Sun Photometry for Introductory Students

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Light and its spectrum are central concepts in many introductory physics,[1] astronomy,[2] geology,[3] and conceptual physics[4,5] courses. The Sun and its spectrum are usually primary examples, likely due to the Sun's everyday familiarity and the full spectrum it generates when dispersed. To enhance such discussions with a hands-on student activity, we've often looked to *sun photometry.*

Sun photometry is a method of optically studying the column of atmosphere that exists between the observer and the Sun over the course of a day. It is ideal for introductory students, since it involves two familiar and readily available quantities: the Sun and the sky. To first order, the change in the thickness of the atmosphere between the Sun and an observer as the day progresses (see Fig. 1) drives any trends in optical measurements. In sun photometry, the intensity of a narrow wavelength band received at ground level throughout the day is the primary observation.

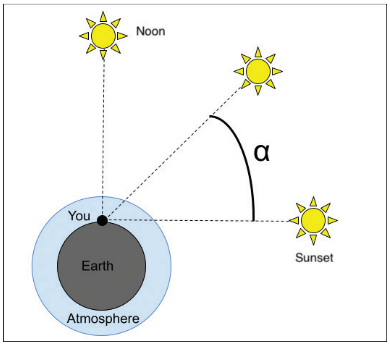

Fig. 1. A schematic showing the changing thickness of the atmosphere as the day proceeds from noon until sunset. The atmosphere between the Sun and observer (i.e., "you") is thinnest at noon and thickest at sunset. The angle α is the altitude of the Sun, which is maximum at noon and smallest (~0°) at sunset.

The student may imagine a beam of light from the Sun traveling through the atmosphere, on its way down to the observer. As it travels through the atmosphere, light may leave the original beam due to reflection off particulates, or atomic/molecular absorption and reemission. These removal mechanisms are collectively called "scattering," and the reduction in light intensity is called "attenuation." Thus, the intensity of light eventually reaching the observer will vary with thickness of the atmosphere between the Sun and observer, and atmospheric conditions at the time of measurement.

Such intensity measurements result in a "Langley plot," which allows for the determination of the attenuation coefficient of a given wavelength, and its extraterrestrial constant (the intensity of a wavelength just above the atmosphere). In addition to the atmospheric thickness, effects of pollutants, haze, and smog can be apparent. Learning outcomes include the Sun's motion throughout the day, the (changing) (optical) thickness of the atmosphere between the observer and Sun as the day progresses, light propagation through the atmosphere, and terrestrial activities that may affect optical properties of the atmosphere.

Homebuilt sun photometers[6,7] based on the spectrally sensitive response of LEDs to *incoming light* are effective and inexpensive. LEDs are known to generate a photocurrent in response to a narrow band of light incident upon them, with the response being at or near the LED's emission wavelength.[6,8] LED-based photometers work by amplifying a small photocurrent generated by an LED using an operational amplifier (op amp) as a current-to-voltage converter. The converted voltage from the op amp (read using a voltmeter) is thus a (linear) proxy of the light intensity. It is difficult, however, to expect introductory students to manage such a project, which involves procuring parts, assembling and testing a circuit involving an op amp, and packaging it all up into a durable and portable form, suitable for convenient and repeated outdoor use.

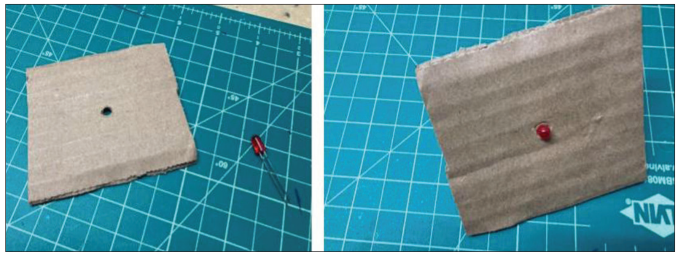

Fig. 2. Red LED and small hole in 2-inch square cardboard (left). The LED should fit snugly in the cardboard (right).

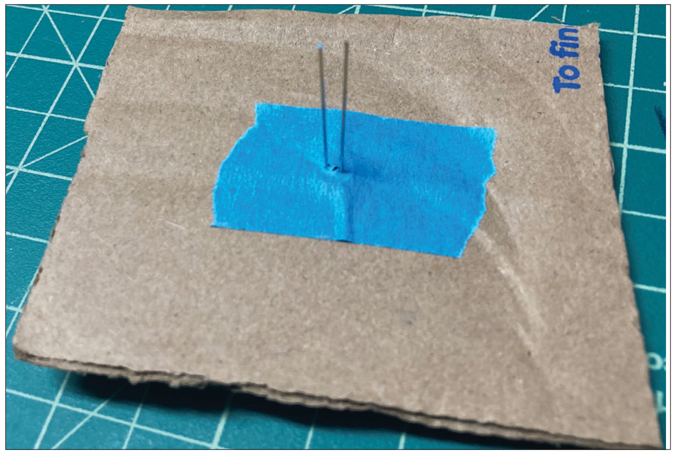

Fig. 3. Taping the back leads of the LED to the cardboard.

