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FASCAL 2: a new NIST facility for the calibration of the spectral irradiance of sources

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Abstract
The facility for automated spectroradiometric calibrations (FASCAL) is the primary facility for calibration of spectral irradiance and spectral radiance at NIST and has been in continuous use since the early 1970s. Due to the increasing demands for spectroradiometric calibration, especially for supporting the monitoring of global environmental changes, a new facility, FASCAL 2, dedicated to calibrating spectral irradiance has been built. This facility will enable faster responses to calibration requests and, ultimately, result in lower uncertainties in the disseminated spectral irradiances. The FASCAL 2 facility is designed with the objective of achieving a signal-to-noise ratio exceeding 1000 : 1 from 250 nm to 2500 nm in a bandwidth of 4 nm to 8 nm when measuring a 1000 W FEL lamp at a distance of 50 cm with a receiving aperture of 1 cm^2. The facility will also be capable of calibrating deuterium lamps from 200 nm to 400 nm. The facility has six independent source stations, with four of the stations dedicated to measurements with spectral irradiance lamps and two stations reserved for the realization of spectral irradiance scales and checking the accuracy of automated wavelength. After verifying that the calibrations of spectral irradiance performed in FASCAL and FASCAL 2 agree within their combined uncertainties, FASCAL 2 will become the primary NIST facility for calibration of spectral irradiance.

1. Introduction

Because of the long history and the wide dissemination of the NIST spectral irradiance scale [1], many national laboratories around the world use spectral irradiance sources calibrated at NIST as their primary standards. These sources are also used globally for calibrating ground-based networks for the measurement of terrestrial solar spectral irradiance [2], and the spectral irradiance sources are also used to derive a spectral radiance scale to calibrate remote-sensing satellites using a plaque of known reflectance [3]. For these and other needs, a new facility for automated spectroradiometric calibrations 2 (FASCAL 2), has been developed at NIST.

This paper describes the optical and mechanical design and the performance characterizations of FASCAL 2. The facility consists of a motorized dual-grating double monochromator with order-sorting filters and three separate detectors for coverage of wavelengths from 200 nm to 2500 nm. Four independent stations for lamp calibration were constructed, along with two additional stations for wavelength characterization and scale realization. The wavelength accuracy and the temporal stability of the spectroradiometer system are discussed. The agreement of the spectral irradiances assigned to sources using FASCAL and FASCAL 2 is shown.

2. Description of the FASCAL 2 facility

Figure 1 shows the physical layout of the FASCAL 2 facility. The sources and the rails for moving the spectroradiometer system are placed on a single 4.23 m by 1.52 m fixed optical table, and the spectroradiometer is placed on a smaller, 1.52 m by 0.91 m, movable optical breadboard for translation between the separate sources. The optical breadboard is placed on linear rails, and the movement is controlled by a ball screw driven by a dc servo motor with feedback control. The

