Directional Response of Apogee and Active Eye/Hydrofarm Quantum Sensors: Impact on PAR Measurements

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Radiometer Directional Response

Directional response, often called angular response or cosine response, is the response of a radiometer to radiation incident at different angles. Ideally, a radiometer designed with a hemispherical, or 180°, field of view should accurately measure radiation emanating from the hemisphere above the radiometer at any angle of incidence. Lambert's cosine law states that radiant intensity is directly proportional to the cosine of the angle between the incident radiation beam and a plane perpendicular to the receiving surface. A radiometer that accurately measures radiation according to Lambert's cosine law is said to be cosine-corrected. In other words, a cosine-corrected radiometer measures accurately at all incidence angles, and perfect cosine correction is zero directional error at all incidence angles. Radiometer directional error is often called cosine error. Directional error in radiation measurements results from imperfect cosine correction of the radiometer.

Radiometer directional response must be considered when measuring the sun in applications where hourly or higher frequency data are required because the sun changes position relative to the radiometer over the course of a day. A radiometer with poor directional response may provide accurate measurements in the middle of the day when the solar zenith angle is low (when the sun is high in the sky and the angle of radiation incident on the radiometer is low), but directional errors may result in large measurement errors when solar zenith angles are higher earlier or later in the day (when the sun is low in the sky and the angle of radiation incident on the radiometer is high). Directional errors can also be significant at higher latitudes in winter when solar zenith angles are high throughout the day. In addition, a radiometer with poor directional response may provide inaccurate measurements when a large proportion of solar radiation is diffuse (for example, in cloudy conditions), resulting in a large proportion of high angle radiation incident on the radiometer.

As with solar measurements, radiometer directional response must be considered when measuring electric lights. A radiometer with poor directional response may provide accurate measurements when it is used in settings where there is a large proportion of low angle radiation incident on the radiometer (for example, positioning a radiometer directly below high pressure sodium or metal halide lamps). However, the measurement may be inaccurate if the radiometer is positioned some distance away from directly below the lamp because there will be a larger proportion of high angle radiation incident on the radiometer. In addition, some electric lights output a high proportion of diffuse radiation (for example, cool white fluorescent tubes), resulting in a large proportion of high angle radiation incident on the radiometer.

There are multiple models of quantum sensors available for measuring photosynthetically active radiation (PAR), the subset of shortwave radiation that drives photosynthesis. PAR is almost universally defined and quantified as photosynthetic photon flux density (PPFD), the sum of photons between 400 and 700 nm in units of micromoles per square meter of area per second [μmol m^{-2} s^{-1}]. Two easy-to-use, handheld models with digital displays that are often used in greenhouses and growth chambers are the Apogee model MQ-500 and Active Eye/Hydrofarm LGBQM quantum PAR meter. The purpose of this work is to: 1. measure the directional response of these two quantum meters, and 2. determine the impact of directional response on PPFD measurements with these quantum meters under multiple radiation sources commonly used for plant lighting.

Measurement of Directional Response

Directional response is often specified as deviation from true cosine response, where a radiation beam of known intensity is used to determine radiometer directional response in the laboratory. True cosine response is beam intensity at a zenith angle of zero multiplied by the cosine of the angle between the direct beam and radiometer. Another method of determining directional response is to compare solar radiation measurements on a clear day against reference solar radiation measurements, which must be assumed to represent 'true values'.

Directional responses of six replicate Apogee SQ-500 quantum sensors (the SQ-500 is the radiometer component of the Apogee MQ-500 quantum meter) and two replicate Active Eye/Hydrofarm LGBQM quantum PAR meters (hereafter referred to as the LGBQM) were determined on a clear summer day in Logan, Utah, by direct comparison to PPFD calculated from global solar (shortwave) irradiance (SW_i, in units of W m^{-2}) measurements from five secondary standard pyranometers. Mean SW_i was calculated from the pyranometers and used to calculate PPFD from a model:

$$\mathrm{PPFD} = \mathrm{SW_i}\frac{\mathrm{PAR/SW_i}}{\mathrm{E_{Content}}} \qquad \text{(Equation 1)}$$

