Comparison of spectral irradiance standards used to calibrate shortwave radiometers and spectroradiometers

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Absolute calibration of spectral shortwave radiometers is usually performed with National Institute of Standards and Technology (NIST) or NIST-traceable incandescent lamps. We compare 18 irradiance standards from NIST and three commercial vendors using the same spectrometer to assess their agreement with our working standard. The NIST procedure is followed for the 1000-W FEL lamps from NIST, Optronics, and EG&G. A modified calibration procedure developed by Li-Cor is followed for their 200-W tungsten–halogen lamps. Results are reproducible from one day to the next to approximately 0.1% using the same spectrometer. Measurements taken four months apart using two similar but different spectrometers were reproducible to 0.5%. The comparisons suggest that even NIST standards may disagree with each other beyond their stated accuracy. Some of the 1000-W commercial lamps agreed with the NIST lamps to within their stated accuracy, but not all. Surprisingly, the lowest-cost lamps from Li-Cor agreed much better with the NIST lamps than their stated accuracy of 4%, typically within 2%. An analysis of errors leads us to conclude that we can transfer the calibration from a standard lamp to a secondary standard lamp with approximately 1% added uncertainty. A field spectrometer was calibrated with a secondary standard, producing a responsivity for the spectrometer that was within 5% of the responsivity obtained by Langley calibration using routine field measurements. © 1999 Optical Society of America

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1. Introduction

Broadband measurements in the Atmospheric Radiation Measurement[1] (ARM) Program have painted a fairly consistent picture of an overestimation of shortwave radiation by clear-sky models relative to the best shortwave measurements available.[2,3] Key to resolving this discrepancy is to find where in the shortwave spectrum the model overestimates occur. To this end we require accurate spectral irradiance measurements throughout the shortwave. Central to good spectral measurements is careful calibration of the instruments and then proper operation in the field.

An initial attempt to compare nine calibration lamps of two different types from three manufacturers yielded results that disagreed significantly in some parts of the spectral range between 400 and 1050 nm even though the lamps were stated to be accurate to 4% or better in this spectral range. Figure 1 is a comparison of these nine lamps by ratioing the stated spectral irradiance of a single National Institute of Standards and Technology[4] (NIST) lamp that we had at our disposal in August 1997 to the manufacturers' stated spectral irradiances of their lamps. One EG&G Gamma Scientific, Inc.[5] (EG&G) lamp (GS0939) is within 1% of the NIST standard, but only for the 400–750-nm range. Li-Cor, Inc.[6] 200-W lamps operated in our Atmospheric Sciences Research Center (ASRC) Li-Cor 1800-02 calibrator show a nearly constant offset with wavelength, but are close to their stated 4% accuracy. As shown in Section 2 many of these discrepancies are tied to the poor performance of the NIST lamp that we used for this initial test.

We report here on a second, more careful and extensive study to resolve the issues regarding absolute spectral calibration conducted in December 1997. We compared 13 1000-W FEL lamps including four

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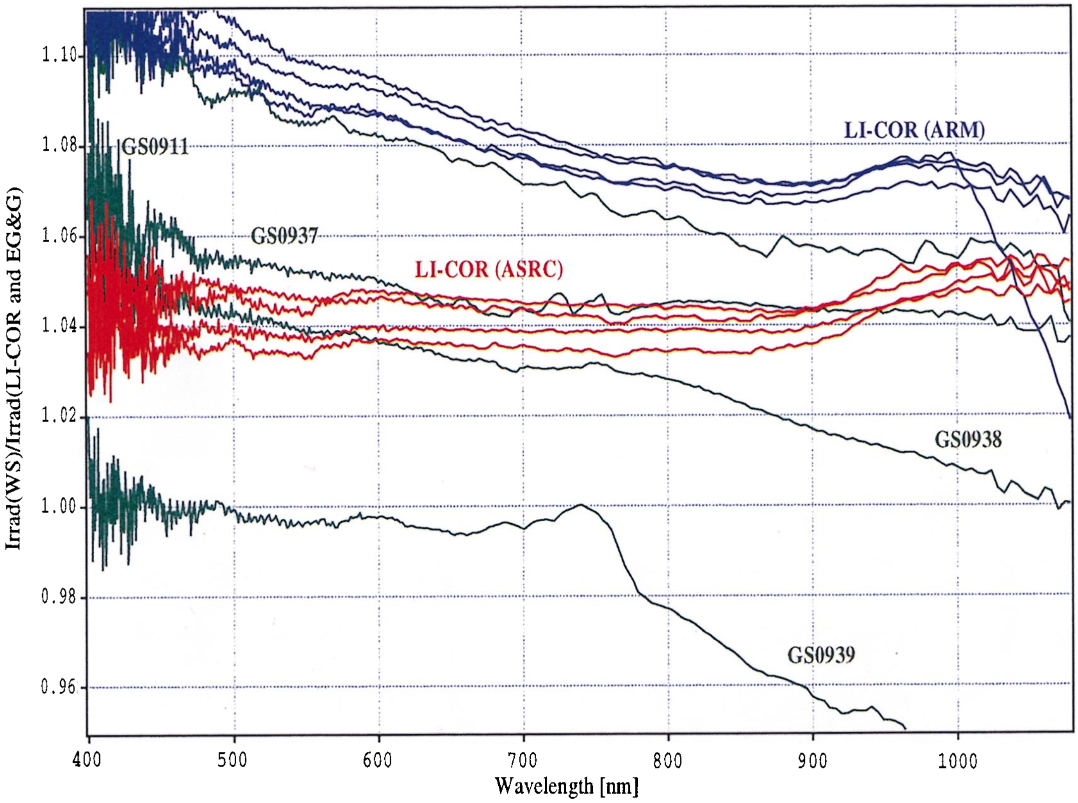