This paper is motivated by the measurement and learning possibilities that sun photometry affords to introductory students. An LED-based sun photometer adapted for this learning group is presented that yields the same results as those cited above, while being even less expensive (approximately US$10) and requiring fewer parts. Further, there is no circuit construction, as it only requires an ammeter with microampere sensitivity connected directly to an LED, both of which can be obtained online.[9] We also present a tested and robust packaging plan, made from scrap cardboard. The entire apparatus may even be constructed at home for use in remote study scenarios. We show how a valid Langley plot is produced, then present a lesson on analyzing the color of sunsets, which ties directly to typical in-class lessons on light and its spectrum.

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Fig. 4. LED leads bent down to the cardboard and taped (and/or stapled) firmly to the cardboard.

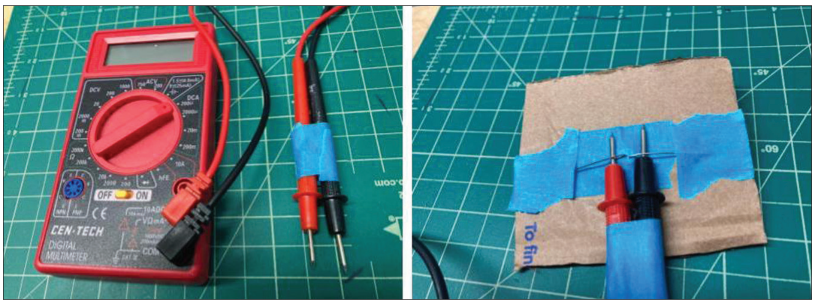

Fig. 5. Voltmeter leads taped together (left) and inserted into small space under the LED leads for a snug electrical connection.

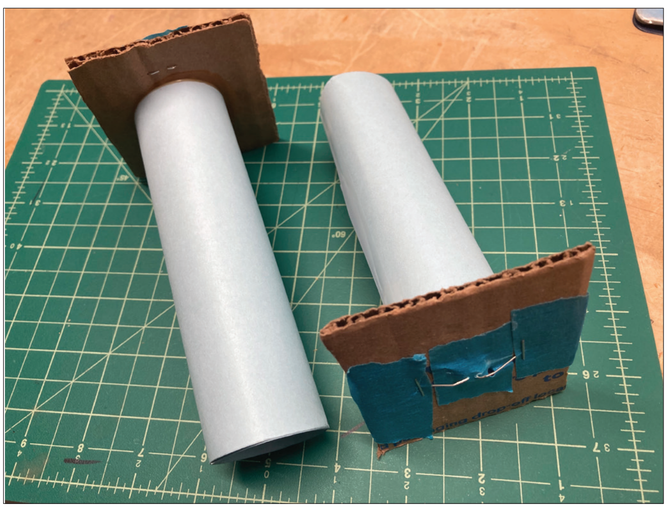

Fig. 6. Two tubes attached to each cardboard square for collimation with the Sun. One assembly is for the blue LED, and the other is for the red.

Apparatus construction

We begin with a voltmeter, a red LED, a blue LED, and some scrap cardboard. First, cut two squares of cardboard, approximately 2 inches on a side. Second, make a small hole at the center of each that tightly fits the LED, as shown in Fig. 2. Third, on the back sides, carefully press a piece of tape over each LED's leads, so the LED will be held snugly in place as shown in Fig. 3. Fourth, slowly fold down each LED's leads, so they are flat with the cardboard as in Fig. 4. Tape the free ends into place, being sure they remain secure (the free ends may be stapled to the cardboard). Fifth, tape the voltmeter probes together and work everything until the probes snugly insert under the folded LED leads, making good electrical contact, as shown in Fig. 5. Be sure that the secured ends of the LED leads remain fixed to the cardboard. A spring-like tension in the folded LED leads should hold the voltmeter leads in place as shown.

Lastly, fashion two ~6-inch-long, ~1.5-inch-diameter tubes out of some opaque material like cardstock, and glue them to be centered over the LED side of each cardboard square. Ours are shown in Fig. 6. This completes the apparatus assembly. As a quick test, insert the ammeter leads, set the meter to 200 μA, and point the tube at a (bright) indoor light. A photocurrent should show on the meter.