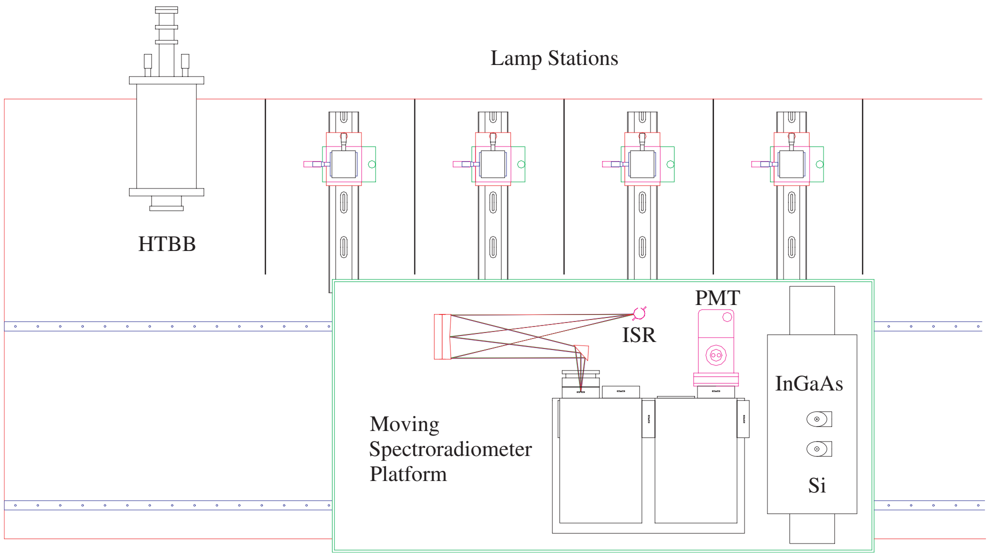

Figure 1. The optical layout showing the monochromator table with the positions of the input and the exit optics. A double monochromator in a Czerny–Turner design is used for dispersion and rejection of stray light.

total range of movement is 3.5 m, and the linear position of the spectroradiometer table is measured using a 4 m long linear encoder; the linear position of the spectroradiometer is reproducible to 2.5 μm. The facility has four separate lamp mounts to calibrate the NIST-disseminated spectral irradiance sources, FEL lamps, which are placed in kinematic lamp mounts with six axes of adjustments for alignment. The electrical power to the lamps is controlled using a calibrated shunt resistor with a temperature coefficient of resistance of 3×10^{-6} °C^{-1}, and the lamp current is actively controlled using 2^{16} bit current regulation. The lamp voltages are also recorded. The last station holds the high-temperature blackbody (HTBB) capable of extended operation near 3000 K. The temperature of the HTBB is detector-based and assigned using filter radiometers calibrated for absolute responsivity to spectral irradiance for realization of the spectral irradiance scale.

The spectroradiometer system is shown in detail in figure 1. The spectral irradiances of the sources are measured using an integrating sphere receiver (ISR) with a circular opening with an aperture area of 1 cm^2. The ISR is a 2.54 cm diameter packed polytetrafluoroethylene (PTFE) sphere for high transmittance throughout the spectral range of measurements. A 2 mm by 10 mm opening is made at the side of the ISR and imaged 1 : 1 using a spherical mirror with a focal length of 30.48 cm. A flat folding mirror is used to couple the light into the monochromator. An additive-dispersive double monochromator (McPherson 2035D[1]) with dual gratings placed in motorized grating turrets is used, and a combination of five different filters is used for second-order rejection from the grating and for further rejection of stray light. The entrance and exit slits of the monochromator are 2 mm wide and 10 mm high and unchanged during the course of the measurements. The intermediate slit is opened to a width of 4 mm with the height kept the same as the entrance and exit slits. The monochromator is a Czerny–Turner design with a focal length of 0.35 m and an effective aperture of $f/4.8$. The angular change of the grating is achieved using a sine-bar mechanism driven with a dc servo motor, with an absolute encoder with 2^{14} or 16 384 pulses per revolution attached to the shaft of the sine-bar mechanism for wavelength measurement. The temperatures of the monochromators are monitored using the platinum resistance thermometers attached to them, and are recorded during the measurement of spectral irradiance. To avoid errors in the wavelength arising from thermal changes in the monochromator, the monochromator section is temperature stabilized using forced air from thermoelectric (TE) coolers to ambient temperature of the laboratory prior to the FEL lamps being switched on. To avoid stray light, the entire monochromator system, including the input optics and the detectors, is covered using a light-tight box.

Three separate detectors with two gratings and spectral selection filters are used for spectral coverage from 200 nm to 2500 nm. The spectral range of the gratings and the detectors is shown in table 1, and although the blaze wavelength is outside the range of the Si diode wavelength, the throughput of the monochromator is adequate. A Hamamatsu R106 low-noise bi-alkali side-on photomultiplier tube (PMT) is used for measurements in the ultraviolet wavelength region. The bi-alkali PMT is chosen for low temporal drift and low dark currents. The temperature of the PMT is stabilized to −26 °C using a temperature-feedback controller, and the PMT is attached to the output port of the monochromator. A fused silica lens is attached to the PMT housing and focuses the image of the output slit onto the PMT with a demagnification factor of 2 : 1. Detectors are selected by the use of a motorized 45° mirror internal to the monochromator. The 2.4 mm by 2.4 mm square silicon (Si) photodiode is temperature stabilized and cooled to −25 °C for low-noise operation. The 2 mm diameter indium gallium arsenide (InGaAs) photodiode is cooled using four-stage TE coolers to −80 °C, and the InGaAs diode is

[1] Certain commercial equipment, instruments or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the material or equipment are necessarily the best available for the purpose.

