Validation of the dissemination of spectral irradiance values using FEL lamps

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ABSTRACT

Scales of spectral irradiance are disseminated by National Institute of Standards and Technology (NIST) using assignment of values to FEL lamp standards for defined conditions. These lamp standards can be used for absolute calibrations of irradiance radiometers, or more typically, be used in conjunction with a diffuse reflectance standard to establish a scale of spectral radiance and for subsequent absolute calibrations of radiance radiometers. The NIST FEL standards are valuable artifacts requiring special care. Many users optimize resources by in-house transfer of their primary standard to working standards. There are a number of sources of uncertainty in utilizing FEL lamps, e.g., lamp current, alignment, distance setting, instrument aperture size, drift, scattered light, and interpolation in the wavelength grid for the specified irradiance values. In this work, we validated the transfer activity by Exelis of their primary, NIST-traceable FEL lamp standards. A portable irradiance bench that had kinematic mounts for an FEL lamp, on-axis baffle, and three different irradiance radiometers was built, tested, and deployed to Exelis in Rochester, NY. We report the results of this comparison activity. An uncertainty budget was developed and it was found that the results agreed well within the combined uncertainties of 1.5 % to 1.6 % ($k = 2$).

Keywords: Calibration, irradiance standard lamps, spectral irradiance scales, uncertainty estimates, validation

1. INTRODUCTION

Scales of spectral irradiance are disseminated from NIST by assignment of values to a specific model of 1000 W quartz halogen, tungsten coiled-coil filament lamp, designated FEL.[1] The calibration is traceable to the optical watt as realized at NIST using absolute cryogenic radiometry, aperture metrology, and high temperature blackbody source standards.[2] These lamp standards can be used for absolute calibration of irradiance radiometers such as those measuring downwelling spectral irradiance. More typically, the FEL irradiance standards are used in conjunction with a diffuse reflectance standard[3] to establish a scale of spectral radiance, and can then be used for absolute spectral radiance calibration of radiance radiometers. For Earth observing satellite sensors with on-board diffusers, laboratory measurements with an FEL lamp illuminating the on-board diffuser can be compared to on-orbit solar illumination results. Hence, in the Earth observing discipline, FEL lamps support traceability of spectral irradiance and radiance as well as validation of spectral reflectance values. The NIST FEL standards are costly, and should be recalibrated when the usage time has reached a predefined value (typically, 20 h to 50 h). To preserve resources and ensure a robust internal calibration paradigm, many users establish in-house spectral irradiance transfer facilities using radiometers to assign spectral irradiance values to working standard lamps from the primary standard lamps.

Whatever the purpose of operating the FEL lamp is, there are a number of sources of uncertainty that must be considered. First is the uncertainty in the reference values, which are stated in the lamp's calibration report, whether it was calibrated by NIST or by a commercial standards laboratory. In addition, there are uncertainty components relevant to the operation at the user facility, e.g. lamp current, alignment, distance setting, instrument aperture size, drift in the lamp output, scattered light in the experimental setup, and interpolation in the wavelength grid for the specified irradiance values.

The Advanced Baseline Imager (ABI) will replace the current imager in the National Oceanic and Atmospheric Administration's (NOAA's) Geostationary Operational Environmental Satellite (GOES) system.[4,5] It is being built by Exelis, Inc. The National Aeronautics and Space Administration (NASA), under the direction

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of NOAA, included in its statement of work the requirement to validate the Exelis scales of spectral irradiance, hence the work described here was executed. The calibration plan for the visible to shortwave spectral region for ABI includes the use of calibrated FEL standard lamps.

We validated the transfer by Exelis of the irradiance values of their primary, NIST-traceable FEL lamp standard to working standard lamps in the ABI program. A portable irradiance bench that had kinematic mounts for an FEL lamp, on-axis baffle, and three different irradiance radiometers were built, tested, and deployed to Exelis in Rochester, NY. In this paper, the experimental configurations, type and manner of data collected, results, and uncertainties are reported. An uncertainty budget was developed and it was found that the results agreed well within the combined uncertainties.

2. EXPERIMENTAL CONFIGURATION

2.1 Exelis spectral irradiance transfer procedure

Calibration of working standard FEL lamps at Exelis's Rochester Optical Radiation Laboratory (ROCL) is performed on an optical bench. The ROCL optical bench comprises a linear mounting rail, alignment lasers, an FEL kinematic mount, FEL alignment jig, non-limiting apertures for control of scattered radiation, an automated spectroradiometer system, a reference standard illuminance detector, and associated electronic equipment such as digital voltmeters, precision shunt resistors, and electrometers. The mounts included multiple-axis adjustment features. The spectroradiometer is manufactured by Optronic Laboratories (OL),[#] a Gooch & Housego Company, model number OL 750 M D. The OL 750 system at ROCL is an additive double monochromator equipped with numerous accessories, including a controller, resulting in a fully automated spectroradiometer system.

To perform a FEL calibration, first the OL 750 is initialized. The wavelength scale is set using OL broadband source attachments and determination of the grating position that corresponds to zero order for each of the gratings in the turret. Two detectors are used, one silicon and one lead sulfide, to provide coverage from 300 nm to 2400 nm. The wavelength scale is validated using Oriel emission line sources. For these tests, the FWHM of the monochromator is set to be 0.25 nm. Otherwise, the FWHM depends on spectral region: 10 nm for 300 nm to 1100 nm; 20 nm from 1110 nm to 1450 nm, and 40 nm from 1460 nm to 2400 nm. The optical axis of the bench is established using optical mounts on the rail and two lasers. The FEL alignment jig is aligned to this axis, and then the entrance aperture of the integrating sphere that is the irradiance foreoptic on the OL 750 is aligned. The distance between the FEL alignment jig and the entrance aperture of the integrating sphere is set to 50 cm.

