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A 5-Year Study of a New Kind of Photosynthetically Active Radiation Sensor¶*

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ABSTRACT

Light-emitting diodes (LED), which are designed as quasi-monochromatic light sources, can also function as spectrally selective photodiodes. This provides a new kind of photosynthetically active radiation (PAR) sensor that is inexpensive and has much better stability over time than interference filters used in some PAR sensors. The action spectrum of photosynthesis in green plants has principle peaks in the blue and red regions. LED with response peaks in the UV-A (380 nm) and red (620 nm) regions have been used to measure PAR at or near solar noon in an ongoing study begun on 30 April 1996. The sum of the signals from the two LED is highly correlated with measurements by a calibrated filterless PAR sensor (Apogee QSO; Logan, Utah) from 13 September 1997 to 16 January 2002 (r^2 = 0.97). The sum of the LED signals is also highly correlated with measurements by a calibrated filter PAR sensor (LI-COR LI-190SA; Lincoln, Nebraska) from 20 April 1998 to 16 January 2002 (r^2 = 0.97). Thus, pairs of spectrally selective LED can function as PAR detectors in economical PAR radiometers. The separate 380 and 620 nm responses also permit an assessment of the differential impact of aerosol events on blue and red PAR and phototropic radiation.

INTRODUCTION

The photosynthetically active radiation (PAR) is the range of light wavelengths that stimulates photosynthesis in green plants (1). The principle photosynthetic pigments are chlorophyll *a* and chlorophyll *b*. Carotenes and phycobilins participate to a lesser extent. Chlorophylls have action spectra with two peaks, one in the blue and a second in the red. The peak of the action spectrum for carotenes and phycobilins is in the green and orange regions, respectively. The peaks of the action spectra for all these pigments are between 400 and 700 nm. This range of wavelengths defines what has become the principle definition of PAR. The magnitude of PAR over the range of 400–700 nm is defined as the photosynthetic photon flux (PPF) and is specified in terms of moles per square meter per second.

The ideal PPF sensor responds equally to all wavelengths between 400 and 700 nm. The action spectrum for the overall photoresponse of plants, however, extends below 400 nm and beyond 700 nm, and there is a significant minimum in the green region. Moreover, there are important differences in the photosynthetic efficiency of the various wavelengths. Thus, the spectral response of the ideal PPF sensor does not perfectly match the photosynthetic response of a green leaf. An alternative sensor for measuring PAR has a response that is reasonably proportional to the action spectrum of chlorophyll from 360 to 760 nm. This sensor measures PAR in terms of yield photon flux (YPF) in the same units as PPF (moles per square meter per second).

Various PPF and YPF sensors are commercially available. Most incorporate one or more optical filters placed over a silicon photodiode. Barnes *et al*. (2) evaluated the spectral response of several PAR sensors and found that none perfectly match the specified quantum response. It would be very difficult and expensive to perfectly duplicate the square-shaped 400–700 nm PPF-response spectrum. It would be similarly difficult to perfectly match the undulating curve that defines the 360–760 nm YPF spectral response. Nevertheless, when calibrated for sunlight or specific artificial light sources, commercial PAR sensors are widely used and are generally considered an acceptable, economical substitute for expensive spectroradiometers that provide a more precise measurement of PAR.

The new kind of very inexpensive PAR sensor described in this study has a similar potential. This sensor uses a pair of blue and red light-emitting diodes (LED) connected as spectrally selective photodiodes that respond near the peaks of the PAR action spectrum without the need for optical filters. The sum of the LED photocurrents is proportional to PAR. A dual-wavelength sensor also permits the differential effects of aerosol events on the UV-A and red wavelengths in sunlight to be monitored. This differential response is important because the blue wavelengths are scattered more by haze and by smoke than are the red wavelengths.

LED used as spectrally selective detectors in various Sun photometers (3) have been tested at Geronimo Creek Observatory, Seguin, TX (29.6N, 97.9W), since February 1990. These studies and annual calibration tests at Mauna Loa Observatory, Hawaii, confirm that LED used as sunlight sensors have excellent long-term stability (4). For example, the total column water vapor has been measured at this site since February 1990 by means of two very stable, near-infrared LED, one of which detects within the 935 nm water vapor absorption band (5).

