

apogee

INSTRUMENTS

OWNER'S MANUAL

QUANTUM SENSOR

Model SQ-212, SQ-222, SQ-215, and SQ-225

Rev: 28-Oct-2020



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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-212, SQ-222, SQ-215, SQ-225
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 ($\mu\text{mol m}^{-2} \text{s}^{-1}$, equal to microEinsteins $\text{m}^{-2} \text{s}^{-1}$). While microEinsteins and micromoles are equal (one Einstein = one mole of photons), the Einstein is not an SI unit, so expressing PPFD as $\mu\text{mol m}^{-2} \text{s}^{-1}$ is preferred. Daily total PPFD is typically reported in units of moles of photons per square meter per day ($\text{mol m}^{-2} \text{d}^{-1}$) 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. Sensors are potted solid with no internal air space, and are designed for continuous PPFD measurement in indoor or outdoor environments. SQ series sensors output an analog voltage that is directly proportional to PPFD under sunlight (e.g., model SQ-215) or electric lights (e.g., model SQ-225). The voltage 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

This manual covers quantum sensor models SQ-212/SQ/222 and SQ-215/SQ-225, which provide a voltage signal. Additional models are covered in their respective manuals.

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



Serial Numbers 10574 (SQ-212), 10274 (SQ-222), 10434 (SQ-215), 10534 (SQ-225) and above: Sensor model number and serial number are located on the bottom of the sensor. If you need the manufacturing date of your sensor, please contact Apogee Instruments with the



Serial Number 0-10573 (SQ-212), 0-10273 (SQ-222), 0-10433 (SQ-215), 0-10533 (SQ-225) 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.

