Designation: G138 – 12

Standard Test Method for Calibration of a Spectroradiometer Using a Standard Source of Irradiance[1]

This standard is issued under the fixed designation G138; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

A standardized means of performing and reporting calibration of the spectroradiometer for spectral irradiance measurements is desirable.

This test method presents specific technical requirements for a laboratory performing calibration of a spectroradiometer for spectral irradiance measurements. A detailed procedure for performing the calibration and reporting the results is outlined.

This test method for calibration is applicable to spectroradiometric systems consisting of at least a monochromator, input optics, and an optical radiation detector, and applies to spectroradiometric calibrations performed with a standard of spectral irradiance with known irradiance values traceable to a national metrological laboratory that has participated in intercomparisons of standards of spectral irradiance. The standard must also have known uncertainties and measurement geometry associated with its irradiance values.

1. Scope

1.1 This test method covers the calibration of spectroradiometers for the measurement of spectral irradiance using a standard of spectral irradiance that is traceable to a national metrological laboratory that has participated in intercomparisons of standards of spectral irradiance.

1.2 This method is not limited by the input optics of the spectroradiometric system. However, choice of input optics affects the overall uncertainty of the calibration.

1.3 This method is not limited by the type of monochromator or optical detector used in the spectroradiometer system. Parts of the method may not apply to determine which parts apply to the specific spectroradiometer being used. It is important that the choice of monochromator and detector be appropriate for the wavelength range of interest for the calibration. Though the method generally applies to photodiode array detector based systems, the user should note that these types of spectroradiometers often suffer from stray light problems and have limited dynamic range. Diode array spectroradiometers are not recommended for use in the ultraviolet range unless these specific problems are addressed.

1.4 The calibration described in this method employs the use of a standard of spectral irradiance. The standard of spectral irradiance must have known spectral irradiance values at given wavelengths for a specific input current and clearly defined measurement geometry. Uncertainties must also be known for the spectral irradiance values. The values assigned to this standard must be traceable to a national metrological laboratory that has participated in intercomparisons of standards of spectral irradiance. These standards may be obtained from a number of national standards laboratories and commercial laboratories. The spectral irradiance standards consist mainly of tungsten halogen lamps with coiled filaments enclosed in a quartz envelope, though other types of lamps are used. Standards can be obtained with calibration values covering all or part of the wavelength range from 200 to 4500 nm.

[1] This test method is under the jurisdiction of ASTM Committee G03 on Weathering and Durabilityand is the direct responsibility of Subcommittee G03.09 on Radiometry.

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1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*[2]

2. Referenced Documents

2.1 *ASTM Standards:*[3]

E772 Terminology of Solar Energy Conversion

E1341 Practice for Obtaining Spectroradiometric Data from Radiant Sources for Colorimetry

2.2 *Other Documents:*

CIE Publication No. 63 [4]The Spectrodiometric Measurement of Light Sources

NIST Technical Note 1927: Guidelines for Evaluation and Expressing Uncertainty of NIST Measurement Results[5]

3. Terminology

3.1 *General terms pertaining to optical radiation and optical measurement systems are defined in Terminology . Some of the more important terms from that standard used in this paper are listed here.*

3.1.1 *bandwidth, n*—the extent of a band of radiation reported as the difference between the two wavelengths at which the amount of radiation is half of its maximum over the given band.

3.1.2 *diffuser, n*—a device used to scatter or disperse light usually through the process of diffuse transmission or reflection.

3.1.3 *integrating sphere, n*—a hollow sphere coated internally with a white diffuse reflecting material and provided with separate openings for incident and exiting radiation.

3.1.4 *irradiance, n*—radiant flux incident per unit area of a surface.

3.1.5 *monochromator, n*—an instrument for isolating narrow portions of the optical spectrum of a light source

3.1.6 *polarization, n*—with respect to optical radiation, the restriction of the magnetic or electric field vector to a single plane.

3.1.7 *radiant flux, n*—the time rate of flow of radiant energy measured in watts.

3.1.8 *spectral irradiance, n*—irradiance per unit wavelength interval at a given wavelength.

3.1.9 *spectroradiometer, n*—an instrument for measuring the radiant energy of a light source at each wavelength throughout the spectrum.

3.1.10 *ultraviolet, adj*—optical radiation at wavelengths below 400 nanometres.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *calibration subsystems, n*—the instruments used to supply and monitor current to a standard lamp during calibration, consisting of a DC power supply, a current shunt, and a digital voltmeter.

3.2.2 *National Metrological Institution (NMI), n*—A nation's internationally recognized standardization laboratory.

3.2.2.1 *Discussion*—The International Bureau of Weights and Measurements (abbreviation BIPM from the French terms) establishes the recognition through Mutual Recognition Agreements. See http://www.bipm.org/en/cipm-mra. The NMI for the United States of America is the National Institute for Standards and Technology (NIST).

3.2.3 *passband, n*—the effective bandwidth (c.f.), or spectral interval, over which the spectroradiometer system transmits at a given wavelength setting. Expressed as full-width at one-half maximum, as in bandwidth. A function of the linear dispersion (nm/mm) and slit or aperture widths (mm) of the monochromator system.

