OWNER'S MANUAL

QUANTUM SENSOR

Model JSQ-500

(including SS model)

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CERTIFICATE OF COMPLIANCE

EU Declaration of Conformity

for the following product(s):

Models: JSQ-500
Type: Quantum Sensor

The object of the declaration described above is in conformity with the relevant Union harmonization legislation:

2014/30/EU	Electromagnetic Compatibility (EMC) Directive
2011/65/EU	Restriction of Hazardous Substances (RoHS 2) Directive

Standards referenced during compliance assessment:

EN 61326-1:2013	Electrical equipment for measurement, control and laboratory use – EMC requirements
EN 50581:2012	Technical documentation for the assessment of electrical and electronic products with respect to the restriction of hazardous substances

Please be advised that based on the information available to us from our raw material suppliers, the products manufactured by us do not contain, as intentional additives, any of the restricted materials including cadmium, hexavalent chromium, lead, mercury, polybrominated biphenyls (PBB), polybrominated diphenyls (PBDE).

Further note that Apogee Instruments does not specifically run any analysis on our raw materials or end products for the presence of these substances, but rely on the information provided to us by our material suppliers.

INTRODUCTION

Radiation that drives photosynthesis is called photosynthetically active radiation (PAR) and is typically defined as total radiation across a range of 400 to 700 nm. PAR is often expressed as photosynthetic photon flux density (PPFD): photon flux in units of micromoles per square meter per second (µmol m^{-2} s^{-1}, equal to microEinsteins per square meter per second) summed from 400 to 700 nm (total number of photons from 400 to 700 nm). While Einsteins and micromoles are equal (one Einstein = one mole of photons), the Einstein is not an SI unit, so expressing PPFD as µmol m^{-2} s^{-1} is preferred.

Sensors that measure PPFD are often called quantum sensors due to the quantized nature of radiation. A quantum refers to the minimum quantity of radiation, one photon, involved in physical interactions (e.g., absorption by photosynthetic pigments). In other words, one photon is a single quantum of radiation.

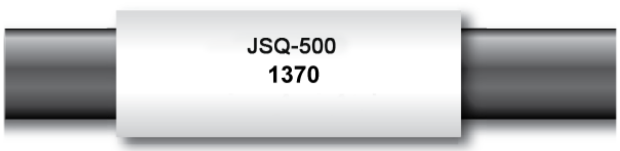
Typical applications of quantum sensors include incoming PPFD measurement over plant canopies in outdoor environments or in greenhouses and growth chambers, and reflected or under-canopy (transmitted) PPFD measurement in the same environments.

Apogee Instruments JSQ series quantum sensors consist of a cast acrylic diffuser (filter), photodiode, and signal processing circuitry mounted in an anodized aluminum housing, and a cable to connect the sensor to a measurement device. JSQ-500 series quantum sensors are designed for continuous PPFD measurement in indoor or outdoor environments. JSQ series sensors output an analog signal that is directly proportional to PPFD. The analog signal from the sensor is directly proportional to radiation incident on a planar surface (does not have to be horizontal), where the radiation emanates from all angles of a hemisphere.

SENSOR MODELS

Apogee JSQ-500 series quantum sensors covered in this manual are unamplified analog versions that provide a voltage output. Additional models are covered in their respective manuals.

Model	Signal
JSQ-500	**Self-powered**
JSQ-512	0-2.5 V
JSQ-515	0-5 V
JSQ-520	USB
JSQ-521	SDI-12
JSQ-522	Modbus



Sensor model number and serial number are located near the pigtail leads on the sensor cable. If you need the manufacturing date of your sensor, please contact Apogee Instruments with the serial number of your sensor.

