Underwater Measurement of Photosynthetically Active Radiation (PAR): Immersion Effect Correction Factors for Apogee quantum sensors

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Introduction

Quantum sensors (often called PAR sensors) are increasingly used to measure photosynthetic photon flux density (PPFD, units of μmol m^{-2} s^{-1}) underwater, which is important for biological, chemical, and physical processes in natural waters and in aquariums. Refraction is different in air and water, thus a correction is required to make accurate PAR measurements underwater when a sensor has been calibrated in air.

More radiation is backscattered out of a radiation sensor diffuser in water than in air because the refractive index of water (1.33) is greater than for air (1.00). This is called the immersion effect. Without correction, sensors calibrated in air provide only relative values underwater (Smith, 1969; Tyler and Smith, 1970).

The Apogee full spectrum quantum sensor (model SQ-500) is more spectrally accurate than the original quantum sensor (model SQ-120), but the unique optics mean that it has a larger immersion effect correction factor (1.32) than the original quantum sensor (1.08).

This paper describes how these multipliers were determined.

Determination of Immersion Effect Correction Factor

Immersion effect correction factors (multipliers) were determined for four replicates of two Apogee quantum sensor models (SQ-120 and SQ-500) following the methods described in Hooker and Zibordi (2005) and Zibordi et al. (2004). The sides of a plastic tub (74 cm diameter, 36 cm depth) were painted flat black to minimize reflection from the walls (Figure 1). Each sensor was mounted in a fixed position at the bottom of the tub. An electric lamp (cool white LED) was maintained at a fixed distance from the sensor (46 cm). A small circular baffle with 2.5 cm diameter (made from flat black construction paper) was placed in front of the lamp to provide direct beam radiation.

An initial measurement in air was made with only the diffuser exposed above the water surface. Air and water temperatures were not identical, so the measurement in air was made with most of the sensor submerged to ensure the sensor temperature during the air measurement was the same as the temperature during the measurements underwater. Following the measurement in air, the tank was filled with water to a depth of 24 cm above the sensor diffuser. After the water surface settled, a measurement was recorded, and then water was removed at 3 cm increments with a measurement made at each water depth (24, 21, 18, 15, 12, 9, 6, 3 cm). All measurements were made with a Campbell Scientific CR1000 datalogger recording at one second intervals. One second data were averaged over sixty seconds to yield the measurements in air and each water depth.

