apogee INSTRUMENTS

OWNER'S MANUAL

QUANTUM SENSOR

Model SQ-521

Rev: 16-Mar-2021

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CERTIFICATE OF COMPLIANCE

EU Declaration of Conformity

This declaration of conformity is issued under the sole responsibility of the manufacturer:

Apogee Instruments, Inc.
721 W 1800 N
Logan, Utah 84321
USA

for the following product(s):

Models: SQ-521
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
2015/863/EU	Amending Annex II to Directive 2011/65/EU (RoHS 3)

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 lead (see note below), mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB), polybrominated diphenyls (PBDE), bis(2-ethylhexyl) phthalate (DEHP), butyl benzyl phthalate (BBP), dibutyl phthalate (DBP), and diisobutyl phthalate (DIBP). However, please note that articles containing greater than 0.1% lead concentration are RoHS 3 compliant using exemption 6c.

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.

Signed for and on behalf of:
Apogee Instruments, January 2021

Bruce Bugbee
President
Apogee Instruments, Inc.

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 almost universally quantified as photosynthetic photon flux density (PPFD), the sum of photons from 400 to 700 nm in units of micromoles per square meter per second (µmol m^{-2} s^{-1}, equal to microEinsteins m^{-2} s^{-1}). While microEinsteins 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. Daily total PPFD is typically reported in units of moles of photons per square meter per day (mol m^{-2} d^{-1}) and is often called daily light integral (DLI).

The acronym PPF is also used and refers to the photosynthetic photon flux. The acronyms PPF and PPFD refer to the same variable. Both terms are used because there is not a universal definition of the term flux. Flux is sometimes defined as per unit area per unit time and sometimes defined as per unit time only. PPFD is used in this manual.

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 measurement of incident PPFD on 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 SQ 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. SQ-500 series quantum sensors are designed for continuous PPFD measurement in indoor or outdoor environments. The SQ-521 sensors output a digital signal using SDI-12 communication protocol.

SENSOR MODELS

This manual covers the SDI-12 communication protocol quantum sensor model SQ-521 (listed in bold below). Additional models are covered in their respective manuals.

Model	Signal
SQ-521	**SDI-12**
SQ-500	Self-powered
SQ-512	0-2.5 V
SQ-515	1-5 V
SQ-520	USB
SQ-522	Modbus

Sensor model number and serial number are located on the bottom of the sensor. If the manufacturing date of a specific sensor is required, please contact Apogee Instruments with the serial number of the sensor.

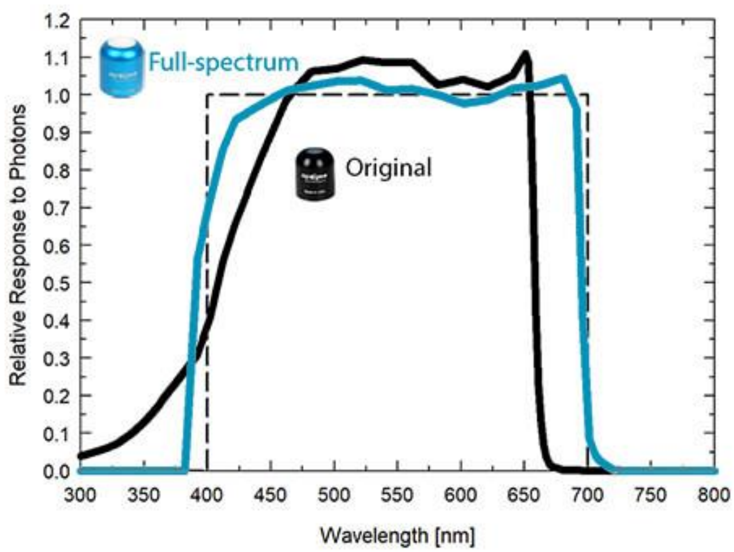
SPECIFICATIONS

	SQ-521
Input Voltage	5.5 to 24 V DC
Current Draw	1.4 mA (quiescent), 1.8 mA (active)
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})
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	0.6 s, time for detector signal to reach 95 % following a step change; fastest data transmission rate for SDI-12 circuitry is 1 s
Field of View	180°
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 45° zenith angle, ± 5 % at 75° zenith angle (see Directional Response below)
Azimuth Error	Less than 0.5 %
Tilt Error	Less than 0.5 %
Temperature Response	-0.11 ± 0.04 % per C (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 Serial # 3033 and above	30.5 mm diameter, 37 mm height
Dimensions Serial # 0-3032	24 mm diameter, 37 mm height
Mass (5 m of cable) Serial # 3033 and above	140 g
Mass (5 m of cable) Serial # 0-3032	100 g
Cable	5 m of shielded, twisted-pair wire; TPR jacket (high water resistance, high UV stability, flexibility in cold conditions); pigtail lead wires; stainless steel (316), M8 connector