The ROCL reference is an FEL lamp that was calibrated by NIST on September 15, 2010. After a 10 min stabilization interval, three scans are acquired and the results used to determine the irradiance responsivity of the OL 750. Background levels are determined using an internal shutter. After the reference lamp is turned off and cooled down, the FEL lamp to be calibrated is placed in the kinematic mount, turned on, and stabilized for 10 min. Three scans are acquired, and the OL software and algorithms are used to determine the calculated illuminance for the working standard spectral irradiance lamps. The working standard lamp is turned off, another inserted, and the process is repeated for the second working standard lamp. Three lamps were calibrated in this manner using the Exelis reference lamp. Next, using the lasers, the bench was reconfigured for measurements of the working standard lamps with a NIST-calibrated illuminance detector. The process of assigning spectral irradiance and illuminance values using the Exelis reference lamp and the OL 750, followed by absolute measurements of using the Exelis illuminance detector, was repeated on a daily basis for a total of five days. The final spectral irradiance values for the working standard lamps were adjusted by applying up to a 0.3 % spectrally-flat correction factor so that the OL 750-determined illuminance values and the measured illuminance values were in agreement. The results were subjected to ROCL's quality assurance protocols, uncertainties were assigned, and the reports presented to the NIST team immediately prior to the comparison tests.

The overall operation of the NIST reference lamp, and the working standard lamps, at Exelis was according to the procedures described by NIST.[1] At both facilities, the lamps were operated constant current at 8.2 A, the receiving aperture was 50 cm from the front of the lamp's bi-post base, non-limiting apertures were used to control stray light and restrict the view of the lamp base, and internal shutters were used to acquire background signals. Differences in procedures were noted. The Exelis warm-up interval was shorter: 10 min vs. 20 min at NIST. The receiving aperture was larger: 31.75 mm diameter vs. 11.28 mm at NIST. At Exelis, a silicon detector was used below 350 nm, not a photomultiplier tube, and a PbS detector was used in the short-wave infrared, not an InGaAs detector.

2.2 NIST portable spectral irradiance bench

The core tests of the validation activities were developed by NIST in collaboration with Exelis, NASA, and NOAA. These tests involved determinations by NIST at Exelis using NIST equipment and independent FEL lamp standards calibrated by NIST specifically for the project. NIST designed and built a portable irradiance bench that included a linear mounting rail, alignment laser, FEL kinematic mount, FEL glass alignment jig, non-limiting apertures for control of scattered radiation, two optical-fiber coupled spectroradiometer systems, a photometer, and associated equipment such as digital voltmeters, a calibrated shunt resistor, and custom computer data acquisition programs. Multiple-axis mechanical mounts provided the necessary adjustments for alignment. The irradiance receivers for the fiber coupled spectroradiometers were made using Ocean Optics FOIS-1 integrating spheres fitted with precision apertures. These 2.54 cm-diameter spheres have a SMA fiber optic connector at 90º to the entrance aperture.

To utilize the NIST irradiance bench, which was constructed using X95 structural rail and carrier system from Newport Corporation, first it was assembled and aligned, either at NIST or Exelis. The FEL mount was aligned to the laser axis using the FEL alignment jig in the FEL kinematic mount. A photometer and one of the spectroradiometers were alternately mounted to a rail-carrier using magnetically-coupled kinematic baseplates. Care was taken so that the optical alignment and distance setting was invariant as the photometer and spectroradiometer were interchanged.

Table 1 lists the main features of the radiometers on the NIST irradiance bench. The photometer was a $V(\lambda)$-filtered silicon photodiode fitted with a diffuse transmitting collector. It was not temperature-stabilized. One of the spectroradiometers was an ASD, Inc. FieldSpec 3 and the other was a Spectral Evolution, Inc. SR-3500. The spectral coverage was similar, 350 nm to 2500 nm, and in both instruments, the dispersion the result of a single grating. Both spectroradiometers have three separate systems: a visible/near infrared (VNIR) spectrograph with a 512 element silicon photodiode array detector (Si PDA) and either two scanning monochromators (FieldSpec 3) or two spectrographs (SR-3500) to cover the shortwave infrared (SWIR) spectral region. Two single element InGaAs detectors are in the FieldSpec 3 and two 256 element InGaAs arrays are in the SR-3500. In both systems, the temperature of the Si PDA is not controlled while the InGaAs detectors are thermoelectrically (TE) cooled. Both systems have internal shutters for dark measurements and adjustable integration times. Internal software on the FieldSpec 3 interpolates the results at the native resolution of the 512 array onto a 1 nm interval; the results from the scanning monochromators (sampling interval 100 ms) are also reported on a 1 nm grid.

Table 1. Radiometers used on the NIST irradiance bench. The stated parameters are from the manufacturer's specifications.

Radiometer	Sub-systems	Spectral Coverage	Bandpass (Sampling)
Photometer	V(λ) filter, silicon photodiode	380 nm to 780 nm	N/A
FieldSpec 3	VNIR spectrograph	350 nm to 1000 nm	3 @700 nm (1.3 nm)
	SWIR1 monochromator	1001 nm to 1800 nm	10 @1400 nm (2 nm)
	SWIR2 monochromator	1801 nm to 2500 nm	10 @2100 nm (2 nm)
SR-3500	VNIR spectrograph	348.4 nm to 999.2 nm	1.5 nm, all λ (0.8 nm to 1.5 nm)
	SWIR1 spectrograph	959.9 nm to 1894.7 nm	3.8 @1500 nm (3.3 nm to4.0 nm)
	SWIR2 spectrograph	1875.0 nm to 2519.4 nm	2.5 @2100 nm (2.1 nm to 2.9 nm)

The reference lamps for the NIST irradiance bench were F-639, F-640, and F-641; these new lamps were calibrated using FASCAL II[1,2] on October 29, 2010. Two of these lamps (F-639 and F-640) were hand carried to ROCL in November 2010 for the validation tests and one lamp (F-641) remained at NIST as a check reference standard. Three other new lamps (F-646, F-647, and F-648) were fully characterized according to the FASCAL II protocols so they could be used blindly by either participant. Two additional lamps that had robust history, F-431 and F-432 were also hand carried to ROCL to serve as available check working standards. Finally, an operational but uncalibrated lamp, E-008, was used to verify the proper operation of the lamp control program. Table 2 summarizes the lamp conditions and usages. The current supplied to the lamp was measured using a 0.1 Ω shunt resistor (model RUG-Z-R100, serial number 005522 from Isotek) that was in series with the lamp filament. This shunt resistor was calibrated on September 6, 2010 by the NIST Quantum Electrical Metrology Division to have a resistance of 0.1000365 Ω ±0.0000002 Ω ($k = 2$) at an operating current of 8.2 A.