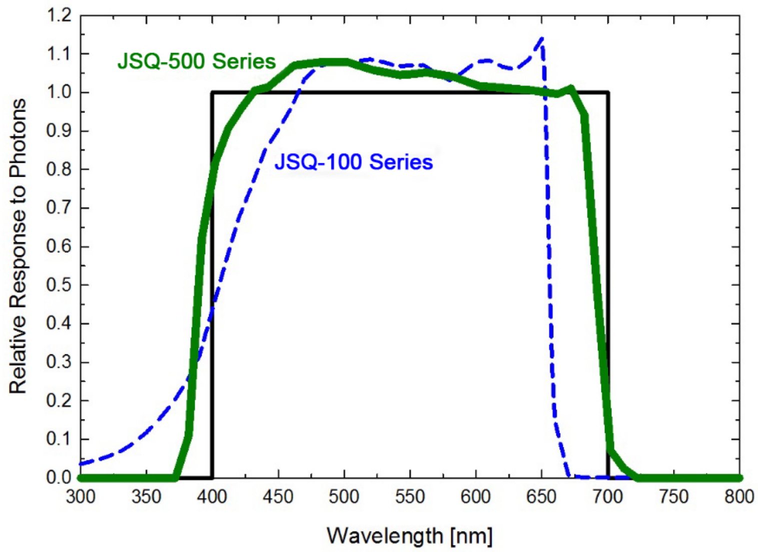
SPECIFICATIONS

	JSQ-500
Power Supply	Self-powered
Sensitivity	0.01 mV per µmol m^{-2} s^{-1}
Calibration Factor	100.0 µmol m^{-2} s^{-1} per mV
Calibration Uncertainty	± 5 % (see calibration Traceability below)
Measurement Range	0 to 4000 µmol m^{-2} s^{-1}
Measurement Repeatability	Less than 1 % (up to 4000 µmol m^{-2} s^{-1})
Calibrated Output Range	0 to 40 mV
Long-term Drift (Non-stability)	Less than 2 % per year
Non-linearity	Less than 1 % (up to 4000 µmol m^{-2} s^{-1})
Response Time	Less than 1 ms
Field of View	180º
Spectral Range	389 to 692 nm ± 5 nm (wavelengths where response is greater than 50 %)
Spectral Selectivity	Less than 10 % from 412 to 682 ± 5 nm (see Spectral Response below)
Directional (Cosine) Response	± 2 % at 45º zenith angle, ± 5 % at 75º zenith angle (see Directional Response below)
Azimuth Error	Less than 0.5 %
Tilt Error	Less than 0.5 %
Temperature Response	-0.11 ± 0.04 % C^{-1} (see Temperature Response below)
Uncertainty in Daily Total	Less than 5 %
Detector	Blue-enhanced silicon photodiode
Housing	Anodized aluminum body with acrylic diffuser
IP Rating	IP68
Operating Environment	-40 to 70 C; 0 to 100 % relative humidity; can be submerged in water up to depths of 30 m
Dimensions	24 mm diameter; 37 mm height
Mass	100 g (with 5 m of lead wire)
Cable	5 m of two conductor, shielded, twisted-pair wire; additional cable available in multiples of 5 m; santoprene rubber jacket; pigtail lead wires

Calibration Traceability

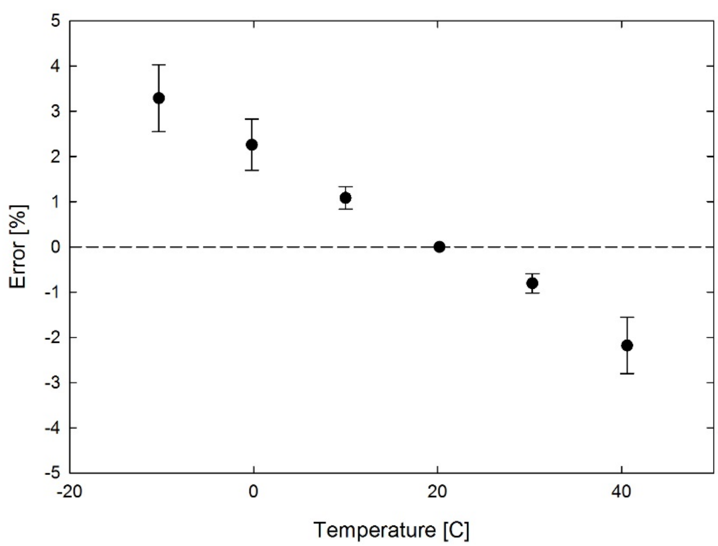
Apogee Instruments HSQ-500 series quantum sensors are calibrated through side-by-side comparison to the mean of four Apogee model HSQ-500 transfer standard quantum sensors under high output T5 cool white fluorescent lamps. The transfer standard quantum sensors are calibrated through side-by-side comparison to the mean of at least three LI-COR model LI-190R reference quantum sensors under high output T5 cool white fluorescent lamps. The reference quantum sensors are recalibrated on a biannual schedule with a LI-COR model 1800-02 and quartz halogen lamp that is traceable to the National Institute of Standards and Technology (NIST).

