Integration of a Constructed Lamp-Based Spectral Calibration Station into a Radiometry Course

Leanne Robinson[a] and Emmett Ientilucci[b]

[a]Labsphere, Inc., North Sutton, New Hampshire, United States
[b]Rochester Institute of Technology, Rochester, New York, United States

ABSTRACT

Radiometric calibration is the process of assigning engineering units and uncertainties to digital counts such that an instrument reading (or image format) conforms to a recognized standard such as radiance. One way to implement spectral radiometric calibration is through the use of an integrating sphere or FEL Lamp/Lambertian plaque setup. Calibrated integrating spheres can be expensive thus in this paper, we (i.e., student and faculty advisor) set out to design, construct, test, and evaluate a NIST-traceable FEL Lamp/plaque setup (as a senior project) for in-house spectral calibration as well as integration into the undergraduate and graduate curriculum at the Center for Imaging Science at the Rochester Institute of Technology. We compared FEL Lamp/plaque spectral radiance measurements to that of a NIST-traceable 20-inch integrating sphere with an uncertainty of 1%. Results showed our set up (with a 1% uncertainty 1000-watt FEL lamp) was on-par with the integrating sphere. As mentioned, this calibration station will be integrated into the lab section of RIT's radiometry course to educate students on how to conduct spectral radiometric calibration, independent of an integrating sphere. There is much to convey to students from classroom lecture-based radiometric concepts on calibration to the actual use of such a station in the lab. This includes, setting up the source, alignment, operation and usage, measurements, etc. Our take-away is to illustrate how others can replicate our station so as to teach students about hands-on spectral radiometric calibration. We will also discuss our success and failures related to the project. As someone now in the "radiometry" industry, thanks to this project, I would like to like to share our project with the educating community.

Keywords: Radiometric Calibration, FEL Lamps, 0/45 Lambertian plaque

1. INTRODUCTION

Calibration is an important aspect of radiometry and image acquisitions. It uses the accuracy of one instrument to help mitigate the uncertainties of another instrument. When a sensor captures light it is quantized to digital counts. Radiometric calibration is the process of converting these digital counts to analytical, physical radiometric values, which can be spectral.[1] These radiometric values are physical, decoded, and measurable values. Radiometric calibration is important to digital sensors because it ensures correct processing and the ability to cross-compare different imaging systems, for example. Without radiometric calibration, there can be incorrect exposure, colorization, and other imaging artifacts.

One way the National Institute of Standards and Technology (NIST) performs radiometric calibration is through the use of integrating spheres. Integrating spheres spatially integrate radiant flux from a source. A detector then measures this spatially integrated radiant flux. Since integrating spheres are highly Lambertian, they show very uniform radiance distributions. This is important for light sources that cannot be measured directly by a detector due to the source's scattering properties. In order to produce uniform radiance, integrating spheres are coated with a highly Lambertian coating. Unfortunately, due to this desired reflectance and Lambertian property, the price of integrating spheres can be very expensive for businesses and universities.

Further author information, send correspondence to:
lrobinson@labsphere.com, Telephone: 508-287-2760
Emmett@cis.rit.edu, Telephone: 585-475-7778

Seventeenth Conference on Education and Training in Optics and Photonics: ETOP 2023,
edited by David J. Hagan, Mike McKee, Proc. of SPIE Vol. 12723, 127231T

Fortunately, another way that NIST implements radiometric calibration is through the use of the more affordable FEL lamp/Lambertian plaque station.[2] The fundamental setup consists of an FEL light source with a known spectral irradiance (given at precisely 50.0 cm using a very stable current supply) which hits a Lambertian surface with a known reflectance value, in which the light reflected from the surface is detected by a sensor.

The Chester F. Carlson Center for Imaging Science at the Rochester Institute of Technology has an integrating sphere, which has been used for spectral radiometric calibration. However, we have noted that some of our imaging systems have a field of view (FOV) larger than the exit port on the integrating spheres. The addition of an FEL lamp/Lambertian plaque station was explored because it could accommodate systems with large field of views (in addition to the construction of a *lower cost* calibration station). The calibration station was then slated to be an undergraduate senior thesis project because of the hours needed for research, designing, building, and analyzing such a station. In the end, the RIT spectral cal. station consisted of a light source that was a NIST-traceable 1000-watt FEL lamp with a spectral calibration from 400 to 2500 nm with an uncertainty of 1 percent in the visible part of the spectrum. The Lambertian surface was an 18 inch Spectralon plaque with a known reflectance (i.e., it came with a reflectance calibration report). This setup was used to calibrate an imaging spectrometer. There were four main goals of the station. The first goal was to *design* the lamp/plaque calibration station. The second goal was to actually *build* the station based on our design. The third goal was to *perform experiments* using the station. Finally, the fourth goal was to *analyze results* from these experiments. The results from the calibration station could then be compared to similar results using our trusted 20 inch calibrated integrating sphere.

The undergraduate senior project was completed in May 2022. Due to the advantages of the station, we feel that other university programs that teach radiometry and radiometric calibration concepts, could benefit from the integration of such a station into their curriculum and/or labs. This paper describes what was performed to create our spectral calibration station while suggesting what other universities or industry-types can do to replicate our set up including strategies on how to cut corners for those on a financial budget.

2. BACKGROUND

This section discusses background related to FEL lamps, Lambertian surfaces and relevant radiometry needed for the analysis of our radiometric calibration station.

2.1 Literary Background

The purpose of sharing this undergraduate senior project with the optics and photonics community was because there were limited resources available to us when considering design choices. Ultimately, the project came to fruition by speaking directly to researchers and scientists at NIST, Labsphere (i.e., the company that manufactured the Lambertian plaque), and the Newport MKS (i.e., the company that produced the optomechanical parts we ordered). The research papers that were found are included in the references section. The hope is that this paper can act as a foundational *guide* to those who wish to build an FEL Lamp/Lambertian plaque station.

2.2 Radiometric Definitions and Relevant Equations

2.2.1 Irradiance

Irradiance is defined as the change of radiant flux (or radiant power) *onto* a surface:

$$E = \frac{d\Phi}{dA}\left[\frac{W}{m^2}\right] \tag{1}$$

in which Φ is the radiant flux measured in *watts* and A is the receiving area (in m^2) of the surface in which the flux falls incident upon.

2.2.2 Exitance

Exitance is defined as the change of radiant flux *leaving* a surface (into the hemisphere). That is,

$$M = \frac{d\Phi}{dA}\left[\frac{W}{m^2}\right] \tag{2}$$

in which Φ is the radiant flux measured in $watts$ and A is the emitting area (in m^2) of the surface in which the flux radiates into the hemisphere above such a surface.

Exitance can be related to irradiance through the expression

$$M = E \cdot \rho \left[\frac{W}{m^2}\right] \tag{3}$$

where ρ is the reflectance of the surface in question (i.e., a hemispherical reflectance). In a more formal sense, the directional aspects of the surface reflectance would need to be considered by characterizing the surface's reflectance behavior through the use of the Bi-Directional Reflectance Distribution Function (BRDF).[3]

2.2.3 Lambertian Surfaces

By definition, a Lambertian surface is a surface in which energy is scattered equally in all directions.[4] For radiance, this would imply that the measured radiance signal, for example, would be the same value at any position in the hemisphere above the surface in question.[5]

2.2.4 Radiance

Radiance is defined as the change of radiant flux onto, passing through, or emerging from a surface in a specified direction. That is,

$$L(\theta, \phi) = \frac{d^2\Phi}{(dA\cos\theta)\, d\Omega}\left[\frac{W}{m^2\, sr}\right] \tag{4}$$

where the directional aspects of radiance are denoted through use of polar coordinate terms θ (zenith) and ϕ (azimuth) along with the solid angle, Ω measured in steradians $[sr]$. Radiance is the most universal term in radiometry as it includes behavior from all other terms. It can describe energy leaving or arriving at a surface.