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Abbreviations: AlGaAs, aluminum gallium arsenide; FWHM, full width, half maximum; GaN, gallium nitride; GaP, gallium phosphide; LED, light-emitting diode; PAR, photosynthetically active radiation; PPF, photosynthetic photon flux; SiC, silicon carbide; YPF, yield photon flux.
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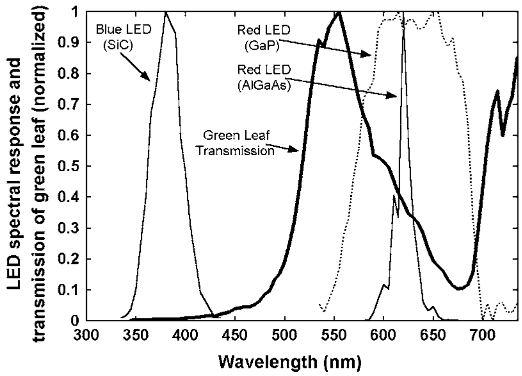

Figure 1. Spectral response of several LED connected as spectrally selective detectors superimposed over the absorption of a green poinsettia leaf (*Euphorbia pulcherima*). All the curves are normalized to enhance their visual clarity.

The Langley calibration method is used to determine the extraterrestrial constant (Io) of a Sun photometer, the signal that would be provided by the instrument if it could be pointed at the Sun from the top of the atmosphere. Annual Langley calibrations from 1996 to 1999 of a microprocessor-controlled Sun photometer with five separate LED sensors show negligible changes in the value of the extraterrestrial constant of all channels. The coefficients of variation (Io(std dev)/Io(mean)) for the 376, 520, and 680 nm channels are 0.0027, 0.0004, and 0.0011, respectively. The calibration of some filter instruments varies considerably more than LED instruments. For example, the Io of a filter Sun photometer used during a research study from 1986 to 1990 declined to only 12.7% of its initial value (6). The degradation of interference filters is unpredictable and can be caused by solarization during prolonged exposure to sunlight and by water vapor.

MATERIALS AND METHODS

Radiometer design. The design of a simple solar radiometer that uses LED as spectrally selective detectors is described elsewhere (7). Mims (7) also described and illustrated the mechanical design of the LED sensor housing and diffuser and suggests using this instrument to measure PAR and phototropic radiation, but the spectral response of the LED and a comparison with a commercial PAR sensor are not provided. The electronic circuit of the radiometer consists of a high-gain, high-input impedance operational amplifier connected as a transimpedance (photocurrent to voltage) amplifier. Selectable feedback resistors provide several gain settings. The same gain setting is used for all measurements made using a particular LED sensor. The amplified signal is displayed on a liquid-crystal readout. The circuit is powered by a miniature 7 V battery that lasts more than a year in normal use. The instrument is housed in a small enclosure equipped with two phone jacks that can receive various LED sensors. The sensors are machined aluminum cylinders in which individual LED soldered to miniature phone plugs are installed. Machined Teflon® (DuPont, Wilmington, DE) diffuser caps are snapped over the end of each sensor to enhance their cosine response. The diffusing portion of these caps is flat and 1 mm thick.

LED spectral response. The spectral response of the LED was measured by projecting upon the diffuser the beam of a standard lamp (LI-COR 1800-02 Optical Radiation Calibrator; Lincoln, NE) through a manually tuned spectrometer having a resolution of 1 nm (Optronics DMC1-02; Ayer, MA). Independent laboratory spectral response measurements conducted by Donald Heath confirmed the response curves of blue, red and green LED measured with the manual spectrometer.

