Underwater Accuracy of Apogee Quantum Sensors

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Introduction

Quantum sensors (photosynthetically active radiation sensors, often called PAR sensors) manufactured by Apogee Instruments are increasingly used to measure photosynthetic photon flux density (PPFD, units of μmol m^{-2} s^{-1}) underwater, especially in the aquarium industry. In 2016, Apogee released a new full spectrum (400-700 nm) quantum sensor (model SQ-500, handheld meter version for underwater measurements is model MQ-510) that is more spectrally accurate than the original quantum sensor (model SQ-120, handheld meter version for underwater measurements is model MQ-210). Shortly after the new full spectrum sensor was released, immersion effect correction factors were derived for both of these quantum sensor models (Blonquist et al., 2016), allowing for absolute PPFD measurements underwater, but accuracy of underwater PPFD measured with the sensors was not quantified. Here, the underwater measurement accuracy of Apogee full spectrum and original quantum sensors is determined by: 1. calculation of spectral error for radiation sources commonly used to illuminate corals in aquariums, and 2. underwater comparison to a LI-COR underwater quantum sensor (model LI-192) under the same radiation sources.

Spectral Measurements and Spectral Error Calculations

Six replicate Apogee quantum sensors of each model (models SQ-500 and SQ-120) were randomly selected. The spectral response of each sensor was determined with a monochromator (Oriel Instruments model 78022). Individual sensors were held in a fixed position in front of the aperture of the monochromator while the wavelength was manually varied from 370 to 730 nm in 10 nm increments, except near 400 nm and the upper cutoff (660 nm for the SQ-120 and 700 nm for the SQ-500) where the increment was reduced to 5 nm. At each wavelength, voltage output from the sensors was measured with a datalogger (Campbell Scientific model CR6). Voltage output at each wavelength was divided by the photon flux density output of the monochromator (in units of μmol m^{-2} s^{-1}) to derive quantum sensor spectral response. Spectral response for each sensor was normalized by the mean spectral response (calculated from 410 to 690 nm for SQ-500 sensors and from 410 to 650 nm for SQ-120 sensors) to yield the relative spectral response.

After measuring the spectral response of both Apogee quantum sensor models, spectral errors were calculated for radiation sources commonly used to illuminate corals in aquariums. Spectral error can be quantified for any quantum sensor used to measure any radiation source as long as sensor spectral response (S_λ), calibration source spectral output ($I_{\lambda \mathrm{Calibration}}$), and measured radiation source spectral output ($I_{\lambda \mathrm{Measurement}}$) are known (Federer and Tanner, 1966; Ross and Sulev, 2000):

$$\mathrm{Error} = \frac{\int S_\lambda I_{\lambda \mathrm{Measurement}} d\lambda \int_{400}^{700} I_{\lambda \mathrm{Calibration}} d\lambda}{\int S_\lambda I_{\lambda \mathrm{Calibration}} d\lambda \int_{400}^{700} I_{\lambda \mathrm{Measurement}} d\lambda} \qquad \text{(Equation 1)}$$

where the integral from 400 to 700 is for the defined photosynthetic response to photons, equal weighting of photons between 400 and 700 nm and no weight given to photons outside this range. Spectral errors were calculated for both quantum sensor models with Equation 1 using the mean relative spectral response, calculated from individual responses from the six replicates of each model, and the measured spectral output from six combinations of fluorescent tubes (measured spectra are shown in Figure 3):

1. Four white tubes (CH Lighting model Bright Color Triphosphor)
2. Four blue tubes (ATI model Blue Plus)
3. Four violet tubes (ATI model Actinic)
4. Two white tubes and two blue tubes
5. Two white tubes and two violet tubes
6. Two blue tubes and two violet tubes

All tubes were 24 W T5 fluorescent tubes and were mounted in a fixture (ATI model SunPower T5 UNI 4x24W) that holds four tubes. Photon flux density measurements of the radiation sources were made with a spectroradiometer (Apogee Instruments model PS-300), where the sensor head was placed at the same position as the quantum sensors, 17.5 cm below water surface (described in next section). Apogee quantum sensors are calibrated under T5 cool white fluorescent lamps in a custom calibration chamber. The spectrum inside the calibration chamber was measured and input for $I_{\lambda Calibration}$ in Equation 1.

