three spectral ranges were set up independently through the use of two blackbodies having temperatures of about 2200 to 2600 K, and 1200 to 1400 K respectively.

The uncertainty assigned to these spectral radiance standards ranged from ±8% at 250 nm to ±3% in the visible and near IR. Although these uncertainties appear rather large, especially when compared to many of the other basic physical quantities measured by NBS, the industry demand for and use of those standards was quite great.

Any significant improvement in the spectral radiance scale was dependent primarily on the ability to measure the blackbody temperature more accurately. More than half of the lamp standard's uncertainties could be attributed to the blackbody temperature measurements.

In 1965, following extensive research into blackbody radiator designs,[7] particularly the freezing point gold furnace, NBS reported the capability of determining spectral radiance of tungsten ribbon-filament lamps with an uncertainty of less than 1%. The same basic approach was used in more recent work; however, a number of refinements in the instrumentation used, the measurement technique employed, and the improvement in realizing the International Practical Temperature Scale (IPTS) resulted in a higher accuracy standard of spectral radiance.

Standards of spectral irradiance

The standards of spectral radiance have found wide use in the calibration of spectroradiometric and other equipment in which the radiance of a small area is to be measured. However, the use of the radiance standard is limited by the small area which can be calibrated, and by the low radiance which the standard provides in the ultraviolet.

For many types of spectroradiometric calibrations, dealing with plasmas, furnaces or incandescent surfaces, a standard of spectral radiance is very useful, and will continue to be useful. The radiance lamp can also be used as an irradiance standard by carefully imaging the filament onto a small, precision slit with an accurately measured opening. The irradiance at a distance from the opening can then be calculated. However, a number of difficulties exist: the source area is quite small, the imaging optics must be calibrated, and the angular field is limited. To eliminate these problems, and also to provide a higher UV irradiance, a quartz-halogen lamp standard of spectral irradiance was developed by NBS in 1963.[8]

A G.E. 200-W quartz-iodine lamp was examined, and found to have acceptable characteristics for use as a standard. It is a rugged lamp in a small quartz envelope of relatively good optical quality. The intensity usually varies little over a considerable solid angle centered normal to the axis of the lamp. The small size of the lamp envelope together with the small area of the filament yields an approximate point source irradiance field at fairly close distances thus permitting placing the lamp within 50 cm of the slit of spectrometer.

Because of its quartz window, and also its high operating temperature, the quartz-halogen lamp emits a significant amount of radiation in the UV unlike the conventional tungsten incandescent lamps. The high temperature is made possible through the unique action of the halogen cycle, which results in the redeposition of evaporated tungsten back to the lamp filament, thereby keeping the envelope clean, and prolonging the useful life of the lamp.

A similar 1000-W lamp was set up in 1965 relative to the 200-W standards. Its output was approximately five times that of the 200-W lamp and was especially useful for UV calibrations where the 200-W lamp was too weak. It is slightly larger, being enclosed in a small quartz envelope of dimensions approximately ⅜ in × 3 in.

The uncertainties assigned to these 200 and 1000-W lamp standards varied from ±8% at 250 nm to ±3% in the visible. The widespread use of these standards, and the need for a higher accuracy standard, led NBS to establish a newer, higher accuracy scale of spectral irradiance in 1973.[9]

The new scale, which also used the same DXW 1000-W lamp, was based on the high accuracy radiance standards, and had estimated uncertainties which were about one-third that of the older 1963 scale. The new irradiance standards were calibrated over the wavelength region of 250–1600 nm.

In 1975, NBS switched from the 1000-W DXW-type lamp to the very similar 1000-W FEL lamps (see Fig. 1). These lamps were converted to a medium bipost base, which could be used with a kinematic lamp holder, allowing the lamps to be removed and replaced exactly in the same position.

Deuterium lamp standard of spectral irradiance

In 1977, NBS set up the deuterium arc lamp as a standard of spectral irradiance,[10] by utilizing a recently developed argon mini-arc as a radiance standard, and by modifying the calibration technique that was used to set up the 1973 spectral irradiance scale.