Spectral Response



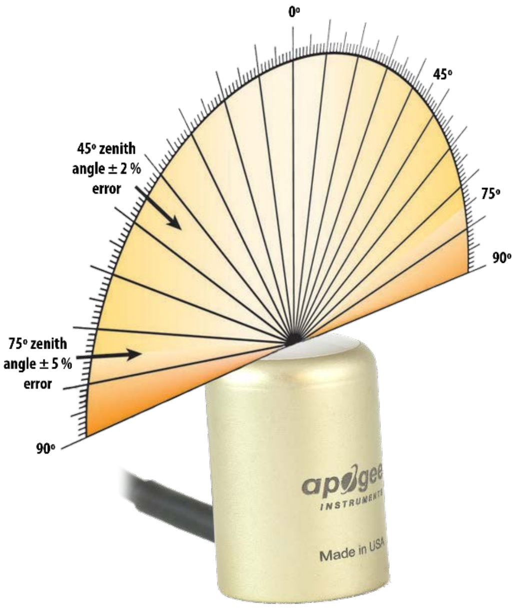
Mean spectral response measurements of six replicate Apogee JSQ-100 and JSQ-500 series quantum sensors. Spectral response measurements were made at 10 nm increments across a wavelength range of 300 to 800 nm in a monochromator with an attached electric light source. Measured spectral data from each quantum sensor were normalized by the measured spectral response of the monochromator/electric light combination, which was measured with a spectroradiometer.

Temperature Response

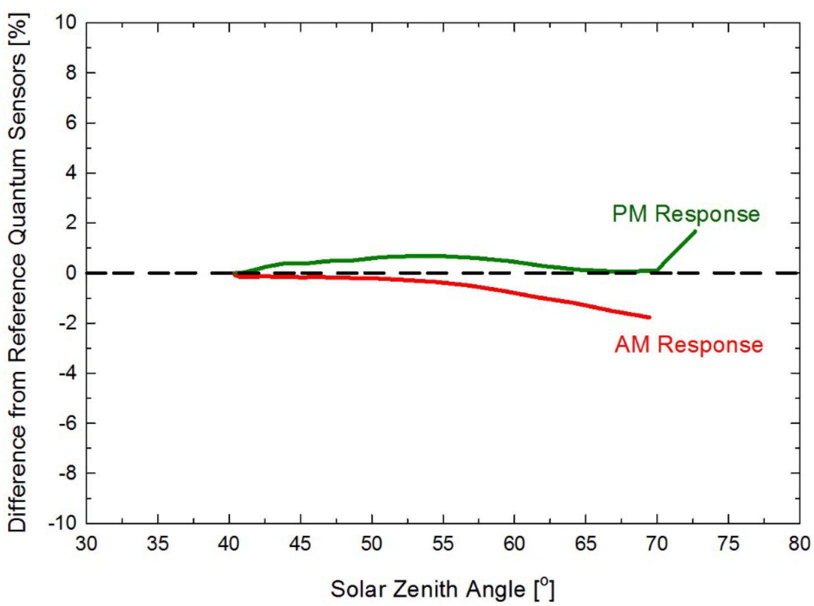


Mean temperature response of ten JSQ-500 series quantum sensors (***errors bars represent two standard deviations above and below mean***). Temperature response measurements were made at 10 C intervals across a temperature range of approximately -20 to 50 C in a temperature controlled chamber under a fixed, broad spectrum, electric lamp. At each temperature set point, a spectroradiometer was used to measure light intensity from the lamp and all quantum sensors were compared to the spectroradiometer. The spectroradiometer was mounted external to the temperature control chamber and remained at room temperature during the experiment.

Cosine Response



Directional, or cosine, response is defined as the measurement error at a specific angle of radiation incidence. Error for Apogee JSQ-500 series quantum sensors is approximately ± 2 % and ± 5 % at solar zenith angles of 45° and 75°, respectively.