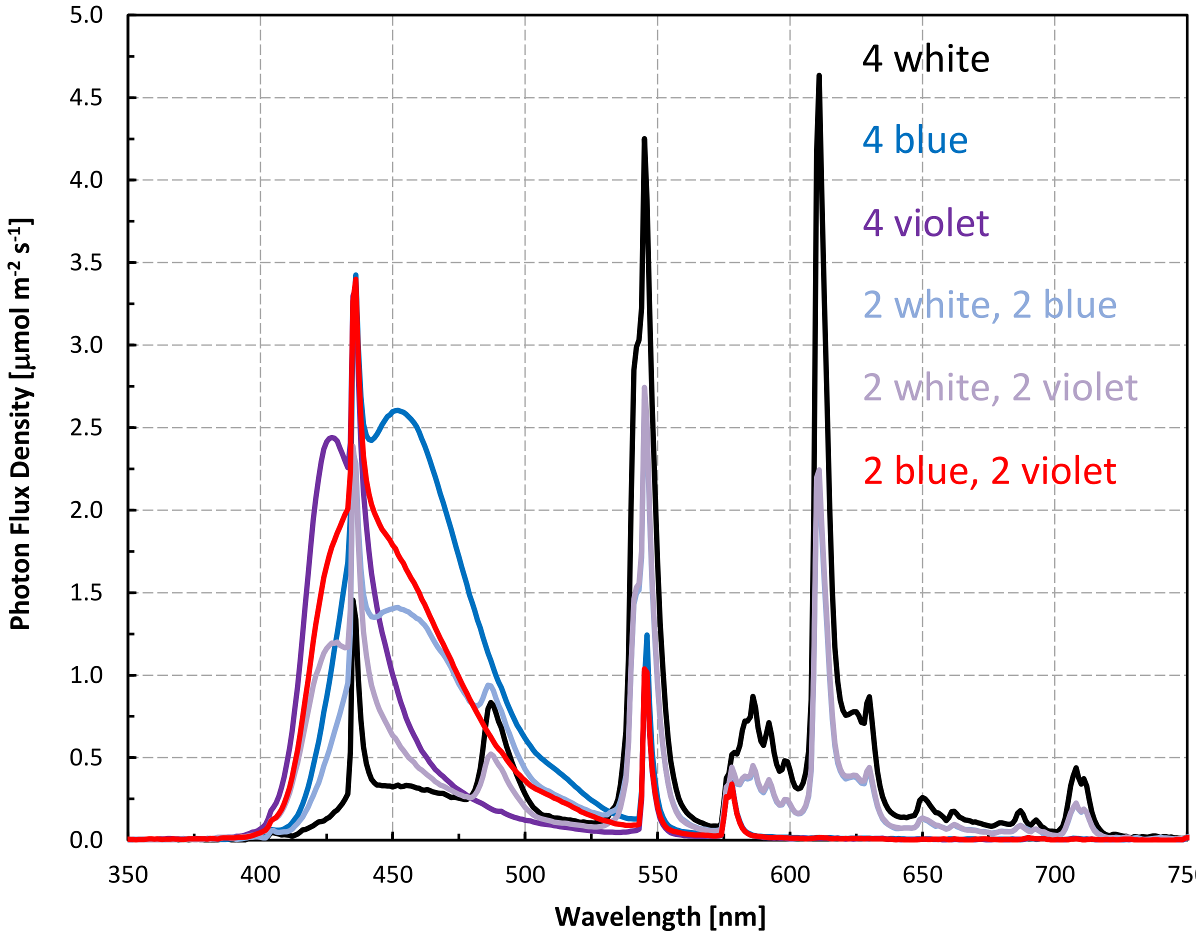

Figure 1: Photon flux density spectra used to make spectral error calculations. All tubes were 24 W T5 fluorescent tubes and were mounted in a fixture (ATI model SunPower T5 UNI 4x24W) that holds four tubes. Measurements were made with a spectroradiometer (Apogee Instruments model PS-300), where the sensor head was placed at the same position as the quantum sensors, 17.5 cm below water surface.