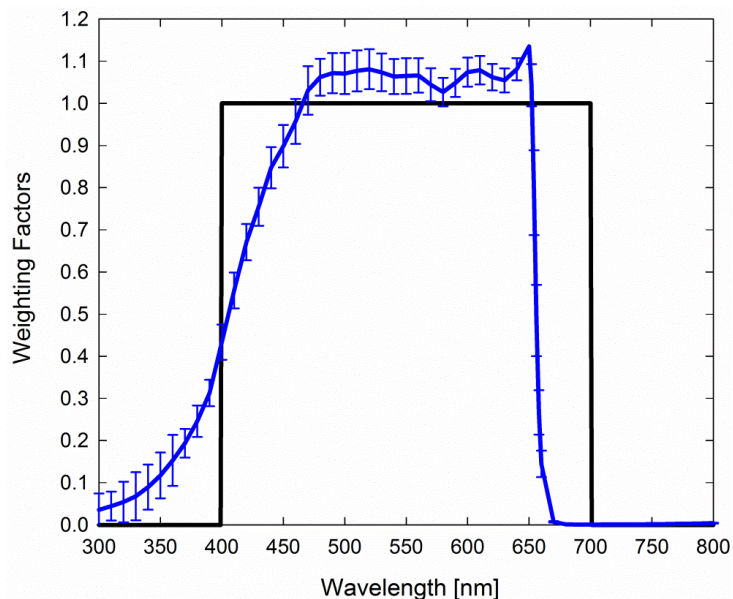
SPECIFICATIONS

	SQ-212/SQ-222-SS	SQ-215/SQ-225-SS
Power Supply	5 to 24 V DC; nominal current draw 300 μ A	5.5 to 24 V DC ^{**} ; nominal current draw 300 μ A ^{**} Sensors with a serial number smaller than 3762 should not be powered with more than 5 V DC
Sensitivity Serial # 8382 and above	0.6 mV per μ mol m ⁻² s ⁻¹	1.25 mV per μ mol m ⁻² s ⁻¹
Sensitivity Serial # 0-8381	1 mV per μ mol m ⁻² s ⁻¹	2 mV per μ mol m ⁻² s ⁻¹
Calibration Factor Serial # 8382 and above	1.6 μ mol m ⁻² s ⁻¹ per mV	0.8 μ mol m ⁻² s ⁻¹ per mV
Calibration Factor Serial # 0-8381	1 μ mol m ⁻² s ⁻¹ per mV	0.5 μ mol m ⁻² s ⁻¹ per mV
Calibrated Output Range	0 to 2.5 V	0 to 5 V
Calibration Uncertainty	\pm 5 % (see Calibration Traceability below)	
Measurement Repeatability	Less than 0.5 %	
Long-term Drift (Non-stability)	Less than 2 % per year	
Non-linearity Serial # 8382 and above	Less than 1 % (up to 4000 μ mol m ⁻² s ⁻¹ ; maximum PPF measurement is 4000 μ mol m ⁻² s ⁻¹)	
Non-linearity Serial # 0-8381	Less than 1 % (up to 2500 μ mol m ⁻² s ⁻¹ ; maximum PPF measurement is 2500 μ mol m ⁻² s ⁻¹)	
Response Time	Less than 1 ms	
Field of View	180°	
Spectral Range	410 to 655 nm (wavelengths where response is greater than 50 % of maximum; see Spectral Response below)	
Spectral Selectivity	Less than 10 % from 469 to 655 nm	
Directional (Cosine) Response	\pm 5 % at 75° zenith angle (see Cosine Response below)	
Temperature Response	0.06 \pm 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 Serial # 10574 (SQ-212), 10274 (SQ-222), 10434 (SQ-215), 10534 (SQ-225) and above	30.5 mm diameter, 37 mm height	
Dimensions Serial # 0-10573 (SQ-212), 0-10273 (SQ-222), 0-10433 (SQ-215), 0-10533 (SQ-225)	24 mm diameter, 33 mm height	
Mass (with 5 m cable) Serial # 10574 (SQ-212), 10274 (SQ-222), 10434 (SQ-215), 10534 (SQ-225) and above	140 g	
Mass (with 5 m cable) Serial # 0-10573 (SQ-212), 0-10273 (SQ-222), 0-10433 (SQ-215), 0-10533 (SQ-225)	100 g	
Cable	5 m of two conductor, 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

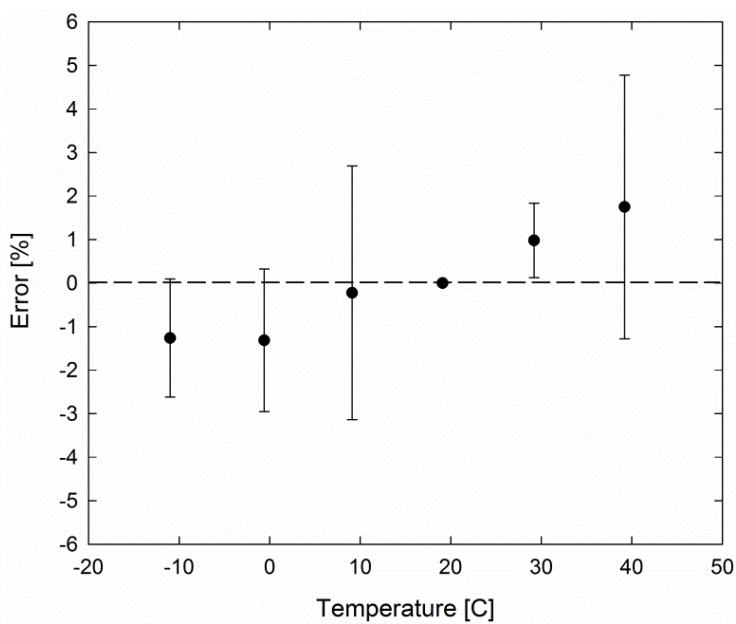
Apogee SQ series quantum sensors are calibrated through side-by-side comparison to the mean of transfer standard quantum sensors under a reference lamp. The reference quantum sensors are recalibrated with a 200 W quartz halogen lamp traceable to the National Institute of Standards and Technology (NIST).