Fig. 1. Ratios of NIST standard lamp F340 irradiance to the irradiance of eight secondary lamps from our initial, limited comparison of standard lamps in August 1997. Li-Cor (ARM) and Li-Cor (ASRC) are the same sources in two different calibration housings. WS, working standard.

NIST standards; four from EG&G, a manufacturer of secondary standards; and five secondary standards from Optronics, Inc.[7] We also compared with our working standard a set of five Li-Cor 200-W tungsten–halogen lamps operating at conditions different from the NIST-recommended configuration, but presumably equivalent to it, and operating in two different Li-Cor 1800-02 calibrators, one owned by ASRC and the other owned by the ARM Program.

2. Comparison of 1000-W FEL Lamps

The spectrometer in our rotating shadowband spectroradiometer[8] (RSS) is used as our transfer detector. It measures irradiance simultaneously in 512 individual wavelength channels. Because lamp irradiances and silicon diode array responsivity are low in the UV, we could not meet our target precision of less than 0.25% in 5 min of exposure; therefore we chose to present data only in 400–1070-nm range. Our newest version of the RSS, which uses a true CCD array detector, should allow us to reach further into the UV.[8]

The prism CCD spectrometer that is the main component of a RSS[8] has significant advantages within its useful working range of 360–1100 nm compared with typical grating monochromators that are more commonly used for comparisons of standard lamps: The optical resolution, number of discrete wavelengths measured, and out-of-band rejection are better. All wavelengths are acquired simultaneously, and each pixel has the advantage of the full integration time. This improves signal-to-noise performance without requiring long lamp burning times.

All 1000-W FEL lamps were calibrated using NIST-recommended procedures.[4] Alignment was achieved using a green He–Ne laser and a special jig with a glass target that ensured that the lamps and spectrometer were horizontal and aligned so that the lamps had the same orientation to the detector as when they were calibrated. The alignment jig, which has the same biposts as the 1000-W FEL lamps, is removed from a kinematic lamp holder, and the FEL lamps are positioned 50.0 cm from the spectrometer. Baffles are placed between the lamps and the receiver and around the receiver, and a light trap is placed behind the lamps to lower the stray light reaching the receiver. A blocked beam measurement is made to assess the amount of stray light reaching the receiver, and this contribution, even though quite small, should be subtracted from each measurement. Current to the lamps was always held to better than 0.001 A.

At the beginning and end of each day of the December comparison, we measured the sensitivity of our spectrometer to the spectral irradiance of one or two lamps. Figure 2 contains plots of these ratios for the four days of the comparison. In general, the ratios are within 0.2%. This demonstrates the sta-