Figure 2 illustrates the spectrum of this lamp as compared with the calibrated 1000-W tungsten quartz-halogen lamp. The spectral irradiance of the two types of lamps is equal at about 280 nm. At 350 nm, the quartz-halogen lamp is stronger by a factor of 30. At 200 nm, the reverse is true, the deuterium lamp is 100 times as intense as the quartz-halogen lamp. The spectrum of the tungsten lamp above 350 nm is not illustrated, but is a continually increasing continuum.

Since the shapes of the spectra of the two lamps illustrated in Fig. 2 are so different, a critical test of a spectroradiometer's UV performance can be applied by irradiating the instrument with each lamp. If the ratio of signals from the two lamps is not equal to the ratio of their calibrated spectral irradiances, it would follow that a systematic source of error is present in the measuring system: for example, scattered light, second-order radiation, poor out-of-band rejection characteristics, or detector nonlinearity.

The total uncertainty in the deuterium lamp calibrations is estimated to be 6%. The uncertainty assigned to the relative spectral irradiance (ratio of the spectral irradiance at any two wavelengths in the calibrated region) is estimated to be 1% plus 0.02% times the nanometer difference between the two wavelengths under consideration.

Absolute radiometers

The ultimate accuracy of the total irradiance scales described here depends upon the accuracy with which the thermodynamic temperature scale can be realized, and the validity of the Stepan-Boltzmann and Planck laws of radiation. Another method of realizing radiometric scales can be classified as absolute radiometry.

By far the most common absolute radiometric measurements are made with thermal detectors which have an electric heater built into their receivers. Here the radiant flux to be measured is compared with the power supplied to the electrical heater. This power can be determined by relatively straightforward voltage and current measurements. In this case, the ultimate accuracy of the radiometric scales will depend upon the accuracy of the (absolute) voltage and current scales.

One of the distinguishing features of the electrically-calibrated radiometer is that a heater is built into the radiation receiver. With the optical beam shutter open, radiation from the lamp is incident on the aperture, frequently a cavity receiver, and absorbed by a black coating. The resultant temperature rise of the device is sensed by either a thermocouple, thermistor or pyroelectric sensor. With the shutter closed, the electrical

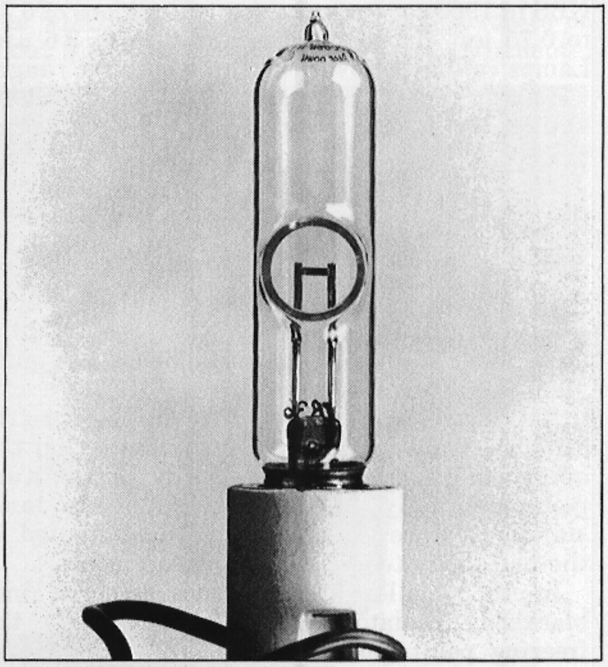

FIGURE 3. The new spectral radiance standards consist of a specially modified tungsten ribbon filament lamp with an optical grade, sapphire window.

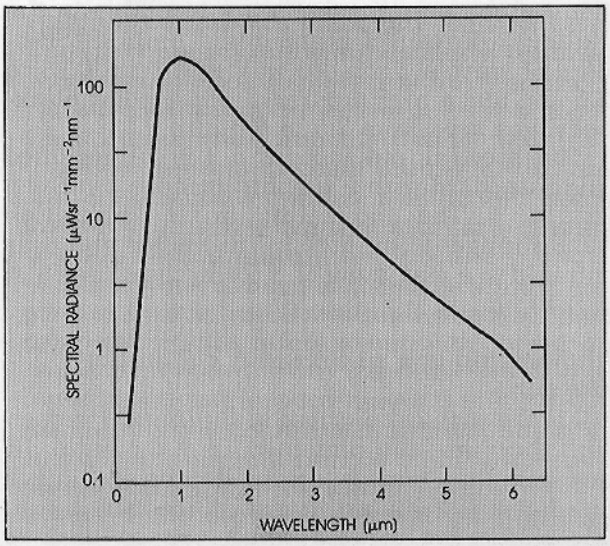

FIGURE 4. Spectral radiance of a typical modified lamp standard with a sapphire window.