Mean cosine response of seven apogee JSQ-500 quantum sensors. Cosine response measurements were made on the rooftop of the Apogee building in Logan, UT. Cosine response was calculated as the relative difference of JSQ-500 quantum sensors from the mean of replicate reference quantum sensors (LI-COR models LI-190 and LI-190R, Kipp & Zonen model PQS 1).

DEPLOYMENT AND INSTALLATION

Mount the sensor to a solid surface with the nylon mounting screw provided. To accurately measure PPFD incident on a horizontal surface, the sensor must be level. An Apogee Instruments model AL-100 leveling plate is recommended for this purpose. To facilitate mounting on a cross arm, an Apogee Instruments model AM-110 mounting bracket is recommended.

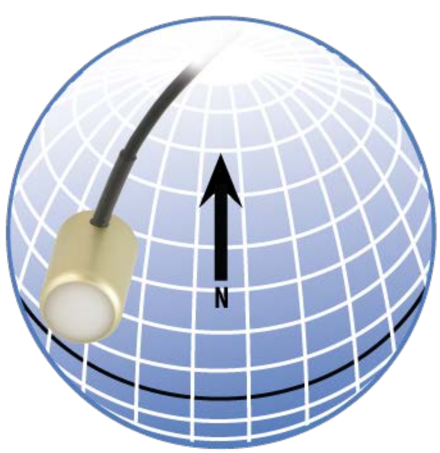
Nylon Screw: 10-32 x 3/8

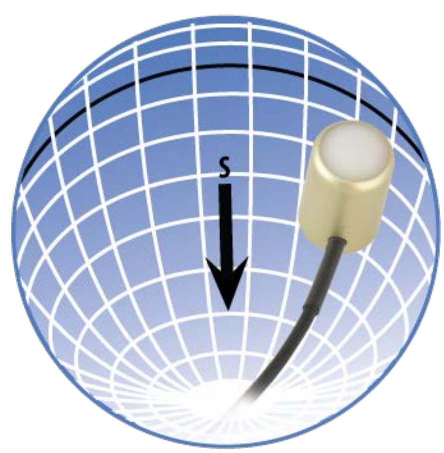
Model: AL-110

Nylon Screw: 10-32 x 3/8

Model: AL-120

To minimize azimuth error, the sensor should be mounted with the cable pointing toward true north in the northern hemisphere or true south in the southern hemisphere. Azimuth error is typically less than 0.5 %, but it is easy to minimize by proper cable orientation.





In addition to orienting the cable to point toward the nearest pole, the sensor should also be mounted such that obstructions (e.g., weather station tripod/tower or other instrumentation) do not shade the sensor. **Once mounted, the green cap should be removed from the sensor.** The green cap can be used as a protective covering for the sensor when it is not in use.

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Cable Connectors

Apogee started offering in-line cable connectors on some bare-lead sensors in March 2018 to simplify the process of removing sensors from weather stations for calibration by not requiring the full cable to be uninstalled back to the data logger.

The ruggedized M8 connectors are rated IP67, made of corrosion-resistant marine-grade stainless-steel, and designed for extended use in harsh environmental conditions.

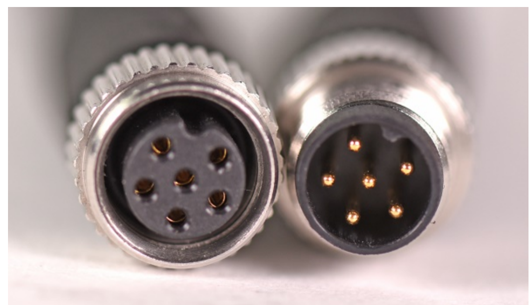
Inline cable connectors are installed 30 cm from the head (pyranometer pictured)

Instructions

Pins and Wiring Colors: All Apogee connectors have six pins, but not all pins are used for every sensor. There may also be unused wire colors inside the cable. To simplify data logger connection, we remove the unused pigtail lead colors at the data logger end of the cable.

If you ever need a replacement cable, please contact us directly to ensure ordering the proper pigtail configuration.

Alignment: When reconnecting your sensor, arrows on the connector jacket and an aligning notch ensure proper orientation.



A reference notch inside the connector ensures proper alignment before tightening.