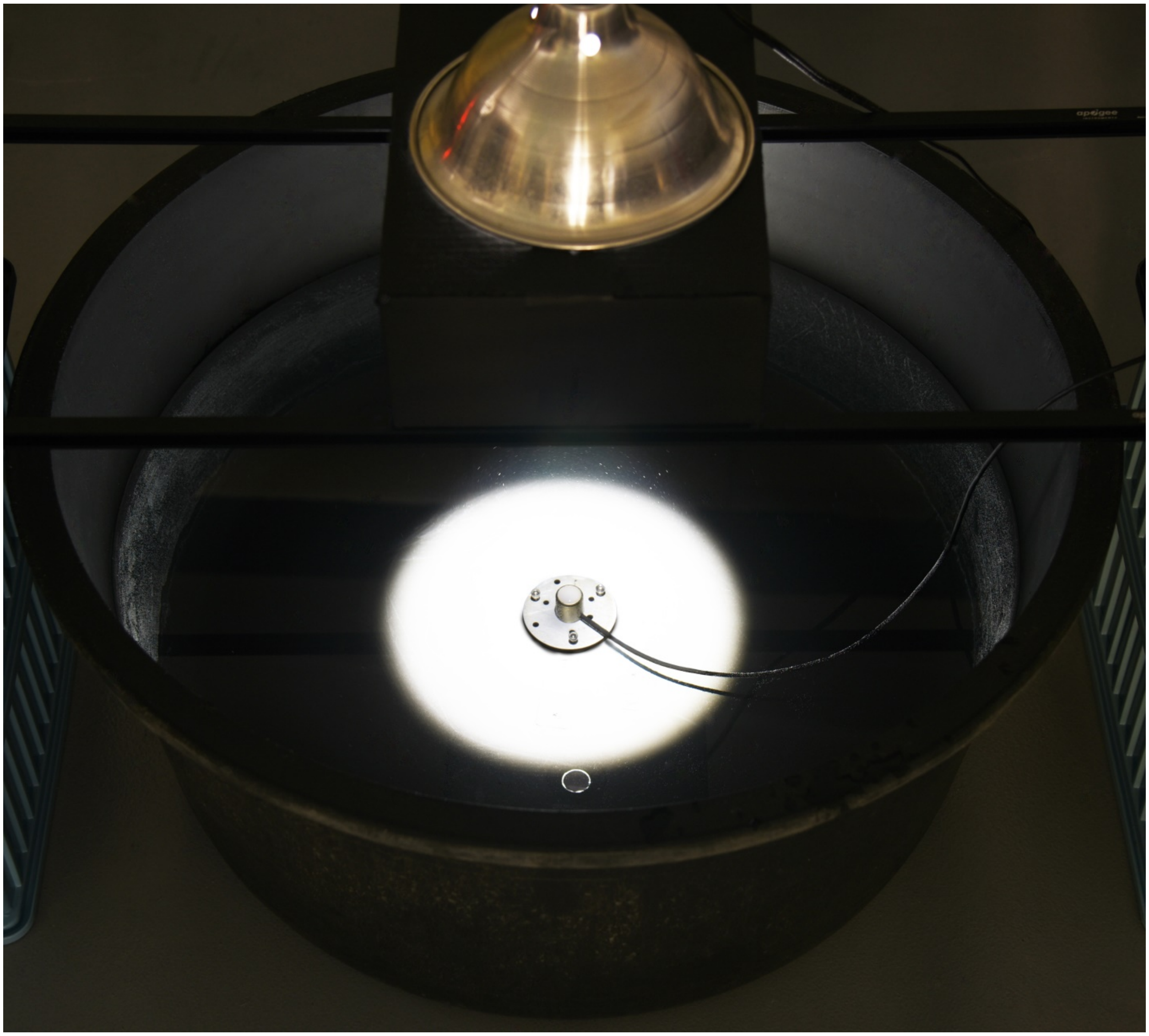

Figure 1: *The experimental set-up used to derive immersion effect correction factors. This example shows an SQ-500 quantum sensor mounted at the bottom of the tub with a 12 cm depth of water above the sensor diffuser.*

The immersion effect correction factor (IECF) is calculated by taking the ratio of the PPFD measurement in air ($PPFD_{air}$) to the PPFD value at the water surface ($PPFD_{water}$) and multiplying by the transmittance of the water surface (τ, equal to 0.979):

$$\mathrm{IECF} = \frac{\mathrm{PPFD}_{\mathrm{air}}}{\mathrm{PPFD}_{\mathrm{water}}}\tau \quad (1)$$

where $PPFD_{water}$ is determined by linearly regressing the underwater PPFD measurements against water depth and extrapolating to a depth of 0 cm. Before the regression, measurements of $PPFD_{water}$ were divided by a geometric correction factor to account for the change in solid angle as a function of water depth and distance between the radiation source and diffuser, as described by Hooker and Zibordi (2005):

$$G = \frac{1}{\sqrt{1 - \frac{z}{d}\left(1 - \frac{1}{1.335}\right)}} \qquad (2)$$

where z is water depth between the water surface and sensor diffuser, d is distance between the radiation source and sensor diffuser, and 1.335 is the refractive index of water for the 400-700 nm wavelength range. The geometric correction factor is required because water focuses the radiation and increases the intensity. In other words, the area illuminated by the radiation source gets smaller when it passes through water. This effect increases with water depth (G calculated from equation 2 increases as z increases). The natural log of the ratio of $PPFD_{water}$ and the geometric correction factor was calculated and regressed against water depth (Hooker and Zibordi, 2005; Zibordi et al., 2004).

Measured immersion effect correction factors were uniform among replicate sensors of the same model, and there was a consistent difference between models (Figure 2; Appendix A). Results were the same when regressing $PPFD_{water}$ and $\ln(PPFD_{water})$ against water depth, so graphical data for $PPFD_{water}$ are shown (Figure 2) instead of $\ln(PPFD_{water})$ because it is more intuitive. The mean values for immersion effect correction factors were 1.083 ± 0.024 for the SQ-120 and 1.323 ± 0.018 for the SQ-500 quantum sensors (uncertainties are two standard deviations around the mean values).