3.2.4 *primary standard of spectral irradiance, n*—a broad spectrum light source with known spectral irradiance values at various wavelengths which are traceable to a national metrological laboratory that has participated in intercomparisons of standards of spectral irradiance.

3.2.5 *responsivity, n*—symbol $R = dS/d\varphi$, S is signal from spectroradiometer detector, φ is radiant flux at the detector.

3.2.6 *secondary standard of spectral irradiance, n*—a standard calibrated by reference to another standard such as a primary or reference standard.

3.2.7 *slit scattering function, n*—symbol $Z(\lambda_o,\lambda)$, the responsivity of the combined detector and monochromator system as a function of wavelengths, λ, in the neighborhood of a given wavelength setting, λ_o. The slit scattering function is the spectral responsivity in the neighborhood of specific wavelength setting, λ_o.

3.2.8 *spectral scattering (stray light), n*— light with wavelengths outside the passband of a spectroradiometer a particular wavelength setting that is received by the detector and contributes to the output signal.

4. Significance and Use

4.1 This method is intended for use by laboratories performing calibration of a spectroradiometer for spectral irradiance measurements using a spectral irradiance standard with known spectral irradiance values and associated uncertainties traceable to a national metrological laboratory that has participated in intercomparisons of standards of spectral irradiance, known uncertainties and known measurement geometry.

4.2 This method is generalized to allow for the use of different types of input optics provided that those input optics are suitable for the wavelength range and measurement geometry of the calibration.

4.3 This method is generalized to allow for the use of different types of monochromators provided that they can be

[2] Available from the CIE, (International Commission on Illumination), http://www.techstreet.com/ciegate.tmpl CIE Central Bureau, Kegelgasse 27, A-1030 Vienna, Austria.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[4] G03

[5] Available from American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036

configured for a bandwidth, wavelength range, and throughput levels suitable for the calibration being performed.

4.4 This method is generalized to allow for the use of different types of optical radiation detectors provided that the spectral response of the detector over the wavelength range of the calibration is appropriate to the signal levels produced by the monochromator.

5. Apparatus

5.1 *Laboratory:*

5.1.1 The room in which the calibrations are performed and especially the area surrounding the optical bench should be devoid of reflective surfaces. The calibration values assigned to the spectral irradiance standard are for direct irradiance from the lamp and any radiation entering the monochromator from some other source including ambient reflections will be a source of error.

5.1.2 The temperature and humidity in the laboratory shall be maintained so as to agree with the conditions under which the calibrations of the spectral irradiance standard and the calibration subsystems were performed (typically 20°C, 25°C, 50 % relative humidity).

5.1.3 Air drafts in the laboratory should be minimized since they could affect the output of electrical discharge lamps.

5.2 *Spectroradiometer*

5.2.1 *Monochromator:*

5.2.1.1 This can be a fixed or scanning, single or multiple, monochromator employing holographic or ruled gratings or prisms or a combination of these dispersive elements. For improved performance in the ultraviolet (UV) portion of the spectrum, it is recommended that a scanning double monochromator be used to achieve lower stray light levels (see Fig. 1). If the monochromator has interchangeable slits, it is important that the manufacturer document the effective bandwidth of the monochromator with all possible combinations of the slits or that these bandwidths be determined experimentally. Configuration of the slits should be such that the bandpass function of the monochromator is symmetric, preferably triangular. The bandwidth should be constant across the wavelength region of interest and maintained between 85 % and 100 % of the measurement wavelength interval. The precision of the wavelength positioning of the monochromator should be 0.1 nm with an absolute accuracy of better than 0.5 nm (see Practice E1341). For improved performance in the uv, it is recommended that high order rejection filters be inserted in the optical path in the monochromator. The purpose of the high order rejection filters is to block radiation in the monochromator of unwanted wavelengths that could otherwise overpower the signals being measured. The effects of variations in temperature and humidity on the performance of the monochromator should be addressed in writing by the manufacturer.

5.2.1.2 The monochromator shall not be subject to shock or mechanical vibration during the calibration. This can be facilitated by the use of a vibration isolated lab table. If any optical parts in the monochromator are configurable by the user, refer to the manufacturer precautions about opening the monochromator and handling any parts therein.

5.2.2 *Optical Radiation Detector:*

5.2.2.1 The optical radiation detector employed by the spectroradiometer shall be selected for optimal response over the wavelength range of interest. It is also important that the detector is sensitive enough to measure the levels of light that will be produced by the monochromator when it is configured for the calibration process. The active area of the detector shall