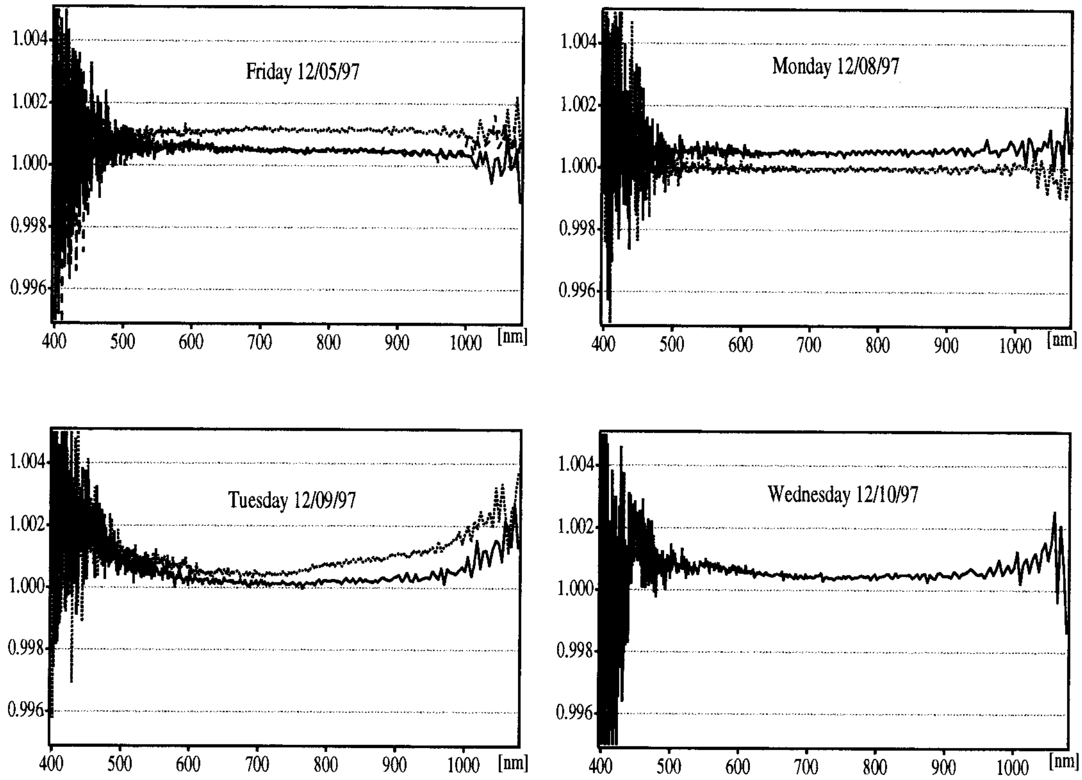

Fig. 2. Ratios of spectral sensitivities of selected lamps at the beginning and end of each day's run.

bility of the power supply and the output of the lamp, the stability of the spectrometer, and our ability to position the lamps at the same distance with the same orientation.

Based on the relative agreement among three of the NIST lamps (F403, F404, and F405), we used their average responsivity in counts/Wm^{-2} nm^{-1} as a working standard for these comparisons. Figure 3 is a plot of the ratio of the irradiance of the working standard to each of the four NIST lamps. Lamps F403, F404, and F405 are almost within 1% of the working standard, which should not be a surprise because these three lamps serve as the basis for the working standard, but it does confirm that they are consistent. Because the NIST uncertainty at the two-standard deviation level is 1.1% or better over these wavelengths (NIST lamp calibrations were based on the 1990 NIST scales of thermal radiometry[9]), lamp F340 is clearly an outlier with variations with wavelength between 4 and 6%. Lamp F340 was the standard adopted in Fig. 1 of this paper, thus explaining many of the discrepancies in Fig. 1. In Fig. 3 the solid and dotted curves, which are barely separated, represent the experiment on different days, leading one to conclude that these results are repeatable to better than 0.2%.

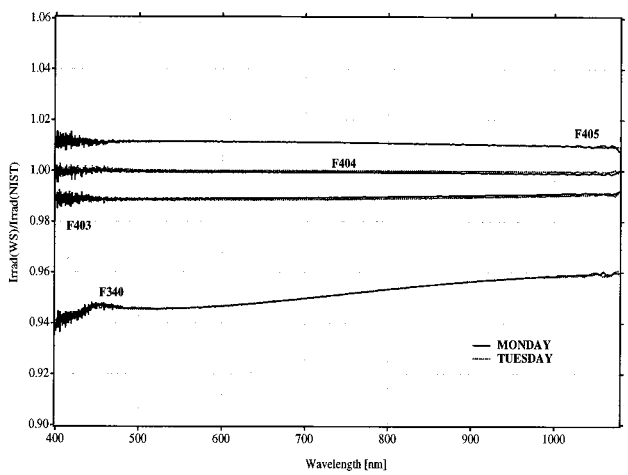

Fig. 3. Ratios of the irradiance of the working standard (WS) to each of the four NIST lamps. The solid and dotted curves denote results from two different days.

Optronics and EG&G buy NIST standard lamps and use them to calibrate 1000-W FEL lamps to sell as secondary standards to customers. These lamps are operated at slightly lower constant current of 8.000 A versus the NIST lamps that operate at 8.200 A, but other than that conditions are the same. The companies state a transfer accuracy of 1%,[4,7] which when added to the NIST uncertainty yields an overall uncertainty of 1.5–1.6%.