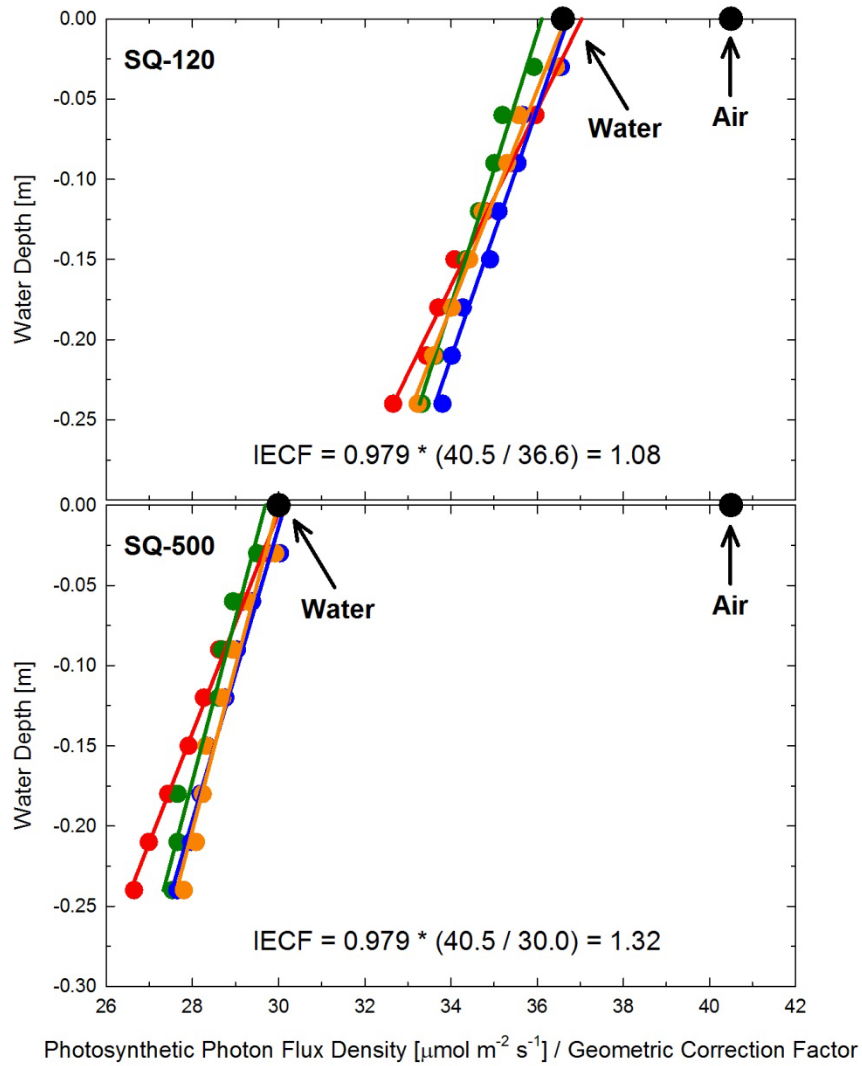

Figure 2: *Air and underwater photosynthetic photon flux density (PPFD) measurements (divided by the geometric correction factor calculated with equation 2) plotted versus water depth for four replicate SQ-120 (upper graph) and four replicate SQ-500 (lower graph) quantum sensors. Photosynthetic photon flux density measurements in air were 40.5 μmol m^{-2} s^{-1} for all sensors (black circle, sensors were matched in air before data were collected). The immersion effect correction factor for each sensor was calculated with equation one and is equal to the transmittance of the water surface (0.979) multiplied by the ratio of PPFD in air ($PPFD_{air}$) to PPFD in water ($PPFD_{water}$, value where each line intersects zero water depth, black circle is the mean).*

Optics for the two sensor models (SQ-120 and SQ-500) are different, and it was anticipated that there would be a difference in the immersion effect correction factors. The difference is 18 %, thus for the same PPFD underwater an SQ-500 quantum sensor reads about 18 % lower than an SQ-120 quantum sensor. The immersion effect correction factor is necessary to scale underwater measurements to absolute values. If all other variables are identical, after multiplication by the immersion effect correction factors, SQ-120 and SQ-500 quantum sensors provide similar results underwater. The geometric correction factor (equation 2) is only required to derive immersion effect correction factors and does not need to be applied for routine underwater measurements.

Verification of Immersion Effect Correction Factors

The measured immersion effect correction factors were verified using three independent sets of measurements in:

1. A typical glass wall aquarium in the laboratory.
2. Identical aquarium as above, but with the walls painted flat black.
3. An outdoor swimming pool.

