Accurate PAR Measurement: Comparison of Eight Quantum Sensor Models

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Summary

Kipp & Zonen model PQS 1, LI-COR models LI-190 and LI-190R, and Apogee model SQ-500 quantum sensors had minimal spectral, directional, calibration, and stability errors, and matched each other within about 4 %, suggesting they can be reliably used for accurate photosynthetic photon flux density (PPFD) measurement. Apogee model SQ-100 quantum sensors performed similarly, except when measuring some LEDs, where spectral errors can be large. Spectrum LightScout and Active Eye/Hydrofarm LGBQM quantum sensors are not research-grade instruments and should be used with caution when making absolute PPFD measurements. The LightScout had large spectral and calibration errors, and the LGBQM had large spectral and directional errors. The LGBQM was also unstable under electric lights. While the LightScout and LGBQM are low cost, the large errors indicate they can only be used to provide a relative indication of PPFD with time for a given radiation source, if the instability is averaged out for the LGBQM.

Photosynthetically Active Radiation (PAR)

Photosynthetically active radiation (PAR) is the subset of shortwave radiation that drives photosynthesis and 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 [$\mu mol\ m^{-2}\ s^{-1}$]. Daily total PAR is the integral of instantaneous PPFD measured over the course of a twenty-four hour period, reported in units of moles per square meter per day [$mol\ m^{-2}\ d^{-1}$], and is often called daily light integral (DLI). The simplest and most common way to measure PPFD is with a quantum sensor, so called because a photon is a single quantum of radiation. Quantum sensors are also called PAR sensors, which is a more intuitive name.

Standard quantum sensors consist of a combination of a photodetector, optical filter(s), and diffuser, all mounted in a rugged housing. These components largely determine performance of a given sensor. There are multiple models of quantum sensors available, designed to provide accurate measurements of PPFD. The purpose of this work is to compare the performance and accuracy of eight commercially available quantum sensors/meters (a quantum meter refers to the combination of a quantum sensor and a handheld meter with digital display).

Sources of Measurement Error

Errors in radiation measurements can be separated into two groups, general use errors and sensor characteristic errors. General use errors are those that arise following deployment that are usually independent of the sensor model. Sensor characteristic errors are those caused by physical properties of components (for example, photodetector sensitivity, optical filter cutoffs, diffuser transmittance) and are dependent on the sensor model. General use errors are briefly reviewed, but only sensor characteristic errors are considered and compared in this study.

General Use Errors

- **Improper mounting:** field of view of a sensor is partially obstructed by surrounding objects (for example, plants, buildings, other sensors on a weather station).
- **Inaccurate leveling:** sensor is not mounted in a horizontal plane.

- **Occlusion of the diffuser:** diffuser on a sensor is partially or completely covered by residual precipitation, condensation, dust, or debris.

Sensor Characteristic Errors

- **Spectral error:** mismatch between sensor spectral response and the definition of PAR. Sensor spectral response is relative (normalized) sensitivity, where sensitivity is electrical output (typically voltage, but amperage for some models) divided by radiation input (μmol m^{-2} s^{-1} of photons) at each wavelength. Defined PAR assigns equal photosynthetic efficiency, defined as moles of carbon fixed per mole of photons absorbed, to all wavelengths between 400 and 700 nm and zero photosynthetic efficiency outside this range. Plant photosynthetic efficiency deviates from this definition, as photosynthetic efficiency is not zero beyond the 400 to 700 nm range and is non-uniform within this range (Inada, 1976; McCree, 1972a), but there is high correlation between single leaf photosynthetic efficiency and this definition (McCree 1972b). Early versions of quantum sensors were built around this definition of PAR (Biggs et al., 1971; Federer and Tanner, 1966).
- **Directional error (often called angular error or cosine error):** improper weighting of radiation incident at non-zero zenith angles. Sensor directional response is the response to radiation incident at different angles. Ideally, a sensor with a hemispherical, or 180°, field of view should accurately measure radiation emanating from the hemisphere above the sensor 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 sensor that measures radiation according to Lambert's cosine law, meaning it measures radiation accurately at all incidence angles, is said to be cosine-corrected.
- **Temperature error:** changes in electrical or optical components caused by temperature changes. Sensor temperature response is the change in signal as a function of temperature. Signal output by a sensor should only respond to changes in radiation incident on the diffuser, but electrical or optical components (for example, photodetector, resistor) may have some temperature sensitivity that affects the measurement.
- **Calibration error:** inaccurate scaling of the signal output by a sensor to match an accurate PPFD reference or scaling the signal output by a sensor to match an inaccurate PPFD reference. There is not an established PPFD standard, so quantum sensors must be calibrated against a trusted PPFD reference. Quantum sensor manufacturers use different PPFD references for calibration. Many quantum sensors are referenced to quartz halogen lamps with NIST-traceable calibrations.
- **Stability error:** long-term instability (drift) is caused by changes in sensor components (for example, photodetector degradation), and short-term instability can be caused by electrical interference (for example, measurement in electrically noisy environments). Sensor stability is dependent on the stability of sensor components. If components degrade, the signal output by the sensor will drift. Some degree of long-term drift can be corrected by periodic recalibration of sensors. However, if drift is erratic or rapid, recalibration is not a solution. If sensor spectral response changes with time, spectral errors will also change. Short-term instability can be averaged out by calculating the mean of multiple measurements if the instability is noise, not bias, and a sufficient number of points can be averaged to yield an accurate mean.