Spectral Response



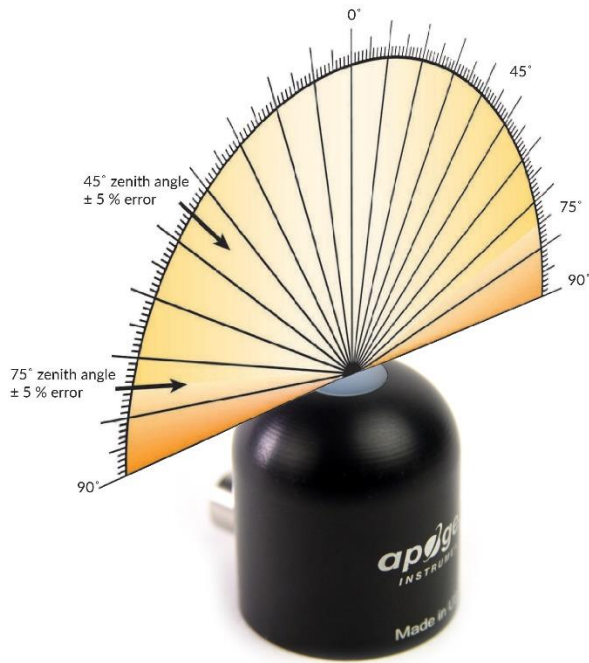
Mean spectral response of six SQ-100 series quantum sensors (**error bars represent two standard deviations above and below mean**) compared to defined plant response to photons. Spectral response measurements were made at 10 nm increments across a wavelength range of 300 to 800 nm with a monochromator 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

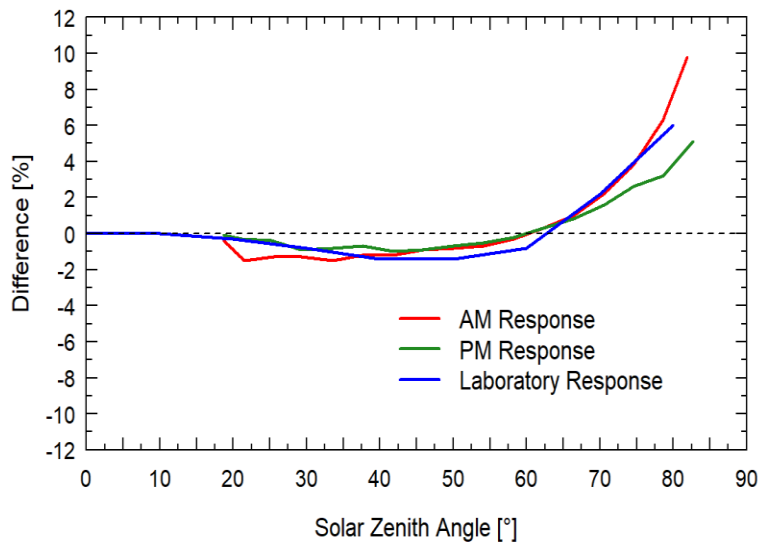


Mean temperature response of eight SQ-100 series quantum sensors (**errors bars represent two standard deviations above and below mean**). Temperature response measurements were made at 10 C intervals across a temperature range of approximately -10 to 40 C in a temperature controlled chamber under a 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-100 series quantum sensors is approximately ± 2 % and ± 5 % at solar zenith angles of 45° and 75°, respectively.



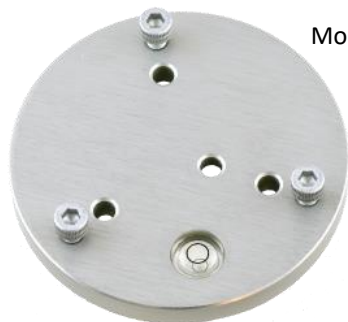
Mean directional (cosine) response of six apogee SQ-100 series quantum sensors. Directional response measurements were made on the rooftop of the Apogee building in Logan, Utah. Directional response was calculated as the relative difference of SQ-500 quantum sensors from the mean of replicate reference 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 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.