heater is activated. Again the resultant temperature rise is sensed by the thermal detector. The device is operated so that there is an approximate equality between the electrical and radiant power. If appropriate corrections are made for the various systematic errors, the radiant power can be calculated from the measured electrical power, and the difference in the thermal detector readings.

Detector response transfer intercomparison package

Calibrated silicon photodiode detectors are also now available that are based on the NBS Detector Response Transfer Intercomparison Package (DRTIP).[11] The NBS DRTIP consists of a carefully designed silicon detector radiometer whose calibration is based on the NBS absolute radiant power scale. Spectral response values for the DRTIP are given at selected wavelengths over the range of 257 to 1064 nm. Commercial radiometric calibration laboratories are now issuing calibrated silicon detectors based on the NBS DRTIP.

Also available for use in the range of 800 to 1800 nm are calibrated thermoelectrically cooled germanium detectors. Calibration of these infrared detectors is performed by first determining the relative spectral response by comparison to a flat or thermal type detector. An absolute calibration at a wavelength of about 1000 nm is then made using the NBS DRTIP for the base reference. The relative spectral response values obtained via comparison to the thermal detector is then normalized to the absolute scale.

Self-calibrated silicon detectors

As another technique for absolute radiometry, which the Electro-Optics Group at NBS has been investigating, is the physics of silicon junction diodes.[12-14] A new technique was developed for investigating the effect of interface recombination on oxide-coated junction diodes. The group demonstrated how this technique, in combination with conventional reverse bias measurements, could be used to determine the absolute quantum efficiency of one type of shallow junction, oxide-coated photodiode. An uncertainty of less than $\pm 0.05\%$ was indicated by experiments using a 633 nm HeNe laser.

This new self-calibration capability represents a significant step forward in detector calibrations. More recent work[15] shows that, in principle, a single inversion layer photodiode can be used *in situ* to establish an accurate scale of radiometry for the visible and near ultraviolet using commonly available laboratory equipment. Detailed measurements show that the electrically-based scale, the absolute-quantum-efficiency-detector scale and the Planckian-radiator scale all agree within the estimated uncertainties (approximately 1% level).

Special purpose calibration standards

Quite frequently there exists a very serious problem when trying to use the "basic radiometric standards" to calibrate certain instrumentation. What is needed in many instances is a specially designed source which will meet the specific calibration requirements.

Accordingly, a number of secondary standards, all of which are based on one of the basic standards, have been set up by various research labs and calibration labs. Calibration standards are available that range from a bare 45-W lamp cost-

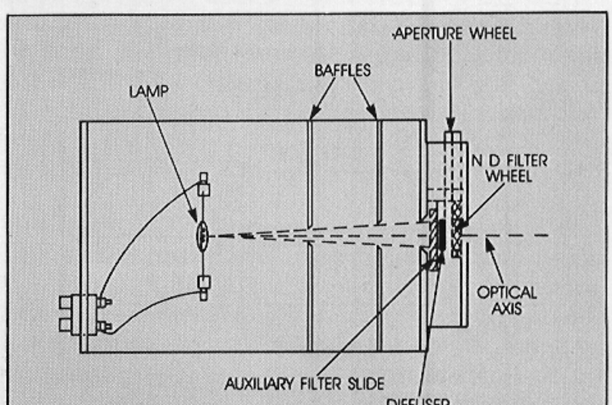

FIGURE 5. An optical schematic of a low-light-level calibration source.

ing a few hundred dollars to rather complicated, expensive sources costing a few thousand dollars. Some of these sources can be used as both standards of spectral radiance and spectral irradiance or alternately as both standards of illuminance and luminance. Some of these secondary standards have flux outputs which can be varied continuously or stepwise over many decades without altering the color temperature, and some have been specially filtered to give a particular spectral distribution.