Quantum Sensor Models

Eight quantum sensor/meter models were compared in this study (Table 1). Prices of sensor models differ and depend on the source from which the sensor is purchased (for example, manufacturer, distributor). To provide a cost comparison, relative sensor prices were calculated from manufacturer prices, where the sensor in the middle of the price range (Apogee SQ-500) was used to normalize prices of all sensors included in the study.

Table 1: Model numbers and relative costs of quantum sensors/meters included in the study. Relative price is the ratio of the approximate manufacturer price to the manufacturer price of the Apogee model SQ-500.

Manufacturer and Model	Relative Price
Apogee SQ-500*	1.0
Apogee SQ-100* (SQ-110 has sunlight calibration; SQ-120 has electric light calibration)	0.5
LI-COR LI-190R	1.3
LI-COR LI-190 (original LI-COR quantum sensor model, replaced by LI-190R in 2014)	NA
Kipp & Zonen PQS 1	1.6
Skye SKP 215	1.7
Spectrum LightScout*	0.7
Active Eye/Hydrofarm LGBQM Quantum PAR Meter	0.5

*Versions connected to a handheld meter with digital readout are available. Apogee model numbers are MQ-500 and MQ-200.

Spectral Error

Spectral error can be quantified for any quantum sensor used to measure any radiation source as long as sensor spectral response (S_λ), calibration source spectral output ($I_{\lambda Calibration}$), and spectral output of the radiation source being measured ($I_{\lambda Measurement}$) are known (Federer and Tanner, 1966; Ross and Sulev, 2000):

$$\text{Error} = \frac{\int S_\lambda I_{\lambda \text{Measurement}} d\lambda \int_{400}^{700} I_{\lambda \text{Calibration}} d\lambda}{\int S_\lambda I_{\lambda \text{Calibration}} d\lambda \int_{400}^{700} I_{\lambda \text{Measurement}} d\lambda} \qquad \text{(Equation 1)}$$

where the integral from 400 to 700 is for the defined photosynthetic response to photons, equal photosynthetic efficiency between 400 and 700 nm and zero photosynthetic efficiency outside this range. Spectral errors were calculated with Equation 1 using measured or published spectral responses for the quantum sensor models included in the study. Spectral responses of six replicate Apogee quantum sensors of each model (SQ-500 and SQ-100) were measured in a monochromator at Apogee Instruments. Details of the measurement procedure are reported in a recent research report published by Apogee Instruments (Blonquist and Isaac, 2018). At least two replicates of the other quantum sensor models were verified in the monochromator using the same procedure, except the SKP 215, which was not measured.

In a recent technical note published by LI-COR Biosciences (LI-COR Biosciences, 2018), detailing quantum sensor spectral responses and spectral errors, it was reported that an Apogee SQ-500 sensor had a long wavelength cutoff about 7 nm further into the far red than the other two SQ-500 sensors tested. We randomly selected six replicate SQ-500 quantum sensors for the spectral response measurements. All six sensors had similar long wavelength cutoffs near 700 nm (Blonquist and Isaac, 2018; see Figure 4), where relative sensitivity was about 0.1 at 700 nm for all six sensors. The filter on the photodetector used in the Apogee SQ-500 quantum sensor was upgraded in October 2017. The sensors in the LI-COR study had an older filter version on the photodetector, which may have resulted in high sensitivity beyond 700 nm for one of the sensors.