Table 2. NIST FEL lamps as used in the irradiance validation exercise. For calibration, the current was set to 8.2 A and the voltage drop was measured at the bi-post connectors. The use was reference standard (RS), working standard (WS), characterization studies (CZ), or testing system (TS).

Lamp	Manf.	Curr. (A)	Volt. (V)	Cal. Date	Use	Location
F-639	Osram Sylvania	8.200	110.65	10/29/2010	RS	NIST, ROCL
F-640	Osram Sylvania	8.200	110.57	10/29/2010	RS, WS	NIST, ROCL
F-641	Osram Sylvania	8.200	110.24	10/29/2010	RS, WS	NIST
F-646	Osram Sylvania	8.200	112.22	03/22/2011	WS	ROCL, NIST
F-647	Osram Sylvania	8.200	N/A	None	WS, CZ	NIST
F-431	Osram Sylvania	8.200	105.42	10/10/2010	WS, RS	ROCL
E-008	Osram Sylvania	8.200	N/A	None	TS	NIST, ROCL

Table 3. Procedure to assign irradiance values from reference to working standard FEL lamps.

Step	Sequence
1. Calibrate either the FieldSpec 3 or the SR-3500 spectroradiometer	
	Install the NIST reference standard lamp, power it on, wait for stabilization
	Place the photometer in position and acquire ambient and light data sets
	Remove the photometer, position the spectroradiometer, and acquire ambient and light data sets
	Repeat the photometer measurements
	Power off the NIST reference standard lamp
2. Calibrate the working standard FEL lamp	
	Repeat Step 1 using the test lamp
3. Recalibrate either the FieldSpec 3 or the SR-3500 spectroradiometer	
	Repeat Step 1 using the reference lamp in Step 1

The NIST procedure, see Table 3, to calibrate a working standard lamp involved two determinations of the spectroradiometer's irradiance responsivity using the same reference lamp and one measurement of the working standard (test) lamp. For each lamp operation, the photometer acquired data before and after the spectroradiometer. An on-axis opaque disc was used to determine a more reasonable level of background signal, termed "ambient," because scattered light from the baffle edges, mounting hardware, and other objects are a source of flux visible to irradiance collectors.

2.3 Comparison measurement procedures

The core tests were executed at Exelis once with the FieldSpec 3 and three times with the SR-3500. At Exelis, the reference was either F-639 or F-640 and the working standards were Exelis lamps designated F-829, F-918, and F-1051. Upon return to NIST, the procedure was followed using the SR-3500 with F-640 as the reference and F-641 as the working standard.

Additional measurements that were designed for testing, characterization, or validation were performed. The wavelength scale of the FieldSpec 3 and the SR-3500 was assessed by scans of Hg and Ar emission line sources. This was done at Exelis for the FieldSpec 3 and at Exelis and NIST for the SR-3500. Using the Exelis the reference standard lamp, the working standard lamp F-431 was calibrated by Exelis at Exelis during the comparison exercise, and lamp F-646 was left at Exelis and calibrated on November 19. Later this lamp was shipped to NIST and calibrated using FASCAL II. Finally, the uncalibrated lamp F-647 was used at NIST after the deployment with the SR-3500 to perform sensitivity studies in support of the uncertainty budget. On November 10, the voltage drop across the shunt resistor in the NIST irradiance bench was monitored by an Exelis digital voltmeter as a verification of lamp operating current. As a result of these tests, we determined the NIST power supply was inaccurate, with a bias of about 11 mA. This was rectified on November 10 by reducing the target value of the current by about 12 mA for both the NIST and Exelis lamps.

2.4 FASCAL reference data

The spectral irradiance values for F-639, F-640, and F-641 were determined at 50 cm distance and 8.200 A current for 35 wavelengths on a non-uniform wavelength grid from 250 nm to 2400 nm, and certificates of calibration issued. The relative uncertainties of the spectral irradiance values at $k = 1$ are also shown in Table 4 at the ABI center wavelengths.[5]

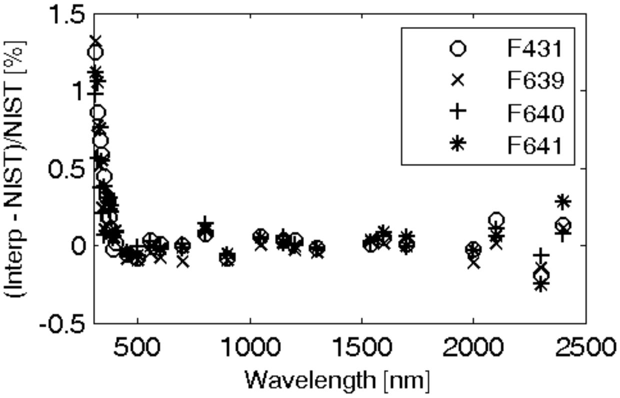

Figure 1. Differences between the interpolated and reference spectral irradiance values for the four calibrated lamps, expressed in percent. The legend identifies which lamp.

The reference lamp irradiance values were interpolated onto a 1 nm grid using a blackbody model with a fourth-order polynomial-modified emissivity, following the model developed at NIST.[6] The differences in the irradiance values at the common wavelengths for the input and 1 nm-interpolated values are shown in Fig. 1 for the 300 nm to 2400 nm spectral region for the four NIST-calibrated lamps. Below 300 nm, the differences increase; this is a result of using a single blackbody temperature for the entire spectral region. This discrepancy does not affect our results, as the comparison begins at the 350 nm. The interpolation uncertainty, see Table 5, is the average standard deviation of the absolute differences from 350 nm to 2400 nm for all four lamps. To analyze the results, the 1 nm data were resampled onto the spectroradiometer wavelength grids using linear interpolation.