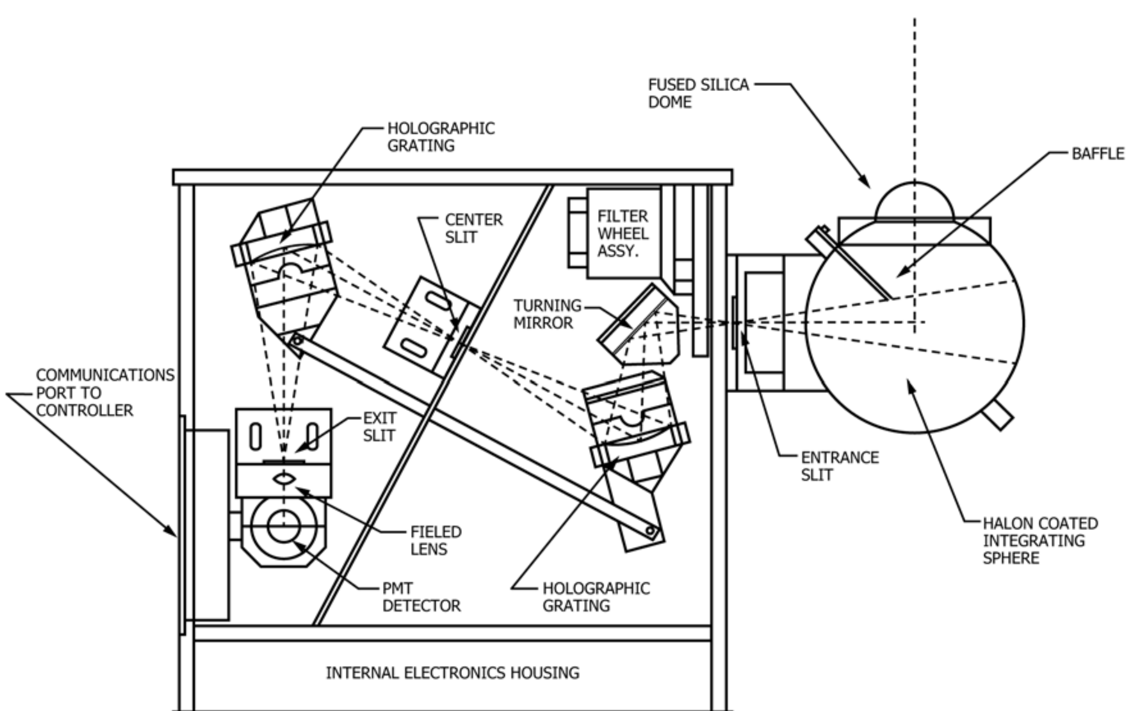

FIG. 1 Typical Double Grating Monochromator Layout (courtesy Optronic Laboratories, Used with Permission)

be evenly illuminated by the radiation leaving the exit slit of the monochromator. A photomultiplier is typically used because of its high responsivity and good signal-to-noise ratio. For this reason it is recommended for use when measuring spectral irradiance in the uv portion of the spectrum.

5.2.2.2 Any effects of variation in temperature and humidity on the response of the detector documented by the manufacturer shall be reported. Of all components of the spectroradiometer, the detector is usually the most sensitive to changes in temperature. Some detectors may require cooling in order to maintain a specific temperature. Avoid mechanical shock to the detector. If the detector requires an amplifier, any reported limitations and uncertainties in the detector system must factor in the contribution of the amplifier.

5.2.3 If a diode array based spectroradiometer system is used, note the following precautions:

5.2.3.1 The diode array spectroradiometer should employ internal focusing optics within the monochromator.

5.2.3.2 When measuring in the ultraviolet, the method of stray light control, such as by the use of high order rejection filters or internal baffling, or both, shall be documented.

5.2.3.3 It is highly recommended that diode array spectroradiometers should not be used for measurements below 300 nm without extensive characterization of stray light characteristics and detector performance.

5.2.4 *Input Optics:*

5.2.4.1 Some means of collecting the incident radiation and guiding it to evenly fill the entrance slit of the monochromator is required. The input optics also can serve several other important purposes.

(1) Cosine Receptor—Ideally, a cosine receptor will accept all radiation from an entire hemisphere and sample radiant flux according to the cosine of the incident angle.

(2) Depolarizer—The components in the monochromator are unfavorably affected by polarized light. A depolarizer such as integrating sphere can produce more consistent results from light sources of any polarization type.

(3) Diffuser—A diffuser can remove hotspots from the incident radiation field and produce even illumination on the entrance slit. It can also serve to depolarize optical radiation.

5.2.4.2 Reflective input optics are more desirable than transmissive optics as they perform all three of the functions previously discussed and are generally more useful over larger wavelength ranges. It is important to take into account the amount of attenuation caused by the input optics as this will affect the signal levels at the detector. Ensure that the input optics are suitable for the wavelength range of interest. The predominant choice of input optics is the integrating sphere.

5.3 *Wide-band Cut-on and Cut-off Filters:*

5.3.1 Wideband cut-on and cut-off filters transmit radiation of longer or shorter wavelengths, respectively, than the indicated (cut-on/-off) wavelengths. These are also known as long-pass or short-pass filters. Such filters are needed to establish the level of stray light in the monochromator. The monochromator is set to a given wavelength in a region where the transmission of the filter is negligible (zero), but has high transmittance in nearby band above (for cut-on filter) or below (for cut-off filter) the test wavelength.

5.3.2 Compare the signal from the detector with the filter in place to the shuttered, or dark signal of the detector. A signal between 10 % and 90 % of the unfiltered signal indicates significant scattered light is reaching the detector, possibly due to a non-light-tight enclosure.