Spectral radiance standards with sapphire windows

A standard was recently set up to serve researchers making measurements out to 6.0 μm.[16] The basic spectral radiance standards with the fused silica windows are calibrated over the 0.25- to 2.5-μm wavelength region. However, the interest in the 3–5-μm range justified a new lamp standard calibrated over a wider wavelength region.

The new spectral radiance standards consist of a specially modified tungsten ribbon filament lamp (18A/T10/2P) with an optical grade, sapphire window (see Fig. 3). The new standards are primarily designed for calibrating radiometers or spectroradiometers operating over all or part of the entire 0.25- to 6.0-μm wavelength region. They serve as an accurate, convenient alternative to the much more costly, high-temperature blackbody systems currently available. Calibrations of the new standards are traceable to the National Bureau of Standards. The NBS Standard of spectral radiance was used from 0.25 to 2.5 μm, and a high accuracy, copper-point blackbody was used from 2.5 to 6.0 μm.

The spectral radiance of a typical modified lamp standard with a sapphire window is shown in Fig. 4. The uncertainty in the calibration values ranges from ±2% in the visible and near infrared to a maximum of ±5% in the ultraviolet at 250 nm.

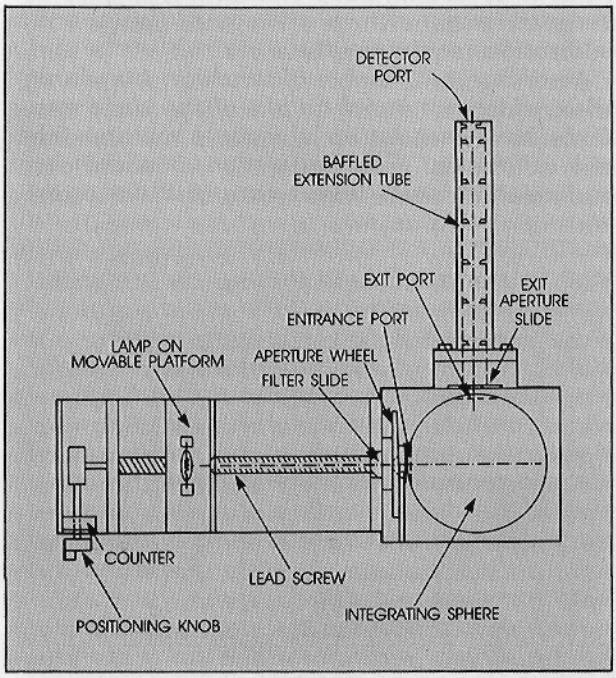

FIGURE 6. An optical schematic of a continuously variable calibration source.

Radiometric and photometric calibration standard

All of the sources described so far operate in open air; they are not contained in a housing. In addition, the sources are calibrated for either irradiance or radiance. Typical of the more versatile calibration sources which can be used to calibrate a wider range of instruments is a low wattage, (typically 45-W), tungsten-halogen lamp mounted in an air-cooled, machined, aluminum housing. The lamp irradiates an opal glass diffuser mounted in the front of the housing. The uniform radiating source thus formed can be calibrated for spectral radiance over the 350-1100 nm wavelength region. The usable wavelength region with the opal is limited on the short wavelength side by the transmittance cutoff of opal below 350 nm. The long wavelength limit is determined by the reduced scattering efficiency of the opal glass above 1100 nm. When the diffuser is removable, the source can also serve as a standard of spectral irradiance over the wavelength range of 250-2500 nm and as a standard of illuminance.

Low-light-level calibration sources

An optical schematic of a low-light-level calibration source, which is similar to the type originally developed at NBS for calibrating ultra-sensitive instrumentation such as astronomical photometers, is shown in Fig. 5.

This source also employs a 45-W tungsten-halogen lamp in combination with a flashed opal glass diffuser. With the lamp operating at 6.50 A dc, the color temperature is about 2900 K. Mounted in front of the diffuser are two wheels. The wheel immediately in front of the diffuser contains four apertures having areas which nominally differ by factors of 10, 100 and 1000. The outer wheel contains a clear aperture and two neutral density filters. The entire source system is calibrated as an integral unit at each level (covering five decades) for spectral irradiance and illuminance. Since the lamp-opal combination provides a uniform, diffuse source, it can be calibrated for spectral radiance and luminance for three levels. The opal diffuser once again limits the calibrated wavelength region to 350–1100 nm. Spectral irradiance levels can be varied in steps of ten by the aperture wheel from 10^{-15}Wcm^{-2}nm^{-1}.