2.5 Exelis comparison data

Exelis supplied spectral irradiance values for the test lamps on a 10 nm grid from 300 nm to 2400 nm. Instead of using a blackbody based model to interpolate the spectral irradiance values for the reference lamp as was done for the NIST irradiance bench, Exelis used a Lagrange interpolation as a localized cubic polynomial fit across every successive set of four input data points. The Exelis combined standard uncertainties were reported in 50 nm-wide spectral bands, applicable from 300 nm to 349 nm, 350 nm to 399 nm, etc.; see Table 4. These uncertainties include components related to the NIST reference lamp and procedures associated with the transfer using the OL 750. For the comparison, the 10 nm data were interpolated onto a 1 nm wavelength grid using the piecewise cubic Hermite interpolating polynomial, and further interpolated onto the native grid of the FieldSpec3 or the SR-3500 using linear interpolation. As a test of the interpolation methods, an Exelis data set at the 10 nm grid and interpolated to the 1 nm grid with the fourth-order Lagrange interpolation by Exelis was compared to the NIST polynomial-modified blackbody fit evaluated on the 1 nm grid. The standard deviation for the differences from 400 nm to 2400 nm was 0.271%.

Table 4. Relative standard uncertainties, stated in percent, for NIST FASCAL calibration of the comparison reference lamps and the Exelis -supplied irradiance values of the test lamps, averaged over the VNIR ABI spectral bands.[5]

Uncertainty	Type	Value [%]					
ABI Bands	Band Center [nm]	470	640	865	1378	1610	2250
	Bandpass [nm]	40	100	39	15	60	50
	Band	1	2	3	4	5	6
NIST	B	0.439	0.352	0.290	0.241	0.235	0.246

Exelis	B	0.889	0.762	0.731	0.727	0.710	0.749

2.6 NIST FEL housekeeping data

The FEL lamps operated on the NIST irradiance bench were under computer control, using an HP6030A power supply without active feedback to set the current. The time of day, voltage drop across the shunt resistor, and voltage drop across the lamp bi-posts were logged to a data file. The measured shunt voltage was converted to current using the calibrated value of the shunt resistor. Figure 2 illustrates the observed currents as a difference between the actual current and the calibrated set current for that lamp. All values are shown, including those during lamp warm-up. The large cross is the mean of the differences for the time interval covering the measurement sequence described in Table 3. The uncertainty in the measured lamp currents, determined from combining the Type A uncertainty in the shunt voltages and the Type B uncertainty of the shunt resistance, was 0.015 mA. The positive offset in the lamp current values of between 10.3 mA and 11.4 mA mentioned earlier is evident in panels (a) and (b) of Fig. 2. Note, however, for each sequence, all three lamp runs (two reference, one test) had similar bias, with differences of 3.5 mA or less. Also, except for the second run of F639 on November 10, the lamp current in the reference lamps repeated to within 0.2 mA.

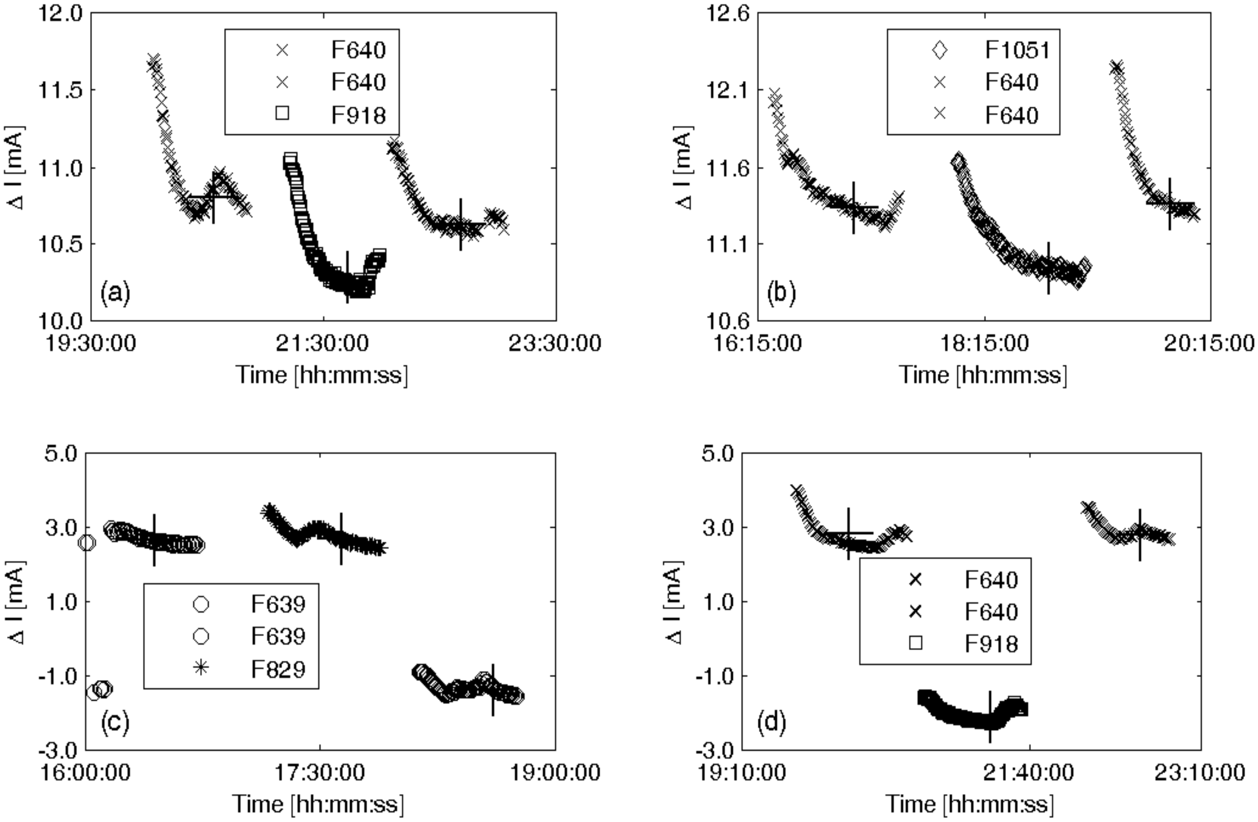

Figure 2. The difference between the actual current and the calibration current for the FEL lamps measured at Exelis; positive values indicate the current was greater than desired. (a) Nov 8; (b) Nov 9; (c) and (d) Nov 10.