Disconnection for extended periods: When disconnecting the sensor for an extended period of time from a station, protect the remaining half of the connector still on the station from water and dirt with electrical tape or other method.

When sending sensors in for calibration, only send the short end of the cable and half the connector.

Tightening: Connectors are designed to be firmly finger-tightened only. There is an o-ring inside the connector that can be overly compressed if a wrench is used. Pay attention to thread alignment to avoid cross-threading. When fully tightened, 1-2 threads may still be visible.

Finger-tighten firmly

OPERATION AND MEASUREMENT

Connect the sensor to a measurement device (meter, datalogger, controller) capable of measuring and displaying or recording a millivolt signal (an input measurement range of approximately 0 to 25 mV is required to cover the entire range of PPFD from the sun). In order to maximize measurement resolution and signal-to-noise ratio, the input range of the measurement device should closely match the output range of the quantum sensor. **DO NOT connect the sensor to a power source. The sensor is self-powered and applying voltage will damage the sensor.**

VERY IMPORTANT: Apogee changed all wiring colors of our bare-lead sensors in March 2018 in conjunction with the release of inline cable connectors on some sensors. To ensure proper connection to your data device, please note your serial number or if your sensor has a stainless-steel connector 30 cm from the sensor head then use the appropriate wiring configuration below.

Wiring for JSQ-500 Serial Numbers within range 0-1558

Red: Positive (signal from sensor)

Black: Negative (signal from sensor)

Clear: Shield/Ground

Wiring for JSQ-500 Serial Numbers 1559 and above or with a cable connector

Black: Negative (signal from sensor)

Clear: Shield/Ground

White: Positive (signal from sensor)

Sensor Calibration

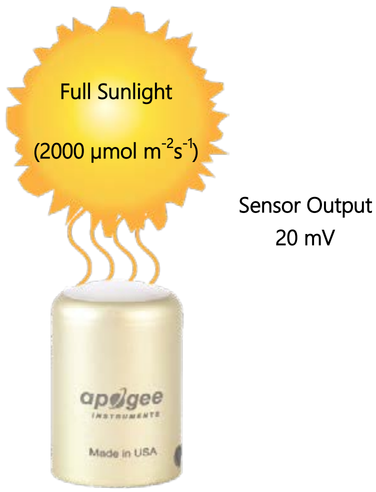
All Apogee un-amplified quantum sensor models (JSQ-500) have a standard PPFD calibration factor of exactly:

100.0 µmol m^{-2} s^{-1} per mV

Multiply this calibration factor by the measured mV signal to convert sensor output to PPFD in units of µmol m^{-2} s^{-1}:

Calibration Factor (100 µmol m^{-2} s^{-1} per mV) * Sensor Output Signal (mV) = PPFD (µmol m^{-2} s^{-1})

100 * 20 = 2000



Example of PPFD measurement with an Apogee JSQ-500 quantum sensor. Full sunlight yields a PPFD on a horizontal plane at the Earth's surface of approximately 2000 µmol m^{-2} s^{-1}. This yields an output signal of 20 mV. The signal is converted to PPFD by multiplying by the calibration factor of 100.0 µmol m^{-2} s^{-1} per mV.

Spectral Error

The combination of diffuser transmittance, interference filter transmittance, and photodetector sensitivity yields spectral response of a quantum sensor. A perfect photodetector/filter/diffuser combination would exactly reproduce the defined plant photosynthetic response to photons (equal weighting to all photons between 400 and 700 nm), but this is challenging in practice. Mismatch between the defined plant photosynthetic response and sensor spectral response results in spectral error when the sensor is used to measure radiation from sources with a different spectrum than the radiation source used to calibrate the sensor (Federer and Tanner, 1966; Ross and Sulev, 2000).

Spectral errors for PPFD measurements made under different radiation sources were calculated for the JSQ-100 and JSQ-500 series quantum sensors using the method of Federer and Tanner (1966). This method requires PPFD weighting factors (defined plant photosynthetic response), measured sensor spectral response (shown in Spectral Response section on page 7), and radiation source spectral outputs (measured with a spectroradiometer). Note, this method calculates spectral error only and does not consider calibration, cosine, and temperature errors. Spectral error data (listed in table below) indicate errors typically less than 5 % for sunlight in different conditions (clear, cloudy, reflected from plant canopies, transmitted below plant canopies) and common broad spectrum electric lamps (cool white fluorescent, metal halide, high pressure sodium), but larger errors for different mixtures of light emitting diodes (LEDs) for the JSQ-100 series. Spectral errors for the JSQ-500 series sensors are smaller than those for JSQ-100 series sensors because the JSQ-500 spectral response is a closer match to the defined plant photosynthetic response.