Figure 1 shows the spectral response of several LED superimposed over the spectral transmission of a green leaf from poinsettia (*Euphorbia pulcherima*). The leaf transmission was measured by placing a cosine response probe of an optical fiber spectrometer (Ocean Optics USB 2000; Dunedin, FL) on the ventral surface of the leaf, which was placed normal to the Sun and the surrounding clear sky. The blue silicon carbide (SiC) LED has a peak spectral response of 380 nm and a band pass of 38 nm at the full-width, half-maximum points (FWHM). This is near one of the UV-A peaks of the phototropic action spectrum and below that of the blue peak of PAR. The red aluminum gallium arsenide (AlGaAs) LED has a narrow spectral response that peaks within the red portion of the PAR absorption band at 620 nm (10 nm FWHM). A much better match to red PAR is provided by a red gallium phosphide (GaP) LED, which has a nearly flat response between 600 and 655 nm (115 nm FWHM) and has a much broader response spectrum than the AlGaAs LED. The GaP LED, however, is more temperature sensitive and was not used in the long-term study. Although the spectral responses of the LED do not provide a perfect match to the principle blue and red PAR bands, the results demonstrate that they are sufficiently close to provide acceptable results. This is because there is relatively little disproportionate change in spectral irradiance caused by atmospheric gaseous absorption and by scattering and absorption by aerosols between the peak spectral responses of the LED and the ideal PAR spectrum.

LED temperature response. The temperature sensitivity characteristics of a green LED operated as a Sun photometer photodetector is <0.003 V/°C (8). This is equivalent to about +0.45%/°C. For this work, the temperature coefficients of SiC blue and AlGaAs red LED similar to those used in the PAR sensor were tested by exposing the LED to a standard lamp while warming the LED from 13°C to 38°C. The temperature coefficient (T_c) for the SiC blue LED is a nearly flat −0.03%/°C. This is because of the very broadband gap of this material. Gallium nitride (GaN) blue LED have a higher temperature coefficient. The T_c for the AlGaAs red LED in the present study is very high, +1.03%/°C. This error is minimized by keeping the instrument at room temperature or in an insulated container before use. This means that the present configuration of the instrument is not suitable for continuous outdoor monitoring. For this purpose, a temperature sensor can be installed within the sensor housing so that the error can be corrected.

Alternatively, the LED sensors can be maintained at a constant temperature. This method has been successfully tested in this study by installing a single red LED as the seventh channel in an automated, seven-channel multifilter shadowband radiometer (Yankee Environmental Systems MFR-7; Turners Falls, MA). This instrument records and saves in a computer observations of the total sky irradiance, the diffuse radiation from the sky and the direct Sun irradiance four times each minute. The instrument was placed in service in September 1999. From October 1999 to October 2001, the drift of the extraterrestrial constant (the inferred signal at zero air mass determined by the Langley calibration method) of the LED was an insignificant +0.01%. The drift of the extraterrestrial constant of the six photodiode–filter pairs ranged from −0.55% (870 nm) to −2.60% (415 nm). Because of the negligible drift of the LED compared with the filters, the radiometer was returned to the manufacturer in March 2002, and all six photodiode–filter pairs were replaced with various LED, including those suitable for continuous PAR and column water vapor monitoring. The instrument was taken to Mauna Loa Observatory, Hawaii, in July 2002 for comparison with various standard instruments. It was then returned to Geronimo Creek Observatory for a long-term test.

LED cosine response. The cosine response of various LED sensors was determined by exposing them to a beam from a high-intensity quartz-halogen illuminator (Dolan-Jenner Industries Fiber-Lite®; Lawrence, MA). Each sensor was rotated in discrete steps while its angle was recorded with respect to the light and its output signal. The signal was then plotted as a function of the angle. Figure 2 shows the cosine response of the original blue and red LED sensors assembled in 1996. The red response is significantly better than the blue response. Because an identical sensor and diffuser assembly provide nearly perfect cosine response when used with a UV detector and a green LED, it is expected that changing the placement, and possibly the geometry, of the blue and red LED will improve their cosine response.

Measurement procedure. Figure 3 shows two LED sensors installed on the radiometer. Measurements are made each day at or near local solar noon when the solar disk is not obscured by clouds. To minimize temperature effects, the radiometer and LED sensors are stored in a closed container placed under a shaded area before use. Measurements are made by placing the radiometer on a level platform 175 cm above an open grass field. Two measurements are made of each channel; first the full sky and then the diffuse sky. The latter measurement is made when the diffuser of the sensor is shaded by a 19 mm diameter disk mounted on a rod.