where PAR / SW_i is the fraction of photosynthetically active radiation in SW_i (here PAR is the sum of solar irradiance from 400 to 700 nm, thus the units are W m^{-2} and PAR / SW_i is a unitless ratio) and $E_{Content}$ is the average energy content of photons in the photosynthetically active range (in units of J μmol^{-1}). Both PAR / SW_i and $E_{Content}$ are dependent on the solar spectrum, which varies with solar zenith angle and atmospheric conditions (for example, degree of cloudiness, water vapor content). Detailed measurements of both of these variables have been made under clear sky and cloudy conditions in Logan, Utah, using reference quantum sensors (Kipp & Zonen model PQS 1 and LI-COR model LI-190R), secondary standard pyranometers, and a spectroradiometer (Advanced Spectral Designs model FieldSpec Pro). For more detail on PPFD estimation from Equation 1, see Blonquist and Bugbee (2018).

To provide an additional data set and verify the directional response measurements under sunlight, directional response of the SQ-500 sensors and LGBQM meters relative to LI-COR LI-190R quantum sensors was measured in the laboratory. PPFD measurements from the six SQ-500 sensors and two LGBQM meters were compared to mean PPFD from two LI-190R quantum sensors underneath a high pressure sodium lamp. The sensors were positioned directly below the lamp, with a distance of 1.0 meter between the lamp and sensors, and then moved away from directly below the lamp at increasingly larger distances to yield higher incidence angles. Measurements were made at positions where the zenith angle of the lamp with respect to the sensors was 0°, 15°, 30°, 45°, and 60°. Measurements were not made beyond an angle of 60° because radiation intensity beyond 60° was minimal. It should be noted, the LGBQM meters were unstable under the high pressure sodium lamp and other electric lights measured in this study. A more complete description of this instability is detailed below. In an attempt to mitigate the instability, multiple measurements were made under all electric lights, data were averaged, and the mean value was used for comparison.

Mean directional response derived under sunlight, where PPFD from Equation 1 was used as the reference, from the SQ-500 quantum sensors was within about 2 % for zenith angles between 20° and 60° and within about 5 % for zenith angles between 60° and 80° (Figure 1). Mean directional response under sunlight from the LGBQM meters indicates large directional errors across the entire range of solar zenith angles (Figure 1), with directional response near -10 % or lower for all angles greater than 30°. Mean directional responses for SQ-500 sensors and LGBQM meters derived under the high pressure sodium lamp (mean PPFD from two LI-COR LI-190R quantum sensors was used as the reference) were similar to those derived under sunlight (Figure 1). The -7 % mean error from the LGBQM meters at the lowest solar zenith angle of 23° suggests the meters may not be calibrated accurately (when compared to reference PPFD calculated from Equation 1), but when directional response data from sunlight were combined with directional response data from the high pressure sodium lamp (mean PPFD from two LI-COR LI-190R quantum sensors was used as the reference) LGBQM meters were accurate within about 5 % for zenith angles between 0° and 20° (Figure 1). Error increased rapidly at higher zenith angles, reaching -10 % at 30° and about -20 % at 60°. Mean directional response from the SQ-500 sensors under the high pressure sodium lamp was within about 2 % for a zenith angle range of 0° to 60°.