Calibration Traceability

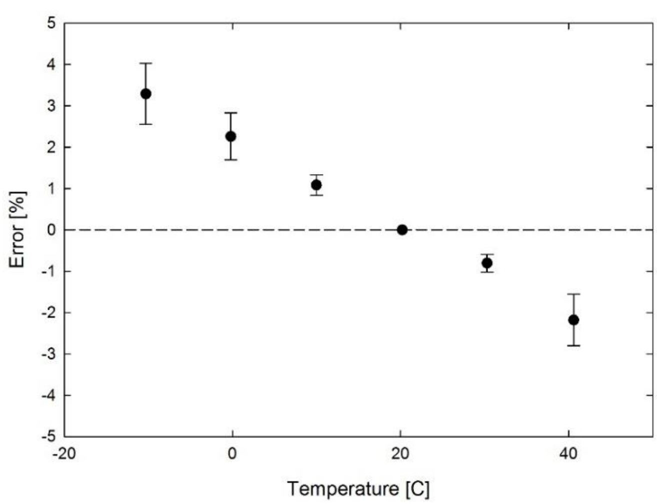
Apogee Instruments SQ-500 series quantum sensors are calibrated through side-by-side comparison to the mean of four transfer standard quantum sensors under a reference lamp. The reference quantum sensors are recalibrated with a quartz halogen lamp traceable to the National Institute of Standards and Technology (NIST).

Spectral Response



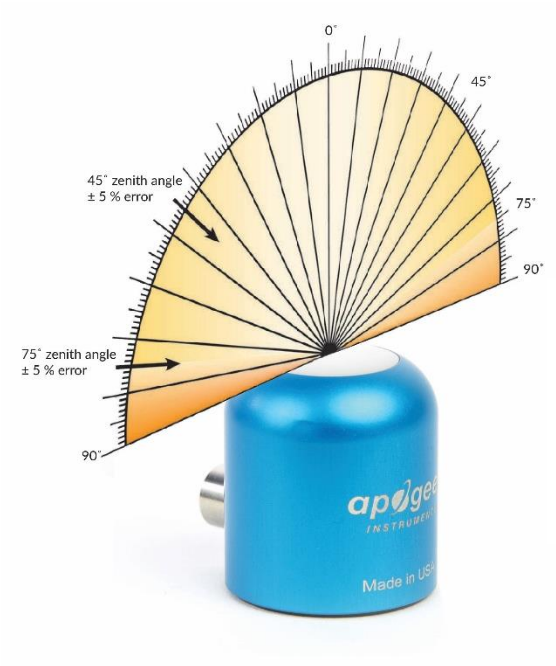
Mean spectral response measurements of six replicate Apogee SQ-100 (original) and SQ-500 (full-spectrum) series quantum sensors. Spectral response measurements were made at 10 nm increments across a wavelength range of 300 to 800 nm with a monochromator and an attached electric light source. Measured 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

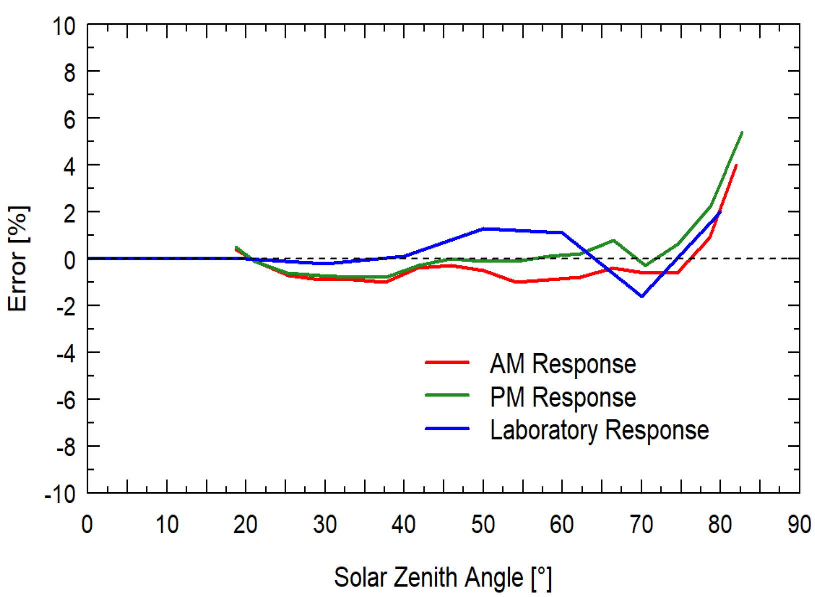


Mean temperature response of ten SQ-500 series quantum sensors (***errors bars represent two standard deviations above and below mean***). Temperature response measurements were made at 10 C intervals across a temperature range of approximately -10 to 40 C in a temperature controlled chamber under a 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 (cosine) response is defined as the measurement error at a specific angle of radiation incidence. Error for Apogee SQ-500 series quantum sensors is approximately ± 2 % and ± 5 % at solar zenith angles of 45° and 75°, respectively.



Mean directional (cosine) response of seven apogee SQ-500 series quantum sensors. Directional response measurements were made on the rooftop of the Apogee building in Logan, Utah. Directional response was calculated as the relative difference of SQ-500 quantum sensors from the mean of replicate reference quantum sensors (LI-COR models LI-190 and LI-190R, Kipp & Zonen model PQS 1). Data were also collected in the laboratory using a reference lamp and positioning the sensor at varying angles.