2.7 NIST photometer data

The photocurrent from the photometer was converted to a voltage using a commercial transimpedance amplifier and logged to a computer file every 0.05 min using a digital voltmeter and custom data acquisition software. The net signals were determined using the ambient results and the average for a 5 min sequence was determined. The $k = 1$ uncertainty in the mean net value was negligible, 0.0025 %. The repeats, taken before and after the spectroradiometer scans for a given lamp lighting, had discrepancies between -0.09 % to +0.365 %, with a mean discrepancy of +0.14 %. In all but one case, the first set of photometer readings was larger. The photometer readings for repeats on the reference lamp upon its relighting for the second spectroradiometer calibration (Step 3 in Table 3) gave discrepancies of between -0.07 % and +0.37 %, with a mean of +0.16 %. These repeats were random in nature. Finally, repeats on F640 between November 8 and 9, when nearly the same current was used, disagree by 1.0%. The reason for the variability in the photometer readings is not known, but could be due in part to the lack of temperature stabilization of the photometer. Alignment repeatability, in particular between November 8 and 9, could also be a factor. On November 10 a special test was done with F-640 to determine the change in photometer output with lamp current by setting the current ±20 mA from its calibration value. A linear fit, excluding the November 8 photometer data, gave a change in photometer net signal with lamp current of 0.39 mV/mA. Hence the daily variability of the photometer's reading of F-640, with the exception of November 8 (which is not understood), is explained in terms the lamp operating current.

2.8 NIST FieldSpec 3

The FieldSpec3 spectroradiometer was operated on the NIST irradiance bench under computer control, using custom software based on device drivers supplied by ASD. The software records all of the FieldSpec 3's housekeeping data and the instrument output when the FieldSpec 3 is acquiring darks. Ten internal scans for each of the 10 repeated, sequential scans in each measurement sequence were acquired. The measurement sequence was the same for the lamp or the on-axis disc. For the VNIR photodiode array, the integration time was 0.544 sec. The time to complete one internal scan set was about 15 sec and measurement sequence took about 2 min 23 sec.

The 10 scans in the SWIR1 and SWIR2 on November 8 for F640 and F918 repeated very well, but the VNIR results were not consistent. The first measurement of F640 and the measurement of F918 showed variability that increased with increasing wavelength, but in the second measurement of F640, a progressive decrease with increasing scan number was observed, with a total change of 1.7 %. Because of this behavior, the use of the FieldSpec 3 was discontinued and the remainder of the tests performed with the SR-3500. On November 8 and 9, the wavelength calibration of the FieldSpec 3 was assessed using Hg and Ar emission lamps as observed in the VNIR and SWIR1 results. The line profiles were fitted to a Gaussian and triangular line shapes and the center values compared to the FieldSpec 3 wavelength scale. The standard uncertainty of the FieldSpec 3 wavelength calibration is 0.59 nm from the differences. The instability of its wavelength calibration, assessed by comparison of the results between the two days, was negligible.

2.9 NIST SR-3500

The SR-3500 spectroradiometer was operated on the NIST irradiance bench under computer control, using the data acquisition software supplied with the instrument. The integration times for each of the three spectrographs was set manually: 50 ms for VNIR and SWIR1, and 30 ms for SWIR2 except on November 9 this was set at 1 ms. Twenty sequential scans, taking about 2 min, were acquired of either the blocking disc or the lamp. The output values included the correction using the internal shutter, so it was not possible to examine detector dark counts. As with the FieldSpec 3, the net signal was determined using the blocking disc and the results were normalized to integration time and averaged over the 20 scans. In portions of the VNIR and SWIR1 spectral regions, the individual scans repeated very well, within ±0.1 % and ±0.2 % in SWIR1, respectively. The SWIR2 was noisier, with increasing variability at the longer wavelengths. For the SR-3500, the values are reported for each detector pixel with the wavelength calibration applied. As noted in Table 1, values are interspersed in the overlap regions between the spectrographs. The overlap regions were parsed and processed to allow for comparison between the spectrographs.

On November 11 at Exelis and November 18 at NIST, the wavelength calibration of the SR-3500 was assessed using Hg and Ar emission lamps. The measured line profiles were analyzed as described above for the FieldSpec 3, resulting in a standard uncertainty of 0.45 nm. Because the irradiance responsivity of the SR-3500 oscillates in the VNIR spectrograph by up to 30 % every 30 nm or so, the stability of its wavelength calibration is critical. On the timescale of these tests, no variability was observed.

The SR-3500 software records three instrument temperatures, corresponding to the three spectrographs. The protocol of repeat scans of the reference lamps F-639 and F-640, along with the data collected November 18 using F-647, allowed for an examination of temperature sensitivity in the system response of the VNIR spectrograph. Using the before and after scans, normalized net signal ratios were determined at the three ABI VNIR bands and fitted using a linear model to the temperature differences, which ranged from -0.24 ºC to +0.97 ºC. At 470 nm and 640 nm, a small negative correlation exists, about -0.2 %/ ºC. At 865 nm there is more scatter and the fitted slope is +0.1 %/ ºC.