Measurements

Acquisition

To take measurements, the voltmeter leads are inserted as shown in Fig. 5, then the tube is pointed at the Sun. After addressing safety issues of not looking at the Sun, it is best to operate the assembly by only looking (down) at the cardboard tube and finding an orientation for it that causes the shadow of the tube on the cardboard square to disappear. This minimizes scattered light and maximizes direct rays from the Sun hitting the LED. For increased Sun safety, it is even possible to take measurements with one's back to the Sun.

The measurement is the photocurrent the LED generates in response to the Sun's light. Thus, the meter must be set to the smallest microampere setting. (This happy advance in consumer-grade voltmeters, namely the ability to read microamperes, obviates the need for the usual circuit and op amp used in other work.) When the tube's shadow disappears, small changes to the tube's orientation will show a clear current maximum on the meter. Data to be recorded is the time of day and the (maximum) current reading.

Preliminary analysis

From the data, a Langley plot is made by plotting the natural log of photocurrent (y-axis) vs. $1/\sin(\alpha)$, the relative thickness (or "air mass") of the atmosphere on the x-axis.[10] Here, α is the Sun's altitude at the time of the measurement. We find altitude values using a National Oceanic and Atmospheric Administration website.[11] To show the throughput of our device, a Langley plot for data taken from noon to sunset on a very clear day (June 15, 2021) in our locality is shown in Fig. 7.[12] Errors in the current are ± 0.1 μA, in time ± 0.003 hours, and in altitude 0.01°. Error bars on all subsequent plots are derived from these values.

Lessons

Typical sun photometry

Our lessons are twofold. First, the slope of the Langley

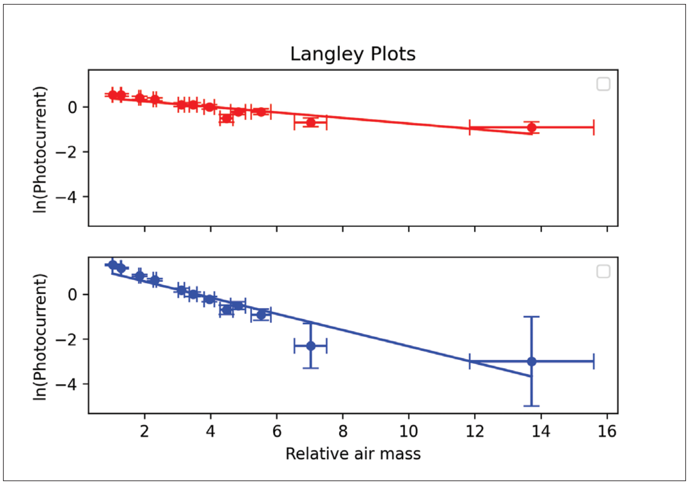

Fig. 7. Langley plot made from data collected from the red (top) and blue (bottom) LEDs from noon until sunset on a very clear day.

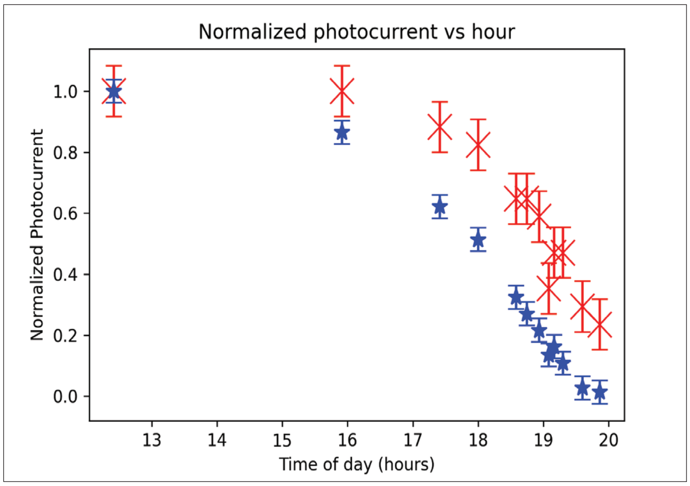

Fig. 8. Normalized photocurrent for the red (×) and blue (*) LEDs, plotted as a function of hour.