5.4 *Optical Radiation Sources*

5.4.1 *Wavelength Calibration Source:*

5.4.1.1 A stable wavelength source is required to calibrate the wavelength positioning accuracy of the monochromator. This can be a gas discharge lamp or a laser. The important thing is that the source have a known spectral emission line(s) of narrow bandwidth.

5.4.1.2 If a laser source is used, occupants of the room should wear eye protection appropriate for the class of laser. Lasers should always be shielded from direct eye view.

5.4.2 *Standard of Spectral Irradiance:*

5.4.2.1 The spectral irradiance standard is a critical component in the calibration process. This standard shall be obtained from a national standards laboratory or a certified commercial laboratory. It must have known spectral irradiance values over the wavelength range of interest. Uncertainties for these spectral irradiance values must also be known in order to compute the total uncertainty of the calibration outlined in this method. The conditions (temperature, relative humidity, calibration distance from the reference plane, orientation and polarity of the lamp current input leads or contacts) under which the standard was calibrated by the supplier must be clearly stated and duplicative. Specifically, the current to the lamp and the measurement geometry must be reported by the supplier in a written document or calibration certificate. The calibration certificate should also contain a physical description of the lamp including materials used in its construction and electrical rating. A unique serial number identifying the standard should also be in the certificate, along with a record of the date on which it was calibrated, and a reference to a specific national metrological laboratory that has participated in intercomparisons of standards of spectral irradiance standard for traceability. Fig. 2 shows the spectral irradiance distribution of a typical tungsten halogen irradiance standard, often used for irradiance calibration over the wavelength range indicated.

5.4.2.2 Care should be exercised when handling the spectral irradiance standard. It should never be necessary to touch the envelope of the lamp. If the envelope is accidentally touched, carefully clean the lamp with denatured alcohol or other appropriate optical cleaner. Never move the lamp when it is lighted. Avoid mechanical shock to the lamp. The lamp current should be ramped up slowly over a period of 10 to 15 seconds to avoid thermal shock to the filament and possible filament breakage. Monitor the lamp current and only perform calibration measurements while the current is stable within a tolerance of +/-0.05% (or less) of the recommended operating current. When not in use, store the lamp in a dust-free enclosure in the geometry (for example, bulb vertical) recommended by the provider of the lamp.

5.4.2.3 The spectral irradiance standard requires recalibration or replacement after a stated period of use stated by the lamp supplier (for example, "50 Hr", as stated for NIST spectral irradiance standard lamps). For this reason, it is

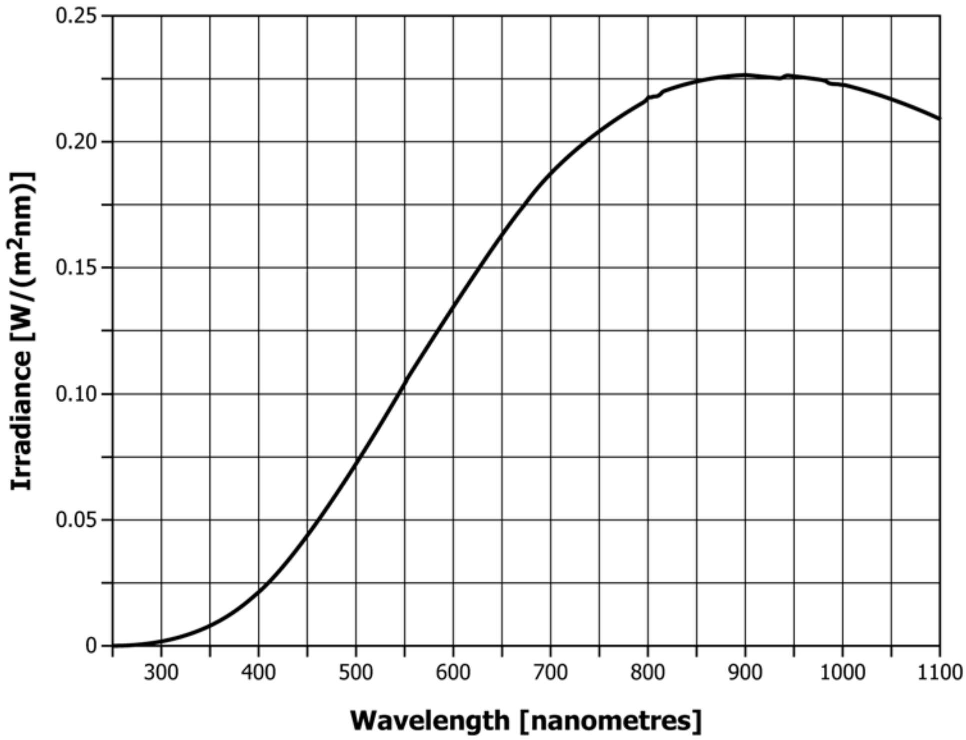

FIG. 2 Spectral Irradiance of Typical Tungsten Filament Quartz Halogen Irradiance Standard

important to keep a record of the amount of time the standard is used during each calibration. The time to ramp the lamp current up and down and reach the stability criteria of 5.4.2.2 are not counted as part of this "period of use". [1]