One can relate the radiance onto a Lambertian surface from the exitance leaving such a Lambertian surface through a scale factor of π steradians. This only works if the surface is considered to be Lambertian such that there is no directional aspect to measured radiance. That is, the radiance is the same in all directions. If this is true, then the radiance can be pulled out of the formal radiance / exitance integral (not shown here) with the solution expressed as

$$L = \frac{M}{\pi}\left[\frac{W}{m^2\, sr}\right] \tag{5}$$

2.2.5 Note on Spectral Quatities

All of the radiometric quantities above can be spectral. That said, the notation changes from:

- E to E_λ
- M to M_λ
- L to L_λ

where the units now include a μm or nm in the subscript of the unit to denote the spectral wavelength dependency.

2.3 FEL Lamps

An FEL lamp is an ANSI standard Quartz-Halogen spectrally calibrated 1000W light source (see Figure 1). In the 1970s, the National Bureau of Standards (NBS) declared that the 1000W FEL lamp would be a standardized light source because of its accurate results and extended calibration to longer wavelengths.[6] In 1963 the 200W quartz-halogen lamps was first used but it was changed to the 1000W bulb since it did not have sufficient spectral irradiance values under 400nm wavelengths. The 1000W FEL lamp used in this project came with a spectral calibration sheet with data from 400 to 2500nm with an uncertainty of 1 percent in the visible part of the spectrum. These lamps can last 50-100 burning hours while maintaining calibration.

Figure 1: Typical 1000W FEL lamp used for spectral calibration.

3. EXPERIMENTAL DESIGN AND CONSTRUCTION

3.1 Design

Before drafting an equipment list, experts in the field of spectral calibration were contacted. First a call with Dr. Howard Yoon, a researcher at NIST who has built an FEL lamp/Lambertian plaque calibration setup, was arranged. From the call, in summary, it was learned that FEL lamps can be dangerous due to the pressure in the enclosure and users should not to be in the direct line-of-sight of the bulb. For our set up, a light baffle would need to be constructed. Once the baffle was built and all experiments were completed, the influence of the baffle needed to be tested as well. This would be achieved by measuring the spectral radinace with and without the baffle and comparing measurements. It was also learned that internal calipers would be needed to precisely measure the distance between the FEL lamp and the Lambertian plaque. Additionally we learned that the FEL lamp could be moved backwards (greater than 50cm away) from the Lambertian plaque if the dynamic range of the sensor was sufficient or if we wanted the illumination pattern on the plaque to be more uniform. Of course, this generates more stray light w/o the use of a baffle.

Chris Durell from Labsphere was contacted to learn more about supporting the plaque in a mechanical holder. With his help, it was determined that the plaque would slide into an aluminum casing that would be bolted to am optical rail. This was constructed for our set up.

Carol Johnson, another scientist from NIST, recommended that similar optomechanical rail equipment as NIST be used for the station. She suggested that the rails should be purchased from Newport MKS Instruments. She also recommended the X95 rail system series. In order to gain more information on these rail systems, Newport MKS was contacted directly. During a few calls with Newport MSK, it was reconfirmed that the X95 rail system was suitable for the purpose of the station.

From these background investigations, a preliminary design of the setup was created. This design was a “to-scale” drawing. However, some equipment parts and size measurements were still missing. Our final design will be shown later in this section.

3.1.1 Field of View Calculation

In order to determine the size of the rail that would hold the test spectrometer, a field of view (FOV) calculator was generated. The possible lengths of the rail were 0.64 meters, 1.0 meter, and 1.5 meters long. The calculator was also generated to see what spot size on the plaque would be seen by the spectrometer. Calculation results can be seen in Table 1.

In Table 1, the chosen FOV of 4 and 11 degrees, correspond to two different spectrometers RIT owns that could be used by the station in the future. These are the SVC HR-1024i Field Spectroradiometer and ASD FieldSpec 4 Hi-Res: High-Resolution Spectroradiometer, respectively. As shown in the table, if a rail with a length of 0.64 meters was used, the spectrometer with a 4 and 11 degree FOV would only be measuring a 2.5 and 6.9 inch long portion of the plaque, respectively. A length of 2.5 inches on the plaque is too small of a measurement so the 0.64 meters rail was no longer being considered. If a rail with a length of 1.5 meters was used, the spectrometer with a 4 and 11 degrees FOV would be measuring a 5.8 and 16.1 inches long portion of the plaque, respectively. A length of 16.1 inches on the plaque is too large of a measurement considering the plaque is 18 inches long so the 1.5 m rail was no longer being considered. With these considerations in place, the 1.0-meter-long rail was chosen. The final version of the rail system design was completed and can be seen in Figure 2.

Table 1: Field of view.

FOV Calculation Results		
Rail Length [m]	FOV [deg]	Length on plaque [in]
0.64	4	2.5
0.64	11	6.9
1.0	4	3.9
1.0	11	10.7
1.5	4	5.8
1.5	11	16.1

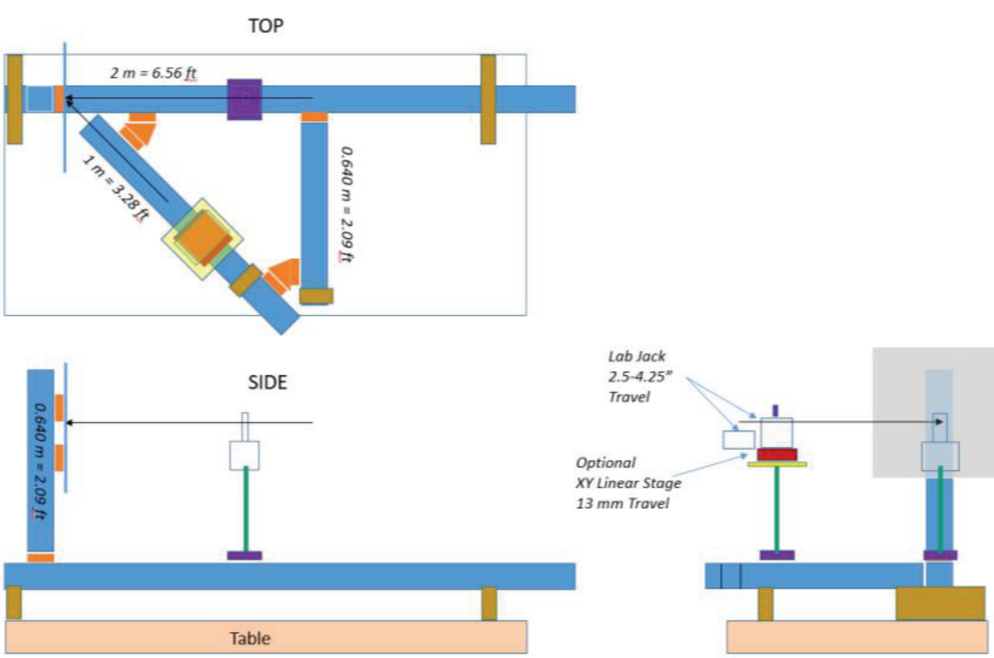

Figure 2: Final FEL lamp/Lambertian plaque calibration design.

3.1.2 Plaque Holder Design

A stand for the plaque was designed so that it could be supported on one of the vertical rails. A piece of aluminum was purchased to be used as the backing plate, along with two brackets. These materials needed holes drilled into them in order to hold onto the vertical rail and the optomechanical parts from Newport-MKS. The backing plate design is shown in Figure 3 and the two bracket designs are shown in Figure 4.