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 AL-120 mounting bracket is recommended.

Nylon Screw: 10-32 x 3/8

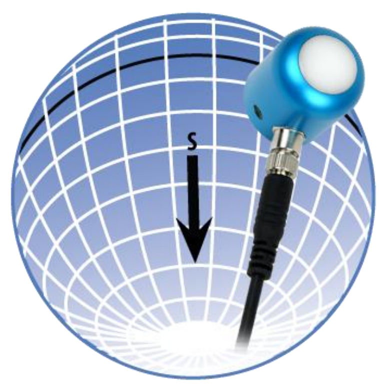
Model: AL-100

Important: Only use the nylon screw provided when mounting to insulate the non-anodized threads of the aluminum sensor head from the base to help prevent galvanic corrosion. For extended submersion applications, more insulation may be necessary. Contact Apogee tech support for details.

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 blue cap should be removed from the sensor.** The blue cap can be used as a protective covering for the sensor when it is not in use.

CABLE CONNECTORS

Apogee offers cable connectors simplify the process of removing sensors from weather stations for calibration (the entire cable does **not** have to be removed from the station and shipped with the sensor).

The ruggedized M8 connectors are rated IP68, made of corrosion-resistant marine-grade stainless-steel, and designed for extended use in harsh environmental conditions.

Cable connectors are attached directly to the head.

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 datalogger connection, we remove the unused pigtail lead colors at the datalogger end of the cable.

If a replacement cable is required, please contact Apogee directly to ensure ordering the proper pigtail configuration.

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

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

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 sensor head.

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.

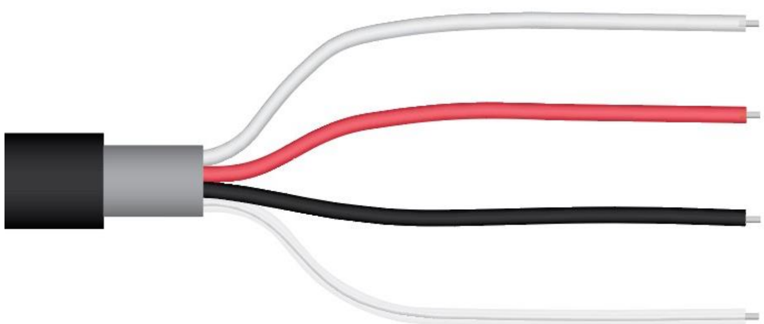
WARNING: Do <u>not</u> tighten the connector by twisting the black cable or sensor head, only twist the metal connector (yellow arrows).

Finger-tighten firmly

OPERATION AND MEASUREMENT

The SQ-521 quantum sensor has a SDI-12 output, where photosynthetically active radiation is returned in digital format. Measurement of SQ-521 quantum sensors requires a measurement device with SDI-12 functionality that includes the M or C command.

Wiring



White: Positive (signal from sensor)

Red: Input Power

Black: Ground (from sensor signal and output power)

Clear: Shield/Ground

Sensor Calibration

All Apogee SDI-12 quantum sensor models (SQ-500 series) have sensor-specific calibration coefficients determined during the custom calibration process. Coefficients are programmed into the microcontrollers at the factory.

SDI-12 Interface

The following is a brief explanation of the serial digital interface SDI-12 protocol instructions used in Apogee SQ-521 quantum sensors. For questions on the implementation of this protocol, please refer to the official version of the SDI-12 protocol: http://www.sdi-12.org/specification.php (version 1.4, August 10, 2016).

Overview

During normal communication, the data recorder sends a packet of data to the sensor that consists of an address and a command. Then, the sensor sends a response. In the following descriptions, SDI-12 commands and responses are enclosed in quotes. The SDI-12 address and the command/response terminators are defined as follows:

Sensors come from the factory with the address of “0” for use in single sensor systems. Addresses “1 to 9” and “A to Z”, or “a to z”, can be used for additional sensors connected to the same SDI-12 bus.

“!” is the last character of a command instruction. In order to be compliant with SDI-12 protocol, all commands must be terminated with a “!”. SDI-12 language supports a variety of commands. Supported commands for the Apogee Instruments SP-521 quantum sensors are listed in the following table (“a” is the sensor address. The following ASCII Characters are valid addresses: “0-9” or “A-Z”).

Supported Commands for Apogee Instruments SQ-521 Quantum Sensors

Instruction Name	Instruction Syntax	Description
Acknowledge Active Command	a!	Responds if the sensor with address a is on the line
Send Identification Command	aI!	Responds with sensor information
Measurement Command	aM!	Tells the sensor to take a measurement
Measurement Command w/ Check Character	aMC!	Tells the sensor to take a measurement and return it with a check character
Change Address Command	aAb!	Changes the sensor address from a to b
Concurrent Measurement Command	aC!	Used to take a measurement when more than one sensor is used on the same data line
Concurrent Measurement Command w/ Check Character	aCC!	Used to take a measurement when more than one sensor is used on the same data line. Data is returned with a check character.
Address Query Command	?!	Used when the address is unknown to have the sensor identify its address, all sensors on data line respond
Get Data Command	aD0!	Retrieves the data from a sensor
Verification Command	aV!	Returns sensor coefficients as multiplier, offset, solar multiplier, and immersion effect correction factor
Running Average Command	aXAVG!	Returns or sets the running average for sensor measurements.