Figure 4 is a similar plot to Fig. 3 in that Optronics's lamps are compared with the working standard based on the three NIST lamps. Three of the lamps are within 2% of the NIST standard and show an almost constant offset with wavelength. A fourth and a fifth lamp show a similar wavelength dependence, i.e., almost neutral, but with a 3.5 and 8% offset. One could conclude that three lamps are

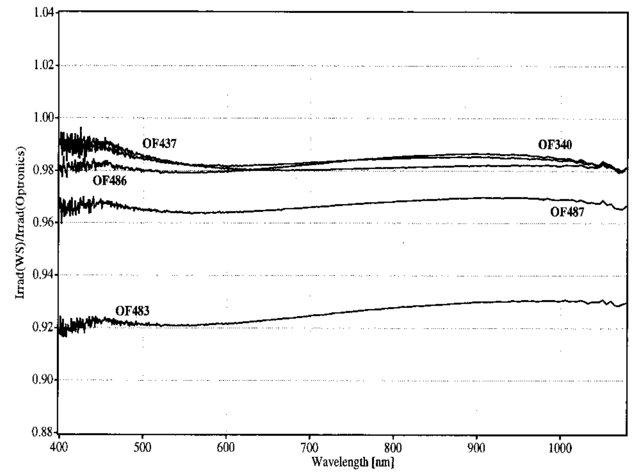

Fig. 4. Ratios of the irradiance of the working standard (WS) to each of Optronics's 1000-W FEL lamps.

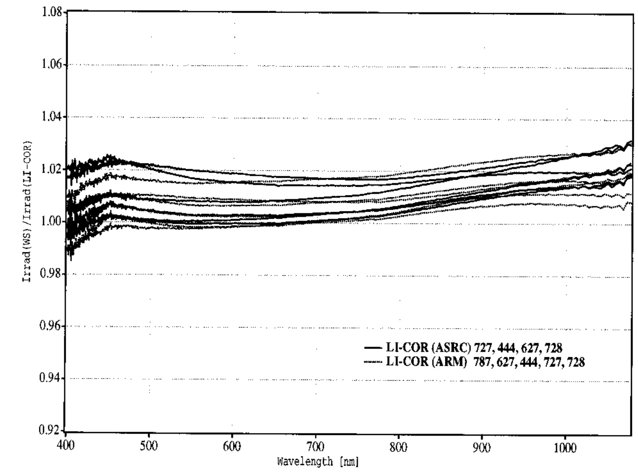

Fig. 6. Ratios of the irradiance of the working standard (WS) to several Li-Cor 200-W tungsten–halogen lamps operated in two different Li-Cor 1800-02 calibrators.

close to our working standard although they fall slightly outside the expected 1.6% uncertainty, but the other two are clearly outliers. Figures 3 and 4 suggest that any single lamp from Optronics, or even NIST, cannot be assumed to be accurate without some effort to corroborate its accuracy.

Figure 5 is a plot similar to Figs. 3 and 4 except that it covers the four FEL lamps that we tested from EG&G. GS937 falls within the expected uncertainty limits at all wavelengths and is nearly independent of wavelength. GS911 and GS938 are within the uncertainty limits at some wavelengths, but not other wavelengths, and their wavelength dependencies are similar but are offset from one another by approximately 4%. GS939 is clearly an outlier, reinforcing the previous conclusion that a single lamp does not give one confidence in the verity of that lamp. Incidentally, this lamp was the one that agreed most closely with our errant NIST lamp in Fig. 1. The solid and dotted curves in Fig. 5 represent the experiment repeated with a four-month interval between runs with different spectrometers, but of the same design. The results are reproducible at the 0.5% level on average.

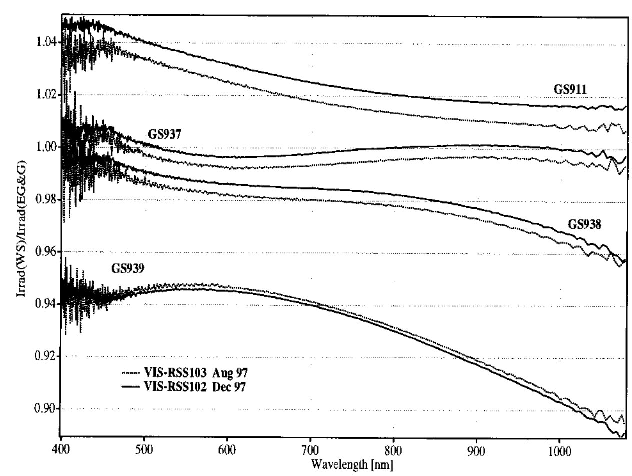

Fig. 5. Ratios of the irradiance of the working standard (WS) to each of EG&G's 1000-W FEL lamps. The solid and dotted curves are from tests 4 months apart using different but similar spectrometers.