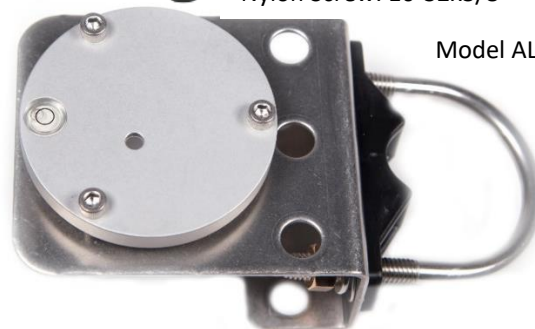
Nylon Screw: 10-32x3/8



Model AL-100



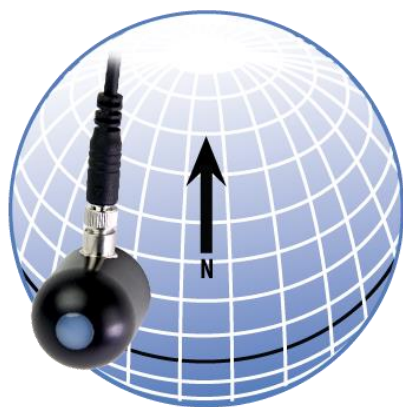
Nylon Screw: 10-32x3/8



Model AL-120

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.

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 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 started offering cable connectors on some bare-lead sensors in March 2018 to 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.

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 connection to a measurement device, the unused pigtail lead wire colors are removed.

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

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.

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 not tighten the connector by twisting the black cable or sensor head, only twist the metal connector (yellow arrows).



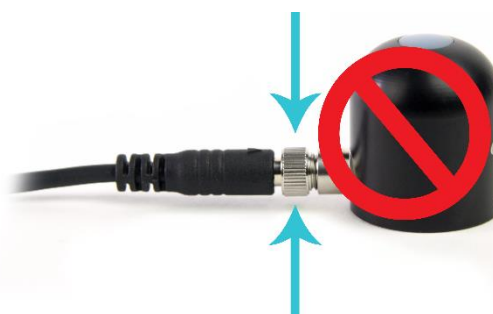
Cable connectors are attached directly to the head.



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



When sending sensors in for calibration, only send the sensor head.