5.4.3 *Secondary Standards of Spectral Irradiance (Control Standards):*

5.4.3.1 The laboratory shall maintain control standards that are of the same type and optical spectral distribution as the primary standard. At least three control standards shall be kept at all times with traceability through a primary standard of spectral irradiance from an NMI that has participated in intercomparisons of standards of spectral irradiance. The control standards shall be measured as soon as possible after the primary standard is assigned calibration values. In addition, regularly scheduled measurements of the control standards will be used to determine the long-term reproducibility of the calibration system, which will be used in determining the calibration uncertainty. If any of the standards, secondary or primary, should vary from its initial calibrated values at any point throughout the spectrum by more than 5 %, the lamp should be replaced.

5.4.4 *Use of Secondary Standards as Calibration Reference*

5.4.4.1 Secondary standards are to be calibrated through the primary standard. In many cases, manufacturers of spectral irradiance standards can supply the same type of lamp used for the standard without calibration values at a significantly reduced price.

5.4.4.2 Secondary standard lamps must go through a burn-in process, as the manufacturer most likely will not have performed this. Run the lamp at its rated current level for 24 h. After this period, continue running the lamp for an additional 8- h period while regularly monitoring its irradiance in 1-h intervals. If at any point during that 8 h, drift of more than 1 % occurs at any wavelength, discard the lamp and use a different one for a secondary standard.[1]

5.4.4.3 In some cases, it may be desirable and cost-efficient to use the primary standard to regularly calibrate secondary standards and then use the secondary standards for daily calibrations of the spectroradiometer.

5.4.4.4 Previous sections of this standard are explicitly written for calibrations based on a primary standard. When using a secondary standard as a standard for the calibration, the following changes or additions must be made to the calibration method thus far described:

Apparatus-The care and handling of secondary standards should be identical to that of a primary standard.

Report-Additional information for the transfer calibration will be necessary. Everything that was listed for the primary standard can be reclassified as information that should be available if requested. The information that was previously required for the primary standard should now be required for the secondary standard.[1,4,5]

Precision and Bias-The uncertainty calculations should reflect the additional step in the calibration transferring from primary to secondary standard.

5.5 *Power Supply System for Spectral Irradiance Standard*

5.5.1 *Stable DC Power Supply:*

5.5.1.1 This is required to power the spectral irradiance standard during the calibration process.

5.5.2 *Current Shunt:*

5.5.2.1 This is required to accurately monitor the current to the spectral irradiance standard. The current shunt must be calibrated by a laboratory capable of performing calibrations that are traceable to an NMI. Documentation must be provided for the calibration of the current shunt including a record of the calibration date, the next due calibration date, uncertainty, and traceability of the calibration.

5.5.3 *Voltmeter:*

5.5.3.1 A precise digital voltmeter (at least 4½ digit) is used in conjunction with the current shunt to accurately monitor the current to the irradiance standard during the calibration process. The current must be monitored extremely closely as a 0.1 % error in the current to the lamp can result in a variation in irradiance of greater than 1 % in the uv portion of the spectrum. The voltmeter must be calibrated by a laboratory capable of performing calibrations that are traceable to an NMI. The calibration documentation must list the calibration date, the next due calibration date, uncertainty, and traceability of the calibration.

5.6 *Optical Bench:*

5.6.1 A sturdy surface on which to mount the input optics, monochromator, and spectral irradiance standard is required. Any necessary mounting hardware should be adjustable and lockable.

5.7 *Lamp Fixture:*

5.7.1 A fixture for holding the spectral irradiance standard is required. The fixture should be designed for the specific lamp type of the spectral irradiance standard. The fixture should hold the lamp securely in place so as to orient the lamp in the same manner each time it is mounted.

5.8 *Narrow Band Monochromatic Source:*

5.8.1 A source of essentially monochromatic light is needed to determine the slit scattering function of the Spectroradiometer. Spectral bandwidth of the "monochromatic" source should be no more than 20 % of the nominal bandwidth of the Spectroradiometer. Preferable is an amplitude-stabilized wavelength-tuneable laser. Acceptable alternatives are wavelength calibration emission lamps. These lamps contain certain materials that when excited produce well defined and documented spectral emission lines at specific wavelengths depending on the material. Examples include mercury (vapor), xenon, krypton, etc. Note the wavelength calibration source described in 5.3.1 may be used as long as the amplitude of emission lines is stable to within 5 %.

6. Procedure

6.1 Determine levels of irradiance to be measured by the spectroradiometer after the calibration. Select a spectral irradiance standard that will produce irradiance levels encompassing the amplitude of the anticipated unknowns.

6.2 Select the appropriate gratings and slits for the monochromator that will produce the desired resolution for this calibration.

6.3 Select the appropriate input optics and attach to the input port of the monochromator.

6.4 Ensure that the detector is properly aligned and secured to the monochromator exit slit.

6.5 *Wavelength Calibration:*

6.5.1 Illuminate the input optics with the wavelength calibration source. A low-pressure mercury lamp as described in 5.4.1.1 is often used for this purpose.

