apogee INSTRUMENTS

OWNER'S MANUAL

QUANTUM SENSOR

Model JSQ-421

(including SS Model)

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CERTIFICATE OF COMPLIANCE

EU Declaration of Conformity

for the following product(s):

Models: JSQ-421
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.

The acronym PPF is also widely used and refers to the photosynthetic photon flux. The acronyms PPF and PPFD refer to the same parameter. The two terms have co-evolved because there is not a universal definition of the term "flux". Some physicists define flux as per unit area per unit time. Others define flux only as per unit time. We have used PPFD in this manual because we feel that it is better to be more complete and possibly redundant.

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.

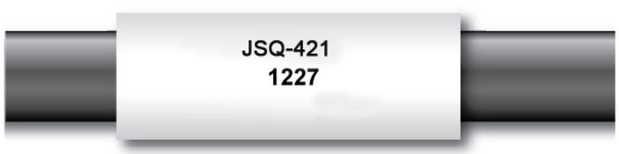
Typical applications of quantum sensors include incoming PPFD measurement over plant canopies in outdoor environments or in greenhouses and growth chambers, and reflected or under-canopy (transmitted) PPFD measurement in the same environments.

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. Sensors are potted solid with no internal air space, and are designed for continuous PPFD measurement in indoor or outdoor environments. JSQ-421 model sensors output a digital signal using SDI-12 communication protocol.

SENSOR MODELS

This manual covers the SDI-12 communication protocol, original quantum sensor model JSQ-421. Additional models are covered in their respective manuals.

Model	Signal	Calibration
JSQ-421	**SDI-12**	**Sunlight and Electric light**
JSQ-110	Self-powered	Sunlight
JSQ-120	Self-powered	Electric light
JSQ-311	Self-powered	Sunlight
JSQ-321	Self-powered	Electric light
JSQ-313	Self-powered	Sunlight
JSQ-323	Self-powered	Electric light
JSQ-316	Self-powered	Sunlight
JSQ-326	Self-powered	Electric light
JSQ-212	0-2.5 V	Sunlight
JSQ-222	0-2.5 V	Electric light
JSQ-214	4-20 mA	Sunlight
JSQ-224	4-20 mA	Electric light
JSQ-215	0-5 V	Sunlight
JSQ-225	0-5 V	Electric light
JSQ-420	USB	Sunlight and Electric light
JSQ-422	ModBus	Sunlight and Electric light



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.