Glass Wall Aquarium Verification

One model MQ-200 quantum meter and one model MQ-500 quantum meter were used to make the verification measurements. The sensors were mounted on a single leveling plate and placed in the middle of the bottom surface of the glass wall aquarium. The aquarium (51 x 26 x 31 cm) was filled with water to a depth of 25 cm above the sensor diffusers (Figure 3). A cool white LED array with 450 individual LEDs was then placed over the top of the aquarium at 2.5 cm above the water surface. A measurement was recorded, then the water was drained to just below the sensor diffusers and a measurement was recorded. The measurements in water were multiplied by the immersion effect correction factor (1.08 for the MQ-200 and 1.32 for the MQ-500), which should yield similar PPFD measurements for the MQ-200 and MQ-500.

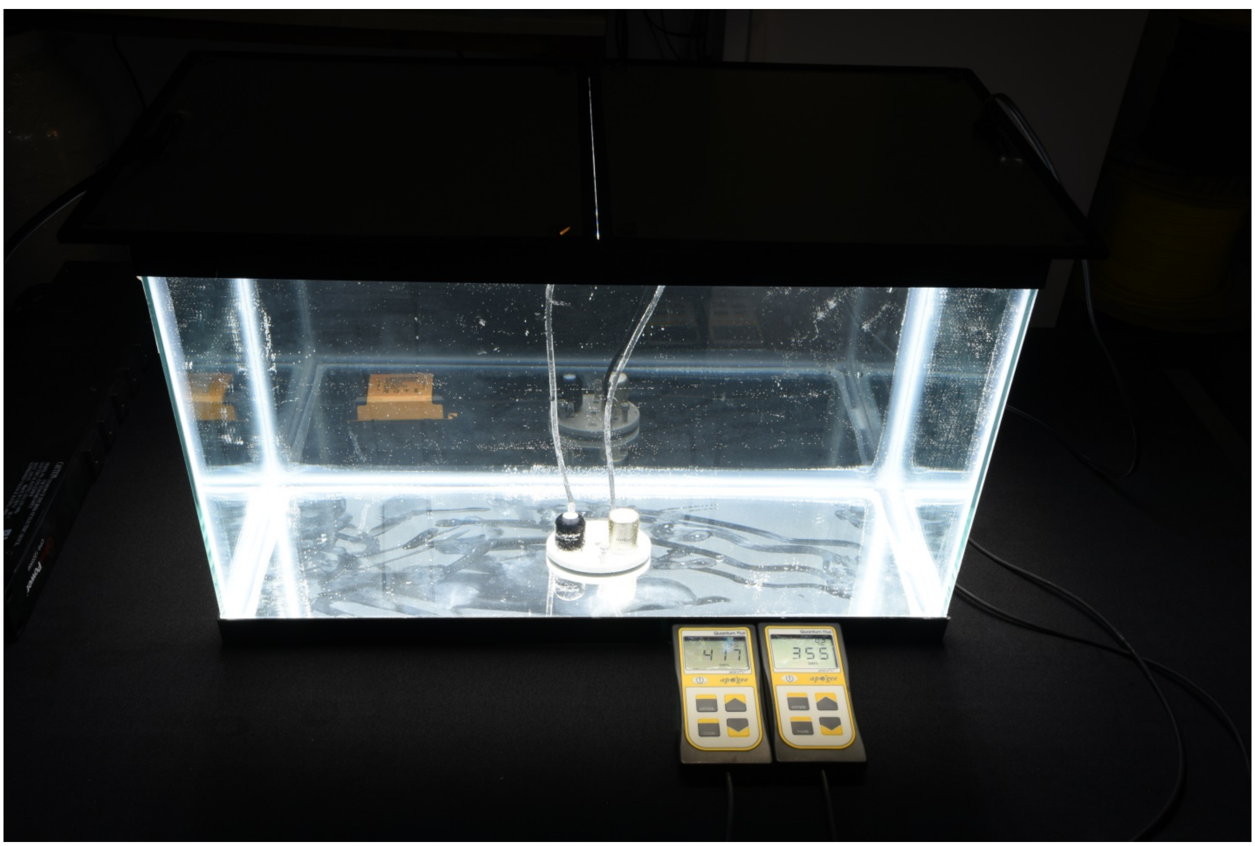

Figure 3: *The glass wall laboratory aquarium used to verify immersion effect correction factors. Sensors attached to MQ-200 and MQ-500 quantum meters were mounted adjacent to each other in the center of the aquarium. Depth of water above the sensor diffusers was 25 cm. The MQ-200 on the left read 417*

μmol m^{-2} s^{-1}. The MQ-500 on the right read 355 μmol m^{-2} s^{-1}. After immersion effect correction factors were applied these PPFD values were 450 and 469 μmol m^{-2} s^{-1}, respectively.

