A Simple Photometer to Study Skylight

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A simple photometer constructed from an LED and an op amp can be used to measure light in a number of physical situations. A variety of LEDs exist to investigate different wavelength ranges. Combined with an inexpensive transit, the LED photometer can be used to carry out skylight studies and atmospheric optical depth measurements. The activities described in this paper can help students understand why the sky is blue and introduce students to the basics of radiation scattering and planetary atmospheres.

Introduction

Sunlight and skylight are excellent resources for teaching electromagnetic theory and its application. (Sunlight is defined as light directly from the Sun, and skylight is the light scattered by the Earth's atmosphere.) These light sources are always present, always changing, and can be presented at various levels of mathematical and scientific sophistication. The measurement of sunlight[1] and skylight[2] provide examples useful for Earth science, meteorology, astronomy, and physics classes.

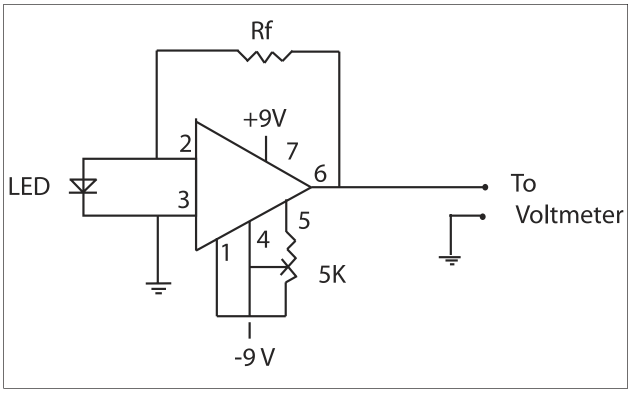

Fig. 1. The current-to-voltage converter circuit used in the photometer.

The blue color of the clear sky was explained in 1871 by Lord Rayleigh after decades of speculation as to its cause. (The color of the sky has been discussed previously in *The Physics Teacher*.[3]) As Rayleigh discovered, the sky is blue due to scattering by nitrogen and oxygen molecules in the air. The observed color is also affected by the solar spectrum and the physiology of human vision.[3]

Rayleigh's theory of scattering applies to molecules that are small compared to the wavelength of the light being scattered. Nitrogen and oxygen molecules are on the order of a fraction of a nanometer in diameter while visible light has a wavelength of 400 (violet) to 700 (red) nm. So Rayleigh scattering is applicable to scattering by the major constituents of the Earth's atmosphere. This theory predicts that radiation will be scattered according to the wavelength to the negative fourth power, λ^{-4}. Shorter visible wavelengths (blue or green in the measurements presented below) are scattered much more than the longer wavelengths (red in the measurements presented below). This scattering results in blue light dominating the skylight, although all wavelengths are scattered to some extent as the observations described below indicate. Rayleigh's initial description of light scattering was based on dimensional analysis arguments and provides motivation for students to understand and appreciate dimensional analysis.[4]

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Fig. 2. A picture of the apparatus. The transit was acquired from Nasco.[9]

Table I. LED Information.[8]

Name (diameter)	Nominal λ (nm)	Measured Emission λ (nm)
Super Red (5 mm)	660	614–671
Mega-brite Green (10 mm)	590	549–590

Particulate matter (aerosols) in the air can affect skylight intensity through scattering, modeled by Mie in 1908.[4] Mie scattering describes the light scattering by spherical particles of all sizes, including those larger than the wavelength of the light. Rayleigh scattering can be considered a subset of Mie scattering for particles with sizes small compared to the wavelengths of the light. One prediction of Mie scattering is that forward scattering is greater than backward scattering for aerosols. Mie scattering is more complicated than Rayleigh scattering and is generally affected by particle size and optical properties.

The Apparatus

The apparatus is based on using an LED in reverse.[5] The LED is used as a light detector with a limited bandwidth. An op-amp[6] circuit is used as a current-to-voltage converter with the LED as the current source. The output voltage of the op amp is proportional to the incident light intensity in a certain wavelength range. The LED is sensitive to the range of wavelengths emitted by the LED.[7] Table I gives information on the LEDs used. The circuit incorporated into the apparatus is shown in Fig. 1. Feedback resistors of 47,000 Ω were used to observe sunlight and several mega-ohms to observe skylight.