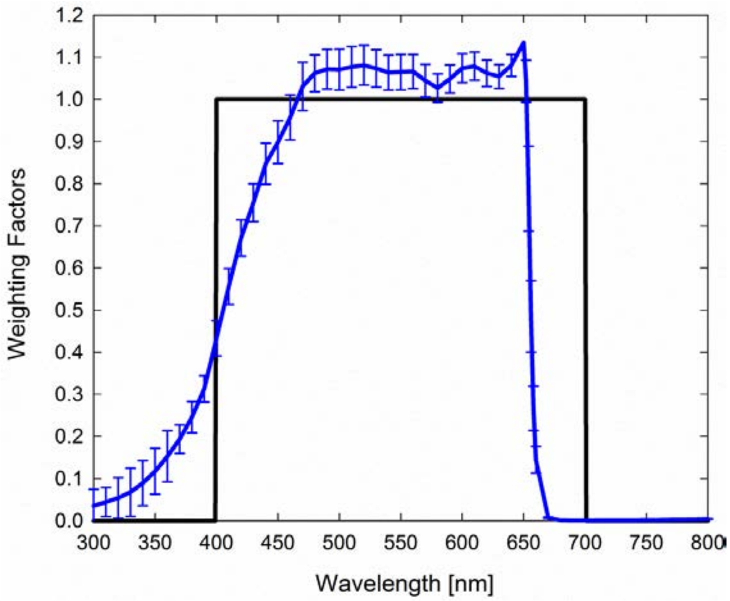
SPECIFICATIONS

	JSQ--421
Input Voltage Requirement	5.5 to 24 V DC
Current Drain	0.6 mA (quiescent), 1.3 mA (active)
Calibration Uncertainty	± 5 % (see Calibration Traceability below)
Measurement Repeatability	Less than 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	180º
Spectral Range	410 to 655 nm (wavelengths where response is greater than 50% of maximum; see Spectral Response below)
Directional (Cosine) Response	± 5 % at 75º zenith angle (see Cosine Response below)
Temperature Response	0.06 ± 0.06 % per C (see Temperature Response below)
Operating Environment	-40 to 70 C; 0 to 100 % relative humidity; can be submerged in water up to depths of 30 m
Dimensions	44.0 mm height, 23.5 mm diameter
Mass	117 g (with 5 m cable)
Cable	5 m of two conductor, shielded, twisted-pair wire, additional cable available in multiples of 5 m; santoprene rubber jacket (high water resistance, high UV stability, flexibility in cold conditions); pigtail lead wires

Calibration Traceability

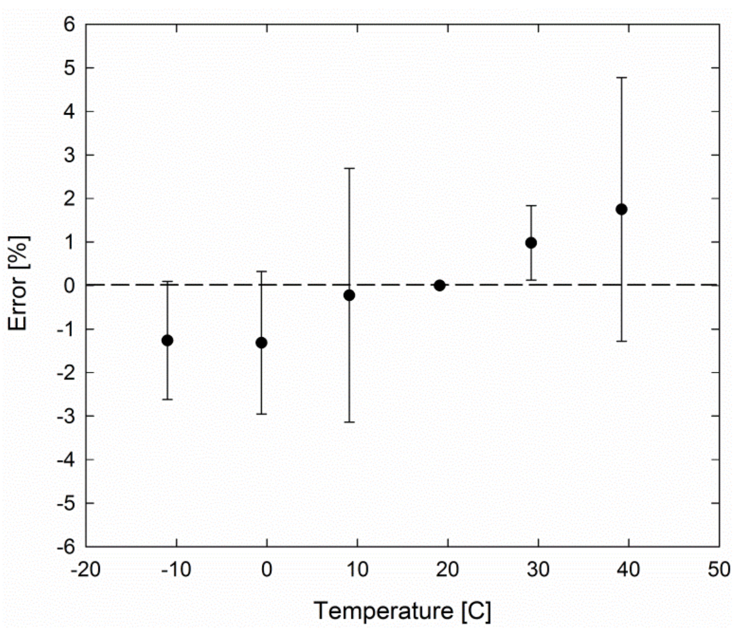
Apogee JSQ original quantum sensor series are calibrated through side-by-side comparison to the mean of four Apogee model JSQ-110 or JSQ-120 transfer standard quantum sensors under high output T5 cool white fluorescent lamps. The transfer standard quantum sensors are calibrated through side-by-side comparison 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 Optical Radiation Calibrator using a 200 W quartz halogen lamp. The 1800-02 and quartz halogen lamp are traceable to the National Institute of Standards and Technology (NIST).

Spectral Response



Mean spectral response of six JSQ original quantum series sensors (***error bars represent two standard deviations above and below mean***) compared to PPFD weighting function. 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.