After applying immersion effect correction factors, similar values of underwater PPFD were measured in the glass wall aquarium with the MQ-200 and MQ-500 quantum meters (Table 1). Spectral error calculations for the sensors for a 25 cm depth of water under cool white LEDs indicate the MQ-200 should read 1.4 % low and the MQ-500 should read 1.0 % high. The measured difference was 3.9 % (19 μmol m^{-2} s^{-1}). Measurements of PPFD underwater in the aquarium were higher, by about 110 % (241 μmol m^{-2} s^{-1}), than PPFD measurements in air because of the geometric effect and reflected radiation from the glass walls of the aquarium. When the aquarium is full of water, more of the incident radiation is backscattered out of the glass walls than when the aquarium is filled with air. This is analogous to the immersion effect for a radiation sensor, meaning it is the same phenomenon that occurs when a radiation sensor is submerged (more incident radiation is backscattered out of the diffuser than when the sensor is surrounded by air). If the geometric correction factor (1.68, calculated with equation 2) is applied to the measurements, then underwater PPFD was only about 25 % higher (55 μmol m^{-2} s^{-1}) than PPFD measured in air. The geometric correction is not required for measurements in an aquarium and was only applied here to show contributions from reflection from the walls of the aquarium and the geometric effect. Most of the difference between underwater and air measurements is due to the geometric effect.

Table 1: Immersion Effect Correction Factor Verification Measurements in a Glass Wall Aquarium under a Cool White LED

PPFD Measurement	MQ-200	MQ-500
Air	218	219
Water (no correction applied)	417	355
Water (immersion effect correction applied)	450	469
Water (geometric and immersion effect corrections applied)*	268	279

**The geometric correction factor is only required to show contributions from reflection of the walls and the geometric effect.*

Black Wall Aquarium Verification

The procedure described above was repeated in an identical aquarium with the walls painted flat black. After applying immersion effect correction factors the two meters measured similar PPFD values (Table 2). The difference was 3.7 % (12 μmol m^{-2} s^{-1}). There was minimal reflection from the flat black walls of the aquarium, allowing comparison of measured values to theoretical values for a water depth of 25 cm. In order to compare to theoretical underwater PPFD, underwater PPFD measurements were also divided by the geometric correction factor (this is not required for PPFD measurements in an aquarium and was only done here to allow comparison to theoretical underwater PPFD). Theoretical underwater PPFD values were derived by multiplying the PPFD measurements in air by the transmission through 25 cm of water. Water transmission for the 400-700 nm wavelength range was calculated from published values of the attenuation coefficient for water (Pope and Fry, 1997; Sogandares and Fry, 1997; Smith and Baker, 1981). Water transmission is dependent on wavelength (blue wavelengths are attenuated the least and red wavelengths are attenuated the most) and depth (Figure 4), thus spectral errors underwater are dependent on the radiation source and the water depth. Spectral errors for the sensors for a 25 cm depth of water under the cool white fluorescent LED indicate the MQ-200 should read 1.4 % low and the MQ-500 should read 1.0 % low. The MQ-200 measured 3.7 % lower than the theoretical value and the MQ-500 measured 0.5 % higher than the theoretical value. Measured error was within about 2 % of predicted spectral error for the MQ-200 and within about 0.5 % for the MQ-500, confirming that immersion effect correction factors result in accurate PPFD measurements underwater.

Table 3: Immersion Effect Correction Factor Verification Measurements in a Flat Black Wall Aquarium under a Cool White LED

PPFD Measurement	MQ-200	MQ-500
Air	201	200
Water (no correction applied)	286	243
Water (immersion effect correction applied)	309	321
Water (geometric and immersion effect corrections applied)*	184	191

**The geometric correction factor is only required for comparison to theoretical underwater PPFD calculated from water transmission.*