Make Measurement Command: M!

The make measurement command signals a measurement sequence to be performed. Data values generated in response to this command are stored in the sensor's buffer for subsequent collection using "D" commands. Data will be retained in sensor storage until another "M", "C", or "V" command is executed. M commands are shown in the following examples:

Command	Response	Response to 0D0!
aM! or aM0!	a0011<cr><lf>	Returns µmol m^{-2} s^{-1}
aM1!	a0011<cr><lf>	Returns millivolt output
aM2!	a0011<cr><lf>	Returns µmol m^{-2} s^{-1}
aM3!	a0011<cr><lf>	Returns immersed µmol m^{-2} s^{-1} for underwater measurements
aM4!	a0011<cr><lf>	Returns angle offset from vertical in degrees. (0 degrees if pointed up, 180 degrees if pointed down.) Available in sensors with serial number 3033 or greater.
aMC! or aMC0!	a0011<cr><lf>	Returns µmol m^{-2} s^{-1} w/CRC
aMC1!	a0011<cr><lf>	Returns millivolt output w/ CRC
aMC2!	a0011<cr><lf>	Returns µmol m^{-2} s^{-1} w/ CRC
aMC3!	a0011<cr><lf>	Returns immersed µmol m^{-2} s^{-1} for underwater measurements w/ CRC
aMC4!	a0011<cr><lf>	Returns angle offset from vertical in degrees w/CRC. (0 degrees if pointed up, 180 degrees if pointed down.) Available in sensors with serial numbers 3033 or greater.

where a is the sensor address ("0-9", "A-Z", "a-z") and M is an upper-case ASCII character.

The data values are separated by the sign "+", as in the following example (0 is the address):

Command	Sensor Response	Sensor Response when data is ready
0M0!	00011<cr><lf>	0<cr><lf>
0D0!	0+2000.0<cr><lf>	
0M1!	00011<cr><lf>	0<cr><lf>
0D0!	0+400.0<cr><lf>	
0M2!	00011<cr><lf>	0<cr><lf>
0D0!	0+2000.0<cr><lf>	

0M3!	00011<cr><lf>	0<cr><lf>
0D0!	0+2000.0<cr><lf>	
0M4!	a0011<cr><lf>	0<cr><lf>
0D0!	0+90.2<cr><lf>	

where 2000.0 is µmol m^{-2} s^{-1}.

Concurrent Measurement Command: aC!

A concurrent measurement is one which occurs while other SDI-12 sensors on the bus are also making measurements. This command is similar to the "aM!" command, however, the nn field has an extra digit and the sensor does not issue a service request when it has completed the measurement. Communicating with other sensors will NOT abort a concurrent measurement. Data values generated in response to this command are stored in the sensor's buffer for subsequent collection using "D" commands. The data will be retained in the sensor until another "M", "C", or "V" command is executed:

Command	**Response**	**Response to 0D0!**
aC! or aC0!	a00101<cr><lf>	Returns µmol m^{-2} s^{-1}
aC1!	a00101<cr><lf>	Returns millivolt output
aC2!	a00101<cr><lf>	Returns µmol m^{-2} s^{-1}
aC3!	a00101<cr><lf>	Returns immersed µmol m^{-2} s^{-1} for underwater measurements
aC4!	a00101<cr><lf>	Returns angle offset from vertical in degrees. (0 degrees if pointed up, 180 degrees if pointed down.) Available in sensors with serial number 3033 or greater.
aCC! or aCC0!	a00101<cr><lf>	Returns µmol m^{-2} s^{-1} w/CRC
aCC1!	a00101<cr><lf>	Returns millivolt output w/ CRC
aCC2!	a00101<cr><lf>	Returns µmol m^{-2} s^{-1} w/ CRC
aCC3!	a00101<cr><lf>	Returns immersed µmol m^{-2} s^{-1} for underwater measurements w/ CRC
aCC4!	a00101<cr><lf>	Returns angle offset from vertical in degrees w/CRC. (0 degrees if pointed up, 180 degrees if pointed down.) Available in sensors with serial numbers 3033 or greater.

where a is the sensor address ("0-9", "A-Z", "a-z", "*", "?") and C is an upper-case ASCII character.

For example (0 is the address):

Command	**Sensor Response**
0C0!	000101<cr><lf>
0D0!	0+2000.0<cr><lf>
0C1!	000101<cr><lf>
0D0!	0+400.0<cr><lf>
0C2!	000101<cr><lf>
0D0!	0+2000.0<cr><lf>
0C3!	000101<cr><lf>
0D0!	0+2000.0<cr><lf>
0C4!	000101<cr><lf>
0D0!	0+90.2<cr><lf>

where 2000.0 is µmol m^{-2} s^{-1} and 400.0 is mV.

Change Sensor Address: aAb!