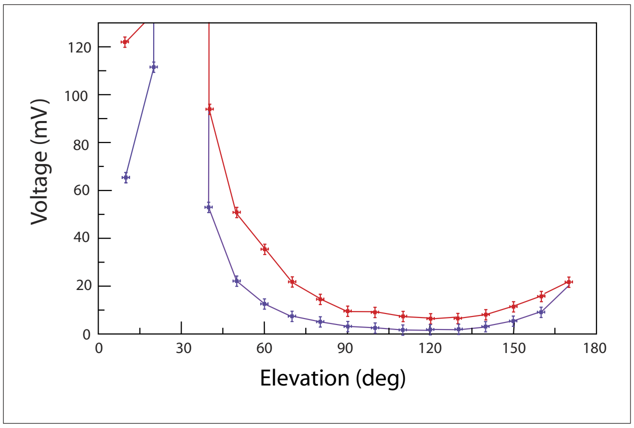

Fig. 3. Voltage proportional to the skylight intensity versus angle along solar vertical. The red line and data points indicate information from June 28, 2002. The black line and data points indicate information from July 22, 2002.

The complete apparatus is displayed in Fig. 2. The LED is secured in a cork and mounted in a pipe to limit the sky solid angle observed. The pipe is lined with black paper to reduce any internal reflections. The pipe has an inside diameter of 1.4 cm and is 20 cm long. These dimensions produce an observed solid angle of approximately 5×10^{-3} sr. The solid angle of the Sun is about 6×10^{-5} sr. The surface of the LED was lightly sanded to reduce the directionality of the component. The pipe is mounted in a transit in place of the usual telescope, and the azimuth and elevation of the sunlight or skylight measurement can be determined. A Styrofoam collar was placed around the pipe to aid in the solar alignment and in polarization measurements to be presented in the future.

A limitation to the accuracy and reproducibility of the LED measurements is the temperature dependence of their output. To minimize the effects of this temperature dependence, the end of the pipe containing the LED can be wrapped with insulation and aluminum foil. The measurements at a particular solar zenith angle should be made relatively rapidly to minimize the effect of direct sunlight on the LED temperature. Between measurements the apparatus should be directed away from the Sun.

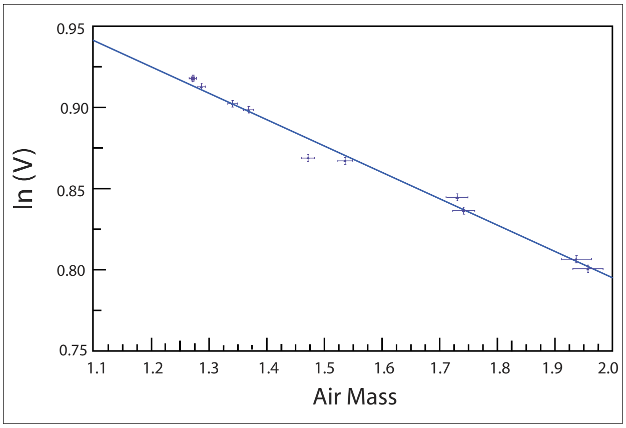

Fig. 4. The natural log of the voltage vs the airmass. The slope of the fit line is equal to the optical depth of one air mass in the red range of the visible spectrum.

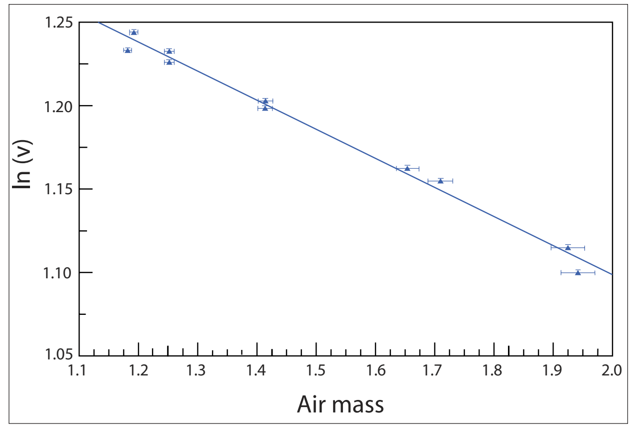

Fig. 5. The same as Fig. 4. for the green range of the spectrum.