Spectral responses of most of the quantum sensors matched defined PAR within a few percent (Figure 1), resulting in spectral errors less than 4 % for almost all of the radiation sources tested (Table 2). The exceptions were the Apogee SQ-100, Spectrum LightScout, and Active Eye/Hydrofarm LGBQM, which did not match defined PAR as well as the other sensors (Figure 1). The SQ-100 and LightScout use gallium arsenide phosphide photodetectors that are insensitive to wavelengths greater than about 660 nm. These quantum sensors can still make accurate PPFD measurements with calibrations for specific radiation sources. The Apogee SQ-100 has a sunlight (model SQ-110) or electric light (SQ-120) calibration. Measurements made under radiation sources with a large proportion of radiation between 650 and 700 nm (for example, halogen bulbs or deep red LEDs) are not recommended because the sensors are not sensitive in this range. The published and measured spectral responses for the LGBQM did not match. The exact cutoffs at 400 and 700 nm in the published data are not characteristic of filters in practice, thus measured spectral response data were used to make spectral error calculations.

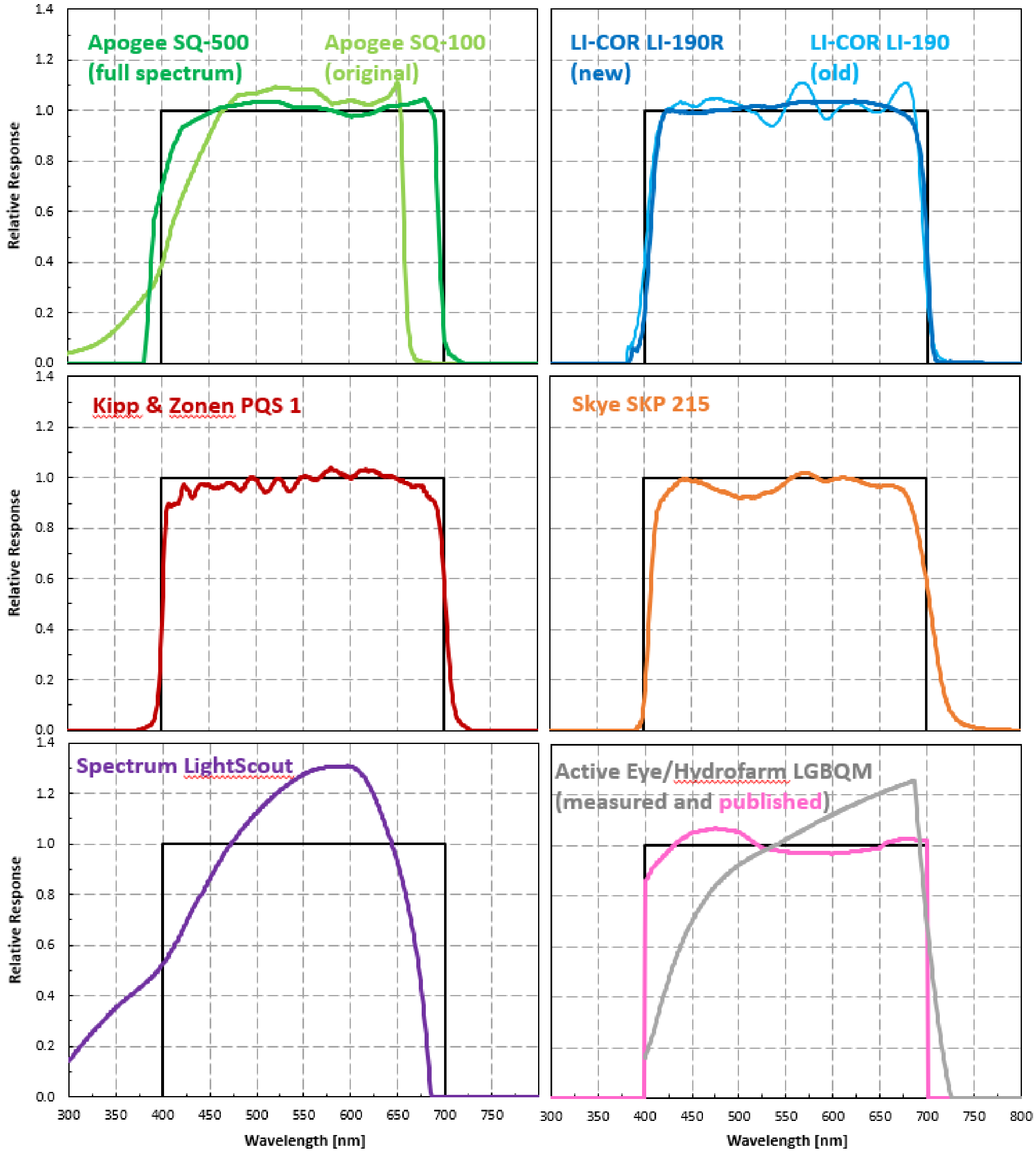

Figure 1: Quantum sensor spectral responses (colored lines) compared to defined PAR (black lines). These sensor spectral responses were used to calculate spectral errors for multiple radiation sources (Table 2). Spectral responses for Apogee quantum sensors were measured with a monochromator. Spectral responses for the other quantum sensors are published values (from user manuals; verified in a monochromator at Apogee Instruments). Empirical data for the LGBQM suggested the actual spectral response did not match the published spectral response, so it was also measured with a monochromator.