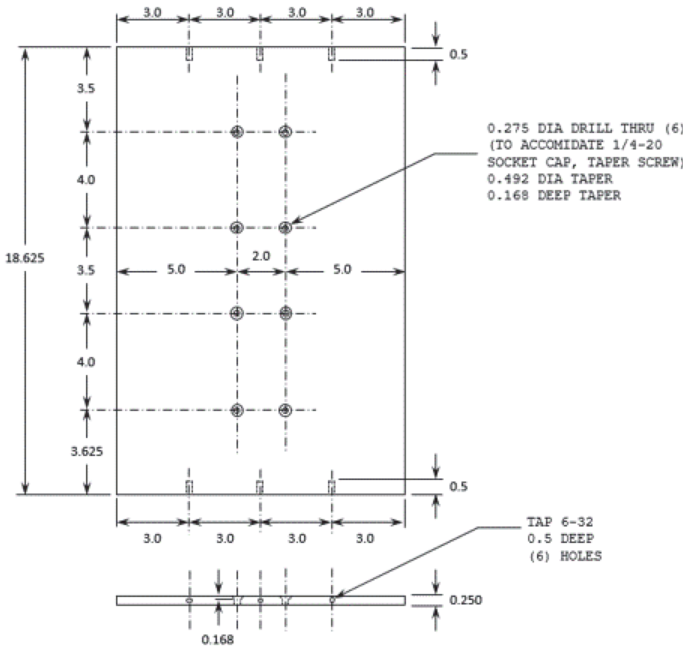

Figure 3: Lambertian plaque backing plate schematic.

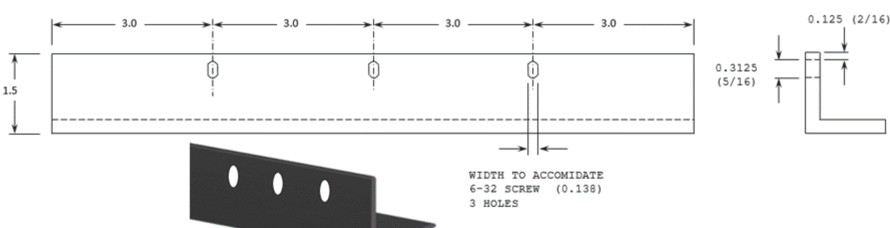

Figure 4: Lambertian plaque bracket schematic.

3.2 Equipment List and Budget

An equipment list was created after speaking with the experts in the filed. Table 2 is the equipment purchased for the setup. The price of the equipment purchased was around $11,000. The bill of materials can be seen in Table 3.

3.3 Construction

The FEL lamp/Lambertian plaque station was constructed and set up in the Optical Calibration Facility (OCF) in the Chester F. Carlson Center for Imaging Science.

Table 2: Equipment list.

Equipment List
Structural Rail, Aluminum, 2000 mm Length
Structural Rail, Aluminum, 1000 mm Length
Structural Rail, Aluminum, 640 mm Length
Angle Bracket, 45°
Angle Bracket, 90°
Right Angle Joint
Optical Rail Carrier, 120 mm Length
Optical Post, 12 in. Height, 0.5 in. Diameter
Optical Post, 6 in. Height, 0.5 in. Diameter
Optical Post, 1 in. Height, 0.5 in. Diameter
Optical Post Holder, Slotted-Base, 2.0 in. Height
Optical Post Holder, Slotted-Base, 3.0 in. Height
Optical Post Holder, Slotted-Base, 4.0 in. Height
Thread Adaptor, M6 Male to 1/4-20 Male
Double Bench Leg, Span Support
Single Bench Leg, Span Support
Optical Breadboard Plate, Solid Aluminum, 8 x 8 in.
Mounting Plate, 6 x 6 in., Double Density 8-32 and 1/4-20 Hole Pattern
Lab Jack, 44.5 mm Travel, 4.375 x 6.5 in. Platform
XY Linear Stage, 13 mm Travel
Black Oxide Screw Kit, 1/4-20
Optical Fiber Holder, Single SMA, Optical Post Mounted
L58SAC Industrial Alignment Laser
2 to 60 in., Satin Chrome Coated, Mechanical Inside Micrometer Set
Heavy Duty Stationary Table Steel, 36 in. High x 72 in. Wide x 36 in. Deep

Table 3: Bill of materials.

Bill of materials	
Product	Cost
Newport MKS	7776.00
Laser Alignment	466.00
Micrometer	1338.53
Lamp Holder	59.97
Lab Upgrades	1197.85
Total	10838.35

3.3.1 Rail System Construction

Once the equipment arrived, the station was ready to be built. The 1000W FEL lamp was placed as close to 50cm from the plaque as possible.[2] The distance was adjusted using the inverse-square law since the distance was not precisely 50.0 cm. The length from the FEL lamp to the plaque was crucial because the given irradiance on the spec sheet is based on the distance being 50.0 cm. A micrometer was used to measure the precise distance from the plaque to the FEL lamp. A rig was assembled to hold the lamp. This rig/stand was placed on a rail. An alignment laser was used to ensure the 50cm from the lamp to the plaque was centered and perpendicular. A stand for the sensor was used to hold the sensor in place. The completed structure without the baffle and plaque holder is shown in Figure 5.

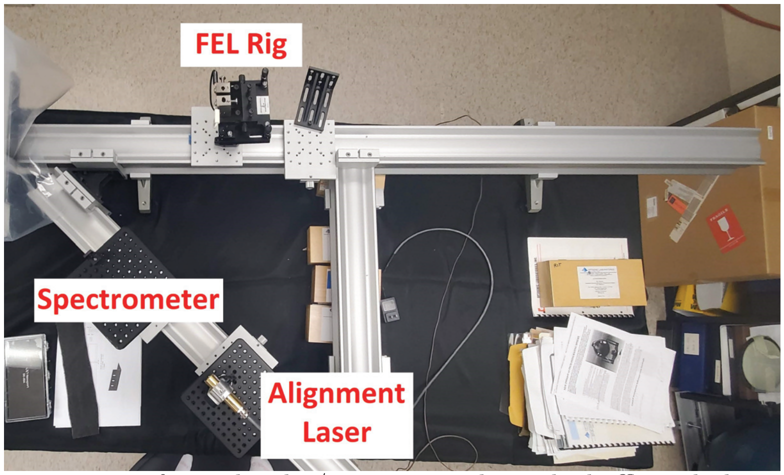

Figure 5: Top view of completed 0/45 set up without the baffle and plaque holder.

3.3.2 Plaque Holder Construction

After the plaque holder was designed, the schematics were given to the Mechanical Engineering machine shop at RIT. The assembled holder is shown in Figure 6. Once the Lambertian plaque was placed into the holder, we verified that the angle between the radiometric sensor and the plaque was 45 degrees.


Figure 6: Lambertian plaque holder.

3.3.3 Baffle Construction

A baffle set up was created to minimize and eliminate stray light from hitting the sensor. There were two iteration of the baffle. The first was a test to see if cardboard could be used. The baffle was placed in front of the FEL lamp with a hole cut in the middle of it. It was ensured that the hole was big enough to provide enough radiance to the sensor (i.e., be a large enough area to be sensed by the FOV of the sensor). This can be seen in Figure 7. The entire constructed baffle can be seen in Figure 8.

After running the FEL bulbs under the baffle it was soon discovered that the bulbs were emitting plenty of heat. This was determined by the smell of burning cardboard! To mitigate this, a second baffle design was constructed. The height of the first baffle was expanded and a small fan was attached to the top so as to allow heat to escape. The improved baffle can be seen in Figure 9. As a side, it was recommended (from Chris Durell at Labsphere) that we might want to have more of an open-air set up and *not* have any force air across or near the FEL bulb (i.e., remove the heat exhaust muffin fan from the set up). We considered this during our spectrometer test phase.