6.5.2 Select an emission line of known wavelength within the wavelength region of interest for this calibration.

6.5.3 Locate the spectral peak by scanning about its approximate location.[6]

6.5.4 Calculate and record the wavelength offset between the location of the spectral peak indicated by the current monochromator configuration and the actual location of the spectral peak.[6]

6.5.5 Compensate for this offset in subsequent steps of the procedure.[6]

6.6 *Measure Spectral Scattering:*

NOTE 1—This test may be conducted both with room lights on and with room lights off, to detect possible light leaks in the monochromator.

6.6.1 Set the monochromator to a wavelength region where the transmission of a given cut-on or cut-off filter is negligible (zero), but has high transmittance in nearby band above (for cut-on filter) or below (for cut-off filter) the test wavelength.

6.6.2 Perform the steps in 6.8 – 6.8.13, using an irradiance source of the same type (that is, an uncalibrated 1000 W lamp) and interposing filters with several different cut-on/off wavelengths as described here:

NOTE 2—It is possible, but not recommended, that spectral irradiance standard lamps be used, since the operational life of these lamps is usually short.

6.6.3 Record the signal from the detector when the input optics are illuminated by the broadband source.

6.6.4 Record the signal from the detector when the input optics are shuttered from the broadband source.

6.6.5 Interpose the cut-on or cut-off filter between the input optic and the source, and open the shutter.

6.6.6 Record the signal from the detector when the input optic is illuminated by the filtered broadband flux.

6.6.7 Compare the signal from the detector with the filter in place to the shuttered, or dark signal of the detector. A signal between 10 % and 90 % of the unfiltered signal indicates significant scattered light is reaching the detector, possibly due to a non-light-tight enclosure. Signal levels for filtered measurements and shuttered measurements that are comparable indicate that scattered light is minimal.

6.7 *Measure the Slit Scattering Function:*

6.7.1 Set the monochromator to a test wavelength, λ_o.

6.7.2 Perform the steps in 6.8 – 6.8.12.3, using the monochromatic irradiance source in place of the spectral irradiance standard. In place of 6.8.13 perform the following procedure:

6.7.3 If using a tuneable laser, the monochromator may be set to the wavelength of interest (λ_o) and the laser tuned to wavelengths from λ_o – (5 × spectrometer bandwidth) to λ_o + (5 × spectrometer bandwidth), in wavelength steps of 1 spectrometer bandwidth.

6.7.4 Record the detector signal at each wavelength step.

NOTE 3—This procedure is the most accurate means of measuring the

[6] Many modern spectroradiometers will perform this function automatically.

slit scattering function. The recorded relative amplitude plot of signal versus wavelength is a direct map of the slit scattering function.

6.7.5 Alternatively, if using emission line source, set the monochromatic source to test wavelength, λ_i, that is at least 5 spectrometer equivalent bandwidth units below the wavelength, λ_o, for which a monochromatic source (laser wavelength or emission line) is available.

6.7.6 Scan the monochromator from λ_i through λ_o, to a wavelength lf at least 5 spectrometer bandwidth units above λo, in wavelength steps of 1 spectrometer bandwidth unit.

6.7.7 Record the detector signal at each wavelength step.

NOTE 4—If the spectral scans of the slit scattering function at widely different wavelengths are not significantly different, then this technique is valid. This procedure is less accurate than the tuneable laser method of measuring the slit scattering function. The recorded relative amplitude plot of signal versus wavelength is a mirror image map of the slit scattering function versus wavelength (see NBS Technical Note 910-4).[7] This method has higher uncertainty in determination of the wings of the slit scattering function if the function is dependent (that is, not independent) of the wavelength setting. See Chapter 4 of Kostkowski[8] for a detailed description.

NOTE 5—The reason for measuring the slit scattering function is that the detector signal at each wavelength during a calibration or measurement results from the convolution, or integral of the products, of the slit scattering function and the source spectral irradiance, and not the actual spectral value. The most accurate estimate of actual spectral value (within error limits set by the noise in the measurement system, or the standard deviation for a sample of measurements at each wavelength) is the deconvolution of the slit scattering function and the measured spectral data. Determination and reporting of the slit scattering function is the only requirement of this standard.

6.8 *Spectral Irradiance Calibration:*

6.8.1 On the optical bench, set up the monochromator and input optics relative to the lamp fixture according to the precise geometry for which the spectral irradiance standard was originally calibrated. For this process, it may be useful to have the lamp fixture mounted on an X-Y-Z table for precise movement in any direction.

6.8.2 When the lamp fixture is properly aligned, carefully place the spectral irradiance standard in the proper orientation in the fixture and secure it without disturbing the alignment.

6.8.3 Ensure that the voltmeter and current shunt are properly attached to the DC power supply.

6.8.4 Ensure that the leads from the DC power supply are properly attached to the standard lamp fixture. Note the polarity.