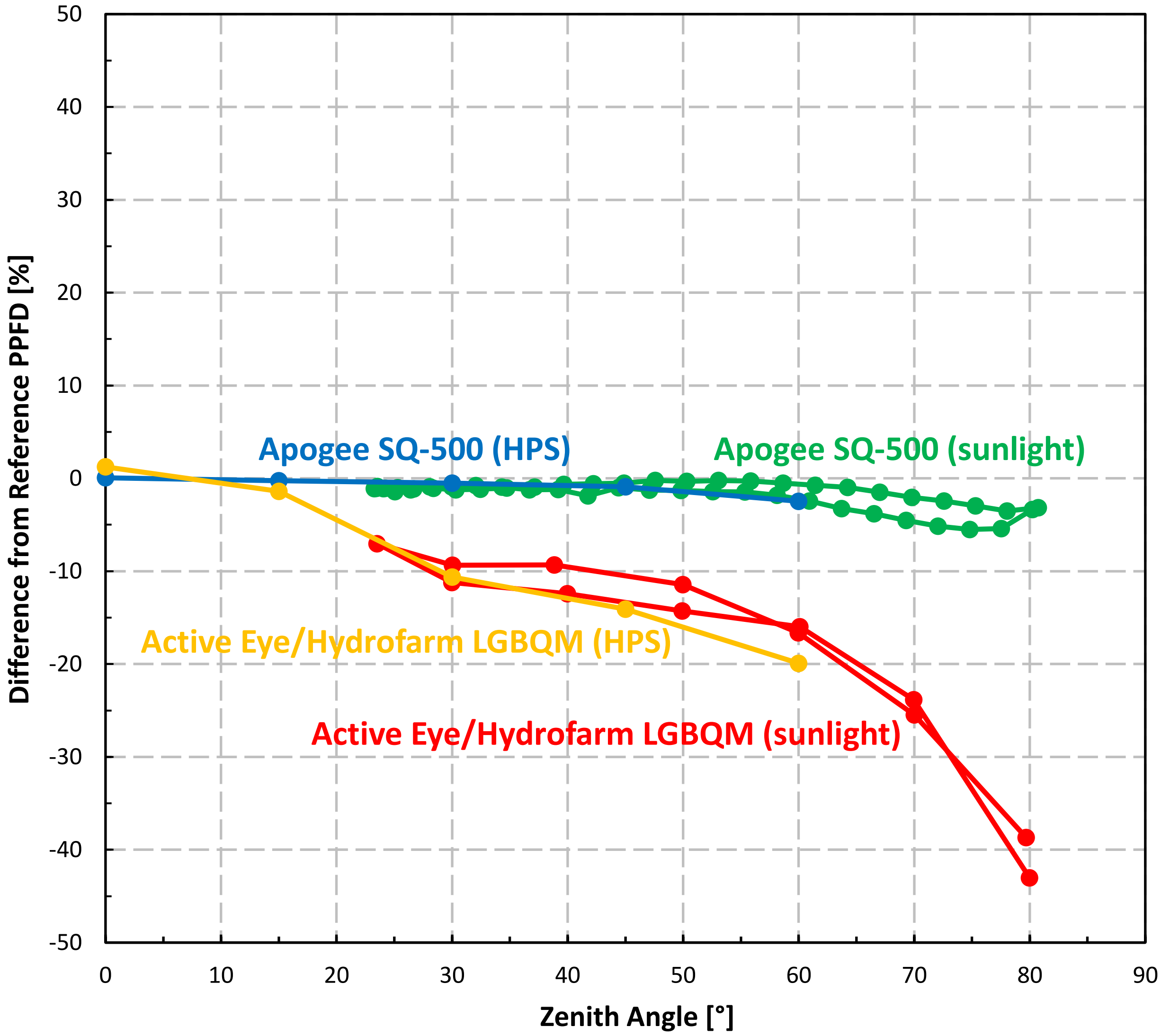

Figure 1: Mean directional response calculated from six replicate Apogee SQ-500 quantum sensors and two replicate ActiveEye/Hydrofarm LGBQM quantum PAR meters. Reference PPFD under sunlight was calculated from Equation 1 using mean global solar irradiance calculated from five secondary standard pyranometers. The two lines for sunlight measurements are AM and PM responses. Reference PPFD under a high pressure sodium (HPS) lamp was mean PPFD calculated from two LI-COR LI-190R quantum sensors. Directional response data from two independent sources match for the SQ-500 and LGBQM.

Impact of Directional Response on Photosynthetically Active Radiation (PAR) Measurements

Directional response data (Figure 1) suggest Apogee SQ-500 series quantum sensors and MQ-500 quantum meters, which include the SQ-500, will measure accurately under radiation sources with nearly any distribution of angles, but Active Eye/Hydrofarm LGBQM meters will only measure accurately under radiation sources with a large proportion of low angle radiation incident on the radiometer (for example, directly underneath a high pressure sodium lamp). To verify this, measurements from each model were compared to the mean of measurements from two LI-COR model LI-190R quantum sensors. Data were collected for the same six replicate SQ-500 sensors and same two replicate LGBQM meters tested under sunlight. Mean relative differences (in percent) from the mean of the LI-190R sensors were then calculated (Table 1).

SQ-500 sensors matched the LI-COR LI-190R quantum sensors within 2.5 % for all radiation sources measured, but LGBQM meters were different from the LI-190R quantum sensors by at least -5 % for all radiation sources and between -15 and -20 % for environments where there is a large proportion of diffuse and high angle radiation incident on the sensor (Table 1). The metal halide and red/white LEDs had the largest proportion radiation incident at low angles. These results are expected for SQ-500 sensors and LGBQM meters based on the directional responses (Figure 1).