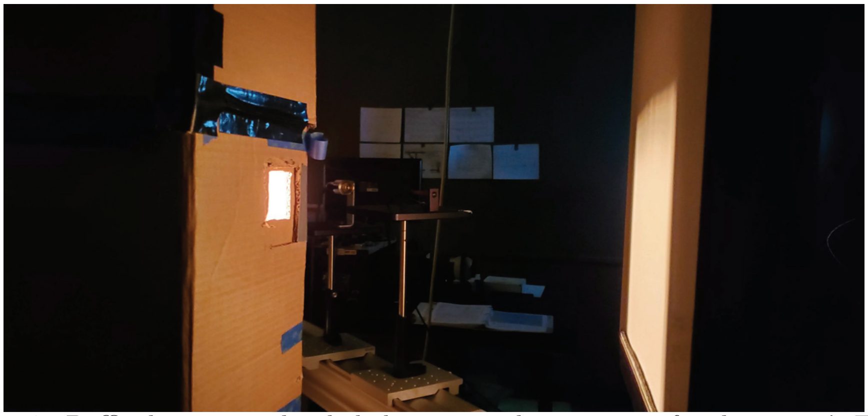

Figure 7: Baffle design 1 with a hole large enough to account for the sensor's FOV.

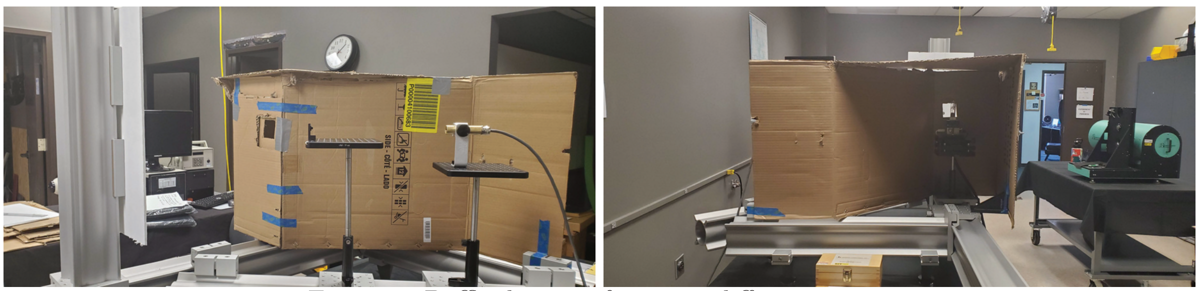

Figure 8: Baffle design 1 from two different views.

4. RESULTS AND DISCUSSION

4.1 Calculation of FEL Lamp/Lambertian Plaque Spectral Radiance

The FEL lamp was placed in its specially designed lamp jig. The radiant flux from the bulb passed through the baffle and hit the Lambertian plaque thus creating a known spectral irradiance reference, E_λ^{ref} (i.e., given to us on the spec sheet). The plaque has a known reflectance factor, ρ_λ (i.e., comes with a calibration sheet) so there is a known exitance, $M_\lambda^{ref} = E_\lambda^{ref} \cdot \rho_\lambda$ leaving the plaque surface. Since the plaque is (very much) Lambertian, the spectral radiance from the surface could be determined as

$$L_\lambda^{ref} = \frac{E_\lambda^{ref} \cdot \rho_\lambda}{\pi} \left[\frac{W}{m^2\, sr\, \mu m}\right] \tag{6}$$

The precise distance of 50cm, to realize the irradiance in the spec sheet, was not achieved, not surprisingly. Thus, the distance that was measured (using our micrometer) was used, along with the inverse square law, to make modification as

$$L_\lambda^{ref} = \frac{E_\lambda^{ref} \cdot \rho_\lambda}{\pi} \left(\frac{d_{ref}}{d}\right)^2 \left[\frac{W}{m^2\, sr\, \mu m}\right] \tag{7}$$

where d_{ref} is the distance provided from the reference (i.e., 50cm) and d is the actual measured distance between the FEL reference lamp and Lambertian plaque. The FOV of the device to be calibrated (i.e., spectrometer) needed to be filled by radiance from the Lambertian plaque. If the device is too far away and there is not proper uniform illumination then errors could be introduced into the process and make the calibration invalid.

Since radiance is invariant with distance, the camera or spectrometer under test will see the known spectral radiance reference. The sensor will then quantize the light into digital counts. Thus, we will have a spectral digital count representation of the radiance signal, S_λ^{ref}, if the spectrometer is not calibrated to physical units.

To actually use L_λ^{ref} and the measurement of it, S_λ^{ref} (in digital count units), from a device to be calibrated we have to set up a proportion as

Figure 9: Baffle design 2 from two angles showing height increase and hole at top for fan (i.e., heat removal).

$$\frac{L_\lambda^{ref}}{S_\lambda^{ref}} = \frac{L_\lambda^{device}}{S_\lambda^{device}} \tag{8}$$

where S_λ^{device} would be the raw measurement (from the device to be calibrated) of an object (e.g., dirt, table surface, a light source, etc.) and L_λ^{device} would be the (to be determined) spectral radiance of said object. This idea of transferring the calibration to another device is called, *transfer calibration*. Thus, we can solve for our desired device radiance as

$$L_\lambda^{device} = \frac{L_\lambda^{ref}}{S_\lambda^{ref}} \cdot S_\lambda^{device} \quad \left[\frac{W}{m^2\, sr\, \mu m}\right] \tag{9}$$

The quantity $\frac{L_\lambda^{ref}}{S_\lambda^{ref}}$ acts as the calibration adjustment factor for this specific device and is determined ahead of time from the calibration process itself. We will call this quantity, K. Thus, we have

$$L_\lambda^{device} = K \cdot S_\lambda^{device} \quad \left[\frac{W}{m^2\, sr\, \mu m}\right] \tag{10}$$

With substitution, the calibration factor takes on the form

$$K = \frac{E_\lambda^{ref} \rho_\lambda}{\pi\, S_\lambda^{ref}} \cdot \left(\frac{d_{ref}}{d}\right)^2 \tag{11}$$

where all quantities are measured in the lab.

4.2 Testing the Power Supply and FEL Lamp with an Infrared Camera

Beforethe baffle was constructed, the power supply and the integrity of three FEL bulbs were tested. The power supply for the FEL bulbs was an OL 410-1000 Precision Lamp Source from Optronic Laboratories. The FEL bulbs are supposed to run at 8.00 amps DC to conform to the calibration reports.

There were three FEL bulbs used throughout the experiments mentioned below: the F-1541, F-864, and F-416. The FEL F-1541 was the most recently calibrated FEL bulb that had never been turned on. The bulb was last calibrated on October 15, 2018 by Optronic Laboratories. FEL F-864 was last calibrated on October 26, 2006 and FEL F-416 was last calibrated on August 23, 1996.

Since the power supply had never been turned on and it was not known when the bulbs were last used, a thermal camera was utilized to visualize if the bulbs turned on. We did not want to provide the lamp with a full 8.0 amps right away for fear that the lamp might break and perhaps injure someone. The thermal camera was a Lepton® 3.5 by Teledyne FLIR.

First, FEL F-416 was placed in its rig and secured. Next, the power supply was turned on and the current was slowly increased. Since the bulb was not emitting visible light, the thermal camera was used to show that the bulb did indeed turn on, as shown in Figure 10. With this knowledge, the current was slowly increased to 8.00 amps and there were no issues. At this point we felt our experiments could continue safely.