Table 2: Quantum sensor spectral errors calculated with Equation 1 using spectral response for each sensor (Figure 1) and spectral output of each radiation source. Calibration to sunlight (clear sky) was used to allow relative comparison, even though sensors are not necessarily calibrated to the sun by the manufacturer. Numbers in parentheses are spectral errors published in recent technical note from LI-COR Biosciences (LI-COR Biosciences, 2018). To allow relative comparison, the LI-COR numbers were scaled so errors were zero under sunlight.

Radiation Source	SQ-500	SQ-100	LI-190R	LI-190	PQS 1	SKP 215	Light Scout	LGBQM
Clear Sky	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0	0.0
Overcast Sky	0.1	0.2	0.1	0.1	0.0	0.1	-0.3	-0.3
Direct Normal	-0.1	-1.1	0.2	0.0	0.2	0.5	-0.9	1.8
Diffuse Blue	0.8	5.7	-1.3	-0.2	-1.1	-2.5	4.9	-9.8
Reflected Canopy	-0.3	3.8	1.1	0.2	1.7	6.7	3.3	4.6
Transmitted Canopy	0.1 (4.9)	4.5 (5.5)	0.7 (1.1)	0.3 (1.6)	0.8 (7.0)	4.5 (20.2)	4.3	0.7
CWF T12	0.4 (-0.9)	-0.8 (0.0)	1.4 (0.8)	1.0 (-0.7)	0.8 (-0.3)	-0.3 (0.4)	13.4	-0.5
CWF T5	0.1	0.0	1.8	0.2	1.2	0.5	13.4	0.7
Metal Halide	0.9 (-0.4)	-2.8 (-4.3)	0.4 (0.8)	0.3 (-1.0)	-0.1 (0.3)	-1.8 (-0.2)	12.0	-3.0
Ceramic MH	0.3	-16.1	1.3	1.0	0.5	0.3	-0.9	6.1
Mogul Base HPS	0.1 (2.2)	0.2 (-2.7)	3.2 (3.3)	1.1 (0.9)	2.3 (3.6)	1.9 (2.9)	21.2	8.1
Dual-ended HPS	-0.1	-5.7	2.8	2.2	2.2	2.4	13.5	11.1
Quartz Halogen	-1.3	-23.1	0.6	-0.4	1.2	3.2	-8.2	10.7
LI1800-02	-1.3 (2.5)	-23.3 (-27.1)	0.6 (0.5)	-0.4 (0.3)	1.2 (2.8)	3.3 (2.0)	-8.4	10.9
Blue (448 nm)	-0.7	-10.5	-0.2	2.0	-2.2	1.1	-14.3	-28.8
Green (524 nm)	3.2	8.8	2.2	-1.6	-1.0	-2.7	20.2	-2.4
Red (635 nm)	0.8	2.6	3.6	0.9	2.8	1.0	9.7	15.7
Red (667 nm)	2.8 (5.2)	-62.1 (-63.4)	0.9 (2.4)	4.2 (3.0)	-0.9 (2.9)	-0.9 (-2.3)	-30.9	19.8
R (80 %) B (20 %)	0.5	0.3	2.9	1.2	1.9	1.1	5.8	7.0
R (80 %) B (20 %)	-3.9	-72.8	-5.0	-2.7	-4.4	-6.1	-60.0	9.0
RGB	1.4	2.5	2.8	0.6	1.3	0.2	7.0	8.4
RWB	-2.0	-35.5	-0.3	-0.5	0.6	2.5	-21.2	13.2
Cool White	0.5	-3.3	2.0	1.2	0.3	0.7	8.4	-2.6
Neutral White	0.5	-5.1	2.0	1.1	0.7	0.9	8.0	1.9
Warm White	0.2	-8.9	2.1	0.9	1.1	1.1	6.0	6.6