Skylight Intensity

The intensity of skylight varies along the solar vertical. (The solar vertical is part of the great circle from the horizon through the Sun and zenith to the opposite horizon.) Naked-eye observations of a clear blue sky will indicate that skylight is brighter and whiter near the horizon and darker and bluer across the zenith from the Sun. Multiple scatters increase the brightness of the sky near the horizon where one sees the effects of a long path length for light through the atmosphere. The darker, bluer sky across the zenith from the Sun indicates that fewer scatters occur in that direction. Near the direction toward the Sun, forward Mie scattering by aerosols generates a bright region. If the aerosol load of the atmosphere increases, the aureole will increase in size and the sky will generally appear brighter in all directions since more wavelength independent scattering is occurring. These qualitative observations can be measured using the apparatus described above.

Figure 3 shows the relative intensity variations measured from the horizon nearer to the Sun for June 28, 2002, at 8:05 a.m. and July 22, 2002, at 8:38 a.m. These measurements were made using the red LED. June 28, 2002, was a clear but hazy day with winds from the southwest. Smoke from forest fires in Colorado in the early summer of 2002 probably contributed to the haze and aerosol load of the atmosphere on this day. July 22, 2002, was a clearer day following the passage of a cold front from the northwest. Notice on both days that the minimum in the sky intensity is approximately 90° away from the Sun. The clearer day exhibited less scatter, is darker at 90° from the Sun, and has a smaller aureole around the Sun. The aureole is produced by the forward scattering from aerosols. The Sun's elevation was 23° for the June 28, 2002, observations and 27° for the July 22, 2002, observations. The voltage measurements near the Sun's elevation are off the graph of Fig. 3.

Atmospheric Optical Depth

Optical depth is a quantity often referred to in physics, optics, and astronomy courses. It describes the attenuation of a beam of light as it passes through a medium. An optical depth of one indicates that the beam has been reduced by $1/e$ of its original intensity. The optical depth of the Earth's atmosphere can be determined and shown to be a function of the wavelength of the incident light.

The photometer described can carry out a measurement of the atmospheric optical depth. When directed at the Sun the voltage measured by the photometer is proportional to the solar intensity. So the voltage can be described by the Beer-Lambert law[7]:

$$V = V_0 e^{-\tau_\lambda m} \tag{1}$$

or

$$\ln V = -\tau_\lambda m + \ln V_0, \tag{2}$$

where V_0 is proportional to the solar radiation intensity at the top of the atmosphere, τ_λ is the optical depth as a function of wavelength for a vertically traveling incident beam, and *m* is the air mass. The air mass is the ratio of the depth of atmosphere through which the beam travels in order to reach the photometer to the depth of one atmosphere. For the approximation of a plane parallel atmosphere, the air mass is one over the sine of the elevation angle. Above an elevation of 30° (air mass of 2), the error associated with assuming a plane parallel atmosphere is less than 0.1% and has been neglected. In Fig. 4 and Fig. 5 the natural logarithm of the voltage output for red and green LEDs is plotted against the air mass for July 1, 2005. (The error bars presented are associated with reading the elevation and voltage. Most of the error probably arises from slight misalignments of the photometer with the Sun. Further sanding of the LED surface might reduce errors associated with the alignment.) The fit value for τ_{red} is 0.146 ± 0.006 and for τ_{green} is 0.174 ± 0.006. These values of optical depth are consistent with those found in the literature.

This result supports the assumption of Rayleigh scattering and provides a measurement to demonstrate why the sky is blue. The optical depth for green light is larger than the optical depth for red light. The shorter wavelength experiences a larger optical depth, indicating a shorter distance traveled between scatters. Attenuation can also affect the optical depth but is neglected in considering Rayleigh scattering.