Variability of the six replicate SQ-500 sensors was about 2 % for sunlight measurements and 1 % or less for all electric lights. The two LGBQM meters were different from each other by about 5 % for sunlight and the electric lights. Under the high pressure sodium lamp, one of the meters was higher than the LI-190R sensors by about 3 % and the other was lower by about 2 %. Under the metal halide lamp, one of the meters was lower than the LI-190R sensors by about 3 % and the other was lower by about 8 %. This indicates the calibrations of the meters do not match. Following data collection, a third LGBQM meter was purchased and compared to these two meters under high pressure sodium and metal halide lamps. This third meter was close to the lower of the two meters, meaning it was about 2 % lower and 8 % lower than the LI-190R sensors under the high pressure sodium lamp and metal halide lamp, respectively.

Table 1: Measured mean relative difference [%] of six replicate Apogee SQ-500 quantum meters and two replicate Active Eye/Hydrofarm LGBQM meters from the mean of two LI-COR LI-190R quantum sensors.

Radiation Source*	Apogee MQ-500 quantum meter (n = 6)	Active/Eye Hydrofarm LGBQM quantum PAR meter (n = 2)
Sun (overcast)	2.5	-16.4
Metal Halide	1.4	-5.2
Cool White Fluorescent (T5)	0.0	-16.5
Red (80 %) and Blue (20 %) LEDs	-1.3	-18.2
Red (65 %) and White (35 %) LEDs	0.1	-5.8
Cool White Fluorescent LEDs	0.3	-19.4

*These radiation sources were chosen because they are commonly used for plant growth lighting. In all cases sensors were centered underneath the electric lights. Sensors were placed 1.0 m below a single metal halide lamp, 0.7 m below cool white fluorescent tubes mounted in a white-sided box similar to a growth chamber, 0.5 m below red and blue LEDs in a small growth chamber with reflective walls, 1.0 m below red and white LEDs in room with an LED panel on the ceiling, and 0.7 m below cool white fluorescent LEDs in a small growth chamber with reflective walls.

Measurement Stability of Meters

As mentioned above, Active Eye/Hydrofarm LGBQM meters were unstable when used to make measurements under electric lights. Measurements from the meters were stable when measurements were made under sunlight. Thus, instability appears to be caused by interference when the meters are used in close proximity to electronics (in an electrically noisy environment). The magnitude of the instability varied under different electric lights. Two data sets were collected to provide examples of the instability. Forty measurements were recorded at a two second interval under a high pressure sodium lamp, where the sensor on the LGBQM was placed directly beneath the lamp at a distance of 1.0 meter. Variability of the measurements from the LGBQM meter was ± 20 % around the mean value, equating to 45 μmol m^{-2} s^{-1} variability around a mean value of 225 μmol m^{-2} s^{-1}. Forty measurements were also recorded at a two second interval in a chamber filled with T5 cool white fluorescent tubes, similar to a growth chamber. The sensor on the LGBQM was placed in the middle of the chamber beneath the tubes at a distance of 0.7 meters. Variability of the measurements from the LGBQM meter was ± 4.5 % around the mean value, equating to 18 μmol m^{-2} s^{-1} variability around a mean value of 398 μmol m^{-2} s^{-1}. All three LGBQM meters were unstable and varied by about the same magnitude under both radiation sources. Stability of Apogee SQ-500 quantum sensors, MQ-500 quantum meters, and LI-COR LI-190R quantum sensors were also tested in the same manner as the LGBQM meters and were stable with less than 0.5 % variability, or within 1 μmol m^{-2} s^{-1}, under both radiation sources.

Implications

Results from this work suggest Apogee SQ-500 quantum sensors and MQ-500 quantum meters can be used to make accurate PPFD measurements for radiation sources with nearly any distribution of zenith angles and are stable in electrically noisy environments. Active Eye/Hydrofarm LGBQM quantum PAR meters had large directional errors that increased as the zenith angle increased, suggesting they can only make accurate measurements of radiation sources with a high proportion of radiation incident at angles less than about 20°. LGBQM meters were also susceptible to electrical noise, resulting in unstable measurements under electric lights. Thus, the Active Eye/Hydrofarm LGBQM quantum PAR meter is potentially useful in limited situations, such as periodic checks of lamp output to determine if output is diminishing over time, but even in this application data must be treated with caution because of the instability under electric lights.

References

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