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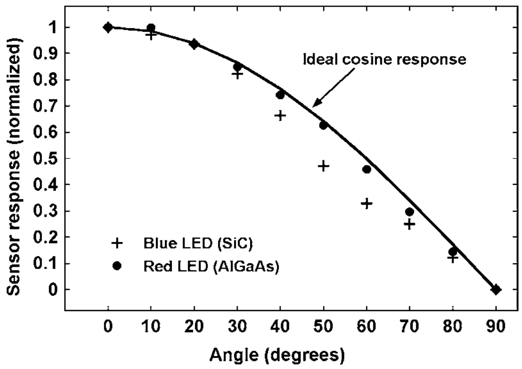

Figure 2. Cosine response of blue and red LED sensors plotted together with the ideal cosine response. The cosine response of a green LED sensor (not shown) nearly matches the ideal response, which suggests that the response of the red and blue sensors can be improved.

RESULTS

Figure 4 is a time series of solar noon measurements made with the blue and red LED sensors and a commercial PAR sensor (LI-COR L1-90SA). Although an empirical calibration can be transferred from the PAR sensor to the LED sensors, in Fig. 4 the sum of the signals from the two LED is plotted instead. This allows subtle corrections to be entered into a single spreadsheet cell for either or both the blue and the red LED voltages in order to quickly determine if they improve the ability of the LED to track the PAR sensor with time. Thus, the correction factor is empirically derived from a comparison with the LI-COR PAR detector. Although the simple empirical summing formula applied in Fig. 4 (PAR ≈ (2 × blue voltage) + red voltage) is provisional and subject to improvement, it tracks the commercial PAR sensor quite well. This is affirmed by the comparison in Fig. 5, a scatter plot of all solar noon data from the PAR sensor and the blue–red LED pair from 20 April 1998 to 16 January 2002.

Measurements were made at or near solar noon on 586 days, and the resulting correlation coefficient (r^2) is 0.97. The sum of the signals from the two LED is also highly correlated with 641 solar noon measurements by a calibrated filterless PAR sensor (Apogee)

Figure 3. Blue and red LED sensors inserted into the simple, economical digital radiometer used in this study since April 1996.

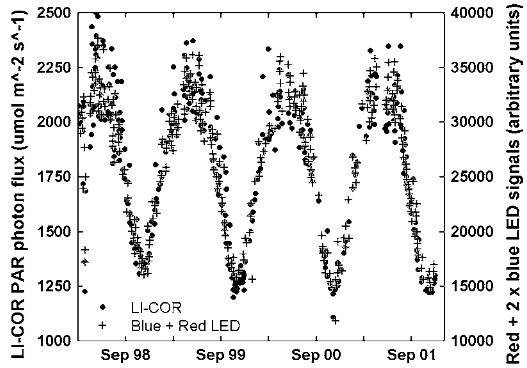

Figure 4. Time series of solar noon observations of PAR measured by a commercial sensor (LI-COR 190SA) and by a blue–red LED pair from 20 April 1998 to 16 January 2002.

from 13 September 1997 to 16 January 2002 ($r^2 = 0.97$). The signal from the red LED alone is also highly correlated with the signal from both commercial PAR sensors ($r^2 = 0.97$). This effect was anticipated in advance and formed the basis for the design of a miniature PAR data logger that I developed for use in Brazil during a 1997 field study of the atmospheric effects of massive smoke pollution during the annual burning season. This sensor used the broadband GaP LED that provides the wide spectral response shown in Fig. 1. It proved especially important to a study in Brazil of the growth of wheat and corn seedlings, a topic to be discussed in a paper in preparation.

DISCUSSION

Figures 4 and 5 are persuasive evidence that an inexpensive pair of LED can function as an effective PAR sensor in natural sunlight. These results give confidence that the measurement series can be extended back to 30 April 1996, when the LED measurements were begun without benefit of a calibrated PAR sensor to check their accuracy. This provides a time series of 5.8 years (69 months).