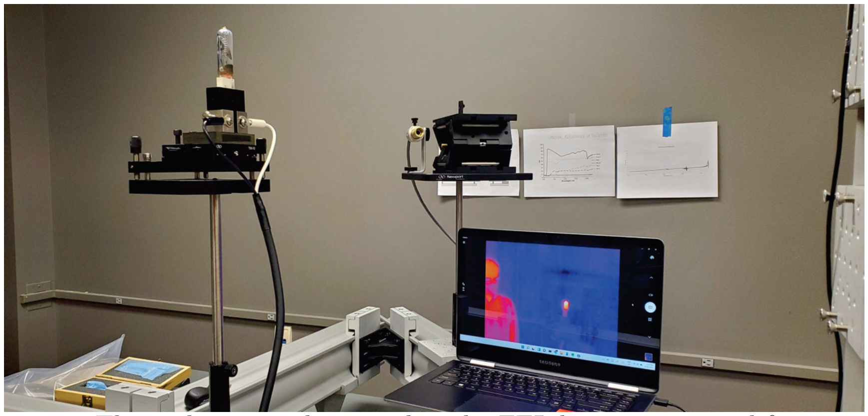

Figure 10: Thermal camera showing that the FEL lamp was on and functioning.

4.3 Verification of Spectral Radiance

A measurement was performed to show a comparison of the calculated spectral radiance from the FEL/Lambertian plaque station vs. measured spectral radiance by a Labsphere calibrated spectrometer. The spectrometer was a CDS-610 350 to 1000nm spectrometer and was last calibrated on March 6, 2020. The data computed using the FEL/Lambertian plaque station was compared to the spectrometer since the spectrometer measurements were trustworthy. Some variables considered: the power supply was set to 8.00 amps; the distance from the plaque to the FEL filament was 48.7553 cm (adjustment factor 1.02553); the FEL lamp was F-416; the distance from the plaque to the spectrometer was 40-50cm away.

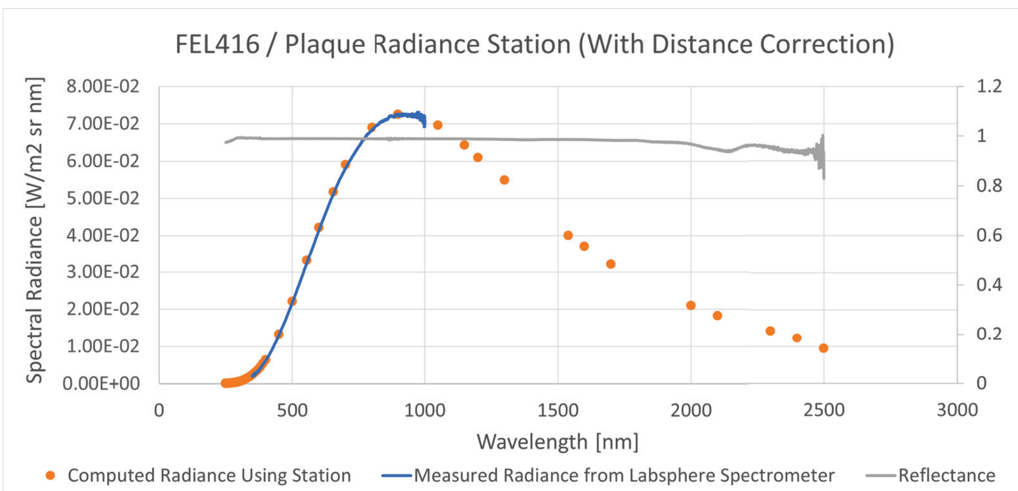

Figure 11: FEL 416 first measurement. Blue is from the calibrated spectrometer. Orange dots are the converted (to radiance) irradiance FEL specification values. Gray line is the reflectance of the Lambertian plaque.

Figure 11 shows the points measured by the Labsphere spectrometer on top of the points produced by the FEL/Lambertian plaque station (i.e., adjusting the values from the FEL irradiance spec sheet). The FEL calibration report provided 36 wavelengths and corresponding spectral irradiances at those wavelengths. Using Eq. (7), the spectral irradiance onto the Lambertian plaque allowed the spectral radiance to be computed. The spectrometer measured the spectral radiance in small increments compared to the computed spectral radiance, as seen in the plot. Unfortunately, FEL F-416 did not come with uncertainty data so we do not know the variability per given wavelength. However, the measured data followed the curve and shape of the computed data which was a pleasant surprise for our first measurement.

In order to make sure that the measurement was precise, a measurement was made again six days later.

Figure 12 shows that the curve follows the same shape, again.

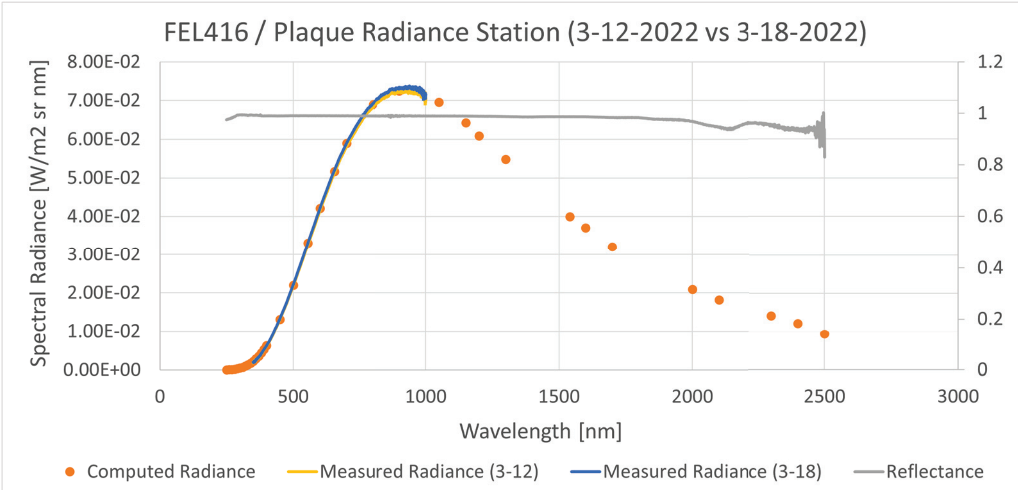

Figure 12: FEL 416 re-measured six days later.

Because both of these measurements went so well, the other two bulbs were also compared to Labsphere spectrometer measurements. For each bulb, a new measurement using the spectrometer was made.

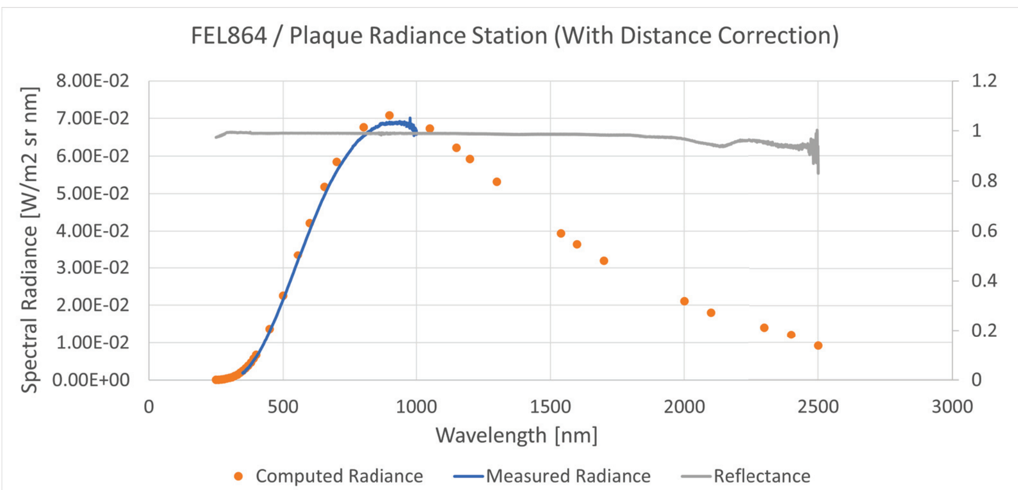

Figure 13: FEL 864 first measurement. Blue is from the calibrated spectrometer. Orange dots are the converted (to radiance) irradiance FEL specification values. Gray line is the reflectance of the Lambertian plaque.