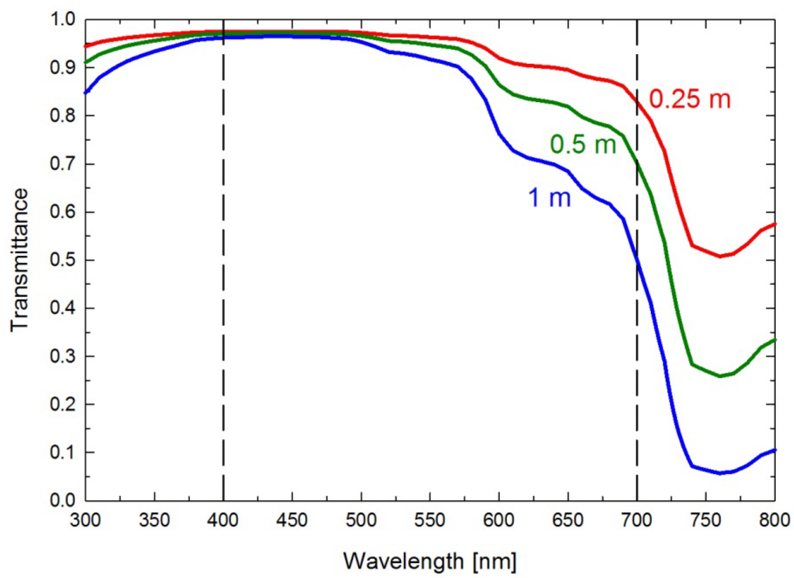

Figure 4: *Spectral transmittance of water calculated from attenuation coefficients from Smith and Baker (1981) for depths of 0.25, 0.5, and 1 m. Similar attenuation coefficients have been published by others (Pope and Fry, 1997; Sogandares and Fry, 1997).Data from Smith and Baker (1981) were used because they made measurements across the entire photosynthetically active range (400-700 nm).*

Outdoor Swimming Pool Verification

Measurements in the swimming pool were made on a clear sunny day. The sensors were placed at a depth of 38 cm and were about 100 cm from the side wall of the pool. A measurement was recorded underwater, and then sensors were removed, dried, placed on a horizontal surface next to the pool, and a measurement was recorded in air. The measurements in water were multiplied by the immersion effect correction factor.

After applying the immersion effect correction factors, similar PPFD values were measured in the swimming pool under sunlight (Table 3). Like the black wall aquarium, PPFD measurements in the swimming pool can be compared to theoretical PPFD values for a water depth of 38 cm because there was negligible reflection from the walls of the swimming pool. Theoretical underwater PPFD values were derived by multiplying the PPFD measurements in air by the transmission through 38 cm of water (again calculated from published values of the attenuation coefficient for water). Spectral errors for the sensors for a 38 cm depth of water under sunlight indicate the MQ-200 should read 2.2 % low and the MQ-500 should read 1.5 % low. The MQ-200 measured 2.3 % lower than the theoretical value and the MQ-500 measured 1.4 % lower than the theoretical value. Measured errors matched predicted spectral errors, confirming that the immersion effect correction factors result in accurate underwater PPFD measurements when the sun is the radiation source.

Table 3: Immersion Effect Correction Factor Verification Measurements in a Swimming Pool Under Sunlight

PPFD Measurement	MQ-200	MQ-500
Air	1366	1383
Water (no correction applied)	1131	945
Water (immersion effect correction applied)	1221	1247

Conclusions

Radiation sensors calibrated in air cannot be used to make absolute measurements underwater because more radiation is backscattered out of the diffuser than when the sensor is in air. An immersion effect correct factor, specific to each sensor model, must be applied. Immersion effect correction factors of 1.08 and 1.32 were derived for Apogee Instruments model SQ-120 and SQ-500 quantum sensors (PAR sensors), respectively. These correction factors must be multiplied by underwater measurements in order to yield accurate PPFD values (otherwise underwater PPFD measurements are only relative values). The correction factors can be applied to all of the new full spectrum sensors and meters (SQ-500 and MQ-500 series) and original sensors and meters (SQ-100, SQ-200, SQ-300, SQ-400, MQ-100, and MQ-200 series).

Acknowledgements

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Appendix A

Table A1: Regression Data and Immersion Effect Correction Factors (IECF) for SQ-120 and SQ-500 Quantum Sensors

Model and Serial Number	$PPFD_{water}$*	IECF	r^2
SQ-120 20495	37.1	1.070	0.992
SQ-120 20496	36.1	1.098	0.987
SQ-120 20498	36.7	1.080	0.971
SQ-120 20499	36.7	1.082	0.987
SQ-500 1049	30.1	1.318	0.996
SQ-500 1051	29.7	1.336	0.950
SQ-500 1052	30.2	1.316	0.973
SQ-500 1053	30.0	1.323	0.950

**All sensors were adjusted to match at the onset of the calibration procedure, thus $PPFD_{air}$ measurements were 40.5 $\mu mol\ m^{-2}\ s^{-1}$ for all sensors.*