Light Source Spectra and Irradiance Distribution

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Light sources emit various colors of light in different proportions. A spectrometer can measure the relative proportion of each color. In this lab, a fiber-coupled spectrometer will be used to measure the spectrum of various broadband light sources.

In addition, the luminaire of a source casts light into unique spatial distributions, radiating different amounts of energy to different directions. The spatial distributions of some sources may be innate to the source construction, but some distributions are modified by their luminaires.

INTRODUCTION

Learning Goals

You just graduated and the company you are working at needs to learn the advantages of using an LED source instead of an incandescent source to illuminate a scene. In this lab you will use a commercially available fiber-coupled spectrometer to measure the spectrum of various broadband sources. You will also explore the unique spatial distribution of the sources.

LED vs Incandescent Source

An incandescent lamp produces light by passing an electric current through a tungsten filament. Electrical resistance heats the filament to approximately 2,500–3,000 K, causing it to emit thermal radiation. The resulting spectrum is broad and continuous, extending from the visible region into the near-infrared.

An LED produces light through electroluminescence. When current passes through a semiconductor junction, electrons and holes recombine and release energy as photons. The semiconductor's bandgap determines the approximate photon energy—and therefore the wavelength—of the emitted light.

Radiometry

Radiometry is the science of measuring electromagnetic radiation, including ultraviolet, visible, and infrared light. Unlike photometry, which weights light according to the sensitivity of the human eye, radiometry measures the physical amount of radiant energy present at each wavelength.

In this experiment, radiometry allows us to move beyond describing a lamp as simply "bright," "warm," or "white." A spectroradiometer separates the light into its component wavelengths and measures the radiant power associated with each wavelength. The resulting graph is called a spectral power distribution, or SPD.

A spectral power distribution shows how a source's optical output is distributed across wavelength. Wavelength is typically shown on the horizontal axis in nanometers (nm), while the vertical axis represents a radiometric quantity such as spectral irradiance. By examining the shape of the spectrum, we can identify emission peaks, determine whether the output is continuous or banded, and compare the ultraviolet, visible, and infrared contributions of different light sources.

Read more about radiometry at StellarNet's learning center here:
https://www.stellarnet.us/systems/radiometers/learning-center/

Common Radiometric Quantities

Radiometric quantities describe light according to how it is produced, transmitted, or received.

Quantity	Description	Common Unit
Radiant energy	Total energy carried by electromagnetic radiation	Joule (J)
Radiant flux	Rate at which radiant energy is emitted or transferred	Watt (W)
Irradiance	Radiant flux received by a surface per unit area	W/m^2
Radiant intensity	Radiant flux emitted in a particular direction	W/sr
Radiance	Radiant flux traveling in a particular direction from a defined source area	$W/(m^2 \cdot sr)$
Spectral irradiance	Irradiance measured per unit wavelength interval	$W/(m^2 \cdot nm)$

For a lamp measurement made at a specific distance, spectral irradiance is often the most useful quantity. It describes how much optical power reaches the detector's measurement surface at each wavelength.

Spectral and Integrated Measurements

The spectroradiometer records a spectral value at many individual wavelengths. These measurements can then be integrated over a selected wavelength range to determine the total irradiance:

$$E = \int_{\lambda_1}^{\lambda_2} E_\lambda (\lambda) d\lambda$$

Where
E is the integrated irradiance in W/m^2,
$E\lambda$ is the spectral irradiance in $W/(m^2 \cdot nm)$,
$\lambda 1$ and $\lambda 2$ define the wavelength range.

The spectral graph and integrated value provide different information. The spectral graph shows where the optical energy occurs, while the integrated value indicates how much energy is present across the selected range.

Radiometric Calibration

A spectrometer initially measures the detector's electrical response, often displayed as raw counts. Raw counts are useful for observing spectral shape, but they do not directly represent optical power. Detector sensitivity, grating efficiency, fiber transmission, and other instrument components can respond differently at different wavelengths.

Radiometric calibration corrects for these wavelength-dependent effects by comparing the instrument response with a source of known spectral output. After calibration, the measurement can be reported in physical units such as $W/m^2/nm$. This allows students to compare the actual spectral irradiance produced by different lamps rather than only comparing detector signal.