3. COMPARISON UNCERTAINTY ANALYSIS

The measurement equation for the spectral irradiance of the test lamp, $E_U(\lambda)$ determined using the NIST irradiance bench is given in Eqn. (1), where $E_R(\lambda)$ is the spectral irradiance of the reference lamp, $S_U(\lambda)$ is the net signal for the test lamp, and $S_R(\lambda)$ is the net signal for the reference lamp. We compare in Figs. 3 – 5 the ratio $E_U(\lambda)$ to values supplied by Exelis, which arise from a similar measurement equation based on the Exelis reference lamp, the OL 750 and the Exelis photometer. The uncertainty components in Table 5 are associated with this ratio determination.

$$E_U(\lambda) = \frac{S_U(\lambda)}{R(\lambda)} = E_R(\lambda)\frac{S_U(\lambda)}{S_R(\lambda)}. \tag{1}$$

Table 5. Relative standard uncertainties, stated in percent, for the comparison uncertainty from the reference lamp to the test lamp according to the procedure outlined in Table 3.

Component	**Type**	**Value [%]**					
ABI band		1	2	3	4	5	6
Interp. in $E_R(\lambda)$	B	0.0911	0.0911	0.0911	0.0911	0.0911	0.0911
F-829, F-918, F-1051	B	0.749	0.691	0.689	0.690	0.692	0.692
Interp. in $E_U(\lambda)$	B	0.0782	0.0782	0.0782	0.0782	0.0782	0.0782
Signal meas., ref. lamp							
FieldSpec 3, Nov 8	A				0.0219	0.0305	0.275
SR-3500, Nov 10, 19	A	0.110	0.0788	0.0949	0.162	0.102	0.267
SR-3500, Nov 9	A						1.32
Signal meas., test lamp							
FieldSpec 3, Nov 8	A				0.0255	0.0363	0.313
SR-3500, Nov 10, 19	A	0.0257	0.0100	0.0252	0.0209	0.0301	0.349
SR-3500, Nov 9	A						2.10
Wavelength							
FieldSpec 3, Nov 8	B				0.0342	0.0389	0.0378
SR-3500	B	0.234	0.0801	0.0063	0.0261	0.0297	0.0288
VNIR Si PDA temp.	B	0.0807	0.0586	0.0311			
Lamp current	B	0.0908	0.0669	0.0505	0.0351	0.0307	0.0319
Perpendicular	B	0.0310	0.0310	0.0310	0.0310	0.0310	0.0310
Centered	B	0.0310	0.0310	0.0310	0.0310	0.0310	0.0310
Total unc., $k = 1$							
FieldSpec 3, Nov 8	B				0.704	0.707	0.819
SR-3500, Nov 10, 19	B	0.812	0.717	0.710	0.722	0.713	0.830
SR-3500, Nov 9	B						2.58

The method of interpolation affects the results, so the NIST interpolation uncertainty (Sec. 2.4) is included in Table 5. The next term is the transfer uncertainty for the Exelis calibration, e.g., the total uncertainty (Table 4) recomputed without the uncertainty in the NIST reference lamp. For the Exelis interpolation step, the standard deviation of the difference between the methods, 0.271 %, was used as the width of a uniform distribution to estimate the uncertainty. The measurement uncertainty corresponds to scans of the reference or test lamps. An error in wavelength results in incorrect assignment of the provided spectral irradiance values. To lowest order, the sensitivity coefficient is $\partial E_R/\delta\lambda$, and we assume that for the purposes of uncertainty estimates, all FEL type lamps have similar spectral shape. The wavelength uncertainties of the FieldSpec 3, $u(\lambda) = 0.59$ nm, and the SR-3500, $u(\lambda) = 0.45$ nm, were used to determine this uncertainty component. We carry a component associated with the SR-3500 VNIR PDA temperature, using the observed temperature differences (-0.24 ºC to +0.97 ºC), a uniform distribution[7] (temperature uncertainty of 0.349 ºC), and sensitivity coefficients determined in Sec. 2.9.

The effect of the lamp current uncertainty was evaluated using sensitivity coefficients measured with F-647 and the SR-3500 at NIST, with the $u(I)$ value of 1.17 mA, a type B estimate based on the maximum deviations observed for the set F-639/F-829/F-639 on November 10. To first order, the current biases of up to 11.4 mA cancel as we assume the sensitivity coefficients are similar for all FEL-type lamps, so it is only the differences in a set that matter. The design of the electrical mount for the FEL lamps[1] leads to negligible variability in distance when a lamp is unmounted and remounted. With respect to scattered light, the magnitude of the spectral irradiance of all of the lamps measured was similar, and all results were determined using the blocking disc for background subtraction, so to lowest order any unidentified bias cancels in Eqn. (1). However, we include uncertainty components associated with alignment, as we observed small changes that were consistent with uncertainty estimates from this source. The uncertainty associated with aligning the lamp to be perpendicular and centered to the spectroradiometer's input aperture was estimated by using Eqns. D.11 and D.14 in Ref. 8. The angular uncertainty for either term was determined to be 0.937 mrad from measured displacements of reflections of the NIST alignment laser during the set up at Exelis. The maximum goniometric distribution term was taken to be 1 %.

4. RESULTS

4.1 Comparisons of lamps on the NIST irradiance bench

The irradiances of the Exelis lamp were determined according to Eqn. 1 using the reference lamp irradiance values and the spectroradiometer output for the two measurements of the reference lamp that bracketed the scans of the Exelis lamp. The net spectroradiometer signal was determined using the blocking disc, and the results were corrected for integration times or gains according to instrument and spectral region.

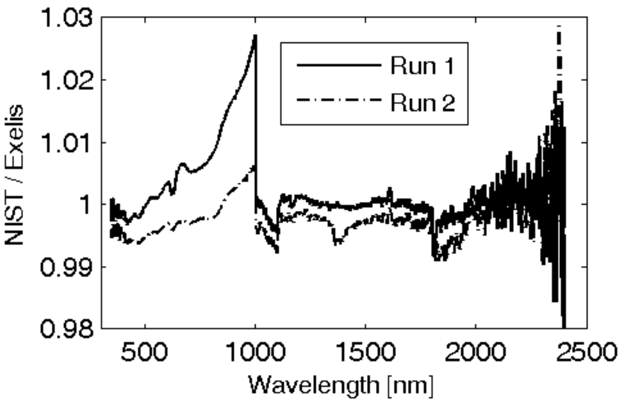

Figure 3. Results for F918 using the FieldSpec 3 and F640 on November 8, 2012.