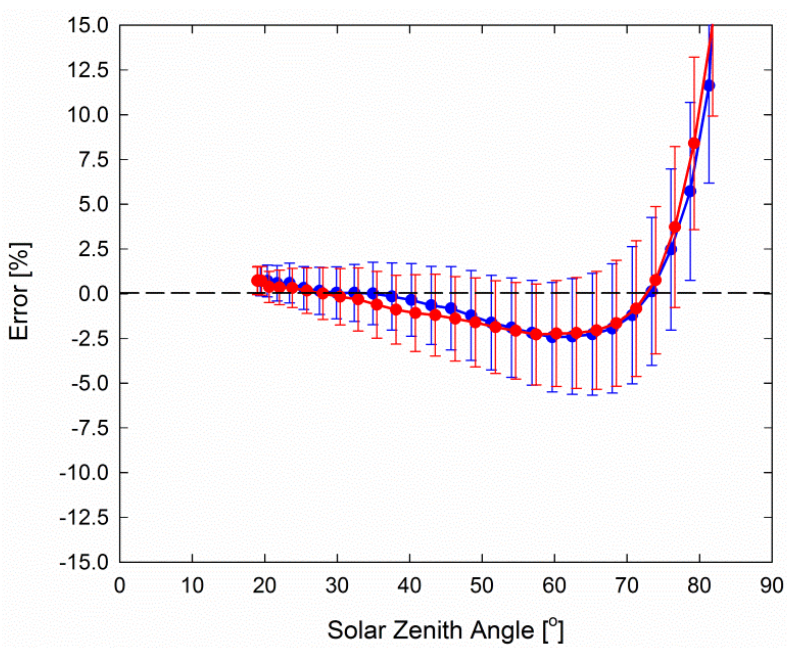
Temperature Response



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



Mean cosine response of twenty-three JSQ original quantum series sensors (***error bars represent two standard deviations above and below mean***). Cosine response measurements were made by direct side-by-side comparison to the mean of four reference thermopile pyranometers, with solar zenith angle-dependent factors applied to convert total shortwave radiation to PPFD. Blue points represent the AM response and red points represent the PM response.

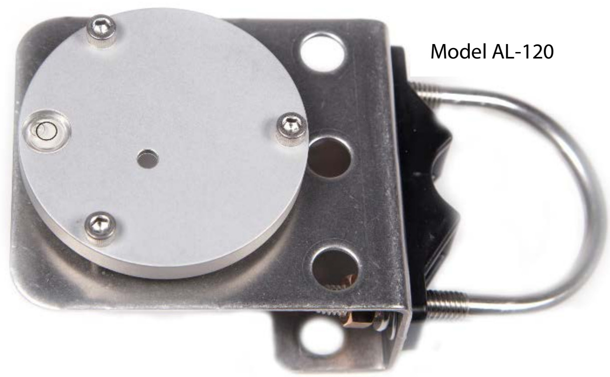
DEPLOYMENT AND INSTALLATION

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 to level the sensor when used on a flat surface or being mounted to surfaces such as wood. To facilitate mounting on a mast or pipe, the Apogee Instruments model AL-120 Solar Mounting Bracket with Leveling Plate is recommended.

Nylon Screw: 10-32 x 3/8

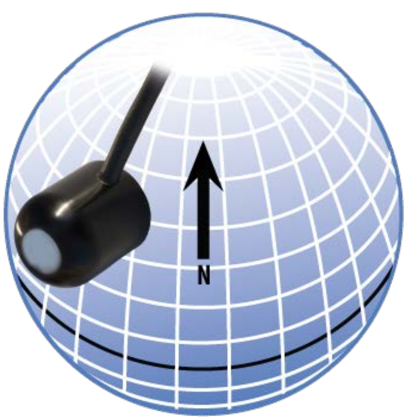
Nylon Screw: 10-32 x 3/8

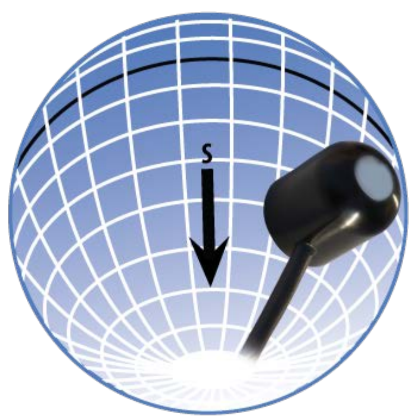
Model AL-100



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 1 %, 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.

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.

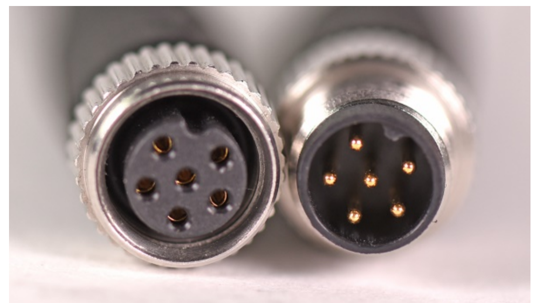
The ruggedized M8 connectors are rated IP67, made of corrosion-resistant marine-grade stainless-steel, and designed for extended use in harsh environmental conditions.

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.



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

Alignment: When reconnecting your 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 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.