The change sensor address command allows the sensor address to be changed. If multiple SDI-12 devices are on the same bus, each device will require a unique SDI-12 address. For example, two SDI-12 sensors with the factory address of 0 requires changing the address on one of the sensors to a non-zero value in order for both sensors to communicate properly on the same channel:

Command	Response	Description
aAb!	b<cr><lf>	Change the address of the sensor

where a is the current (old) sensor address (“0-9”, “A-Z”), A is an upper-case ASCII character denoting the instruction for changing the address, b is the new sensor address to be programmed (“0-9”, “A-Z”), and ! is the standard character to execute the command. If the address change is successful, the datalogger will respond with the new address and a <cr><lf>.

Send Identification Command: aI!

The send identification command responds with sensor vendor, model, and version data. Any measurement data in the sensor's buffer is not disturbed:

Command	Response	Description
"aI!"	a13Apogee SP-521vvvxx…xx<cr><lf>	The sensor serial number and other identifying values are returned

where a is the sensor address (“0-9”, “A-Z”, “a-z”, “*”, “?”), 521 is the sensor model number, vvv is a three character field specifying the sensor version number, and xx...xx is serial number.

Running Average Command

The running average command can be used to set or query the number of measurements that are averaged together before returning a value from a M! or MC! command. For example, if a user sends the command “0XAVG10!” to sensor with address 0, that sensor will average 10 measurements before sending the averaged value to the logger. To turn off averaging, the user should send the command “*a*XAVG1” to the sensor. To query the sensor to see how many measurements are being averaged, send the command “*a*XAVG!” and the sensor will return the number of measurements being averaged (see table below). The default for sensors is to have averaging turned off.

Command Name	Characters Sent	Response	Description
Query running Average	*a*XAVG!	*an*	a = sensor address, *n* = number of measurements used in average calculation. Note: *n* may be multiple digits.
Set running Average	*a*XAVG*n!*	*a*	a = sensor address, *n* = number of measurements to be used in average calculation. Note: *n* may be any value from 1 to 100.

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 match the defined plant photosynthetic response to photons (equal weighting to all photons between 400 and 700 nm, no weighting of photons outside this range), 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 common radiation sources for growing plants were calculated for Apogee SQ-100 and SQ-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, directional (cosine), temperature, and stability/drift errors. Spectral error data (listed in table below) indicate errors 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 SQ-100 series sensors. Spectral errors for the SQ-500 series sensors are smaller than those for SQ-100 series sensors because the spectral response of SQ-500 series sensors is a closer match to the defined plant photosynthetic response.

Quantum sensors are the most common instrument for measuring PPFD, because they are about an order of magnitude lower cost the spectroradiometers, but spectral errors must be considered. The spectral errors in the table below can be used as correction factors for individual radiation sources.

Spectral Errors for PPFD Measurements with Apogee SQ-100 and SQ-500 Series Quantum Sensors

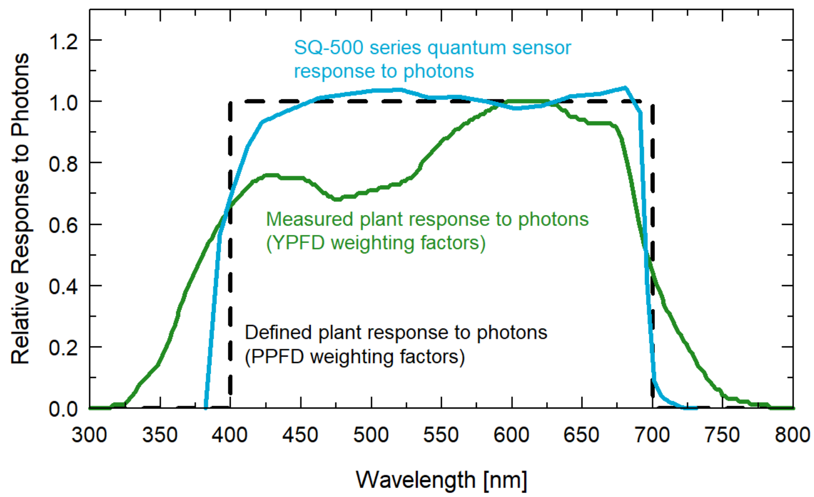
Radiation Source (Error Calculated Relative to Sun, Clear Sky)	SQ-100 Series PPFD Error [%]	SQ-500 Series PPFD Error [%]
Sun (Clear Sky)	0.0	0.0
Sun (Cloudy Sky)	0.2	0.1
Reflected from Grass Canopy	3.8	-0.3
Transmitted below Wheat Canopy	4.5	0.1
Cool White Fluorescent (T5)	0.0	0.1
Metal Halide	-2.8	0.9
Ceramic Metal Halide	-16.1	0.3
High Pressure Sodium	0.2	0.1
Blue LED (448 nm peak, 20 nm full-width half-maximum)	-10.5	-0.7
Green LED (524 nm peak, 30 nm full-width half-maximum)	8.8	3.2
Red LED (635 nm peak, 20 nm full-width half-maximum)	2.6	0.8
Red LED (667 nm peak, 20 nm full-width half-maximum)	-62.1	2.8
Red, Blue LED Mixture (80 % Red, 20 % Blue)	-72.8	-3.9
Red, Blue, White LED Mixture (60 % Red, 25 % White, 15 % Blue)	-35.5	-2.0
Cool White LED	-3.3	0.5
Warm White LED	-8.9	0.2