Why Measurement Geometry Matters

Radiometric results depend not only on the lamp itself but also on how the measurement is performed. Important variables include:

- Distance between the lamp and detector
- Angle of the lamp relative to the detector
- Detector collection area and field of view
- Lamp beam pattern
- Ambient light
- Integration time and detector saturation

Irradiance generally decreases as the distance from a source increases because the emitted power spreads over a larger area. Therefore, the same detector position and orientation should be used when comparing LED and incandescent lamps.

Application to This Experiment

LED and incandescent lamps generate light through different physical mechanisms and consequently produce different spectral power distributions. Radiometric measurement makes it possible to observe these differences objectively. Students will compare the distribution of radiant energy across wavelength, identify characteristic spectral features, and relate the measured spectra to the technologies used to produce the light.

Two lamps may appear similarly bright or similarly white while producing very different radiometric spectra.

PRELAB QUESTIONS

1. How does an incandescent lamp product light?
2. How does an LED produce light?
3. How does a phosphor-coated white LED produce light that appears white? wavelength?
4. Sketch your predicted spectral power distribution for an incandescent lamp and a white LED. Label any expected peaks or broad spectral regions.
5. Do you expect the incandescent lamp or LED to produce more near-infrared radiation? Explain your prediction.
6. How is radiometry different from photometry?
7. Why should the lamp-to-detector distance and measurement angle remain consistent?
8. Why is it necessary to record a dark spectrum before measuring the lamps?

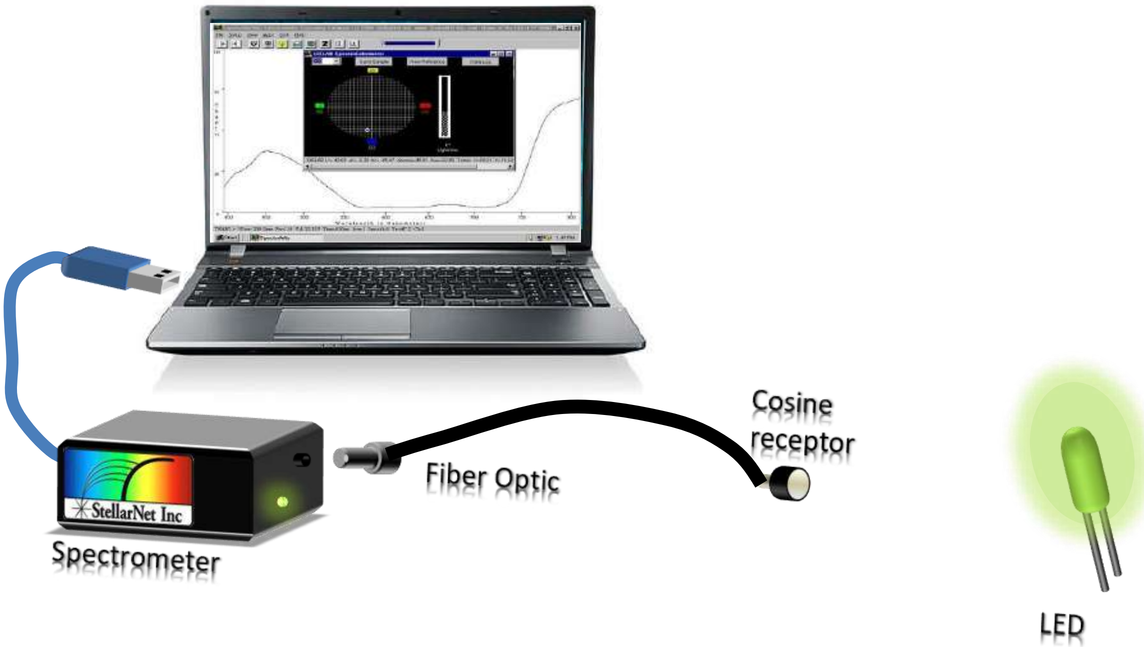
PROCEDURE

Materials and Equipment

- ✓ One optical breadboard
- ✓ One fiber-coupled spectrometer with input fiber, cosine receptor, calibration, computer, and software
- ✓ One LED source in a common 5-mm luminaire
- ✓ One other optical source – incandescent, fluorescent, or another LED luminaire

System Configuration

1. Configure the spectrometer hardware as shown in the figure below and as described in the next step. Connect the spectrometer to the computer via the USB cable, and the fiber optic cable to the front of the spectrometer. The other end of the fiber optic cable will have a cosine receptor on it.