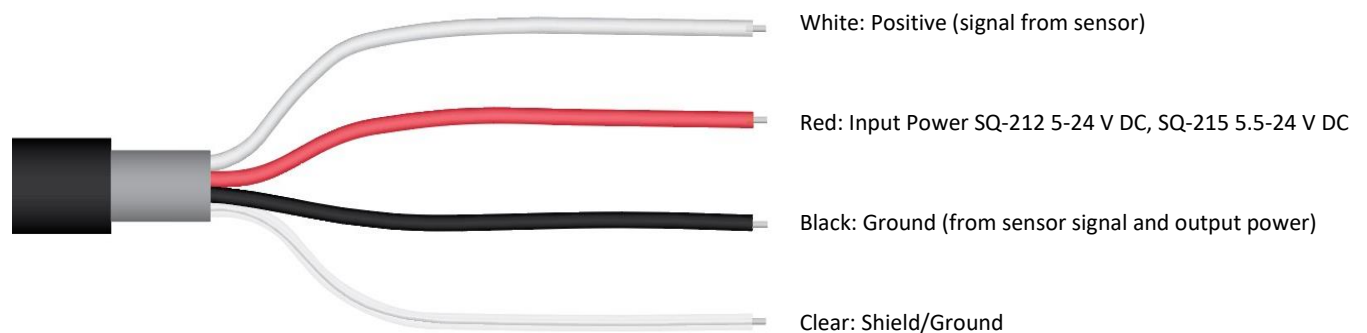
Finger-tighten firmly

OPERATION AND MEASUREMENT

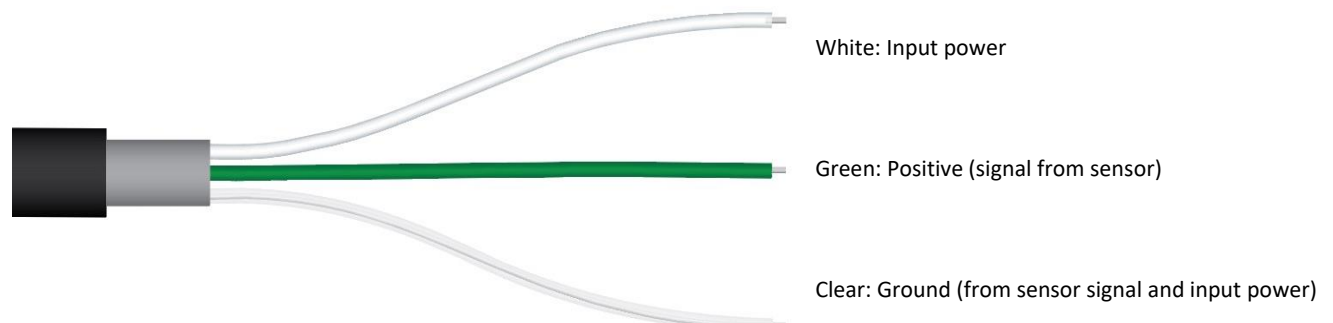
Connect the sensor to a measurement device (meter, datalogger, controller) capable of measuring and displaying or recording a voltage signal with a range of 0-2.5 V (SQ-212/222) or 0-5 V (SQ-215/225) to cover the entire range of PPFD from the sun. In order to maximize the measurement resolution and signal-to-noise ratio, the signal input range of the measurement device should closely match the output range of the quantum sensors. The amplification circuit requires a power supply of 5-24 VDC (SQ-212/222) or 5.5-24 VDC (SQ-215/225). NOTE: To prevent sensor damage, **DO NOT connect the sensor to a power source greater than 24 VDC.**

VERY IMPORTANT: Apogee changed the wiring colors of all 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 listed below. With the switch to connectors, we also changed to using cables that only have 4 or 7 internal wires. To make our various sensors easier to connect to your device, we clip off any unused wire colors at the end of the cable depending on the sensor. If you cut the cable or modify the original pigtail, you may find wires inside that are not used with your particular sensor. In this case, please disregard the extra wires and follow the color-coded wiring guide provided.

Wiring for SQ-212 and SQ-215 with Serial Numbers 7598 and above or with a cable connector



Wiring for SQ-212 and SQ-215 within Serial Number range 0-7597



Sensor Calibration

Serial Number Range 0-8381. Apogee amplified quantum sensor models have a standard PPFD calibration factor of exactly:

SQ-212, SQ-222: 1.0 $\mu\text{mol m}^{-2} \text{s}^{-1}$ per mV
SQ-215, SQ-225: 0.5 $\mu\text{mol m}^{-2} \text{s}^{-1}$ per mV

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

Calibration Factor (0.5 $\mu\text{mol m}^{-2} \text{s}^{-1}$ per mV) * Sensor Output Signal (mV) = PPFD ($\mu\text{mol m}^{-2} \text{s}^{-1}$)

0.5	*	4000	=	2000
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Serial Numbers 8382 and above. Apogee amplified quantum sensor models have a standard PPFD calibration factor of exactly:

SQ-212, SQ-222: 1.6 $\mu\text{mol m}^{-2} \text{s}^{-1}$ per mV
SQ-215, SQ-225: 0.8 $\mu\text{mol m}^{-2} \text{s}^{-1}$ per mV

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

Calibration Factor (0.8 $\mu\text{mol m}^{-2} \text{s}^{-1}$ per mV) * Sensor Output Signal (mV) = PPFD ($\mu\text{mol m}^{-2} \text{s}^{-1}$)

0.8	*	2500	=	2000
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SQ-215/225

Sensor Output: 2.5 V
 Conversion Factor: 0.8 $\mu\text{mol m}^{-2} \text{s}^{-1}$ per mV

SQ-212-222

Sensor Output: 1.25 V
 Conversion Factor: 1.6 $\mu\text{mol m}^{-2} \text{s}^{-1}$ per mV

Serial Number Range 0-8381. Example of PPFD measurement with an Apogee quantum sensor. Full sunlight yields a PPFD on a horizontal plane at the Earth’s surface of approximately 2000 $\mu\text{mol m}^{-2} \text{s}^{-1}$. This yields an output signal of 4000 mV for the 0-5 V option or an output signal of 2000 mV for the 0-2.5 V option. The signal is converted to PPFD by multiplying by the calibration factor.