Figures 13 and 14 show the points measured by the Labsphere Spectrometer on top of the converted irriadicne (to radiance) points from the spec sheets FEL F-864 and F-1541, respectively. Both plots show similar results as Figure 11 with the exception that the F-1541 plot includes error bars from the calibration report. As shown in the F-1541 plot, the data measured by the Labsphere spectrometer fits inside the error bars. This means that the station is trustworthy in its report spectral radiance.

4.4 Cross-Checking Calibration of a PR-655 Spectroradiometer

The PR-655 is a JADAK spectroradiometer that has the ability to measure spectral radiance, luminance, irradiance, and illuminance and has a spectral range of 380–780 nm. At RIT, the PR-655 is primarily used by Motion Picture Science students to calibrate projectors and displays. The PR-655 was chosen as a device to calibrate so as to demonstrate how the FEL/Lambertian plaque station can be interdisciplinary and be useful to other programs at RIT with radiometric hardware.

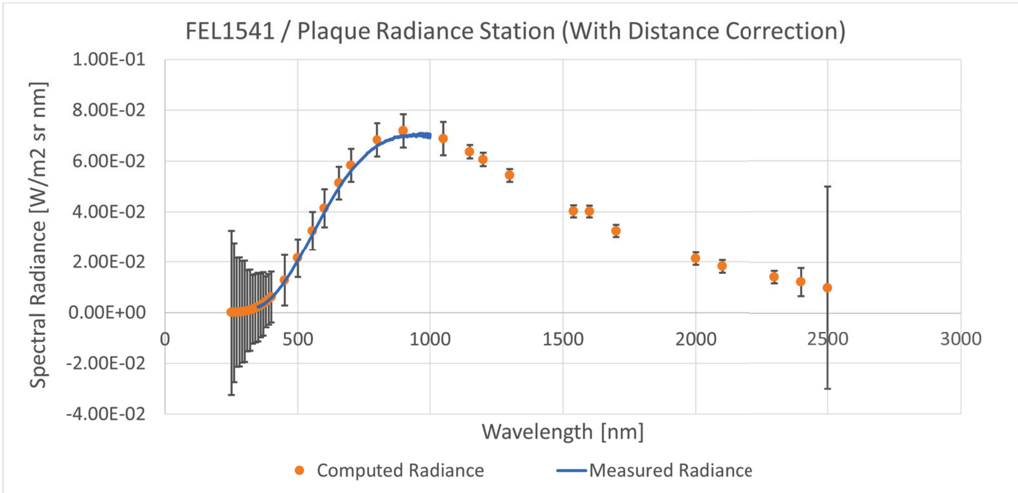

Figure 14: FEL 1541 first measurement. Blue is from the calibrated spectrometer. Orange dots are the converted (to radiance) irradiance FEL specification values. Gray line is the reflectance of the Lambertian plaque.

This experiment was to see whether or not the PR-655 was out of calibration. This was done by measuring the radiance from the station and comparing it to the computed radiance from the station. A similar procedure was implemented as previously outlined (i.e., “station vs Labsphere Spectrometer” experiment), except now it is the PR-655 taking the spectral measurements, not the Labsphere spectrometer. Figure 15 shows our set up of the PR-655 taking a spectral radiance measurement of the plaque with baffle in place.

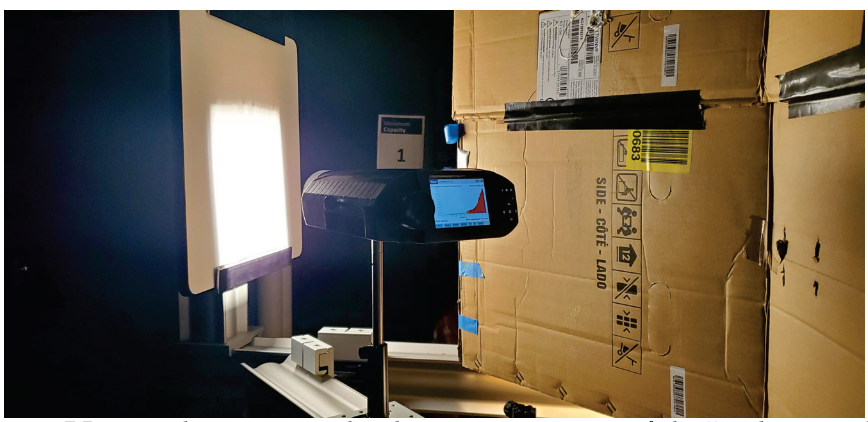

Figure 15: PR-655 taking a spectral radiance measurement of the Lambertian plaque.

Figure 16 shows the spectral radiance measured by the PR-655 compared to the computed spectral radiance from the station. Figure 17 shows the spectral radiance measured by the PR-655 compared to the computed spectral radiance from the station, but in the spectral wavelength range of the PR-655. This plot better shows that the PR-655 is still measuring spectral radiance adequately, considering it was last calibrated 4-5 years ago.

4.5 Influence of the Baffle Test

As previously mentioned in the “Experimental Design” section, Dr. Yoon recommended that the influence of the baffling system be examined. This was performed once all of the other radiometric experiments were completed.

A few different iterations of testing the baffle was performed. The first version was taking a regular measurement, i.e., a measurement with the baffle as was done for the previous experiments. Figure 9 showed this set up. The next measurement was testing the influence of the cardboard by placing black felt around the area of the baffle. Figure 18 shows this set up. A third experiment involved taking the baffling off, except for the side.

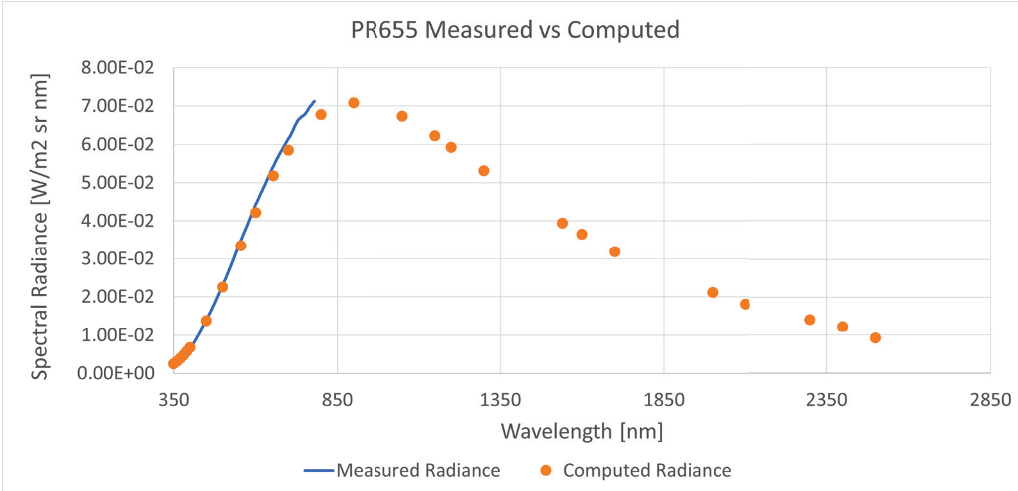

Figure 16: PR-655 spectroradiometer (blue line) compared to computed radiance (orange dots) from the FEL station.