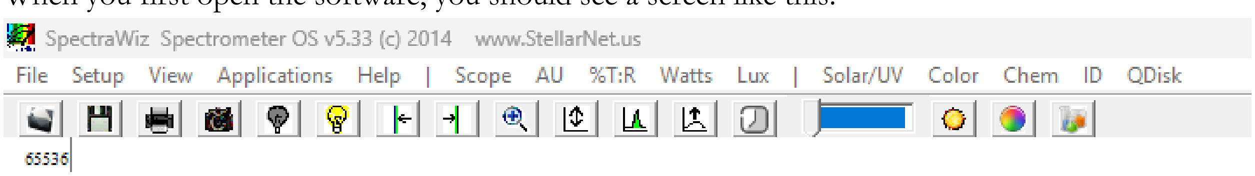


2. Mount the optical source securely to the optical breadboard and position its output to be emitted about 100mm above the surface of the breadboard

Spectral Measurements

1. Open the spectrometer software, StellarPro or SpectraWiz. This procedure will utilize SpectraWiz.

2. When you first open the software, you should see a screen like this:



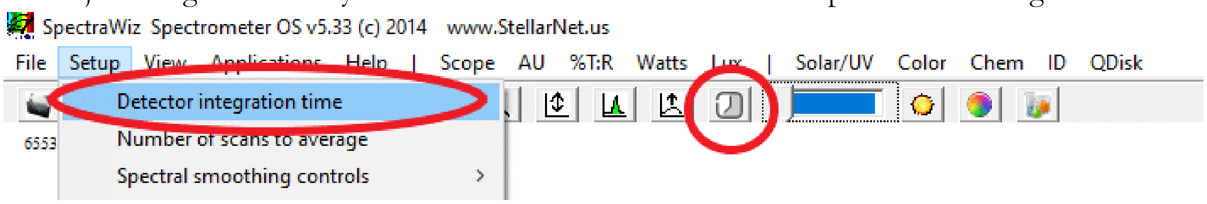
3. With the ambient lights and source powered off, collect a dark measurement by clicking on the dark light bulb icon.  "Save dark spectrum/Zero dark". If you accidentally take your dark

with the lights on, right-click on the dark bulb to remove any previously taken dark measurements.

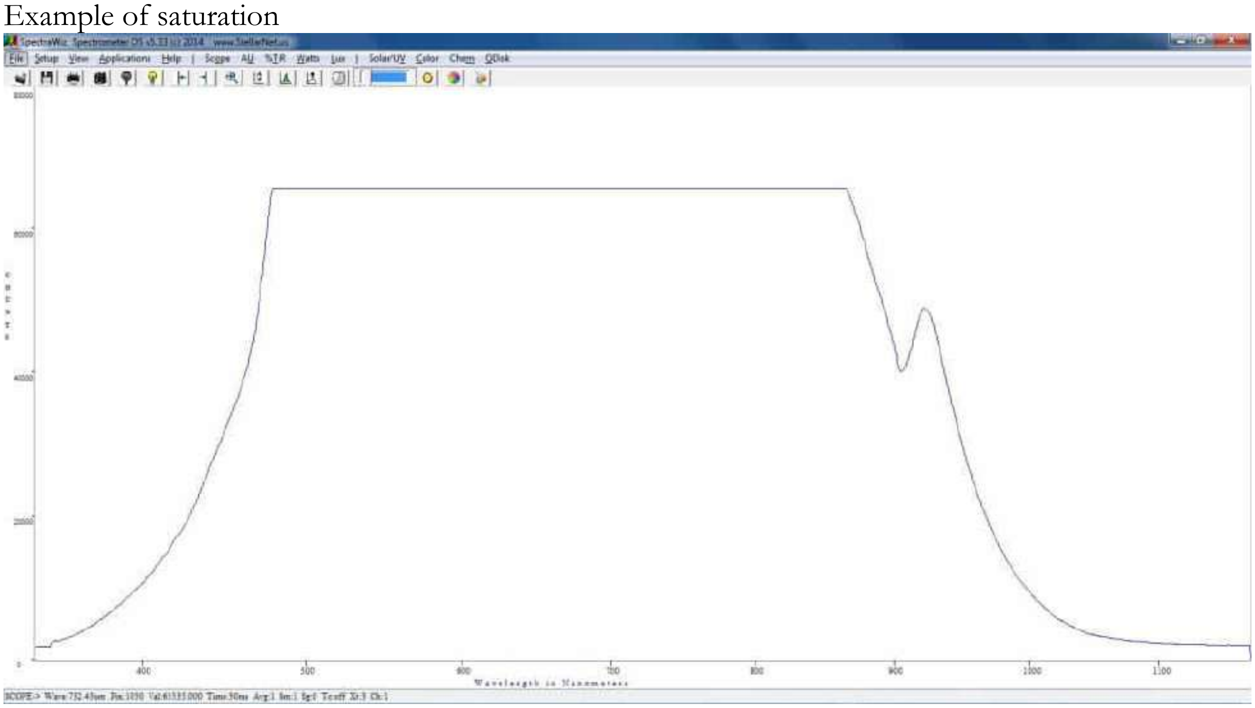
4. Power on your source and begin spectral acquisition. Use SCOPE mode in SpectraWiz.