*The Apogee SQ-100 has separate calibrations for sunlight (model SQ-110) and electric lights (model SQ-120).

Directional (Cosine) Error

Directional response is often specified as deviation from true cosine response, where a radiation beam of known intensity is used to determine sensor 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 sensor. Directional responses of four replicate Apogee SQ-500 and SQ-100 quantum sensors were determined by mounting them about one meter from a halogen lamp, with two baffles to maximize direct beam radiation, and making measurements at multiple zenith angles.

Another method of determining directional response is to compare PPFD measurements on a clear day against reference PPFD measurements, which must be assumed to represent true values because there is not a standard for PPFD measurement. Directional responses of at least two replicates of all the sensor models tested in this study, except the SKP 215, were determined by direct comparison to PPFD calculated from global solar (shortwave) irradiance (SW_i, in units of W m^{-2}) measurements from four secondary standard pyranometers. Only data from clear sky conditions were included. Mean SW_i was calculated from the pyranometers and used to calculate PPFD from a model:

$$\mathrm{PPFD} = \mathrm{SW_i}\,\frac{\mathrm{PAR/SW_i}}{\mathrm{E_{Content}}} \qquad \text{(Equation 2)}$$

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). Measurements of these variables made at Apogee Instruments in Logan, Utah, were used in the PPFD calculation with Equation 2. Further details are reported in a recent research report published by Apogee Instruments (Blonquist and Johns, 2018). For more detail on PPFD estimation from Equation 2, see Blonquist and Bugbee (2018).

Directional differences, determined by comparison to PPFD calculated from solar irradiance measurements from pyranometers, for most of the quantum sensors were less than 2 % up to zenith angles of 60° and less than 5 % up to zenith angles of 75° (Figure 2). The exceptions were the Spectrum LightScout and Active Eye/Hydrofarm LGBQM, which both underweight, or are less sensitive to, radiation incident at high zenith angle. The LGBQM had particularly poor directional response. The Apogee and LI-COR directional responses determined from solar radiation measurements matched laboratory (Apogee) and published (LI-COR) responses, providing evidence the responses determined from solar measurements provide an accurate estimate of directional response.

To demonstrate the effect of poor directional response, PPFD measurements from the Active Eye/Hydrofarm LGBQM were compared to the Apogee SQ-500 and LI-COR LI-190R under radiation sources with a large proportion of radiation incident at relatively high angles. The SQ-500 and LI-190R matched within 2.5 % under all radiation sources, but the LGBQM was low by 15 to 20 % (Table 3).

Table 3: Difference of Apogee SQ-500 and Active Eye/Hydrofarm LGBQM from LI-COR LI-190R, demonstrating the direct effect of directional response on PPFD measurements. The mean of six SQ-500 sensors and three LGBQM meters were compared to the mean of three LI-190R sensors under radiation sources with a large proportion of radiation incident at relatively high angles. The SQ-500 and LI-190R match because directional errors are small. The LGBQM has large directional errors.