The total optical depth τ for clear skies includes several terms:

$$\tau = \tau_R + \tau_A + \tau_g, \tag{3}$$

where the subscripts represent Rayleigh scattering, absorption by aerosols, and absorption due to various other gases in the atmosphere including ozone.[10]

Since light scattering depends on particle size, it is possible to measure the atmospheric optical depths at various wavelengths and use the measurements to determine the particulate size distribution.[11] Further analysis can be carried out on the measurements described in this paper. The values for the optical depths due to Rayleigh scattering and other gases have been tabulated[4] and modeled[12] and can be removed from the measurement. The remaining optical depth is dependent on the aerosol load. This calculation of aerosol optical depth is more sophisticated than determining the total optical depth but is important in determining the aerosol load of the atmosphere.

Discussion

The measurements and results described above can be used as an example of a planetary atmosphere. Discussions of the skylight of other bodies can follow. For example, the Moon's sky will be very dark because the extremely low density atmosphere will not scatter sunlight. Venus' sky, at some elevation, will be bright from multiple scatterings. At the surface the sky may be fairly dark due to absorption of light by the dense atmosphere.

The optical depth measurements also clearly indicate why stellar photometry requires a nearby calibration star in order for the light from both stars to travel through nearly the same optical depth to the observer.

The optical depth measurements provide a measurement proportional to the intensity of sunlight at the top of the Earth's atmosphere, V_0 in Eq. (1) and Eq. (2). The solar intensity should vary by about 4% as the Earth goes around the Sun in its elliptical orbit. Accurate observations over the course of a year should provide a measurement of the fractional variation in the solar intensity due to the changing distance of the Earth from the Sun.

Atmospheric aerosols play a role in the energy budget of the planet. For example, see section 7 of *The World Meteorological Organization/Global Atmosphere Watch Report 153*[10] or Chapter 5 of *Climate Change 2001: The Scientific Basis*.[13] These publications discuss the measurement procedures and importance of aerosol optical depth measurements on the Earth's radiation budget.

Acknowledgment

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References

1. G.E. Shaw, "Sun photometry," *Bull. Am. Meteor. Soc.* **64**, 4–10 (1983).
2. *Scattering in the Atmosphere,* edited by C. Bohren (SPIE Press, Bellingham, WA, 1989). This reference includes many interesting articles on atmospheric optics.

3. C. Bohren and A.B. Fraser, "Colors of the sky," *Phys. Teach*. **5**, 267–272 (May 1985).
4. K.L. Coulson, *Polarization and Intensity of Light in the Atmosphere* (A. Deepak Publishing, Hampton, VA, 1988).
5. F.M. Mims III, *Engineer's Mini-Notebook Environmental Projects* (Siliconcepts, USA, 1995).
6. A National Semiconductor LF411CN was used in the circuit.
7. Y.B. Acharya, A. Jayaraman, S. Ramachandran, and B.H. Subbaraya, "Compact light-emitting-diode sun photometer for atmospheric optical depth measurements," *Appl. Opt*. **34**, 1209–1214 (1995).
8. The LEDs were purchased from Digikey Corp. and are manufactured by Lumex. Lumex part numbers Super Red SSL-LX5093SRC/E and Mega-brite Green SSL-LX100133XGC.
9. Nasco can be contacted at custserv@eNASCO.com.
10. http://www.wmo.ch/web/arep/reports/gaw153.pdf.
11. M.D. King, D.M. Byrne, B.M. Herman, and J.A. Reagan, "Aerosol size distribution obtained by inversion of spectral optical depth measurements," *J. Atmos. Sci.* **35**, 2153–2167 (1978). For the earliest discussion of such a procedure, see A. Angstrom, "On the atmospheric transmission of Sun radiation and on dust in the air," *Geograf. Ann.* **12**, 130–159 (1929). This article is reprinted in Ref. 2.
12. See, for example, A.S. Zakey, M.M. Abdelwahab, and P.A. Makar, "Atmospheric turbidity over Egypt," *Atmos. Environ*. **38**, 1579–1591 (2004) and the references therein.
13. http://www.pnl.gov/aisu/pubs/eemw/papers/ipccreports/workinggroup1/index.htm.

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