5. Move the fiber tip toward or away from the source to appropriately expose the spectrometer sensor: Too much light will saturate the camera, seen a flat line at the top of a portion of the spectrum; too little light with cause no signal to appear on the display. Move the fiber so that the most intense part of the source spectrum creates a signal at ~90% of the full dynamic range (65536 counts) of the spectrometer sensor. If the source output is too low or high, the spectrometer sensor's integration time may be increased or decreased accordingly.

To adjust integration time you can use the clock icon or click Setup>Detector integration time

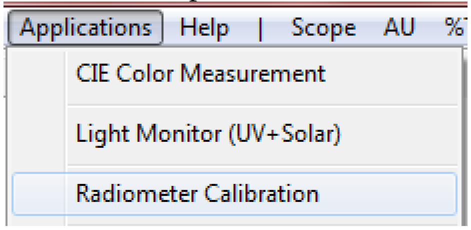


Example of saturation



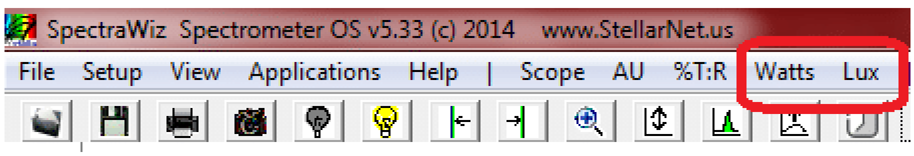
Don't forget to take a new dark measurement after adjusting the integration time!

6. Load your calibration file by navigating to Applications -> Radiometer Calibration. You will be offered three options – choose "Yes" to load your calibration.