Spectral Errors for PPFD and YPFD Measurements with Apogee JSQ Series Quantum Sensors

Radiation Source (Error Calculated Relative to Sun, Clear Sky)	JSQ-100 Series PPFD Error [%]	JSQ-500 Series PPFD Error [%]
Sun (Clear Sky)	0.0	0.0
Sun (Cloudy Sky)	1.4	0.5
Reflected from Grass Canopy	5.7	0.0
Transmitted below Wheat Canopy	6.4	1.1
Cool White Fluorescent (T5)	0.0	2.2
Metal Halide	-3.7	3.1
Ceramic Metal Halide	-6.0	1.9
High Pressure Sodium	0.8	2.2
Blue LED (448 nm peak, 20 nm full-width half-maximum)	-12.7	3.0
Green LED (524 nm peak, 30 nm full-width half-maximum)	8.0	5.2
Red LED (635 nm peak, 20 nm full-width half-maximum)	4.8	0.2
Red LED (668 nm peak, 20 nm full-width half-maximum)	-79.1	-1.9
Red, Blue LED Mixture (84 % Red, 16 % Blue)	-65.3	-1.2
Red, White LED Mixture (79 % Red, 21 % Blue)	-60.3	-0.8
Cool White Fluorescent LED	-4.6	2.2

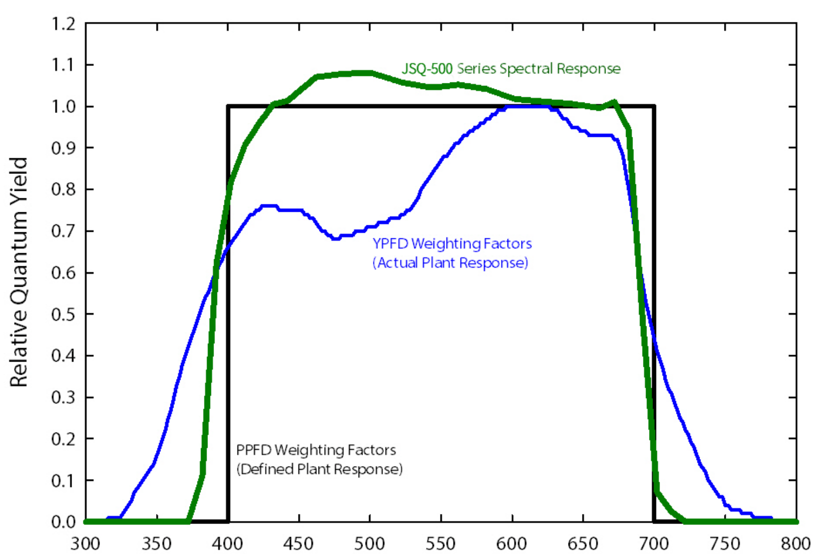
Quantum sensors can be a very practical means of measuring PPFD and YPFD from multiple radiation sources, but spectral errors must be considered. The spectral errors in the table above can be used as correction factors for individual radiation sources.

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

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

Yield Photon Flux Measurements

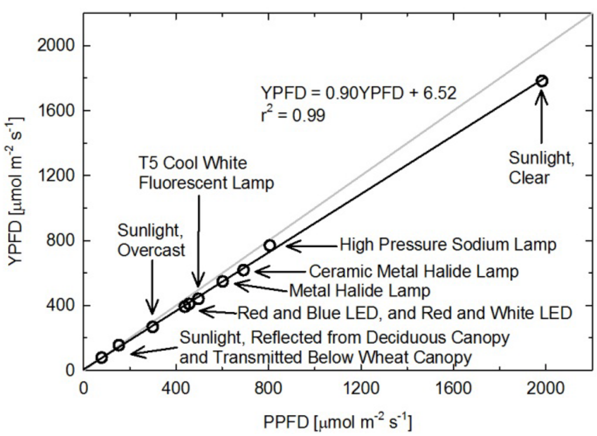
Photosynthesis in plants does not respond equally to all photons. Relative quantum yield (photosynthetic efficiency) is dependent on wavelength (blue line in figure below) (McCree, 1972a; Inada, 1976). This is due to the combination of spectral absorptivity of plant leaves (absorptivity is higher for blue and red photons than green photons) and absorption by non-photosynthetic pigments. As a result, photons in the wavelength range of approximately 600-630 nm are the most efficient.