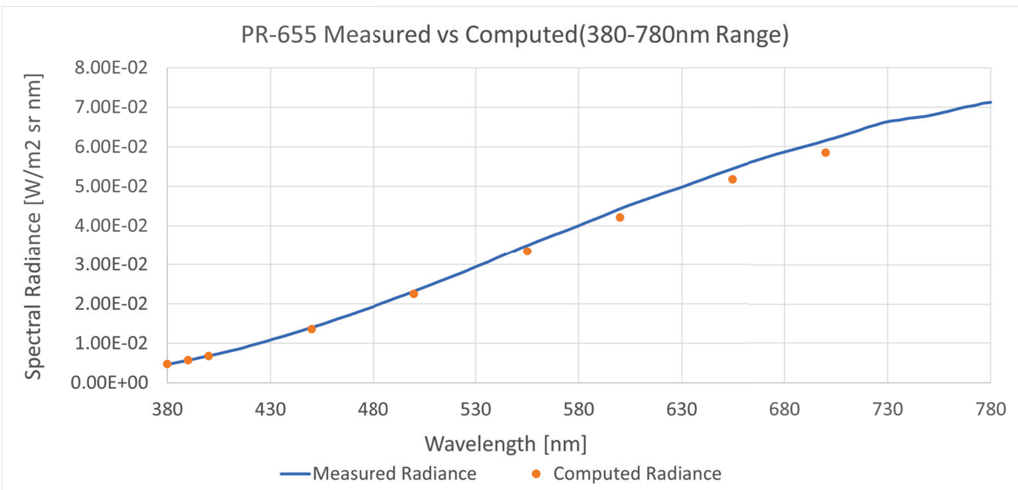

Figure 17: PR-655 spectroradiometer (blue line) compared to computed radiance (orange dots) from the FEL station in the wavelength range of380-780nm.

This would test if stray light would be hitting the sensor. Figure 19 shows this setup. The last measurement was taking down the entire baffle all-together, as shown in Figure 20.

Spectral radiance measurements were made using the Labsphere spectrometer. Each measurement was compared to the "regular baffle" setup. The first comparison was the regular setup compared to the baffle with felt. Figure 21 shows the plot with these two measurements. As shown, the measurement with the felt is slightly smaller than the regular baffle. This means that the baffle's cardboard does have a slight effect to the measurement, especially in the higher wavelength range.

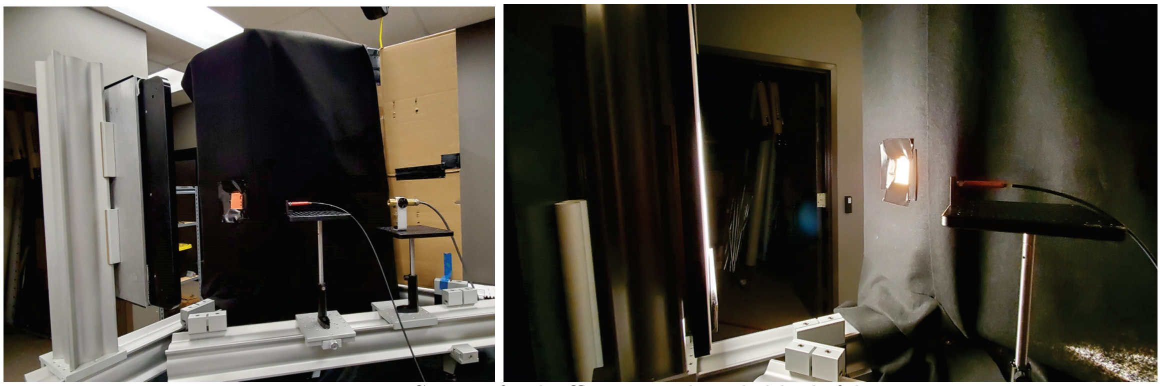

Figure 18: Set up for baffle covered with black felt.

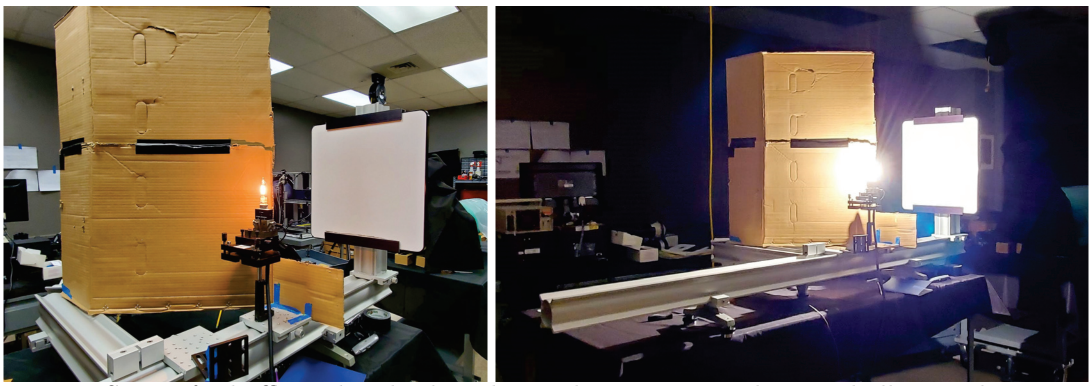

Figure 19: Set up for baffle with only the side panel. We now see the FEL bulb is in the open air.

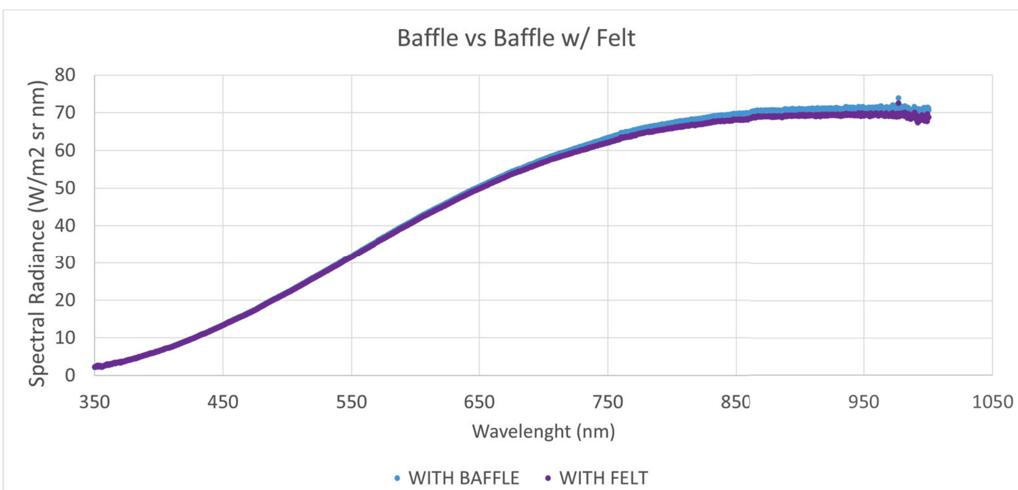

Figure 20: Regular baffle set up vs. baffle covered with black felt.

The second comparison was the regular setup compared to the baffle with only a side structure. Figure 22 shows the plot with these two measurements. As shown, the measurement with only the side baffle is slightly larger than the regular baffle. This means that there is stray light that can be picked up by the sensor, especially in the higher wavelength range.

Figure 21: Set up with no baffle. Both the sensor and FEL lamp are in the open air.