6.8.5 Turn on the voltmeter.

6.8.6 Turn on the DC power supply and slowly increase the current to the standard lamp until the voltmeter agrees with the power level at which the spectral irradiance standard was originally calibrated.

6.8.7 Turn off any overhead or background lights in the laboratory. As an added precaution from stray light, dim, cover, or redirect radiation from any computer monitors or indicator lights that may be located near the monochromator input optics.

6.8.8 Cover or remove any reflective surfaces near the optical bench.

6.8.9 Let the standard lamp stabilize for a period of 10 min.

6.8.10 Check the voltmeter again and make any final adjustments to the DC power supply.

6.8.11 *Dark Current:*

6.8.11.1 Shutter the monochromator and take a dark current reading from the optical detector.[6]

6.8.11.2 Record the dark current reading for application to the calibration values.[6]

6.8.11.3 Alternatively, an optical chopper may be used to obtain dark current readings at each wavelength of measurement during the final scan.

6.8.12 *Precursory Scan:*

6.8.12.1 Perform a precursory scan of the source at each wavelength desired for the calibration.

6.8.12.2 This will provide an indication of the approximate power levels the detector produces during the calibration.

6.8.12.3 As indicated by the results of the precursory scan, make any necessary adjustments to the monochromator optics or detector configuration in order to optimize the signal levels of the detector.

6.8.13 Proceed with the calibration scan. Record the detector output (amps) at each wavelength to be calibrated. It is recommended that multiple readings are taken and averaged, at each wavelength, to reduce the effects of noise.

6.8.13.1 When complete, shutter the monochromator.[6]

6.8.13.2 Slowly decrease the current to the spectral irradiance standard and turn the DC power supply and voltmeter off.

6.8.13.3 Record the temperature and relative humidity of the laboratory.

6.8.13.4 Allow the spectral irradiance standard to cool for several minutes before handling.

6.8.13.5 Remove the spectral irradiance standard from the fixture and return it to its dust-free storage enclosure.

7. Mathematical Treatment

7.1 *Computing the Spectral Response Function:*

7.1.1 The following equation is used to calculate the spectral irradiance response function of the spectroradiometer:

$$K(\lambda) = \frac{S(\lambda)}{R(\lambda) - i(\lambda)} \tag{1}$$

where:

$S(\lambda)$ = the known spectral irradiance values of the primary standard (Wm^2),
$R(\lambda)$ = the detector flux readings taken during the calibration scan (amps),
$i(\lambda)$ = the dark current reading (amps); this can be either a spectral quantity or a constant factor depending on the method of dark current acquisition, and
$K(\lambda)$ = the spectral irradiance response function of the spectroradiometer ((Wm^2)amp).

7.1.2 The spectral response function is computed separately for each wavelength in the calibration.[6]

[7] Nicodemus, F., (ed.), "Self Study Manual on Optical Radiation Measurements," NBS Technical Notes 910-1 through 910-8, 1975-1985, available on CD-ROM from National Institute of Standards and Technology 100 Bureau Drive, MS 8441 Gaithersburg, MD 20899-8441.

[8] Kostkowski, H., *Reliable Spectroradiometry*, Spectroradiometry Consulting, PO Box 2747, La Plata, MD 20646, 1997.

NOTE 6—The spectral response function described here may be generated automatically using application software specific to the instrument, and a data file of the known spectral irradiance wavelengths and magnitudes. It is also possible that the automatically generated "response function" is the reciprocal of eq. 1, if automatic measurements divide the signal by the generated response function.

7.2 *Application of the Spectral Response Factor:*

7.2.1 When using this calibration to perform measurements on unknown irradiance sources, multiplying the detector reading (adjusted for the dark current) at each wavelength during the measurement by the spectral response function ($K(\lambda)$) for the corresponding wavelength.[6]

7.2.2 If there is a significant difference in the temperature of the laboratory between the calibration procedure and the measurement procedure, it may be necessary to compensate for the effects on the detector response.[6]

7.3 *Interpolation:*

7.3.1 Spectral irradiance values are typically reported in evenly spaced wavelength increments of 1, 2, 5, or 10 nm. If the reported values for the spectral irradiance standard are at greater than desired wavelength intervals, interpolating to smaller wavelength intervals will be necessary. If interpolation is required, some degree of error will be introduced by the process. In this case there are two options for the interpolation process.

7.3.1.1 Perform a linear interpolation of the assigned values for the spectral irradiance standard before calibration. This is the preferred method. The spectral irradiance standard has a very smooth spectral distribution. Interpolating this smooth curve will introduce the least error.

7.3.1.2 Perform a linear interpolation of the spectral response function ($K(\lambda)$) after taking readings of the spectral irradiance standard. The spectral response function curve can be very irregular due to the spectral response of the detector being used. If the monochromator employs high order rejection filters, these can also cause singularities in the spectral calibration curve. For these reasons, it is undesirable to interpolate the spectral response function, as significant errors can arise.

8. Report

8.1 A report should accompany any irradiance data issued by the laboratory that was produced with this calibration.

8.1.1 The report of measured irradiance data should include at least the last calibration date, spectral calibration uncertainty, spectral measurement uncertainty, and traceability of the calibration.