Table 1. Specifications of the monochromator system and the detectors used to measure spectral irradiance.

Beginning wavelength/ nm	End wavelength/ nm	Grating (grooves mm^{-1})	Grating blaze/ nm	Dispersion/ (nm mm^{-1})	Bandwidth/ nm	Type of detector	Mode of operation
200	450	1200	300	2	4	Bi-alkali PMT	dc
350	1100	1200	300	2	4	TE-cooled Si diode	dc
900	2500	600	1250	4	8	TE-cooled extended InGaAs diode	ac

selected for extended responsivity to 2500 nm. The output of the monochromator is coupled to the Si and the InGaAs diodes using aluminium and gold-coated off-axis ellipsoid mirrors respectively with a 5 : 1 demagnification of the exit slit. Both the Si diode and the PMT are used in dc current measurement mode, and the InGaAs detector is used with a frequency-stabilized chopper wheel (not shown) and lock-in detection techniques for better signal-to-noise ratios in the short-wave infrared wavelength region. The Si and the InGaAs photodiodes are placed on a computer-controlled translation stage for repeatability. The helium–neon laser (not shown) on the detector stage is used in the alignment of the source to the optical axis of the spectroradiometer. For the long-term stability of the responsivity of the system, both the monochromator and the detector stage are purged using a dry-air generator to reduce the atmospheric absorption and to increase the long-term stability of the internal mirrors and gratings. The section in front of the optics (the foreoptics) is not purged since optical access from the source to the monochromator entrance is necessary.

3. Performance characterizations of the FASCAL 2 facility

A primary goal of the FASCAL 2 facility is the calibration of the spectral irradiance of 1000 W FEL lamps with a signal-to-noise ratio of more than 1000 : 1 from 250 nm to 2500 nm and subsequent assignment of spectral irradiance to other lamps. In order to achieve the desired signal-to-noise ratio, the spectral throughput of the spectroradiometer system has to be sufficient. The typical spectral irradiance of an FEL lamp at 50 cm is plotted in figure 2 along with the the percentage change in the spectrometer's response to spectral irradiance found using the three detectors. Each detector is used to measure the spectral irradiance of an FEL lamp at a distance of 50 cm, current-stabilized at 8.2 A. The lamp is measured using each detector three times over a time period of ~1 h. The percentage differences of the individual signals from the mean

$$\Delta S = \frac{100(S_i - (1/n)\sum_i^n S_i)}{(1/n)\sum_i^n S_i} \qquad (1)$$

are plotted in figure 2 using the PMT, Si and InGaAs photodiodes.

The spread in the signals below 300 nm is due to the combined effects of the instability of the FEL lamp and the low signals, but the spread in the signals is still well below the total uncertainty of the spectral irradiance scale in this spectral region. Although the PMT is sensitive to 600 nm, the Si diode is the preferred detector from 350 nm to 1100 nm due to the low noise and better temporal stability. Since the Si diode is temperature stabilized, any changes in the responsivity due to the temperature-dependent shift in the band gap are minimized. In figure 2, the measurements with the extended InGaAs diode show greater fluctuations, especially at 2400 nm. Since the foreoptics of the monochromator is not purged, the increase in the difference between the signals at 1400 nm and at 1800 nm is due to the presence of absorbed water vapour at these wavelengths, leading to increased fluctuations in the measured signals. With the exceptions of the measurements at 1400 nm, 1800 nm and at 2400 nm, our goal of achieving a signal-to-noise ratio of 1000 : 1, as determined by the standard uncertainty of the measurement at a set wavelength, is met.