Radiation weighting factors for PPFD (black line, defined plant response to radiation), YPFD (blue line, measured plant response to radiation), and Apogee JSQ-500 Series Quantum Sensors (green line, sensor sensitivity to different wavelengths of radiation).

One potential definition of PAR is weighting photon flux density [µmol m^{-2} s^{-1}] at each wavelength between 300 and 800 nm by relative quantum yield and summing the result. This is defined as yield photon flux density (YPFD) [µmol m^{-2} s^{-1}] (Sager et al., 1988). There are uncertainties and challenges associated with this definition of PAR. Measurements used to generate the relative quantum yield data were made on single leaves under low radiation levels and at short time scales (McCree, 1972a; Inada, 1976). Whole plants and plant canopies typically have multiple leaf layers and are generally grown in the field or greenhouse over the course of an entire growing season. Thus, actual conditions plants are subject to are likely different than those the single leaves were in when measurements were made by McCree (1972a) and Inada (1976). In addition, relative quantum yield shown in figure above is the mean from twenty-two species grown in the field (McCree, 1972a). Mean relative quantum yield for the same species grown in growth chambers was similar, but there were differences, particularly at shorter wavelengths (less than 450 nm). There was also some variability between species (McCree, 1972a; Inada, 1976).

McCree (1972b) found that equally weighting all photons between 400 and 700 nm and summing the result, defined as photosynthetic photon flux density (PPFD) [µmol m^{-2} s^{-1}], was well correlated to photosynthesis, very similar to correlation between YPFD and photosynthesis. As a matter of practicality, PPFD is a simpler definition of PAR. At the same time as McCree's work, others had proposed PPFD as an accurate measure of PAR and built sensors that approximated the PPFD weighting factors (Biggs et al., 1971; Federer and Tanner, 1966). Correlation between PPFD and YPFD measurements for several radiation sources is very high (figure below). As an approximation, YPFD = 0.9PPFD. As a result, almost universally PAR is defined as PPFD rather than YPFD, although YPFD has been used in some studies. The only radiation sources shown (figure below) that don't fall on the regression line are the high pressure sodium (HPS) lamp, reflection from a plant canopy, and transmission below a plant canopy. A large fraction of radiation from HPS lamps is in the red range of wavelengths where the YPFD weighting factors are at or near one. The factor for converting PPFD to YPFD for HPS lamps is 0.95, rather than 0.90. The factor for converting PPFD to YPFD for reflected and transmitted photons is 1.00.



Correlation between photosynthetic photon flux density (PPFD) and yield photon flux density (YPFD) for multiple different radiation sources. YPFD is approximately 90 % of PPFD. Measurements were made with a spectroradiometer (Apogee Instruments model PS-200) and weighting factors shown in previous figure were used to calculate PPFD and YPFD.

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.

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.

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.

Sager, J.C., W.O. Smith, J.L. Edwards, and K.L. Cyr, 1988. Photosynthetic efficiency and phytochrome photoequilibria determination using spectral data. Transactions of the ASAE 31:1882-1889.

Underwater Measurements and Immersion Effect

When a quantum sensor that was calibrated in air is used to make underwater measurements, the sensor reads low. This phenomenon is called the immersion effect and happens because the refractive index of water (1.33) is greater than air (1.00). The higher refractive index of water causes more light to be backscattered (or reflected) out of the sensor in water than in air (Smith,1969; Tyler and Smith,1970). As more light is reflected, less light is transmitted through the diffuser to the detector, which causes the sensor to read low. Without correcting for this effect, underwater measurements are only relative, which makes it difficult to compare light in different environments.

The JSQ-500 series sensors have an immersion effect correction factor of 1.32. This correction factor should be multiplied to measurements made underwater.