Serial Numbers 8382 and above. Example of PPFD measurement with an Apogee quantum sensor. Full sunlight yields a PPFD on a horizontal plane at the Earth’s surface of approximately 2000 $\mu\text{mol m}^{-2} \text{s}^{-1}$. This yields an output signal of 2500 mV for the 0-5 V option or an output signal of 1250 mV for the 0-2.5 V option. The signal is converted to PPFD by multiplying by the calibration factor.

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 PPF measurements made under common radiation sources for growing plants were calculated for Apogee SQ-100/300 and SQ-500 series quantum sensors using the method of Federer and Tanner (1966). This method requires PPF 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 PPF, 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 PPF Measurements with Apogee SQ-100 and SQ-500 Series Quantum Sensors

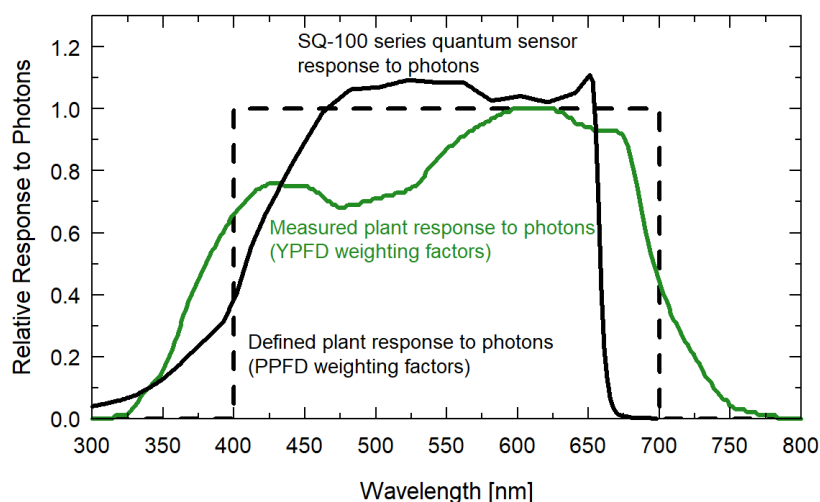
Radiation Source (Error Calculated Relative to Sun, Clear Sky)	SQ-100/300 Series PPFD Error [%]	SQ-500 Series PPFD Error [%]
Sun (Clear Sky)	0.0	0.0
Sun (Cloudy Sky)	0.2	0.1
Reflected from Grass Canopy	3.8	-0.3
Transmitted below Wheat Canopy	4.5	0.1
Cool White Fluorescent (T5)	0.0	0.1
Metal Halide	-2.8	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 (YFPD) Measurements

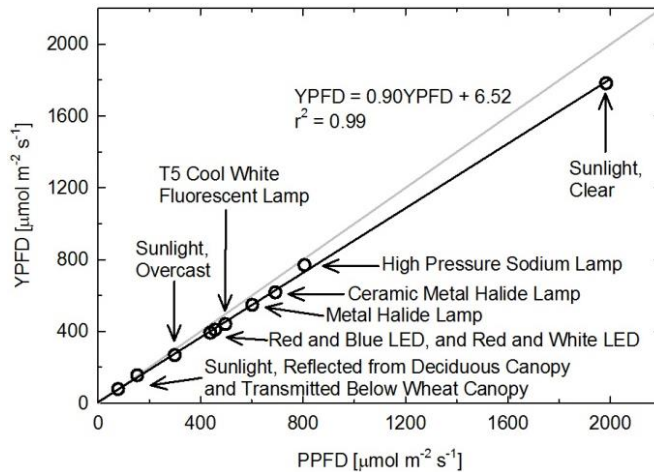
Photosynthesis in plants does not respond equally to all photons. Relative quantum yield (plant photosynthetic efficiency) is dependent on wavelength (green line in figure below) (McCree, 1972a; Inada, 1976). This is due to the combination of spectral absorptivity of plant leaves (absorptivity is higher 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 YFPD), and SQ-100 series and SQ-300 series quantum sensor response to photons (sensor spectral response).