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 Density (YPFD) Measurements

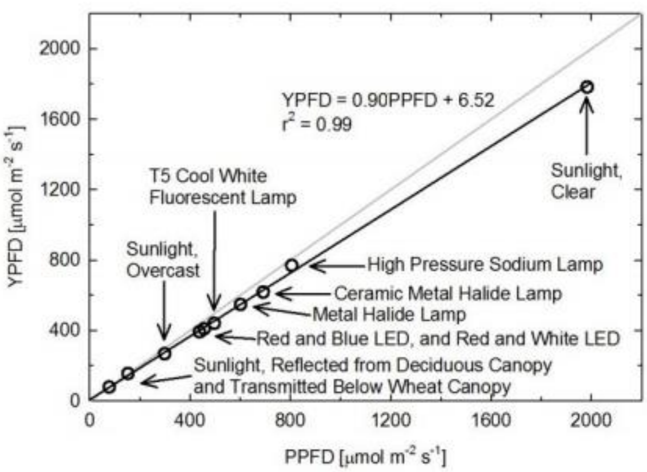
Photosynthesis in plants does not respond equally to all photons. Relative quantum yield (plant photosynthetic efficiency) is dependent on wavelength (green line in figure below) (McCree, 1972a; Inada, 1976). This is due to the combination of spectral absorptivity of plant leaves (absorptivity is higher 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.



Defined plant response to photons (black line, weighting factors used to calculate PPFD), measured plant response to photons (green line, weighting factors used to calculate YPFD), and SQ-500 series quantum sensor response to photons (sensor spectral response).

One potential definition of PAR is weighting photon flux density in units of μmol m^{-2} s^{-1} at each wavelength between 300 and 800 nm by measured relative quantum yield and summing the result. This is defined as yield photon flux density (YPFD, units of 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 the 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, in units of μmol m^{-2} s^{-1}), was well correlated to photosynthesis, and 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 (measured relative quantum yield) 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 the 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.

Immersion Effect Correction Factor

When a radiation sensor is submerged in water, more of the incident radiation is backscattered out of the diffuser than when the sensor is in air (Smith, 1969; Tyler and Smith, 1970). This phenomenon is caused by the difference in the refractive index for air (1.00) and water (1.33), and is called the immersion effect. Without correction for the immersion effect, radiation sensors calibrated in air can only provide relative values underwater (Smith, 1969; Tyler and Smith, 1970). Immersion effect correction factors can be derived by making measurements in air and at multiple water depths at a constant distance from a lamp in a controlled laboratory setting.

Apogee SQ-500 series quantum sensors have an immersion effect correction factor of 1.25. This correction factor should be multiplied by PPFD measurements made underwater to yield accurate PPFD.

Further information on underwater measurements and the immersion effect can be found on the Apogee webpage (http://www.apogeeinstruments.com/underwater-par-measurements/).

Smith, R.C., 1969. An underwater spectral irradiance collector. Journal of Marine Research 27:341-351.

Tyler, J.E., and R.C. Smith, 1970. Measurements of Spectral Irradiance Underwater. Gordon and Breach, New York, New York. 103 pages.

MAINTENANCE AND RECALIBRATION

Blocking of the optical path between the target and detector can cause low readings. Occasionally, accumulated materials on the diffuser of the upward-looking sensor can block the optical path in three common ways:

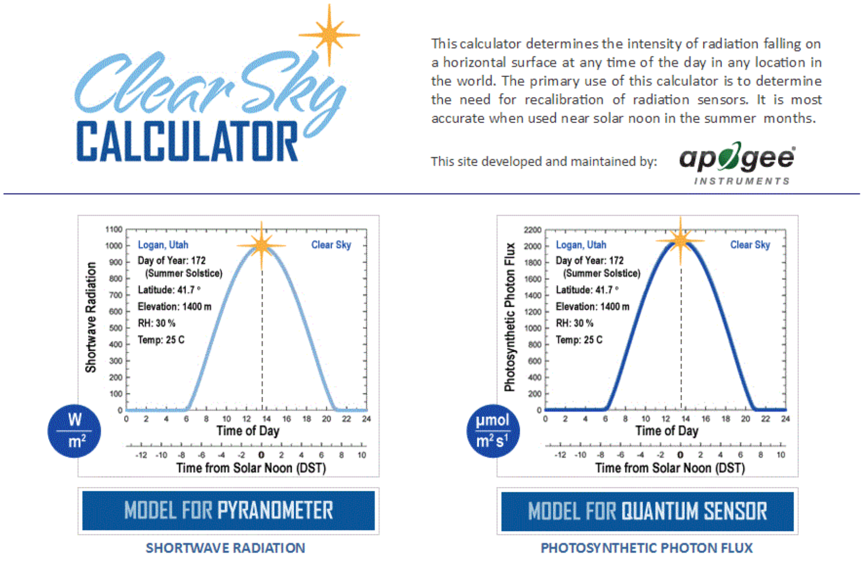
1. Moisture or debris on the diffuser.
2. Dust during periods of low rainfall.
3. Salt deposit accumulation from evaporation of sea spray or sprinkler irrigation water.