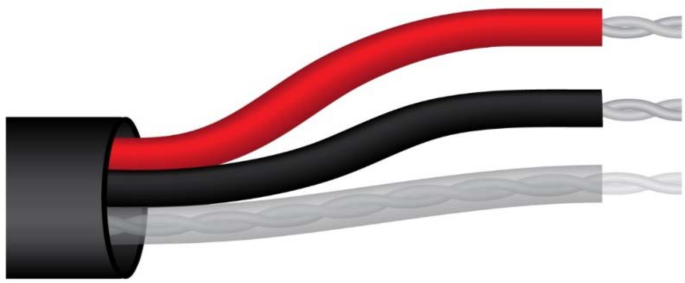
Finger-tighten firmly

OPERATION AND MEASUREMENT

The JSQ-421 quantum sensor has a SDI-12 output, where shortwave radiation is returned in digital format. Measurement of JSQ-421 quantum sensors requires a measurement device with SDI-12 functionality that includes the M or C command.

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-421 Serial Numbers within the range 0-2052

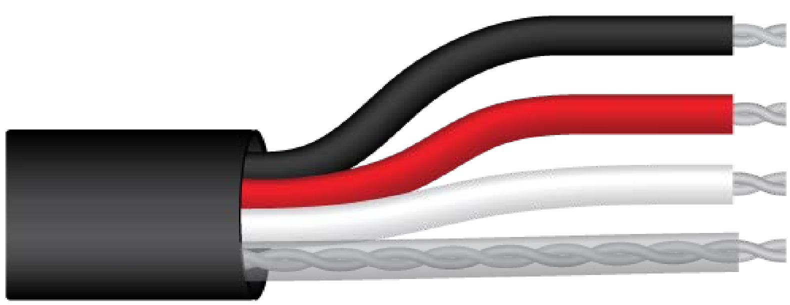


Red: Power In (4.5-24 V DC)

Black: SDI-12 Data Line

Clear: Ground (shield wire)

Wiring for JSQ-421 Serial Numbers 2053 and above or with a cable connector



Black: Ground

Red: Power In (5.5-24 V DC)

White: SDI-12 Data Line

Clear: Shield/Ground

Sensor Calibration

All Apogee SDI-12 JSQ-400 series quantum sensors 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 JSQ-421 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 JSQ-421 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 JSQ-421 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

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} using electric light calibration
aM1!	a0011<cr><lf>	Returns millivolt output
aM2!	a0011<cr><lf>	Returns µmol m^{-2} s^{-1} using sunlight calibration
aM3!	a0011<cr><lf>	Returns immersed µmol m^{-2} s^{-1} for underwater measurements with electric light calibration
aMC0!	a0011<cr><lf>	Returns µmol m^{-2} s^{-1} using electric light calibration w/CRC
aMC1!	a0011<cr><lf>	Returns millivolt output w/ CRC
aMC2!	a0011<cr><lf>	Returns µmol m^{-2} s^{-1} using sunlight calibration w/ CRC
aMC3!	a0011<cr><lf>	Returns immersed µmol m^{-2} s^{-1} for underwater measurements with electric light calibration w/ CRC

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>	

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

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} using electric light calibration
aC1!	a00101<cr><lf>	Returns millivolt output
aC2!	a00101<cr><lf>	Returns µmol m^{-2} s^{-1} using sunlight calibration
aC3!	a00101<cr><lf>	Returns immersed µmol m^{-2} s^{-1} for underwater measurements with electric light calibration
aCC! or aCC0!	a00101<cr><lf>	Returns µmol m^{-2} s^{-1} using electric light calibration w/CRC
aCC1!	a00101<cr><lf>	Returns millivolt output w/CRC
aCC2!	a00101<cr><lf>	Returns µmol m^{-2} s^{-1} using sunlight calibration w/CRC
aCC3!	a00101<cr><lf>	Returns immersed µmol m^{-2} s^{-1} for underwater measurements with electric light calibration w/CRC

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>

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 JSQ-421vvvxx…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", "*", "?"), 421 is the sensor model number, vvv is a three character field specifying the sensor version number, and xx...xx is serial number.