3. Comparison of 200-W Li-Cor Lamps

Li-Cor has developed a self-contained optical radiation calibrator. The lamp used is a 200-W tungsten–halogen cycle lamp that operates at constant power. The operating distance from the filament of the lamp is 20 cm, which is approximately 11 mm beyond the front surface of the box allowing adaptor plates to be built that will hold the detector rigidly at the fixed 20-cm distance. Within the box are the power supplies, electronics, and baffles to reject extraneous light.

As can be seen in Fig. 1, the Li-Cor calibrator labeled ASRC and the one labeled ARM gave very different results. When the ARM Li-Cor calibrator was returned to the factory, the shunt resistor that was used to measure current was found to be out of tolerance and was replaced. In Fig. 6 the Li-Cor lamps operating in two different calibrator housings are compared with the working standard. The mean bias error from the working standard is only approximately 1% with all values within 3% for this wavelength range. The stated uncertainty of these lamps is 4%. There is no outlier and the lamps seem to operate almost equivalently in either calibrator housing.

4. Lamp Transfer Errors

The daily stability checks performed with selected FEL lamps and presented in Fig. 2 do not estimate the actual transfer calibration errors. Although the errors measured this way include lamp, power supply, and detector stability and positioning repeatability, they are not complete as they do not include additional sources of errors such as out-of-band rejection error. To obtain a conservative error estimate, we present the following itemized error budget.

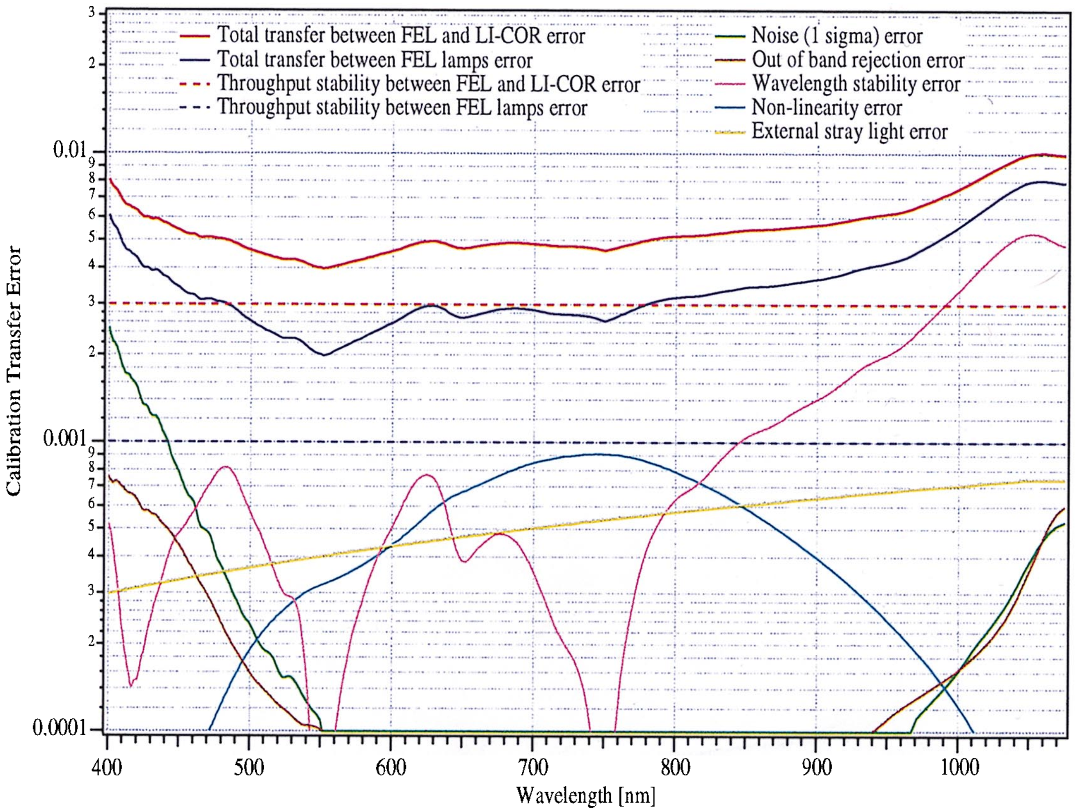

Fig. 7. Sources of fractional error that arise in transferring calibrations within the laboratory between spectral irradiance standards.