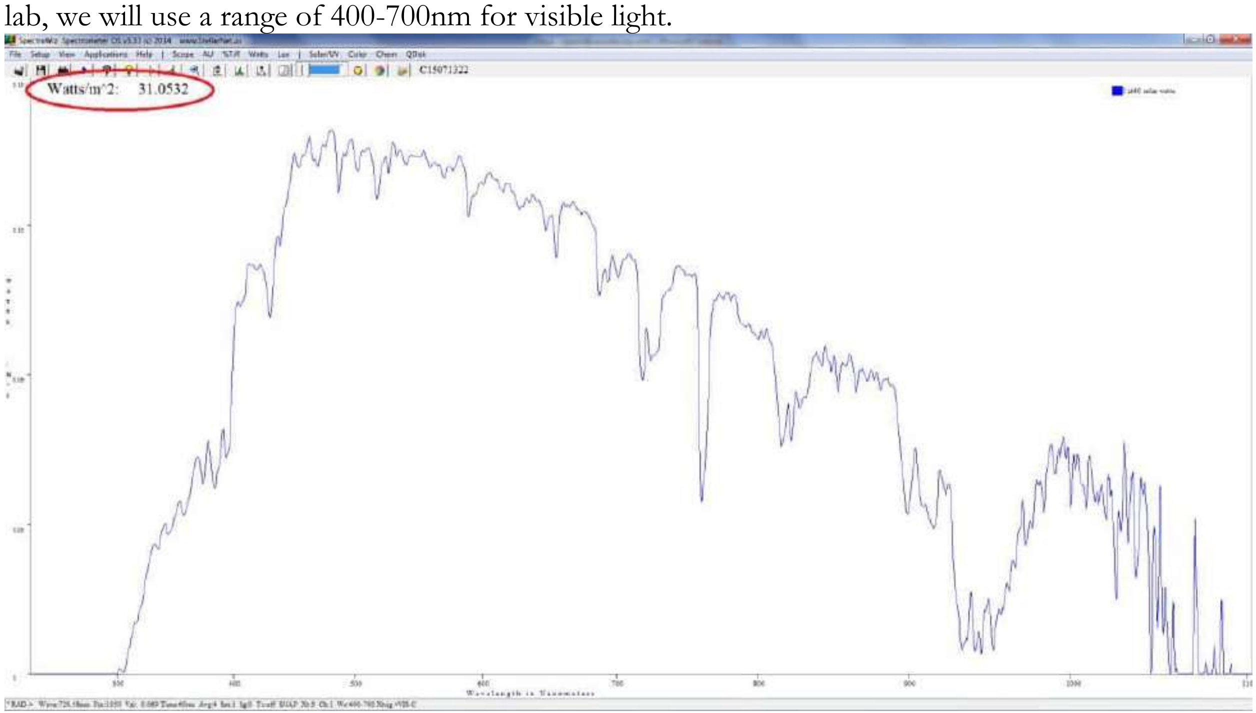


7. Navigate to your calibration file and load the file.

8. Change to "Radiometer Mode" to view the irradiance spectrum by clicking on "Watts" at the top of the icon bar.



9. The left corner has the integrated value over a specific range – this range can be adjusted by navigating to View -> Radiometer -> Setup Range for Watt and Rflux Measurement. For this lab, we will use a range of 400-700nm for visible light.



10. Save your data in both SCOPE (.SSM) and Radiometer modes (.IRR) These are a tab-delimited text file of spectra with wavelength in one column and either the relative response in counts (for SCOPE mode) or intensity in W/m^2.

Spatial Measurements

1. Next position the source so the output fills the volume above the optical breadboard. Even though all sources radiate in three dimensions, measurements will only be made on the horizontal plane for simplicity.

2. Take a photograph of the hardware configuration for your lab notebook.

3. Draw or photograph how the irradiance distribution changes along a measurement plane. It helps to case the source onto a screen to observe the full distribution.

4. Designate measurement planes at five axial distances from the source, as shown in the figure below. The first plane should be at an axial distance of ~100 mm from the source, the second at ~200 mm, the third at ~300 mm, the fourth at ~400 mm, and the fifth at ~500 mm. Ensure source is positioned on the edge of the breadboard so the 500-mm span fits atop the breadboard.

5. Start with the detector at an axial distance of ~100 mm from the source. Cast the source onto a large white screen to observe the full irradiance distribution. Move the detector along this plane until you locate the position where the maximum power is measured. Mark this position. Measure and document the maximum power at this 100-mm axial distance.

6. Maintain this same axial distance of 100 mm, and move the detector laterally (along the breadboard) to collect five measurements on either side of the maximum along this plane, ranging from ~10% to 100% of the maximum value. Document the lateral position of each measurement.

7. Move the detector to the measurement plane that is 200 mm from the source, and collect five measurements on either side of the maximum along this plane, ranging from ~10% to 100% of the maximum value. Document the lateral position of each measurement.

8. Move the detector to the measurement plane that is 300 mm from the source, and collect five measurements on either side of the maximum along this plane, ranging from ~10% to 100% of the maximum value. Document the lateral position of each measurement.

9. Move the detector to the measurement plane that is 400 mm from the source, and collect five measurements on either side of the maximum along this plane, ranging from ~10% to 100% of the maximum value. Document the lateral position of each measurement.

10. Move the detector to the measurement plane that is 500 mm from the source, and collect five measurements on either side of the maximum along this plane, ranging from ~10% to 100% of the maximum value. Document the lateral position of each measurement.