Metadata Commands

Identify Measurement Commands

The Identify Measurement Commands can be used to view the command response without making a measurement. The command response indicates the time it takes to make the measurement and the number of data values that it returns. It works with the Verification Command (aV!), Measurement Commands (aM!, aM1! … aM9!, aMC!, aMC1! … aMC9!), and Concurrent Measurement Commands (aC!, aC1! … aC9! , aCC!, aCC1! … aCC9!).

The format of the Identify Measurement Command is the address, the capital letter I, the measurement command, and the command terminator ("!"), as follows:

<address>I<command>!

The format of the response is the same as if the sensor is making a measurement. For the Verification Command and Measurement Commands, the response is atttn<CR><LF>. For the C Command, it is atttnn<CR><LF>. For the High Volume Commands, it is atttnnn<CR><LF>. The address is indicated by a, the time in seconds to make the measurement is indicated by ttt, and the number of measurements is indicated by n, nn, and nnn. The response is terminated with a Carriage Return (<CR>) and Line Feed (<LF>).

Identify Measurement Command example:

3IMC2!	The Identify Measurement Command for sensor address 3, M2 command, requesting a CRC.
30032<CR><LF>	The response from sensor address three indicating that the measurement will take three seconds and two data values will be returned.

Identify Measurement Parameter Commands

The Measurement Parameter Commands can be used to retrieve information about each data value that a command returns. The first value returned is a Standard Hydrometeorological Exchange Format (SHEF) code. SHEF codes are published by the National Oceanic and Atmospheric Administration (NOAA). The SHEF code manual can be found at http://www.nws.noaa.gov/oh/hrl/shef/indexshef.htm. The second value is the units of the parameter. Additional fields with more information are optional.

The Measurement Parameter Commands work with the Verification Command (aV!), Measurement Commands (aM!, aM1! … aM9!, aMC!, aMC1! … aMC9!), and Concurrent Measurement Commands (aC!, aC1! … aC9! , aCC!, aCC1! … aCC9!).

The format of the Identify Measurement Parameter Command is the address, the capital letter I, the measurement command, the underscore character ("_"), a three-digit decimal number, and the command terminator ("!"). The three-digit decimal indicates which number of measurement that the command returns, starting with "001" and continuing to "002" and so on, up to the number of measurements that the command returns.

<address>I<command>_<three-digit decimal>!

The format of the response is comma delimited and terminated with a semicolon. The first value is the address. The second value is the SHEF code. The third value is the units. Other optional values may appear, such as a description of the data value. The response is terminated with a Carriage Return (<CR>) and Line Feed (<LF>).

a,<SHEF Code>,<units>;<CR><LF>

Identify Measurement Parameter Command example:

1IC_001!	The Identify Measurement Parameter Command for sensor address 1, C command, data value 1.
1,RW,Watts/meter squared,incoming solar radiation;<CR><LF>	The response from sensor address 1, SHEF code RW, units of Watts/meter squared, and additional information of incoming solar radiation.

Sunlight and Electric light Calibration

Apogee JSQ-421 quantum sensors are calibrated to measure PPFD for both sunlight and electric light. The difference between the calibrations is 12 %. The electric light calibration (calibration source is T5 cool white fluorescent lamps) will read approximately 12 % low in sunlight. The aM!, aMC!, aC!, or aCC! commands return the sensor PPFD measurement with electric light calibration. The aM2!, aMC2!, aC2!, or aCC2! commands return the sensor PPFD measurement with sunlight calibration.

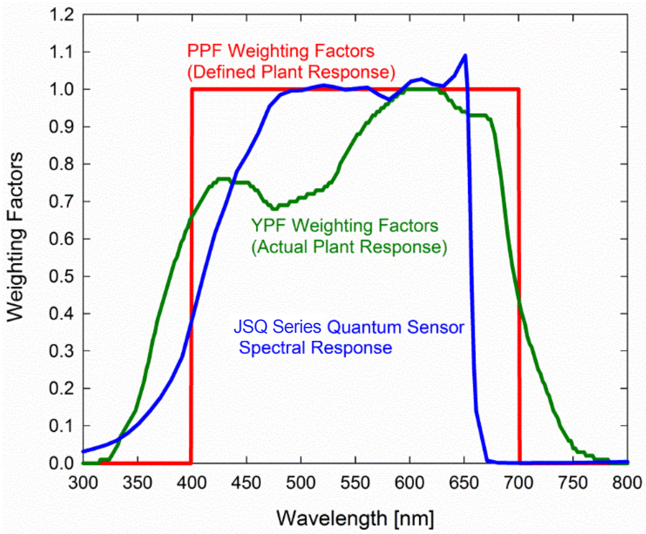
Spectral Errors and Yield Photon Flux Measurements