One potential definition of PAR is weighting photon flux density in units of $\mu\text{mol m}^{-2} \text{s}^{-1}$ 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 (YFPD, units of $\mu\text{mol m}^{-2} \text{s}^{-1}$) (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 $\mu\text{mol m}^{-2} \text{s}^{-1}$), was well correlated to photosynthesis, and very similar to correlation between YFPD 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 YFPD measurements for several radiation sources is very high (figure below), as an approximation, $\text{YFPD} = 0.9\text{PPFD}$. As a result, almost universally PAR is defined as PPFD rather than YFPD, although YFPD 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 YFPD weighting factors (measured relative quantum yield) are at or near one. The factor for converting PPFD to YFPD for HPS lamps is 0.95, rather than 0.90. The factor for converting PPFD to YFPD 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-100 series and SQ-300 series quantum sensors have an immersion effect correction factor of 1.08. 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 calibration drift is normal for all research-grade sensors. To ensure maximum accuracy, recalibration every two years is recommended. Longer time periods between recalibration may be warranted depending on tolerances. See the Apogee webpage for details regarding return of sensors for recalibration (<http://www.apogeeinstruments.com/tech-support-recalibration-repairs/>).

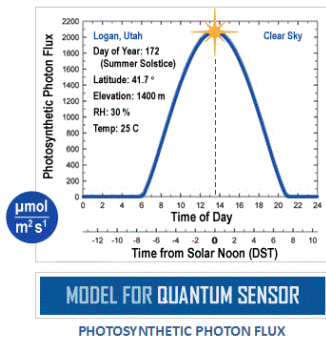
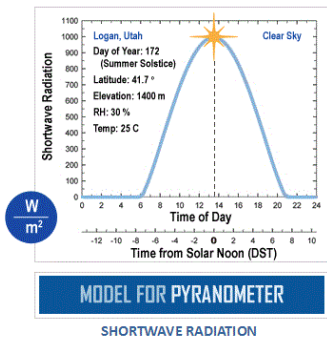
To determine if a specific sensor needs recalibration, the Clear Sky Calculator (www.clearskycalculator.com) website and/or smartphone app can be used to indicate PPFD incident on a horizontal surface at any time of day at any location in the world. It is most accurate when used near solar noon in spring and summer months, where accuracy over multiple clear and unpolluted days is estimated to be $\pm 4\%$ 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 PPFD can exceed PPFD predicted by the Clear Sky Calculator due to reflection from thin, high clouds and edges of clouds, which enhances incident PPFD. 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 PPFD measurements to calculated PPFD for a clear sky. If sensor PPFD measurements over multiple days near solar noon are consistently different than calculated PPFD (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).

Clear Sky CALCULATOR

This calculator determines the intensity of radiation falling on a horizontal surface at any time of the day in any location in the world. The primary use of this calculator is to determine the need for recalibration of radiation sensors. It is most accurate when used near solar noon in the summer months.

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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

Input Parameters for Estimating Photosynthetic Photon Flux (PPF):

Output from Model:

- For best accuracy, comparison should be made on clear, non-polluted, summer days within one hour of solar noon.
- Enter input parameters in the blue cells at right. Definitions are shown below.
- Sensor must be level and perfectly clean. Enter your measured solar radiation in the blue "Measured PPF" cell at far right.
- Difference between the model and your sensor is shown in the yellow "DIFFERENCE FROM MODEL" cell at right.
- Run the model on replicate days. Contact Apogee for recalibration if the measured value is more than 5 % different than the estimated value. You will be contacted within two business days.

For a discussion on model accuracy and sensitivity of input parameters, [CLICK HERE](#).

Latitude =

Longitude =

Longitude_{tz} =

Elevation = m

Day of Year =

Time of Day = (6 min = 0.1 hr)

Daylight Savings = hr

Air Temperature = C

Relative Humidity = %

Model Estimated PPF = $\mu\text{mol m}^{-2} \text{s}^{-1}$

Measured PPF = $\mu\text{mol m}^{-2} \text{s}^{-1}$

DIFFERENCE FROM MODEL = %

[CONTACT APOGEE FOR RECALIBRATION](#)

Name:

E-mail:

Phone:

Serial #:

Comments:

Please include all requested information.