A. Noise

The noise when measuring FEL and Li-Cor lamps is dominated by the silicon photodiode readout noise, particularly in the UV and near-infrared (NIR) regions. Consequently the relative error is inversely proportional to signal. For this reason the relative noise was lower when measuring Li-Cor lamps as their irradiance is 1.5 times greater in the UV and 1.3 times greater in the NIR than FEL lamps. The standard deviation of noise at each pixel was estimated during each lamp measurement, i.e., it was calculated as a standard deviation of fifty 1.5-s individual exposures. The relative standard deviation for the least bright lamp (the worst case) is plotted in Fig. 7. This is the standard deviation of sensor responsivity; when the sensor is used to transfer calibration from one lamp to another lamp this factor increases by $\sqrt{2}$.

B. Throughput Stability and Lamp Placement Repeatability

This error was estimated as the ratio of counts obtained with the same FEL lamp in measurements at the beginning and end of each day's run. In principle it is a systematic error, but in practice it must be treated as a random error. Plots in Fig. 2 indicate that the combined throughput stability and lamp placement repeatability were within 0.1%. In some cases errors in the NIR region were larger and were attributed to wavelength registration shifts that were measured and corrected (see Subsection 4.C).

When Li-Cor lamps were measured, a temperature-related throughput increase that was as large as +0.3% occurred. This systematic error was attributed to the higher temperature of the foreoptics because of poorer ventilation and higher output of the Li-Cor source that was butted up to the RSS's receiver. In principle it is fully characterizable, but we chose not to correct it. Consequently, we estimate throughput stability and lamp placement repeatability error when estimating the calibration transfer from FEL to Li-Cor lamps to be three times larger than when transferring calibration between FEL lamps or between Li-Cor lamps (see Fig. 7).

C. Wavelength Registration Stability

A Hg–Cd spectral lamp was measured at the beginning and end of every day from which wavelength-to-pixel assignments were computed. A new wavelength registration was used to interpolate lamp irradiance each time the lamp was changed. The effect of wavelength shifts on RSS responsivity was the greatest in spectral ranges where the responsivity (see solid curve in the top portion of Fig. 8) has the largest first derivative, mainly in the NIR. In the bottom two plots of Fig. 2 the curved shape of count ratios is attributed to a wavelength registration change. We conservatively estimate that a residual pixel shift of ±0.05 pixels remained uncorrected because of our inability to find the exact centers of Hg–Cd lines in the NIR region. These shifts could

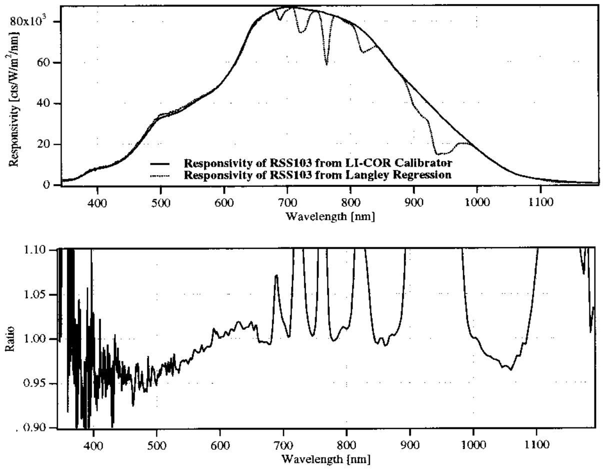

Fig. 8. Responsivity of a RSS field unit as measured using a Li-Cor lamp and using the Langley approach described in the text in absolute terms (top) and as a ratio (bottom). The standard Langley technique fails in strong molecular bands, e.g., near 940 nm. The largest discrepancy outside molecular bands is approximately 5% near 475 nm.

cause ±0.5% radiometric errors at wavelengths longer that 1000 nm (see Fig. 7).

D. Out-of-Band Rejection

The ratio of two lamp irradiances is equal to the ratio of signals measured by the sensor. This is true only when there is no stray light in the optical system. The slit functions that define stray light level were measured at three laser wavelengths (see Fig. 9). The slit functions show that the amount of energy transferred from a central wavelength to the far ends of the spectrum is not larger than 10^{-5}. The combined effect of low lamp irradiance in the UV and lower responsivity of the silicon photodiode array in the UV and the NIR results in larger than 10^{-5} out-of-band rejection errors in these regions. It should be noted that the out-of-band rejection errors are absent in the curves of Fig. 2 as they cancel in the ratio of counts produced by sources with the same color temperature. The out-of-band rejection error for the RSS is correctable as the spectroradiometer is well characterized with respect to slit functions and responsivity. The stray light can be removed from the signal using a method of deconvolution, which, unlike the deconvolution for the purpose of improved resolution, is stable as it is concerned with retrieval of low spectral frequencies affected by the wings of the slit function. Nevertheless, the errors were not corrected, but the deconvolution was used to estimate the worst error among all tested sources. We identified the two sources with the most different color temperature and envelope spectral transmittances. At its worst it is 0.08% at 400 nm and smaller everywhere else (see Fig. 7).