Radiation Source	SQ-500 Mean Difference [%]	LGBQM Mean Difference [%]
Sun (overcast sky)	2.5	-16.4
CWF T5	0.0	-16.5
HPS (45° angle)	-0.9	-14.1
Red and Blue LEDs	-1.3	-18.2
CWF LEDs	0.3	-19.4

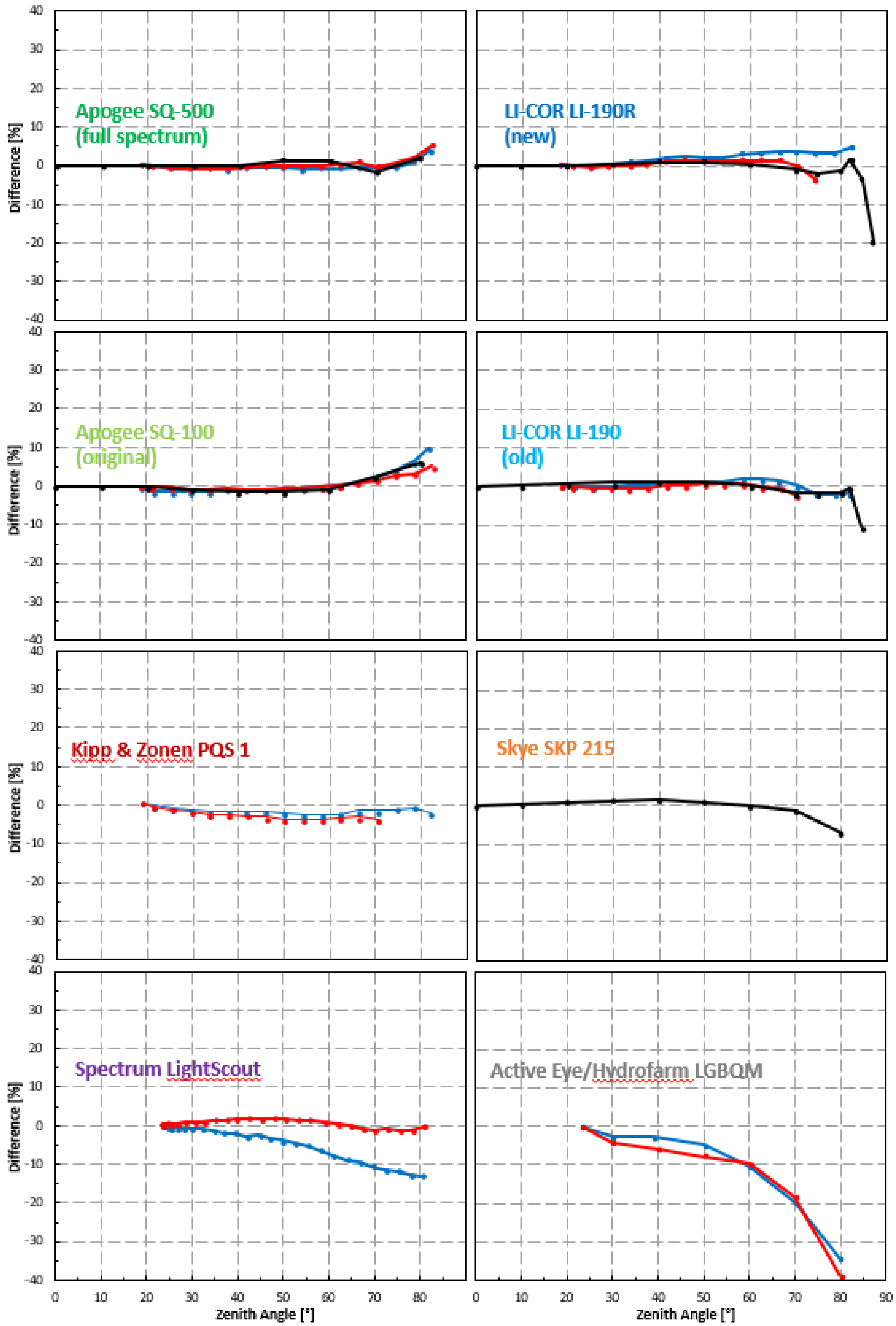

Figure 2: Quantum sensor directional differences from reference PPFD calculated with Equation 2 using solar irradiance measurements from secondary standard pyranometers (blue lines are AM responses and red lines are PM responses). Directional responses for Apogee sensors were also measured in the laboratory (black lines). Published directional responses are included for LI-COR and Skye sensors (black lines; from user manuals).