INPUT AND OUTPUT DEFINITIONS

Latitude = latitude of the measurement site [degrees]; for southern hemisphere, insert as a negative number; info may be obtained from <http://touchmap.com/latlong.html>

Longitude = longitude of the measurement site [degrees]; expressed as positive degrees west of the standard meridian in Greenwich, England (e.g. 74° for New York, 260° for Bangkok, Thailand, and 358° for Paris, France).

Longitude_{tz} = longitude of the center of your local time zone [degrees]; expressed as positive degrees

This site is developed and maintained by: **apogee** INSTRUMENTS

calibration@apogee-inst.com

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

TROUBLESHOOTING AND CUSTOMER SUPPORT

Independent Verification of Functionality

Apogee SQ-200 series quantum sensors provide an amplified voltage output that is proportional to incident PPF. A quick and easy check of sensor functionality can be determined using a DC power supply and a voltmeter. Power the sensor with a DC voltage by connecting the positive voltage signal to the red wire from the sensor and the negative (or common) to the black wire from the sensor. Use the voltmeter to measure across the white wire (output signal) and black wire. Direct the sensor head toward a light source and verify the sensor provides a signal. Increase and decrease the distance from the sensor head to the light source to verify that the signal changes proportionally (decreasing signal with increasing distance and increasing signal with decreasing distance). Blocking all radiation from the sensor should force the sensor signal to zero.

Compatible Measurement Devices (Dataloggers/Controllers/Meters)

Serial Numbers 0-8381. SQ-200 series quantum sensors are calibrated with a standard calibration factor of 1.0 $\mu\text{mol m}^{-2} \text{s}^{-1}$ per mV (SQ-212 and SQ-222) or 0.5 $\mu\text{mol m}^{-2} \text{s}^{-1}$ per mV (SQ-215 and SQ-225), yielding a sensitivity of 1 mV per $\mu\text{mol m}^{-2} \text{s}^{-1}$ (SQ-212 and SQ-222) or 2 mV per $\mu\text{mol m}^{-2} \text{s}^{-1}$ (SQ-215 and SQ-225). Thus, a compatible measurement device (e.g., datalogger or controller) should have resolution of at least 1 mV to provide PPF resolution of 1 $\mu\text{mol m}^{-2} \text{s}^{-1}$.

Serial Numbers 8382 and above. SQ-200 series quantum sensors are calibrated with a standard calibration factor of 1.6 $\mu\text{mol m}^{-2} \text{s}^{-1}$ per mV (SQ-212 and SQ-222) or 0.8 $\mu\text{mol m}^{-2} \text{s}^{-1}$ per mV (SQ-215 and SQ-225), yielding a sensitivity of 0.6 mV per $\mu\text{mol m}^{-2} \text{s}^{-1}$ (SQ-212 and SQ-222) or 1.25 mV per $\mu\text{mol m}^{-2} \text{s}^{-1}$ (SQ-215 and SQ-225). Thus, a compatible measurement device (e.g., datalogger or controller) should have resolution of at least 0.6 mV to provide PPF resolution of 1 $\mu\text{mol m}^{-2} \text{s}^{-1}$.

Cable Length

When the sensor is connected to a measurement device with high input impedance, sensor output signals are not changed by shortening the cable or splicing on additional cable in the field. Tests have shown that if the input impedance of the measurements device is greater than 1 mega-ohm there is negligible effect on the calibration, even after adding up to 100 m of cable. All Apogee sensors use shielded, twisted pair cable to minimize electromagnetic interference. For best measurements, the shield wire must be connected to an earth ground. This is particularly important when using the sensor with long lead lengths in electromagnetically noisy environments.

Modifying Cable Length:

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 $\mu\text{mol m}^{-2} \text{s}^{-1}$. 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 in 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, accrual 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 be 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 agreement

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