The results for the FieldSpec 3 on November 8 for Exelis lamp F918 are shown in Fig. 3. The results are presented as the spectral irradiance of F918 as determined using F640 and the NIST irradiance bench normalized by the spectral irradiance of F918 assigned by Exelis during their calibration procedures prior to the validation exercise. The two reference scans (Run 1 and Run 2) are in good agreement in the SWIR1 and SWIR2 spectral regions, and they also show good agreement between Exelis and NIST. Note the discontinuity between SWIR1 and SWIR2 at 1800 nm and the indication of variability in the region of the 1380 nm water vapor absorption feature.

The VNIR spectral region is less satisfactory, with the first F640 set being disparate at 1000 nm by 2.7 % and the second F640 set giving better agreement, 0.65 %. The F640 lamp current repeated to better than 0.17 mA (Fig. 3a) and the four photometer readings agreed to better than 0.13 %. This, combined with the SWIR behavior, indicates that the lack of VNIR irreproducibility is due to the FieldSpec 3, not the lamp current, instrument alignment, etc. Therefore, the FieldSpec 3 VNIR results are discarded from this comparison exercise.

The results for the SR-3500 at Exelis on November 9 and 10 for lamps F1051, F829, and F918 and at NIST on November 19 for lamp F641 are shown in Fig. 4. For the SR-3500, the derived responsivities from the two measurements of the reference lamp that bracketed each measurement of the test lamp agreed to within ±0.25% for the majority of the spectral region. Therefore, the average S_R for Runs 1 and 2 were applied in Eqn. 1 for each test lamp measurement set.

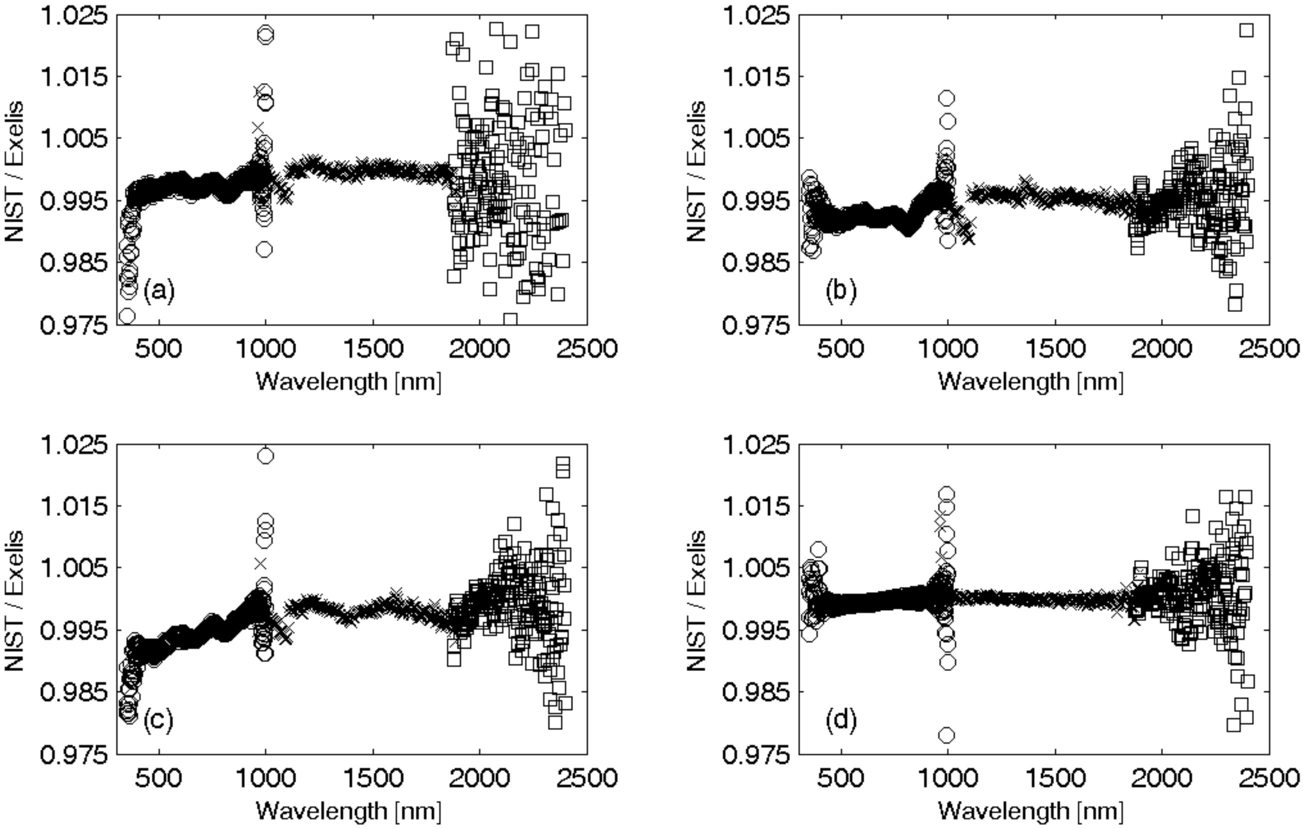

Figure 4. Results using the SR-3500 for the three Exelis lamps (at Exelis) and one reference lamp (at NIST), shown as the measured irradiance normalized by the irradiances provided by Exelis. (a) F-1051 using F-640 as the reference on November 9; (b) F-829 using F-639 as the reference on November 10; (c) F-918 using F-640 as the reference on November 10; and (d) F-641 using F-640 as the reference on November 19.

4.2 Comparisons with F-431 and F-646

On November 9 during the validation exercise, the NIST lamp F-431 was calibrated by Exelis using the Exelis calibration bench and referenced to the Exelis standard lamp. The NIST lamp F-646 was left at Exelis and calibrated on their bench on November 19, 2010, again by reference to the Exelis standard lamp. The lamp was shipped back to NIST and calibrated on FASCAL II on March 22, 2011.