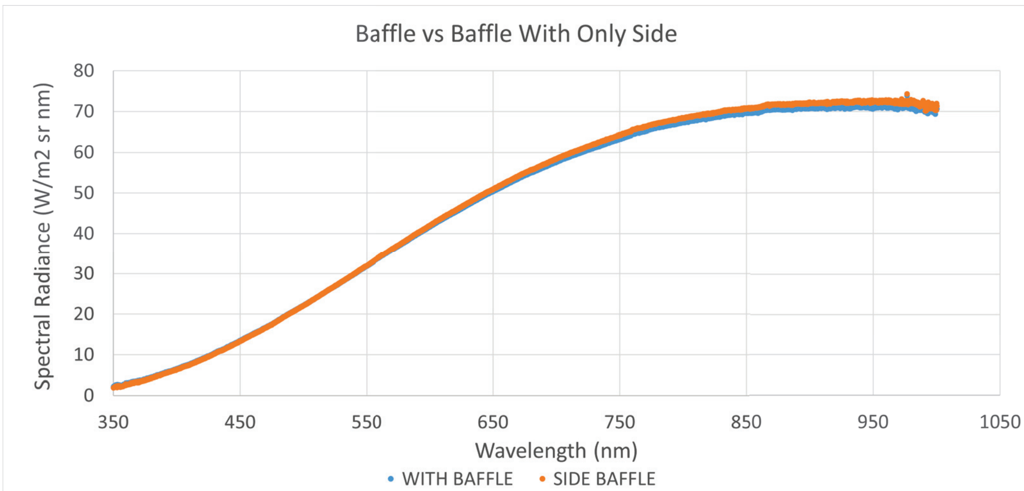

Figure 22: Regular baffle set up vs. baffle with only side structure.

The last comparison was the regular setup compared to the station with no baffling at all. Figure 23 shows the plot with these two measurements. As shown, the measurement with no baffle is slightly larger than the regular baffle. However, it does not differ that much compared to the version with only the side baffle.

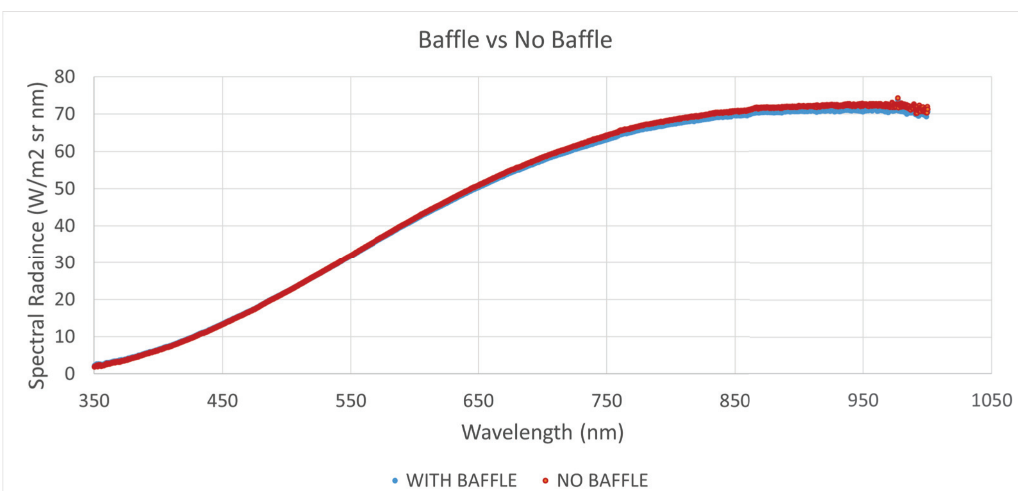

Figure 23: regular baffle set up vs. no baffling at all.

4.6 Suggestions and Practical Considerations

With the intention of a station being built, the three main components of the station had already been purchased before it was turned into a senior project. This included the FEL lamp with the calibration data from Gooch and Housego, the Lambertian plaque from Labsphere, and multiple spectrometers, including the Labsphere CDS-610 spectrometer, SVC HR-1024i Field Spectroradiometer, and ASD FieldSpec 4 Hi-Res: High-Resolution Spectroradiometer. We were lucky to have this equipment available and to have the budget for the optomechanical rails, alignment laser, micrometer, and lab upgrades. We understand that some other universities or industry facilities may not have this type of budget thus we would like to make suggestions on how to make this station less expensive yet still convey concepts or tolerate larger uncertainties as a trade off for exspense.

This type of project is most likely not practical for high school labs. We suggest teaching radiometric concepts such as spectra reflectance and spectral irradiance vs. spectral radiance. Basic lessons on Lambertian surfaces can be explained using something with a Lambertian-like property, such as a stack of white copy paper (with slight specularity). The use of a photographer's light meter can demonstrate the difference between irradiance and radiance, though typically this is photometric (i.e., illuminance and luminance).

It is assumed that universities that teach radiometry should have spectrometers available. If not, one might be able to rent such hardware from spectrometer manufacturers or borrow from other universities. A calibrated FEL lamp could be purchased for a couple of thousand dollars (depends on level of uncertainty), as can a Lambertian plaque, though manufactures are phasing out 1000W FEL lamps. If the concepts and theories behind this station are the key reason for building such a station, the optomechanical rails might not be needed, nor the alignment laser or micrometer used for precise distance measurements. These parts were purchased for the senior project because RIT plans on using this station for in-house spectral calibrations. Simple rail-like structures could be assembled in a 0/45 set up as outlined in this project. Even our expensive 1000W NIST-traceable FEL lamp can be replaced with an open-air projector bulb, (i.e., no retro reflectice housing or coating), for example. One would just have obtain an estimate of its spectral radiance knowing that the power supply (i.e., the wall plug) is not all that stable. Using a set up with a projector lamp, basic rails, rough alignment, stack of copy paper, no baffle, etc. still conveys the concepts of a spectral radiance calibration station.

5. CONCLUSIONS AND FUTURE WORK

For this project, there were four main goals. The first goal was to design an FEL lamp/Lambertian plaque station. This was accomplished after months of research and help from scientists in the imaging science field. Soon after, our final design was brought to life. The rail system was built, along with additions of the Lambertian plaque holder and different versions of baffles. Before the station was used, the integrity of the FEL lamp and power source was successfully tested with an infrared camera. The station was then tested and compared to the Labsphere spectrometer and the results concluded that the station was, in-deed, built correctly. The station was then used to cross-check the spectral radiance calibration of a PR-655 Spectroradiometer and to demonstrate how the station could be interdisciplinary and be useful to other programs at RIT. Finally, the baffle's influence on the station was tested.

For the future, the uncertainty of each measuring device needs to be recorded so as to perform an uncertainty analysis. There was not enough time to include this in the senior project. The temperature of the room the station is built in needs to be checked for variation. The room's temperature should remain constant so as to not interfere with the spectrometers, which can be sensitive to temperature. A proper procedure and set of protocols will need to be established, such as letting the lamp warm up for x-minutes, what piece of equipment to turn on first, where to position the camera or spectrometer, etc. An FEL lamp transfer calibration will be performed with two other un-calibrated FEL lamps. Inexpensive spectrometers used in other student-based radiometric labs will be radiometrically calibrated, using the station, in a new lab for students at the undergraduate level. Lastly, a transfer calibration can be done with other light sources, such as an Ocean Insight light sources, which we have in our lab.

In conclusion, the design and construction of the FEL lamp/Lambertian plaque spectral radiometric station was a success. It will be used by the Chester F. Carlson Center for Imaging Science to spectrally calibrate instruments and educate students in various imaging science courses. We hope that other universities that teach radiometry concepts will take our research and suggestions so as to create their own station in their laboratories.

6. ACKNOWLEDGEMENTS

The authors wish to thank David Conrad from Rochester Institute of Technology, Dr. Howard Yoon and Carol Johnson from NIST, Chris Durell from Labsphere, and the Digital Imaging and Remote Sensing Laborator (DIRS) at Rochester Institute of Technology.

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