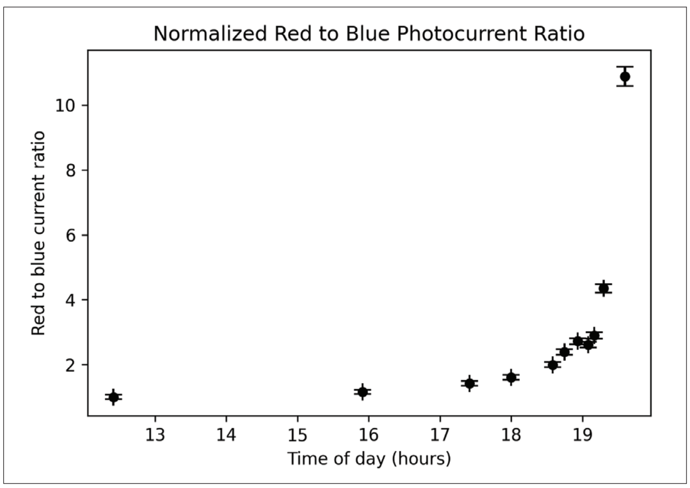

Fig. 9. Ratio of normalized red to blue photocurrents, showing a significantly higher fraction of red light received by the observer at sunset. ***[AUTHOR: Please verify change from "significant fraction" to "significantly higher fraction".]*** OK

plot (from a best-fit line) allows for the determination of the attenuation coefficient for a given color. For the student, the attenuation coefficient is a measure of the amount of reduction of the original light beam, alluded to in the introduction. For red, we found this to be 0.12, and for blue, 0.64. Both of these values are consistent with other work.[6,7] From these and a discussion of the Beer-Lambert law,[13] evidence of a reddening sky is already at hand by direct comparison of these two numbers: blue is being attenuated more than red. Second, a common extrapolation is to find the photocurrent at zero air mass, which is the y-intercept of the fit (but could also be found graphically). For the data in Fig. 7, we obtained 0.50 for red and 1.29 for blue, which would give photocurrents of $e^{0.5} = 1.65\ \mu\text{A}$ and $e^{1.29} = 3.63\ \mu\text{A}$. These are the photocurrents the LEDs would generate if taken to the top of Earth's atmosphere and aimed at the Sun. (We find this to be a thought-provoking example of an "impossible observation" made possible by data extrapolation.)

Adaptation for introductory students

Second, we enjoy discussing colors found in nature as part of a unit on light in introductory courses. In particular, we discuss reasons for the blue sky and red sunsets, which are part of the Next Generation Science Standards[14] and are of broader interest.[15] A lesson on these topics can be directly linked to this photometry experiment by presenting the data in a way not typically seen in previous sun photometry work.

Our lesson is driven by Fig. 1, which shows a model of the Sun at noon, midafternoon, and sunset. Although not to scale, it illustrates the changing thickness of the Sun-to-observer atmosphere as the altitude of the Sun progresses from its maximum at noon (thinnest atmosphere) to its minimum at sunset (thickest atmosphere). Thus, the scattering that selectively filters blue light from the Sun's optically white beam should be more pronounced at sunset.

Figure 8 (which was made from the data) illustrates this point. The photocurrent from each LED is normalized by dividing each photocurrent sample by the extraterrestrial constant for a given LED, presumably removing any LED-specific biases (quantum efficiency, etc.) These data are plotted vs. time of day, which shows a clear trend of more red light being received than blue, with a gap that appears to widen as the sunset approaches. Figure 9 shows the normalized ratio of red to blue light. At sunset ~~(rightmost on the graph)~~, 10 Remove times more red light is arriving at the observer than blue light, which is a convincing numerical outcome, quantifying red sunsets. Naked-eye observations of the sky can also be made to corroborate such results.

Conclusions

In this paper, we have presented an LED-based sun photometer, adapted specifically for introductory students. Construction of the photometer is straightforward and does not involve building a circuit. We have also presented a lesson that quantitatively demonstrates red/blue color trends from noon to sunset on a clear day.

For generation of a Langley plot, data are only needed in some half of a given day, either sunrise to noon, or noon to sunset, with points recorded approximately every hour. If one's focus is only the red/blue color trends of midday to sunrise or sunset, we suggest working from noon to sunset, as students seem to be more familiar with the general blueness of the sky during the day, with reddening as the Sun sets. For this, a baseline of one or two hourly readings in midafternoon should start things off, followed by readings at 15-min intervals within 1–1.5 h of sunset.[16]

If regular measurements are made to generate a daily Langley plot, the attenuation coefficients could be found for each day, and assembled onto an ongoing plot showing attenuation coefficient vs. day, perhaps as part of a term-long class project. Students would likely be able to correlate their readings to local air quality on a given day. Those in urban environments might see the effects of smog and pollution. Those is more rural areas might see effects of vegetation fires, airborne dust, or agricultural work.[17] In either case, students could always be on the lookout for some event that may alter their local atmosphere (a volcanic eruption, forest fire, sand or dust storm, etc.), even those at a distant source, and see if their photometry data are sensitive to it. Ideally, data from a "very clear sky" day would always serve as a basis for comparison. The use of different colored LEDs (other than strictly red or blue, including UV and IR) is possible.