8.2 The following information is the minimum requirement for the calibration report:

8.2.1 Wavelength(s) used for wavelength calibration.

8.2.2 Type of source used for wavelength calibration including bandwidth information if applicable (that is, for a laser emission line).

8.2.3 Configuration of the monochromator optics as applicable.

8.2.4 Effective bandwidth of the monochromator.

8.2.5 Spectral scattering (stray light) measurements,

8.2.5.1 Type of source used for spectral scattering test,

8.2.5.2 Test wavelengths used for spectral scattering test, and

8.2.5.3 Description of filters used for spectral scattering test, including cut-on/off wavelength and passband.

8.2.6 Slit scattering function test results.

8.2.6.1 Type of source and method (6.7.1 – 6.7.4 or 6.7.5 – 6.7.7) used for slit scattering function test,

8.2.6.2 Test wavelengths, λ_o, used for slit scattering test, and

8.2.6.3 Test wavelengths, λ_o, used for slit scattering test, and Table of slit scattering function values versus wavelength, λ, for each test wavelength, λ_o.

8.2.7 Ambient temperature of the laboratory environment.

8.2.8 Relative humidity in the laboratory environment.

8.2.9 Manufacturer, model number, and serial number of the primary standard of spectral irradiance.

8.2.10 A statement of uncertainty for the calibrated values. The uncertainty calculations described in this procedure only apply to the uncorrected (not deconvoluted) spectral response function of the spectroradiometer. Any measurement process beyond that of the calibration will add to the overall uncertainty. A description of what values the uncertainties apply to must also be included in the report.

8.2.11 Identification (serial number, test report number) of a standard of the national metrological laboratory to which the primary standard is traceable.

8.2.12 Spectral Response Function data (if generated manually, or available through the application software provided by the instrument manufacturer) and the file name and location associated with the new response function.

8.2.12.1 If the application software provided does not provide the ability to print, edit, or list separately the spectral response function data, the file name and location shall be reported (if known).

8.3 The following additional information should be available for every calibration in case it is requested:

8.3.1 Noise equivalent irradiance (NEI) of the spectroradiometer at specific wavelengths. This information is usually found in technical manuals, or may be obtained from the instrument manufacturer.

8.3.2 Actual wavelengths of the original primary standard calibration.

8.3.3 Uncertainty of the primary standard relative to values of the standard of the national metrological laboratory.

8.3.4 Measurement geometry that was used during calibration.

8.3.5 Input current to the standard lamp during calibration.

8.3.6 Last calibration date of the standard lamp.

8.3.7 Number of hours the standard lamp has been used since its last calibration.

8.3.8 General physical description or designation of standard lamp including, where possible, a list of any materials it is composed of (filament, envelope, gases, etc.).

8.3.9 Calibration certification for both the current shunt and voltmeter should include the following:

8.3.9.1 A statement of Uncertainty, and type (expanded or standard).

8.3.9.2 Date calibrated.

8.3.9.3 Date of next due calibration.

8.3.9.4 Statement from the manufacturer or calibration lab describing how the uncertainty values were computed.

8.3.9.5 Statement from the manufacturer or calibration lab tracing this calibration to a national metrological laboratory that has participated in intercomparisons of standards of spectral irradiance..

8.3.9.6 Name of manufacturer.

8.3.9.7 Model number.

8.3.9.8 Serial number.

8.3.10 Name of manufacturer, model number, and serial number of the DC power supply.

9. Precision and Bias

9.1 The uncertainty shall be derived from a model of the calibration system which includes the uncertainties (as applicable) caused by:

9.1.1 Original calibration uncertainty quoted for the spectral irradiance standard [1-3].

9.1.2 Long term reproducibility of measurement system.

9.1.3 Instrument geometry (calibration distance uncertainty; alignment of receiver-lamp optical axis). [1]

9.1.4 Instrument wavelength accuracy (specifications or experimentally from wavelength calibration tests). [1,5]

9.1.5 Optical radiation detector linearity noise equivalent power, temperature response, and any other available detector specifications. [1,4,5]

9.1.6 Other factors as appropriate to the particular spectroradiometer system being used (polarization, bandwidth, stray light, room reflections). [1-8]

NOTE 7—Information for computing the uncertainties can be found in NIST Technical Note 1927, Guidelines for Evaluation and Expressing Uncertainty of NIST Measurements Results. This publication summarizes uncertainty analysis based on the Guide to Uncertianty in Measurements published by the BIPM. [9]

9.2 Expected range of uncertainties

9.2.1 NMI provided spectral irradiance standard lamp uncertainties range from 2% in the UV (250 nm to 350 nm) to 1% or less in the visible (350 nm to 900 nm) and increasing to 2% to 5% in the near infrared beyond 900 nm.[1-3] Instrument specifications are the most common sources of uncertainty sources. Empirical testing using uncalibrated but stable light sources are highly recommended for establishing instrument specific characteristics such as slit scattering function shape, stray light rejection, wavelength repeatability and biases, detector stability, etc. [5-8]

10. Keywords

10.1 calibration; irradiance; spectral; spectroradiometer

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