Temperature Error

Temperature errors are challenging to determine because they are small compared to other sources of error. Sensor temperature response is often determined by placing sensors inside a temperature controlled chamber and measuring sensor output across a range of temperature. Typical temperature response specifications for quantum sensors are ± 0.10 to 0.15 % per degree C. Analysis of data collected outdoors for the Apogee, LI-COR, and Kipp & Zonen quantum sensors across a wide temperature range (about 0 to 40 C) suggests temperature errors are less than this specification. The Skye, Spectrum, and Active Eye/Hydrofarm sensors were not tested for temperature errors. Temperature errors will likely be much less than other sources of error, especially in indoor measurement applications where temperatures are often near the temperature at which quantum sensors were calibrated.

Calibration Error

There is not a standard for PPFD measurement, so calibration error was quantified relative to PPFD calculated from mean solar irradiance measured with four secondary standard pyranometers, using Equation 2 because it represents an independent measure of PPFD. PPFD calculated from solar irradiance is most accurate on clear days near solar noon. Only data on cloud-free days, where the solar zenith angle was less than 30° to minimize directional effects, were included. Most manufacturers list calibration accuracy of quantum sensors at ± 5 %. Relative to reference PPFD calculated from solar irradiance, mean differences for all sensors except the LightScout were within this range (Table 4). It should be noted, one LGBQM was near 3 % high, while two others were near 6 % low. The SKP 215 was not measured.

Table 4: Mean difference of quantum sensors from PPFD calculated with Equation 2 using solar irradiance measured with four secondary standard pyranometers. Data provide an indication of calibration error, using PPFD calculated from solar irradiance as an independent reference.

Sensor Model	Mean Difference (± Standard Deviation) [%]
SQ-500	1.1 ± 0.4 (n = 6)
SQ-100	0.5 ± 1.3 (n = 6)
LI-190R	-0.5 ± 0.5 (n = 6)
LI-190	0.4 ± 1.4 (n = 3)
PQS 1*	-1.0, 4.1 (n = 2)
LightScout*	15.9, 10.1 (n = 2)
LGBQM	-3.0 ± 5.1 (n = 3)

*Only two replicates were measured, so both differences are listed rather than mean difference and standard deviation.

Stability Error

Quantum sensors that were deployed outdoors continuously for at least two years were compared against PPFD calculated with Equation 2 using mean solar irradiance measured with four secondary standard pyranometers to determine long-term stability (Table 5).

Table 5: Drift of quantum sensors measuring sunlight continuously for two (SQ-500) or three (SQ-100, LI-190, PQS 1) years, where reference PPFD was calculated with Equation 2 using solar irradiance measured with secondary standard pyranometers, provides an estimate of long-term stability.

Sensor Model	Drift [% yr^{-1}]
SQ-500	< 1 (n = 6)
SQ-100	< 1 (n = 6)
LI-190*	< 1 (n = 2)
PQS 1	< 1 (n = 2)

*Three sensors were deployed, but one suffered from moisture intrusion and drifted significantly. Measurements were typically low, by as much as 50 %, but were erratic. The signal recovered once the sensor was dried out by sealing it in bag of desiccant for a few days.

The Active Eye/Hydrofarm LGBQM was unstable when measuring electric lights. Relative to mean values, variability was ± 20 % under HPS lamps, ± 5 % under CWF T5 lamps, and ± 10 % under red LEDs. Frequency of variation was 1 to 2 seconds. This instability was not present under sunlight, suggesting electrical interference. Short-term measurements from all other quantum sensors tested in this study were stable under all radiation sources.