Apogee Instruments upward-looking sensors have a domed diffuser and housing for improved self-cleaning from rainfall, but active cleaning may be necessary. Dust or organic deposits are best removed using water, or window cleaner, and a soft cloth or cotton swab. Salt deposits should be dissolved with vinegar and removed with a cloth or cotton swab. **Salt deposits cannot be removed with solvents such as alcohol or acetone.** Use only gentle pressure when cleaning the diffuser with a cotton swab or soft cloth to avoid scratching the outer surface. The solvent should be allowed to do the cleaning, not mechanical force. **Never use abrasive material or cleaner on the diffuser.**

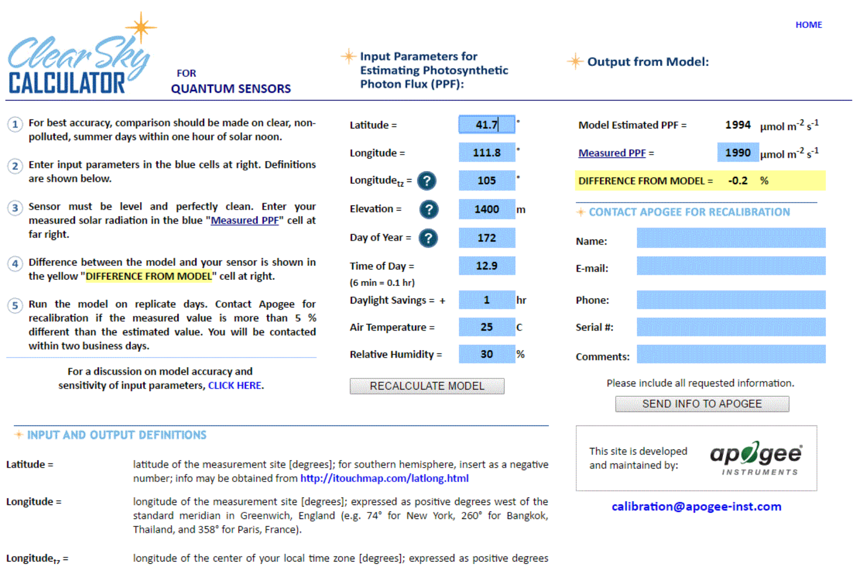
Although Apogee sensors are very stable, nominal accuracy drift is normal for all research-grade sensors. To ensure maximum accuracy, we generally recommend sensors are sent in for recalibration every two years, although you can often wait longer according to your particular tolerances.

To determine if your sensor needs recalibration, the Clear Sky Calculator (www.clearskycalculator.com) website and/or smartphone app can be used to indicate the total shortwave radiation incident on a horizontal surface at any time of day at any location in the world. It is most accurate when used near solar noon in spring and summer months, where accuracy over multiple clear and unpolluted days is estimated to be ± 4 % in all climates and locations around the world. For best accuracy, the sky must be completely clear, as reflected radiation from clouds causes incoming radiation to increase above the value predicted by the clear sky calculator. Measured values of total shortwave radiation can exceed values predicted by the Clear Sky Calculator due to reflection from thin, high clouds and edges of clouds, which enhances incoming shortwave radiation. The influence of high clouds typically shows up as spikes above clear sky values, not a constant offset greater than clear sky values.

To determine recalibration need, input site conditions into the calculator and compare total shortwave radiation measurements to calculated values for a clear sky. If sensor shortwave radiation measurements over multiple days near solar noon are consistently different than calculated values (by more than 6 %), the sensor should be cleaned and re-leveled. If measurements are still different after a second test, email calibration@apogeeinstruments.com to discuss test results and possible return of sensor(s).



Homepage of the Clear Sky Calculator. Two calculators are available: one for quantum sensors (PPFD) and one for pyranometers (total shortwave radiation).



Clear Sky Calculator for quantum sensors. Site data are input in blue cells in middle of page and an estimate of PPFD is returned on right-hand side of page.

TROUBLESHOOTING AND CUSTOMER SUPPORT

Independent Verification of Functionality

If the sensor does not communicate with the datalogger, use an ammeter to check the current drain. It should be near 0.6 mA when the sensor is not communicating and spike to approximately 1.3 mA when the sensor is communicating. Any current drain greater than approximately 6 mA indicates a problem with power supply to the sensors, wiring of the sensor, or sensor electronics.

Compatible Measurement Devices (Dataloggers/Controllers/Meters)

Any datalogger or meter with SDI-12 functionality that includes the M or C command.

An example datalogger program for Campbell Scientific dataloggers can be found on the Apogee webpage at https://www.apogeeinstruments.com/content/Quantum-Digital.CR1.

Modifying Cable Length

SDI-12 protocol limits cable length to 60 meters. For multiple sensors connected to the same data line, the maximum is 600 meters of total cable (e.g., ten sensors with 60 meters of cable per sensor). See Apogee webpage for details on how to extend sensor cable length (http://www.apogeeinstruments.com/how-to-make-a-weatherproof-cable-splice/).