Second Source

1. Repeat the full collection of spectral and irradiance distribution measurements using a different optical source with a different luminaire.

DATA ANALYSIS

Part 1: Spectral Output

1. Import the .IRR files for both sources into a spreadsheet or data-analysis program.

2. Plot the calibrated spectral irradiance of both sources on the same graph:
   - o Horizontal axis: Wavelength (nm)
   - o Vertical axis: Spectral irradiance W/(m2\nm)

3. Label each spectrum clearly and include a descriptive figure caption.

4. For each source, record:
   - o Wavelength of maximum spectral irradiance
   - o Maximum spectral irradiance
   - o Integrated visible irradiance from 400–700 nm
   - o Major peaks, bands, or continuous spectral regions
   - o Any detectable output beyond 700 nm, if it falls within the calibrated range of the instrument

Part 2: Spatial Distribution

1. Create a table for each source that includes:

Axial distance, z (mm)	Lateral Position, x (mm)	Irradiance, E (W/m²)	Normalized irradiance E/Emax

2. For each axial measurement plane:
a) Identify the maximum measured irradiance, Emax.
b) Calculate the normalized irradiance at every lateral position:

$$E_{norm} = \frac{E(x)}{E_{max}}$$

3. Plot irradiance against lateral position:
   - Horizontal axis: Lateral position, x (mm)
   - Vertical axis: Irradiance, E (W/m^2)

4. Create a second plot using normalized irradiance. Plot the normalized distributions for all five axial distances on the same graph.

5. Record the maximum irradiance and FWHM for each axial distance:

Axial Distance (mm)	Maximum Irradiance (W/m^2)	FWHM
100		
200		
300		
400		
500		

7. Plot maximum irradiance against axial distance for each source.

Part 3: Comparing the Sources

Prepare a final comparison that addresses both spectral and spatial performance.

Characteristic	**Source 1**	**Source 2**
Spectral distribution		
Peak wavelength		
Visible irradiance		
Near-infrared contribution		
Bean Shape		
Change in irradiance with distance		
Change in beam width with distance		
Potential illumination advantages		
Potential illumination disadvantages		

DISCUSSION QUESTIONS

1. How did the measured spectra compare with your pre-lab predictions?

2. Was each spectrum continuous, banded, or composed of several distinct features? Explain how the observed shape relates to the source's light-generation mechanism.

3. What spectral features allowed you to distinguish the LED from the second source?

4. If a white LED was measured, identify the blue LED emission and the broader phosphor emission. How do these components combine to produce light that appears white?

5. Which source produced the greater integrated irradiance between 400 and 700 nm under the measurement conditions used?

6. Which source produced more detectable radiation above 700 nm? How does this relate to heat generation and the physical mechanism producing the light?

7. Why might two sources that appear similarly bright or similarly white to the eye have different spectral power distributions?

8. How did normalization affect the comparison of the spectra? What information is lost when a spectrum is normalized?

9. How did irradiance change as axial distance increased? Did the measured values follow the inverse-square relationship? Quantitatively compare the measured and predicted results.

10. What experimental factors could cause the irradiance measurements to deviate from the inverse-square law?

11. How did the width of the irradiance distribution change with distance from the source?

12. Was the spatial distribution symmetric about its maximum? If not, what features of the source, luminaire, alignment, or measurement system might explain the asymmetry?

13. How did the two luminaires affect the direction and spread of the emitted light?

14. Which source produced the more concentrated beam? Which produced more uniform illumination across the measurement plane?

15. Why is comparing only the maximum irradiance insufficient when evaluating a source for illuminating a large area?

16. How could ambient light, detector alignment, distance uncertainty, or source instability affect the results?

17. Why should saturated spectral measurements be rejected rather than corrected during data analysis?

18. Based on both the spectral and spatial measurements, what advantages did the LED demonstrate over the comparison source?

19. What disadvantages or limitations of the LED were revealed by the measurements?

20. Which source would you recommend for illuminating the proposed scene? Support your recommendation using at least three quantitative results from the experiment.

21. What additional measurements would be necessary to compare the electrical efficiency of the sources?

22. How might the results change if the sources were compared using total radiant flux rather than irradiance at a particular location?

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