The wavelength accuracy is critical, particularly in the ultraviolet wavelength region where the slope of the spectral irradiance with respect to wavelength is especially steep. The uncertainties in the spectral irradiance due to uncertainty in wavelength can be estimated by approximating the spectral shape of the FEL lamp with a 3000 K blackbody. Using the Wien approximation, the derivative with respect to wavelength is

$$\frac{\mathrm{d}L}{L} = \left(\frac{c_2}{\lambda T} - 5\right)\frac{\mathrm{d}\lambda}{\lambda} \qquad (2)$$

where c_2 is the second radiation constant, T is temperature and λ is wavelength. The wavelength accuracy of the spectroradiometer was checked using low-pressure Hg, Ne and Ar spectral-line lamps. The residuals of the linear fit to the wavelength calibrations are shown in figure 3. The wavelength uncertainties are found to be less than ± 0.1 nm ($k = 2$) from 200 nm to 1000 nm. The residuals of the linear fits for the short-wave infrared wavelength region are shown in figure 4. Higher-order polynomials were also used to correct the wavelength errors but did not lead to significant reduction in the wavelength uncertainties. The wavelength uncertainties are less than ± 0.15 nm ($k = 2$) from 1000 nm to 2500 nm. The uncertainty in spectral irradiance due to a 0.1 nm wavelength error is estimated from equation (2) to be <0.6% at 250 nm, and the uncertainty in spectral irradiance decreases with wavelength to <0.1% past 500 nm since the spectral irradiance of the FEL lamp peaks near 900 nm. The wavelength positioning is reproducible to ± 0.015 nm with changes in the gratings using the motorized grating turret.

The reduction of stray light is critical if sources with different spectral shapes are to be compared. Since the FASCAL 2 facility will also be used to transfer the calibration to deuterium (D_2) lamps with a peak in spectral irradiance near 200 nm, low levels of stray light are especially necessary in the wavelength region from 200 nm to 400 nm. The stray light in the wavelength region from 250 nm to 300 nm was determined using two glass cut-on filters (which transmit above the specified wavelength) at 320 nm and at 550 nm with

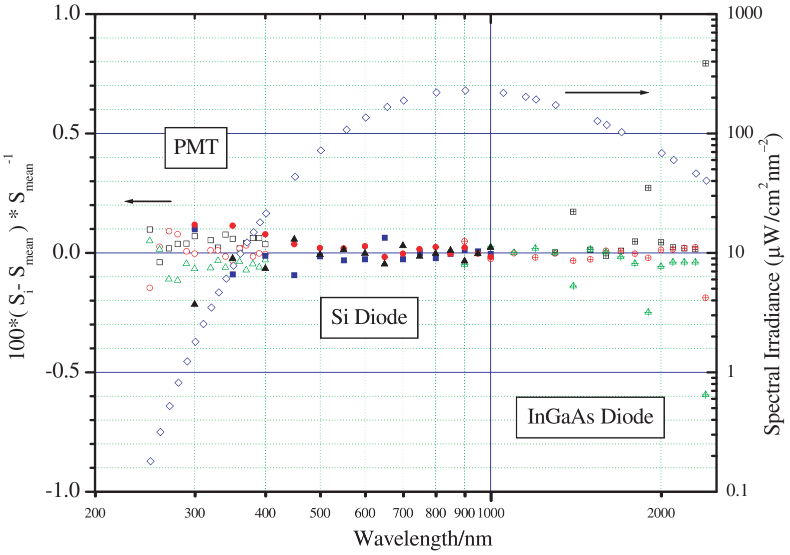

Figure 2. The left axis denotes the percentage differences from the mean of the spectral irradiances measured over a duration of 1 h. A total of three consecutive measurements were performed with the individual measurements denoted by squares, triangles and circles. The right axis indicates the typical spectral irradiance of a 1000 W FEL lamp. The spectral irradiances were measured using the PMT (open symbols), the Si diode (solid symbols) and the InGaAs diode (open-crossed symbols).