Special versions of these sources utilize spectral shaping filters which modify the spectral distribution to simulate that of a particular star or other desired source.

Still another version of the same source incorporates a filter wheel containing narrow band-pass interference filters along with "open" and "shutter" positions. With the filter wheel in the "open" position, the source operates in the normal manner. By positioning each of the filters in the optical path, discrete spectral irradiances can be obtained at each of the wavelengths.

This type of source can be used to accurately:

- *Calibrate spectroradiometers.* With the interference filter wheel in the "open" position, the unit serves as a standard of spectral irradiance and spectral radiance over the 350 to 1100 nm wavelength region.
- *Measure absolute spectral response of photodetectors.* By placing the various interference filters in position, detector responsivity (AW^{-1}cm^{-2}) can be quickly determined.
- *Calibrate photometers.* With the interference filter wheel in the "open" position, the unit serves as a standard of illuminance and luminance.
- *Measure linearity.* Since the source is calibrated over five decades for irradiance and illuminance, it can also be used to measure the linearity of photometers, radiometers, etc.

Integrating-sphere calibration sources

All of the special purpose calibration sources described so far incorporate flashed opal glass as the diffusing mechanism. As previously mentioned, opal is a good diffuser in the visible and near infrared. However, opal does not transmit below 350 nm, and loses its diffusing properties beyond about 1100 nm. In addition, some of these sources use neutral density filters for the lowest levels of attenuation. Since neutral density filters are not truly neutral, the color temperature or spectral distribution of these standards changes when the filters are used. Special purpose sources utilizing integrating spheres were set up for those researchers requiring: a wider wavelength range 250 to 2500 nm; a wider range in radiance and luminance levels; and a constant color temperature at every level of operation.

A typical integrating-sphere calibration source consists of a six-inch integrating sphere and a stable, compact, 45-W tungsten-halogen lamp mounted inside a machined, light-tight enclosure. Usually a precision aperture wheel is positioned between the lamp and the entrance port of the sphere which enables the radiant flux entering the sphere to be attenuated by factors of 10. Located directly in front of the exit port of the sphere is an aperture slide or wheel. Radiance levels ranging from 10^{-7} to 10^{-13} Wsr^{-1} cm^{-2} nm^{-1} and irradiance levels from 10^{-9} to 10^{-15} Wcm^{-2} nm^{-1} can be obtained.

The integrating sphere radiates a uniform, highly diffuse flux from its exit port. The attenuation factors and spectral measurements are accurately calibrated relative to the NBS standards of spectral irradiance. An important feature of the source is that the attenuation factors do not alter the relative spectral distribution of the lamp-integrating sphere combination.

A continuously-variable integrating-sphere calibration source can be obtained by varying the distance from the lamp to the sphere. If the lamp is mounted on an optical carriage which enables the lamp-sphere distance to be accurately varied, a 10:1 attenuation can be obtained. An optical schematic of a continuously variable calibration source is shown in Fig. 6.

Collimated sources

Many researchers require specially designed calibration sources that produce a collimated beam of light. These sources simulate stars or naturally collimated sources. They frequently use low-level opal sources (as previously described) with telescopes mounted on the front, and produce a low-level collimated, diffuse source. Some other users need extremely high degrees of collimation for star simulation, and image a ribbon filament lamp onto a pinhole aperture located at the focal plane of the collimator. Calibration of these sources is more difficult than the diffuse sources due to the optical design and low-light level. Normal spectroradiometric calibration techniques such as the use of an input diffuser or integrating sphere cannot be used for low light levels. Specially calibrated telespectroradiometers must be used.

Summary

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 for operation over various spectral regions, and having different sensitivities, are also available. In all cases, the type of standard used to calibrate the measurement system is dependent 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 can be made using the irradiance standards, and applying an appropriate area factor. With these simple guidelines in mind, selecting the appropriate standard is somewhat simplified.

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