Yet, the LED results could be better, as demonstrated by the fact that measurements with the two commercial PAR sensors used in this study are better correlated with one another ($r^2 = 0.99$) than either is with the dual-LED sensor ($r^2 = 0.97$). If the LED cosine error is primarily responsible, one would expect more scatter in the lower levels of PAR that occur during winter when the solar zenith

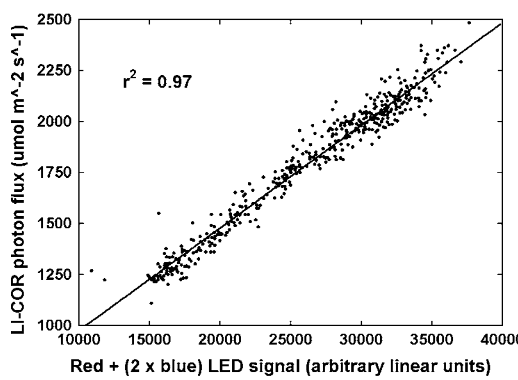

Figure 5. Scatter plot comparing PAR measured by a calibrated commercial sensor (LI-COR 190SA) and a pair of blue and red LED from 20 April 1998 to 16 January 2002.

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angle is high. Nevertheless, a new sensor with an improved cosine response is being designed. The new instrument will include a temperature sensor, so that temperature errors can be corrected. Meanwhile, the radiometer and current LED sensors will continue to be stored in a closed container placed under a shaded area until shortly before they are used.

The spectral response of a two-wavelength LED PAR sensor more closely resembles a YPF sensor than a PPF sensor. A significant advantage of this response and the measurement of PAR using independent blue and red sensors is that this provides a means for better understanding and quantifying the disproportionate reduction of blue light with respect to red and far-red wavelengths that is caused by scattering and absorption during significant haze, dust and smoke events. Another advantage is that separate LED detectors provide a simple means for investigating phototropic- and red-response wavelengths of plants in various environments, as under and within forest canopies. These advantages are highlighted by measurements made in this study at Geronimo Creek Observatory during the summer of 1995 that show that diffuse subcanopy irradiation in the blue is higher on hazier days than on days with little haze. This could have an effect on the phototropic response of subcanopy vegetation during the extended hazy periods that occur during invasions of smoke from Central America during spring and the arrival of sulfur dioxide haze during spring and summer. This phenomenon would not have been detected with a conventional PAR detector.

The multiple detector concept can be expanded to include an AlGaAs near-infrared LED, which emits at 880 nm and detects at 820 nm, that can be added to serve as a far-red sensor. Other LED can also provide important spectral response bands. For example, an AlGaAs LED that emits at 850 nm has a peak spectral response of 680 nm (14 nm FWHM), which almost matches the chlorophyll red absorption peak. One reason the emission wavelength of the LED is higher than its detection wavelength is because the forward-biased flow of current causes the heating of the diode's pn junction.

Changes in LED technology have caused the compositional chemistries of the semiconductor chips used in some previously important LED to become obsolete. SiC LED, for example, were the first commercial blue LED. They have been replaced by GaN and related chemistries that provide much brighter blue LED. The spectral response of these and various other newer LED that might be suitable for detecting PAR has been examined. For example, a GaN blue LED measured by Donald Heath in support of this work has a narrow detection peak at 370 nm (9 nm FWHM), with a broad shoulder extending to 475 nm (90 nm FWHM). This LED can be used with an inexpensive plastic film UV-A absorption filter to provide a reasonably close match to the blue PAR band. Alternatively, the blue shoulder can be blocked with a cutoff filter to provide good response in the UV-A phototropic region.

CONCLUSIONS

An ongoing multiyear comparison of solar noon measurements using two commercial PAR sensors and a pair of inexpensive blue and red LED shows that the LED sensor yields results that are well correlated ($r^2 = 0.97$) with the PAR sensors. Moreover, the LED sensor provides far better stability over time than the interference filters used in some PAR detectors. Thus, spectrally selective LED provide suitable detectors for economical PAR radiometers and Sun photometers for use by students and horticulturists. The two-channel LED PAR sensor also permits the differential effects of aerosols on blue and red PAR to be separated and analyzed. The principle drawback of LED as PAR sensors is that their temperature coefficient (up to $\sim$1%/°C) is higher than that of silicon photodiodes. This is not a serious objection when the LED sensor is used over a modest temperature range. For continuous outdoor use, however, the LED PAR sensor requires temperature regulation or temperature data logging and a subsequent correction.

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