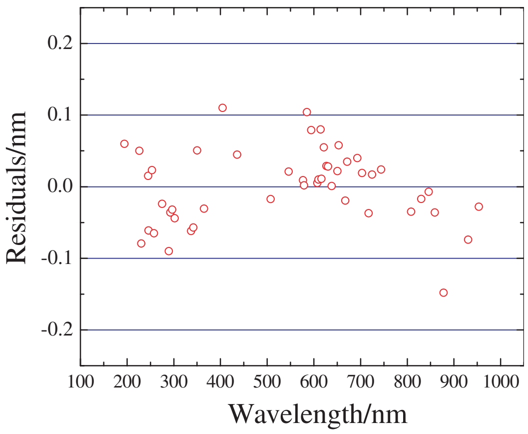

Figure 3. The residuals of the linear fit to the wavelength calibrations performed using various low-pressure lamp sources for the wavelength region from 200 nm to 1000 nm.

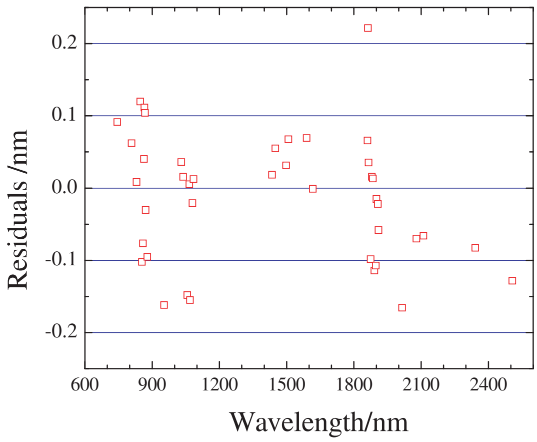

Figure 4. The residuals of the linear fit to the wavelength calibrated using various spectral line sources for the near-IR wavelength region.

ultraviolet blocking plastic filters. The stray light at 250 nm is at or below the measurement limit of the PMT with a reduction of at least 10^{-5} in the signal from the FEL measurements. Using an FEL source, an increase in the stray light from 10^{-5} at 250 nm to 10^{-2} at 275 nm is found due to light from the wavelength region from 320 nm to 500 nm. If no light is allowed to pass below 550 nm with the cut-on filter, then the stray light falls below 10^{-7} at 275 nm. The stray light which peaks at 275 nm is attributed to the zeroth-order (undispersed) light from the grating reflected from the first spherical mirror in the spectrometer and directed back to the grating where it is mixed in with the first-order dispersed light. The second reflection of the undispersed light is inherent in the design of the monochromator due to the short focal length and the small f number. The back reflection can be avoided with the grating at higher angles, and a decision was made to change the grating in the visible wavelength region to one with a higher groove density of 1800 grooves mm^{-1}.

Since each NIST-issued spectral irradiance standard is measured at least three times in one of the four stations against one of the NIST working standard lamps, the invariance of the spectral irradiance of the standards with respect to changing lamp stations is also examined. The measurements with different power supplies and shunt resistors guard against possible systematic errors in the current and the power supply in the calibration of the standard. The use of different lamp stations also eliminates systematic effects of scattered light and other position-dependent effects from the measurement of spectral irradiance. The measurement of a common FEL lamp in each of the four stations shows reproducibility to 0.1% in the wavelength region from 350 nm to 1000 nm.