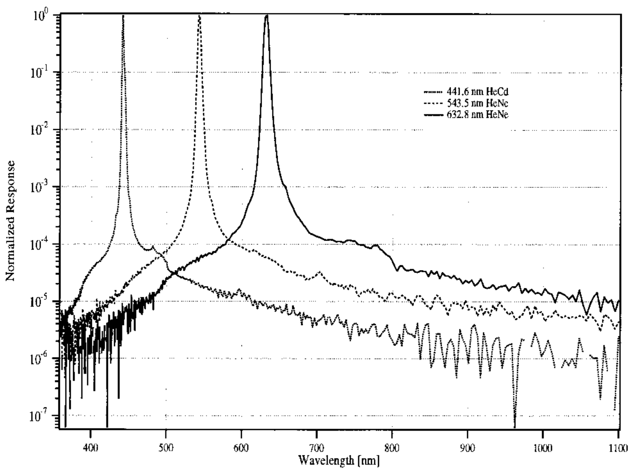

Fig. 9. Slit functions for the spectrometer (RSS) used in the transfer of calibration between lamps based on the response at three laser wavelengths.

E. Nonlinearity

We estimate that the silicon photodiode array that was used in the RSS exhibits nonlinearity not larger than 1% in its full usable range. The resulting nonlinearity error when comparing sources of similar irradiances, as was the case here, is smaller. In the worst case it is less than 0.1% at 750 nm (see Fig. 7).

F. External Stray Light

When measuring FEL lamps, we performed additional measurements as prescribed by NIST to estimate the amount of light that reaches the sensor (surface of the RSS diffuser) indirectly, i.e., by reflections from objects in the field of view. According to NIST procedures this signal needs to be subtracted from the measurement when the source is not blocked. We found that this correction was always positive and only slightly wavelength dependent and less than 0.08%. We chose not to subtract this error as part of data reduction.

G. Total Calibration Transfer Error

Except for noise all errors are in fact systematic. For this reason we estimate the calibration transfer error as the sum of the absolute values of all errors, including the $\sqrt{2}$ times one standard deviation of noise. The resulting conservative total error is less than ±1% when transferring calibration between FEL and Li-Cor lamps and ±0.8% when transferring calibration between FEL lamps only or between Li-Cor lamps only.

5. Langley Calibration

Absolute calibration refers to the determination of the absolute response of a radiometer in terms of the units output by the radiometer (usually voltage or counts) for a given spectral irradiance incident on the instrument. An alternate approach to absolute spectral calibration using lamps is to use Langley regressions to determine instrument output at the top of the atmosphere and then to divide this output by spectral-response-weighted extraterrestrial spectral irradiances, for example the one by Wehrli.[10] The Bouguer–Lambert–Beer law can be written as

$$V = V_0 \exp(-\tau m)$$

and then linearized by taking the natural logarithm of both sides of the equation

$$\ln(V) = \ln(V_0) - \tau m,$$

where V is the output of the radiometer at the surface, V_0 is the output of the radiometer at the top of the atmosphere, τ is the total optical depth, and m is the air mass relative to a value of 1 in the zenith direction. For clear, stable days, when aerosol loading is approximately constant with time, a least-squares fit to the plot of $\ln(V)$ versus air mass m yields a straight line whose intercept is an estimate of the $\ln(V_0)$. In fact, several days are typically required to determine a robust estimate of V_0 because the assumption of a stable atmosphere is difficult to confirm. We used the 20 nearest Langley plots in time to determine a robust estimate of V_0 for the RSS operating at the ARM Program Southern Great Plains site in Oklahoma. We determined the instrument constants in counts for all 512 channels of the RSS, although the assumptions made in applying the Langley technique fail for strong water-vapor and oxygen absorption bands. We then divided by the extraterrestrial spectrum of Kurucz[11] to obtain absolute responsivity of the RSS in units of counts/$\mathrm{Wm}^{-2}\,\mathrm{nm}^{-1}$. Figure 8 (top) is a plot of the spectral response of the RSS based on the method just described and based on the lamp calibrations described above. It is obvious that the Langley calibration fails for the water-vapor and oxygen bands in the red and NIR but the two response plots match within 5% or better outside these bands (Fig. 8, bottom). Reagan *et al.*[12] introduced a modified Langley technique for deriving the extraterrestrial response in strong water bands that was not applied here.