Conclusions

- Spectral errors for all quantum sensors tested were typically less than 4 % for all radiation sources, except the Apogee SQ-100, Spectrum LightScout, and Active Eye/Hydrofarm LGBQM. The SQ-100 and LightScout use gallium arsenide phosphide (GaAsP) photodetectors, which are insensitive to wavelengths greater than about 660 nm. Separate calibrations for sunlight and electric light can partially account for spectral errors, but sensors with GaAsP photodetectors must be used with caution to measure absolute PPFD and should not be used to measure LEDs without first verifying the sensor under the given LEDs. Published and measured spectral responses for the LGBQM do not match, and spectral errors were large when calculated using the measured spectral response.
- Directional differences measured under sunlight, where reference PPFD was calculated from solar irradiance measurements from the mean of four secondary standard pyranometers, matched laboratory measured directional responses for Apogee quantum sensors and published directional responses for LI-COR quantum sensors, suggesting directional errors for these sensors should be less than 2 % for zenith angles up to 60° and less than about 5 % for zenith angles up to 80°. Directional differences measured under sunlight for the Kipp & Zonen PQS 1 were also small. Skye SKP 215 sensors were not measured under sunlight. The LightScout and LGBQM had larger directional differences from reference PPFD, resulting in PPFD measurement errors. Directional errors were particularly large for the LGBQM, about 15 to 20 % low for radiation sources with a large proportion of radiation incident at high zenith angle.
- Temperature errors were likely present, but were difficult to quantify because they are small compared to other sources of error. Thus, temperature errors can likely be ignored, especially for greenhouse and growth chamber measurements where temperatures are usually in the 15 to 35 C range.

- Calibration errors for Apogee, LI-COR, and Kipp & Zonen quantum sensors were small under sunlight, typically near 1 %, although one Kipp & Zonen sensor was about 4 % high, compared to reference PPFD calculated from solar irradiance measurements from secondary standard pyranometers. The LightScout was high by 10 to 16 %. One of three LGBQM meters was within 3 %, but the other two were low by about 6 %. The SKP 215 was not compared.
- Multiple Kipp & Zonen, LI-COR, and Apogee quantum sensors continuously deployed outdoors for two to three years did not change by more than 1 % per year in any year compared to reference PPFD calculated from solar irradiance measurements from secondary standard pyranometers, with the exception of one LI-COR LI-190 that suffered from moisture intrusion. The LightScout and LGBQM were not continuously deployed outdoors, so long-term stability was not determined. Under electric lights the LGBQM varied by as much as 20 % from the measured mean PPFD. Measurements were stable under sunlight, when removed from the electrical environment, indicating electrical interference caused instability.

References

Biggs, W., A.R. Edison, J.D. Eastin, K.W. Brown, J.W. Maranville, and M.D. Clegg, 1971. Photosynthesis light sensor and meter. Ecology 52:125-131.

Blonquist Jr., J.M., and B. Bugbee, 2018. Solar, Net, and Photosynthetic Radiation. In J. Hatfield, M. Sivakumar, and J. Prueger (editors) Agroclimatology: Linking Agriculture to Climate. American Society of Agronomy, Madison, Wisconsin.

Blonquist Jr., J.M., and M.A. Isaac, 2018. Underwater accuracy of Apogee quantum sensors. Apogee Instruments Research Report, published online May 2018 (https://www.apogeeinstruments.com/content/Underwater-Accuracy-of-Apogee-Quantum-Sensors.pdf).

Blonquist Jr., J.M., and J.A. Johns, 2018. Directional response of Apogee and Active Eye/Hydrofarm quantum sensors: Impact on PAR measurements. Apogee Instruments Research Report, published online May 2018 (https://www.apogeeinstruments.com/content/Directional-Response-of-Apogee-and-ActiveEyeHydrofarm-Quantum-Sensors.pdf).

Federer, C.A., and C.B. Tanner, 1966. Sensors for measuring light available for photosynthesis. Ecology 47:654-657.

Inada, K., 1976. Action spectra for photosynthesis in higher plants. Plant and Cell Physiology 17:355-365.

LI-COR Biosciences, 2018. Comparison of quantum sensors with different spectral sensitivities. LI-COR Biosciences Technical Note, published online February 2018 (https://www.licor.com/documents/oi26ib7eb6wm5y5u9ebv4b3jodm09tf9).

McCree, K.J., 1972a. The action spectrum, absorptance and quantum yield of photosynthesis in crop plants. Agricultural Meteorology 9:191-216.

McCree, K.J., 1972b. Test of current definitions of photosynthetically active radiation against leaf photosynthesis data. Agricultural Meteorology 10:443-453.

Ross, J., and M. Sulev, 2000. Sources of errors in measurements of PAR. Agricultural and Forest Meteorology 100:103-125.