4.3 All results

The results at the ABI bands for F-1051, F-829, F-918, F-641 (Fig. 4) and F-431 and F-646 are given in Fig. 5 as the NIST FASCAL II values normalized by the Exelis result for the spectral irradiance. The average discrepancy over all ABI bands for the SR-3500 is -0.234 %, while the expanded comparison uncertainties ($k = 2$) are 1.42 % to 1.67 %.

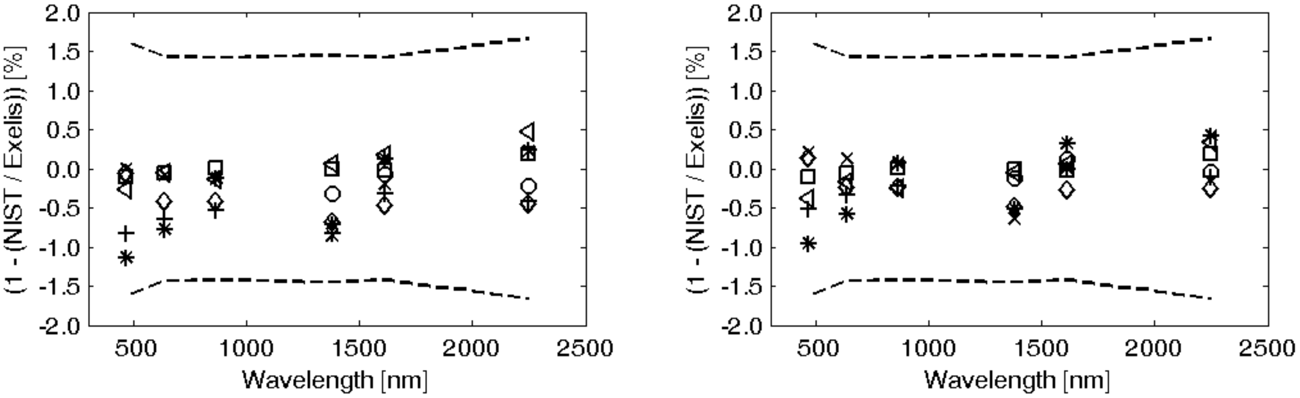

Figure 5. Results of the validation exercise, band-averaged at the ABI bands, with the term 1 - NIST/ Exelis in percent. Circles are F-918 (FieldSpec 3), X's are F-1051 (SR-3500); + are F-829 (SR-3500); * are F-918 (SR-3500); squares are F-641 (SR-3500); diamonds are F-431 (OL 750); and triangles are F-646 (OL 750). The left panel is as reported by Exelis and the right panel is without the scaling to the Exelis photometer measurements during their calibration procedure.

5. DISCUSSION

The average of the ratios for the three cases of instrument and spectral range reported are all within the $k = 2$ estimated uncertainties for the comparison presented in Table 5. The level of agreement may indicate the comparison uncertainty budget is overestimated. The dominant component in the comparison uncertainty is the uncertainty in the transfer of spectral irradiance values by Exelis from the Exelis reference lamp to the working standard lamp. This indicates the transfer uncertainty of the NIST irradiance bench is small—thus validating use of the irradiance bench for transfers. However, many of the results have a negative bias, see the left panel in Fig. 5. Inspection of the correction factor implemented by Exelis using the calibrated photometer indicates the OL750-determined spectral irradiance values were increased by 0.217 %, 0.192 %, 0.309 %, and 0.191 % for F-1051, F-918, F-829, and F-431, respectively, and decreased by 0.119% for F-646. Note that the F-640/F-641/F-640 results from November 19, where no photometer correction factor was applied, are on average close to unity (Fig. 4d). If the photometer correction factor is not applied, the average discrepancy for the SR-3500 results (excluding the SWIR2 on November 9) improves by 0.13%. The photometer based correction at Exelis is intended to correct for the larger port on the OL750 integrating sphere foreoptic, as the photometer has the FASCAL II-sized 1 cm^2 input aperture area. Although a small correction, this work indicates an investigation of this procedure may be of interest.

Regarding the interpolation of spectral irradiance data for FEL type lamps from the coarse to fine wavelength grids, there are advantages and disadvantages to the approaches outlined here. The polynomial times the blackbody scaling described by NIST[6] is physically based and does not force the fit through the supplied data. However, it cannot account for spectral features that may exist in the source under consideration. The Lagrange polynomial-based interpolation, or any spline-based method, matches the input values exactly, even though they have associated uncertainty. There can be issues with estimates near the end points, but if real spectral features are present (not variability from atmospheric absorption), then this method will account for them. For either method, it is recommended, however, to avoid a global fit to a data set spanning the entire spectral range. Better results will be achieved by splitting the spectral range into two or three overlapping regions, e.g., 250 nm to 400 nm; 350 nm to 1200 nm; 800 nm to 2400 nm, and then splicing the results at 350 nm and 900 nm. It is good practice to try both or additional methods as otherwise there is no way to evaluate for outliers in the input data set.

In general, the equipment functioned well. The FieldSpec 3 was returned for repair to the manufacturer after subsequent testing at NIST failed to identify the problem with the VNIR repeatability. The results with the SR-3500 indicate that for best, e.g. standards-quality results, the Si PDA needs to be temperature stabilized. It is also evident that with full access to raw detector output, complete housekeeping data including detector, housing, electronic temperatures, correction for instrument performance can be implemented.

6. CONCLUSIONS

The results of a validation of the Exelis spectral irradiance transfer from a NIST reference irradiance standard lamp to their working standard lamps was successful, with the measured discrepancies falling within the estimated uncertainties. The success was due, we believe, to a number of factors, including planning, flexibility in approach while at Exelis, verification of steps such as the distance measurement, access to the dimensional metrology laboratory at Exelis, robustness of the NIST irradiance bench, and stability of the lamps and spectroradiometers.

7. ACKNOWLEDGMENTS

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Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

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