We estimate that our uncertainty in determining V_0 is better than 1% outside the strong molecular bands and would be 1.5–2% using modified Langleys in the strong absorption bands based on our previous experience. To obtain I_o, i.e., extraterrestrial spectral irradiance, requires use of an extraterrestrial spectrum that is ultimately tied to a calibration involving lamp standards. Schmid *et al.*[13] have recently demonstrated the relatively large differences among published extraterrestrial spectra in their Figs. 6 and 7. If the extraterrestrial irradiance uncertainty is similar to NIST lamp uncertainty, then calibration of the RSS or any other sunphotometer using the Langley approach is equivalent in terms of uncertainty to lamp calibration using a secondary standard because approximately 1% uncertainty is added in both cases. The Langley approach does have the advantage in that both measurements and models can be linked to the same extraterrestrial spectral irradiance when comparing models and measurements.

6. Summary and Conclusions

Adopting three reasonably consistent NIST lamps as a working standard, we have compared 18 irradiance standards from four sources using a diode array spectrometer. One NIST lamp was clearly outside the uncertainty limits set by NIST using this working standard; all the Optronics's lamps were outside the uncertainty limits using this working standard, although three of the five were close to these limits with a nearly constant offset with wavelength; three of the four EG&G lamps were outside the uncertainty limits at some or all the wavelengths; and the Li-Cor lamps were all within their stated uncertainty using two different Li-Cor calibrator housings.

In Figs. 3, 4, and 5 outliers in the 1000-W FEL lamps were obvious. A possible explanation, but one that is not possible to verify, is damage in the process of shipping the lamps. Other possibilities are that shelf life or burn time, even within the 50-h limit set by the manufacturers, could affect the lamps. Referring to Fig. 3, our NIST lamp F340, which was outside the uncertainty limits of our working standard, was unused for four years before the first measurements. The other three NIST lamps were calibrated three and a half years before these measurements with the longest burn time on any of the three under 7 h. Referring to Fig. 4, Optronics lamp OF340 had more than 50 h of burn time and lamp OF437 had just under 50 h of burn time, but these two were the nearest Optronic lamps to our working standard along with OF486, which had not been burned. There was a three-year difference between the original calibration of OF340 and OF437. OF483 and OF487 were the outliers, they had no burn time, and they had been calibrated at nearly the same time as OF486. Referring to Fig. 5, EG&G lamp GS911 had over 50 h of burn time, but agreed with our working standard about as well as GS938 that was calibrated two years after GS911 and had not been burned. GS937 and GS939 had no burn time and were calibrated at nearly the same time as GS938. Only one Li-Cor lamp had more than 1 h of burn time before these tests, and it had more than 50 h of operation; however, there is no obviously distinct behavior in Fig. 6 among the lamps tested. To summarize, there is no pattern based on shelf time, or even burn time, that helps explain differences between our working standard and any of the 1000-W FEL or 200-W Li-Cor lamps.

The lamps used to establish our working standard disagree with one another by a little more than a percent with the difference a constant with wavelength. This strongly suggests that these differences are related to some geometric effect. Because we do not know the exact procedures used, we can only speculate that these could be caused by calibrating at different distances or by loss of light through different optical elements in the system. The stability of the offset from blue to NIR suggests good control of the current to the lamps, otherwise color temperature differences would cause differences with wavelength.

Optronics's lamps in Fig. 4 had almost the same offset (within a percent) at every wavelength for a particular lamp. This suggests that Optronics was using a different working standard that could be affected by some geometric shift, e.g., a distance problem or some light loss in the transfer process.

EG&G lamps in Fig. 5 show large differences with wavelength suggesting a color temperature effect. This could be associated with the stability of the current supplied to the lamps under test at the factory. Figure 5 does suggest that these lamps store well because they have similar responsivities over the four-month period between the August and December 1997 comparisons.

Although we believe that we can transfer calibration within the laboratory from one lamp to the next with 1% uncertainty, the true uncertainty is larger than this because the absolute accuracy of the working standard must be added. Based on Fig. 3, that uncertainty is at least of the order of 1% and perhaps higher.

These comparisons were done within the laboratory among sources with similar color temperatures; field calibration will add uncertainty to measurements made with radiometers and spectroradiometers. In the field, temperatures cannot be controlled as they are in the laboratory, particularly calibration lamp temperatures. (Because most radiometers are temperature controlled, there should be little difference in detector temperature between laboratory and field measurements caused by the ambient temperature.) Furthermore, the spectrum of the radiation measured in the field, most often the Sun or the scattered light from the Sun, is different from the calibration lamps' spectra leading to more uncertainty, for example, that associated with out-of-band rejection.

The topic of Section 5 concerning Langley calibration versus lamp calibrations was studied extensively in a recent publication by Schmid *et al*.[13] Their conclusions are similar to ours in that lamp and Langley calibrations agree fairly well at some wavelengths, but are 4–5% off at other wavelengths. The future of Langley field calibrations depends on significant improvements in specifying extraterrestrial spectral irradiances.

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