In addition to PPFD measurements, Apogee JSQ series quantum sensors can also be used to measure yield photon flux density (YPFD): photon flux density weighted according to plant photosynthetic efficiency (McCree, 1972) and summed. YPFD is also expressed in units of µmol m^{-2} s^{-1}, and is similar to PPFD, but has been reported to be more closely correlated to photosynthesis than PPFD in some studies. PPFD is usually measured and reported because the PPFD spectral weighting function (equal weight given to all photons between 400 and 700 nm; no weight given to photons outside this range) is easier to define and measure, and as a result, PPFD is widely accepted. The calibration factor for YPFD is 4.50 and 4.45 µmol m^{-2} s^{-1} per mV for sunlight and electric light measurements, respectively.

The weighting functions for PPFD and YPFD are shown in the graph below, along with the spectral response of Apogee JSQ series quantum sensors. The closer the spectral response matches the defined PPFD or YPFD spectral weighting functions, the smaller spectral errors will be. The table below provides spectral error estimates for PPFD and YPFD measurements from light sources different than the calibration source. The method of Federer and Tanner (1966) was used to determine spectral errors based on the PPFD and YPFD spectral weighting functions, measured sensor spectral response, and radiation source spectral outputs (measured with a spectroradiometer). This method calculates spectral error and does not consider calibration, cosine, and temperature errors.

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

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



Radiation weighting factors for PPFD (defined plant response to radiation), YPFD (measured plant response to radiation), and Apogee JSQ Series quantum sensors (sensor sensitivity to different wavelengths of radiation).

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

Radiation Source (Error Calculated Relative to Sun, Clear Sky)	PPFD Error [%]	YPFD Error [%]
Sun (Clear Sky)	0.0	0.0
Sun (Cloudy Sky)	1.4	1.6
Reflected from Grass Canopy	5.7	-6.3
Reflected from Deciduous Canopy	4.9	-7.0
Reflected from Conifer Canopy	5.5	-6.8
Transmitted below Grass Canopy	6.4	-4.5
Transmitted below Deciduous Canopy	6.8	-5.4
Transmitted below Conifer Canopy	5.3	2.6
Radiation Source (Error Calculated Relative to Cool White Fluorescent, T5)		
Cool White Fluorescent (T5)	0.0	0.0
Cool White Fluorescent (T8)	-0.3	-1.2
Cool White Fluorescent (T12)	-1.4	-2.0
Compact Fluorescent	-0.5	-5.3
Metal Halide	-3.7	-3.7
Ceramic Metal Halide	-6.0	-6.4
High Pressure Sodium	0.8	-7.2
Blue LED (448 nm peak, 20 nm full-width half-maximum)	-12.7	8.0
Green LED (524 nm peak, 30 nm full-width half-maximum)	8.0	26.2
Red LED (635 nm peak, 20 nm full-width half-maximum)	4.8	-6.2
Red, Blue LED Mixture (85 % Red, 15 % Blue)	2.4	-4.4
Red, Green, Blue LED Mixture (72 % Red, 16 % Green, 12 % Blue)	3.4	0.2
Cool White Fluorescent LED	-4.6	-0.6
Neutral White Fluorescent LED	-6.7	-5.2
Warm White Fluorescent LED	-10.9	-13.0

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.

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-400 series sensors have an immersion effect correction factor of 1.08. The immersion effect correction factor is automatically applied to the sensor measurement when using the aM3!, aMC3!, aC3!, and aCC3! commands. These commands return an electric light calibration PPFD value that has been multiplied by the immersion effect correction factor of 1.08. The immersion effect correction factor will need to be multiplied to all other measurement and concurrent commands when the sensor is used for underwater measurements.