Acknowledgments
I thank the students of ASTR-101 at Cal Poly, taught during virtual instruction from Fall 2020 to Summer 2021, for their patience in running early versions of the activity presented here. I am also grateful to the two referees for many excellent suggestions that greatly strengthened the arguments presented in this article.

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2. J. Bennett et al., *The Cosmic Perspective,* 9th ed. (Addison-Wesley, 2019), Chap. 5. Hoboken.
3. C. C. Plummer et al., *Physical Geology*, 16th ed. (McGraw Hill, 2019), Chap. 23. New York.
4. P. G. Hewitt, *Conceptual Physics,* 13th ed. (Pearson, 2014), Chaps. 26–27. Hoboken.
5. L. A. Bloomfield, *How Things Work*, 5th ed. (Wiley, 2016), Chap. 13. New York.
6. F. M. Mims, "Sun photometer with light-emitting diodes as spectrally sensitive detectors," *Appl. Opt.* **31**, 6965–6967 (1992).
7. G. McIntosh, "A simple photometer to study skylight," *Phys. Teach*. **44**, 540–544 (2006).
8. As pointed out by a referee, the LED photocurrent generation via incident light is more complicated than our presentation here supposes. LEDs can generate a photocurrent from light that exceeds its band-gap energy, making LEDs behave more as high-pass optical filters, not strictly narrow band filters (see Ref. 1 contained in Ref. 6 of this paper). The (colored) plastic cases on an LED may also aid in filtering incoming light. We have two anecdotal responses to these important points. In other work (unpublished), we investigated LED response to incident light using a wavelength selector as a filter to broadband light incident upon the LED. We found a given LED's response negligible to wavelengths outside of a small region near its emission wavelength. We also tried the photometry experiment presented here using transparent colored plastic sheets as filters in front of a silicon photodiode. We were unable to produce a proper Langley plot with such, as the Langley analysis demands the capture of only *narrow* optical bands arriving from the Sun. Without discounting the referee's points, this supports the LED behavior as "enough" of a narrow band filter for work in sun photometry. Lastly, we found the transmission spectrum of the plastic filters to contain a large amount of infrared light ($\lambda > 750$ nm), definitely casting them as band-pass filters, undoubtedly affecting the LED response and polluting the Langley plot (plastic LED housings likely exhibit similar behavior).
9. See https://www.amazon.com/Neoteck-Multimeter-Portable-Transistor-Continuity/dp/B08S2PNPDQ/ and https://www.amazon.com/MCIGICM-Circuit-Assorted-Science-Experiment/dp/B07PG84V17/. Another voltmeter is https://www.harborfreight.com/7-function-digital-multimeter-63759.html. Any meter with a 200-µA setting will work.
10. We note an important contrast between Fig. 1 and $1/\sin(\alpha)$. The former is a cartoon used to illustrate atmospheric thickening due to the Sun's apparent motion. It has an obviously round atmospheric interface, while the $1/\sin(\alpha)$ term is "flat interface" approximation. Curve fits of our data using a round interface air-mass term had negligible effects on our fit results.
11. For finding the altitude of the Sun, we use https://gml.noaa.gov/grad/solcalc/. The student will have to know the latitude and longitude of their location and the time of day of each measurement. It is also possible to have students also measure the Sun's angle using a device like that found in Fig. 2 of Philip M. Sadler and Christopher Night, "Daytime celestial navigation for the novice," *Phys. Teach.* **48**, 197–199 (2010), which is a plumb bob and protractor.
12. We always find it surprising that a line results from two such highly nonlinear inputs.
13. Y. B. Acharya et al., "Compact light-emitting diode sun photometer for atmospheric optical depth measurements," *Appl. Opt*. **34**, 1209–1214 (1995).
14. MS-PS4-2, "Waves and their Applications in Technologies for Information Transfer," https://www.nextgenscience.org/pe/ms-ps4-2-waves-and-their-applications-technologies-information-transfer.
15. https://lightandcolorinnature.org.
16. As sunset approaches, there will be a time when the photocurrent from the blue LED will be zero, but not so for the red. Certainly some of this behavior is LED specific, but it also consistent with the expected coloring of a sunset.
17. M. Almaraz et al., "Extrapolation of point measurements and fertilizer-only emission factors cannot capture statewide soil NOx emissions," *Sci. Adv.* **4**, eaau7373 (2018).

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