Unit Conversion Charts

Apogee SQ series quantum sensors are calibrated to measure PPFD in units of µmol m^{-2} s^{-1}. Units other than photon flux density (e.g., energy flux density, illuminance) may be required for certain applications. It is possible to convert the PPFD value from a quantum sensor to other units, but it requires spectral output of the radiation source of interest. Conversion factors for common radiation sources can be found on the Unit Conversions page in the Support Center on the Apogee website (http://www.apogeeinstruments.com/unit-conversions/; scroll down to Quantum Sensors section). A spreadsheet to convert PPFD to energy flux density or illuminance is also provided on the Unit Conversions page in the Support Center on the Apogee website (http://www.apogeeinstruments.com/content/PPFD-to-Illuminance-Calculator.xls).

RETURN AND WARRANTY POLICY

RETURN POLICY

Apogee Instruments will accept returns within 30 days of purchase as long as the product is in new condition (to be determined by Apogee). Returns are subject to a 10 % restocking fee.

WARRANTY POLICY

What is Covered
All products manufactured by Apogee Instruments are warranted to be free from defects in materials and craftsmanship for a period of four (4) years from the date of shipment from our factory. To be considered for warranty coverage an item must be evaluated by Apogee.

Products not manufactured by Apogee (spectroradiometers, chlorophyll content meters, EE08-SS probes) are covered for a period of one (1) year.

What is Not Covered
The customer is responsible for all costs associated with the removal, reinstallation, and shipping of suspected warranty items to our factory.

The warranty does not cover equipment that has been damaged due to the following conditions:

1. Improper installation or abuse.

2. Operation of the instrument outside of its specified operating range.

3. Natural occurrences such as lightning, fire, etc.

4. Unauthorized modification.

5. Improper or unauthorized repair.

Please note that nominal accuracy drift is normal over time. Routine recalibration of sensors/meters is considered part of proper maintenance and is not covered under warranty.

Who is Covered
This warranty covers the original purchaser of the product or other party who may own it during the warranty period.

What Apogee Will Do
At no charge Apogee will:

1. Either repair or replace (at our discretion) the item under warranty.

2. Ship the item back to the customer by the carrier of our choice.

Different or expedited shipping methods will be at the customer’s expense.

How To Return An Item
1. Please do not send any products back to Apogee Instruments until you have received a Return Merchandise

Authorization (RMA) number from our technical support department by submitting an online RMA form at www.apogeeinstruments.com/tech-support-recalibration-repairs/. We will use your RMA number for tracking of the service item. Call (435) 245-8012 or email techsupport@apogeeinstruments.com with questions.

2. For warranty evaluations, send all RMA sensors and meters back in the following condition: Clean the sensor's exterior and cord. Do not modify the sensors or wires, including splicing, cutting wire leads, etc. If a connector has been attached to the cable end, please include the mating connector – otherwise the sensor connector will be removed in order to complete the repair/recalibration. ***Note:*** *When sending back sensors for routine calibration that have Apogee's standard stainless-steel connectors, you only need to send the sensor with the 30 cm section of cable and one-half of the connector. We have mating connectors at our factory that can be used for calibrating the sensor.*

3. Please write the RMA number on the outside of the shipping container.

4. Return the item with freight pre-paid and fully insured to our factory address shown below. We are not responsible for any costs associated with the transportation of products across international borders.

Apogee Instruments, Inc.
721 West 1800 North Logan, UT
84321, USA

5. Upon receipt, Apogee Instruments will determine the cause of failure. If the product is found to be defective in terms of operation to the published specifications due to a failure of product materials or craftsmanship, Apogee Instruments will repair or replace the items free of charge. If it is determined that your product is not covered under warranty, you will be informed and given an estimated repair/replacement cost.

PRODUCTS BEYOND THE WARRANTY PERIOD

For issues with sensors beyond the warranty period, please contact Apogee at techsupport@apogeeinstruments.com to discuss repair or replacement options.

OTHER TERMS

The available remedy of defects under this warranty is for the repair or replacement of the original product, and Apogee Instruments is not responsible for any direct, indirect, incidental, or consequential damages, including but not limited to loss of income, loss of revenue, loss of profit, loss of data, loss of wages, loss of time, loss of sales, accruement of debts or expenses, injury to personal property, or injury to any person or any other type of damage or loss.

This limited warranty and any disputes arising out of or in connection with this limited warranty ("Disputes") shall be governed by the laws of the State of Utah, USA, excluding conflicts of law principles and excluding the Convention for the International Sale of Goods. The courts located in the State of Utah, USA, shall have exclusive jurisdiction over any Disputes.

This limited warranty gives you specific legal rights, and you may also have other rights, which vary from state to state and jurisdiction to jurisdiction, and which shall not be affected by this limited warranty. This warranty extends only to you and cannot by transferred or assigned. If any provision of this limited warranty is unlawful, void or unenforceable, that provision shall be deemed severable and shall not affect any remaining provisions. In case of any inconsistency between the English and other versions of this limited warranty, the English version shall prevail.

This warranty cannot be changed, assumed, or amended by any other person or agreements