A comparison of the spectral irradiance transferred in FASCAL 2 to secondary standard lamps using the FASCAL-issued FEL lamps was performed. The known spectral irradiance of an FEL lamp is used to determine the spectral

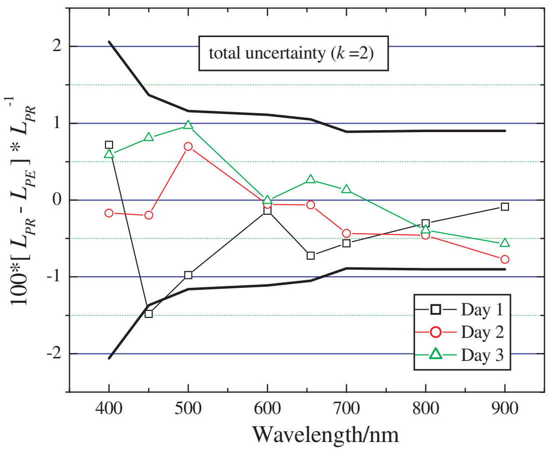

Figure 5. The percentage differences of the spectral radiances of the irradiance plaque found using the RFL and the known spectral irradiances from the FEL and the reflectance factors.

radiance of the irradiated reflectance plaque using the equation

$$L_{PE} = \frac{E(50\,\text{cm})}{\pi} \frac{(50+\delta)^2}{(d+\delta)^2} R\left(\frac{0}{45}, \lambda\right) \qquad (3)$$

where R is the 0°/45° reflectance factor and d is the distance of the plaque from the FEL. E is the spectral irradiance of the FEL lamp and δ is the distance correction for the optical centre of the FEL. Although the optical centre could be determined using measurements at various distances, for these measurements we assumed the optical centre offset to be 3.18 mm (±0.05 mm), the radius of the FEL lamp electrical pins. The spectral radiance of the plaque, L_{PR}, is also determined using a tungsten ribbon-filament lamp (RFL),

$$L_{PR}(\lambda) = L_R(\lambda) \frac{G_R}{v_R} \frac{v_P}{G_P} \qquad (4)$$

where L_R is the calibrated spectral radiance of the lamp, G_R and G_P are the gain factors used in measuring the RFL and the plaque respectively and v_R and v_P are the measured voltages when measuring the RFL and the plaque. Figure 5 shows that comparisons of spectral radiance for the three separate days are within the combined uncertainties of the measurement.

4. Continued objectives

One of the primary objectives in building the FASCAL 2 is to determine if the responsivity of the spectroradiometer system to spectral irradiance can remain temporally stable to 0.1% from 250 nm to 2500 nm over periods of months. The temperature and environmental stabilization of the spectroradiometer can reduce changes in the responsivity due to effects of the changes in the physical alignment arising from thermal drift as well as the degradation of the optical elements. If the responsivity of the spectroradiometer to spectral irradiance can be made stable, then the possibility exists of directly calibrating spectral irradiance lamps without the use of working standards. The responsivity of the spectroradiometer to spectral irradiance can be assigned by the use of filter radiometers calibrated for absolute responsivity to spectral irradiance derived from the NIST High-Accuracy Cryogenic Radiometer with the HTBB near 3000 K [4]. Initially, working standard FEL lamps will be used to assign the spectral irradiance of the issued lamps, but if the responsivity to spectral irradiance remains stable to 0.1%, standards could be issued without the use of the working standards with direct measurements with the spectroradiometer.

All the lamps calibrated in FASCAL 2 will also be measured using filter radiometers. In conjunction with the assignment of spectral irradiance, the lamps can also be measured for an absolute response to spectral irradiance

$$i = \int s(\lambda) E(\lambda)\, \mathrm{d}\lambda \qquad (5)$$

where s is the detector-based responsivity to spectral irradiance and E is the spectral irradiance, to determine the agreement of the assignment of spectral irradiance with the calculated values using the calibrated filter radiometers. Further work needs to be done to implement detector-based monitoring.

5. Conclusion

A new facility for calibration of spectral irradiance, FASCAL 2, is described. Performance characterizations such as wavelength accuracy, rejection of stray light and signal-to-noise ratios in measuring an FEL lamp at 50 cm are described. Comparison of the spectral radiances with the FASCAL 2 derived spectral irradiances is shown and found to be in agreement with the combined uncertainties from 400 nm to 900 nm. Further testing and characterization of the facility will include long-term monitoring stability and scale realizations with the possibility of implementing spectral irradiance calibrations without the need for working standard lamps.

Acknowledgments

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