Underwater Measurements and Differences from a Reference Sensor

LI-COR underwater quantum sensors are widely used for underwater measurements in limnology and oceanography applications. The LI-COR underwater quantum sensor with hemispherical field of view (model LI-192) was used as a reference for comparison. A plastic tub (74 cm diameter, 36 cm depth) was painted flat black and filled with water to a depth of 33.0 cm. The fluorescent light fixture (ATI model SunPower T5 UNI 4x24W) was placed 4.8 cm from the surface of the water. The fluorescent light fixture held four T5 fluorescent tubes. A 3D printed fixture placed in the bottom of the tub held the LI-COR and Apogee sensors at the same height (Figure 2). Diffusers on both sensors were 17.5 cm beneath the water surface, and 22.3 cm away from the light fixture (Figure 3).

One at a time, each replicate Apogee sensor was placed in the 3D printed fixture next to the LI-COR sensor. After the water surface settled, measurements from both sensors were recorded. Apogee sensors were connected directly to a handheld meter so PPFD measurements were recorded directly from the digital output. The LI-COR sensor was connected to a Campbell Scientific datalogger (model CR1000X), and measurements were recorded directly from laptop computer connected to the datalogger.

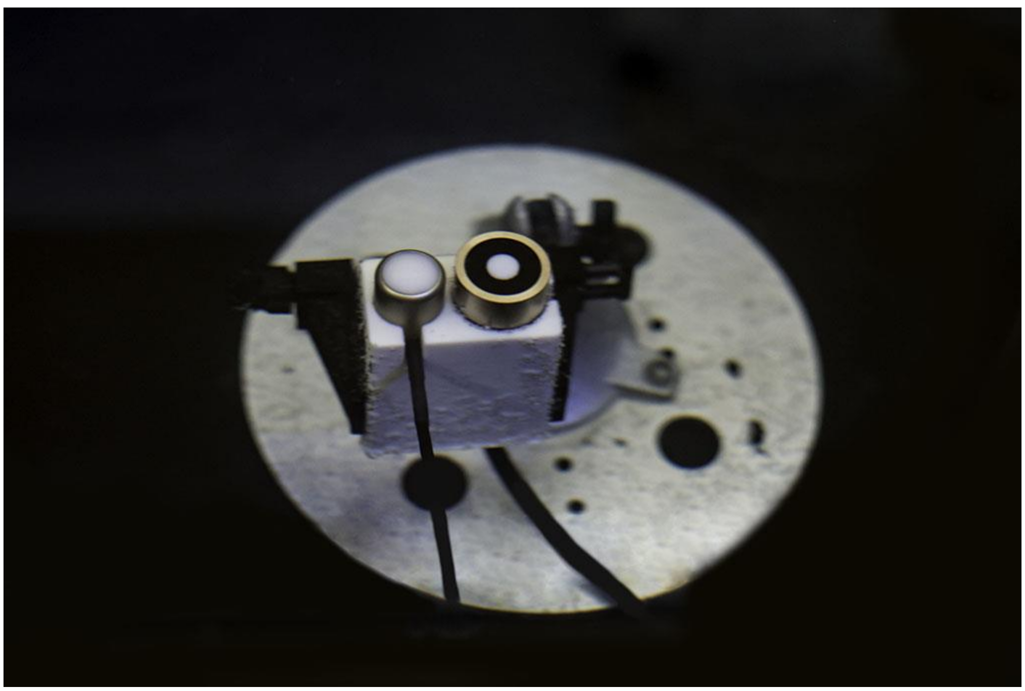

Figure 2: Apogee (model MQ-510, left side; the MQ-510 is a model SQ-500 quantum sensor connected to a handheld meter) and LI-COR (model LI-192, right side) quantum sensors mounted in the 3D printed fixture and deployed underwater. The 3D printed fixture was held by a small vise that was bolted to an aluminum plate. The quantum sensors were centered underneath the fixture holding the fluorescent tubes (Figure 3).

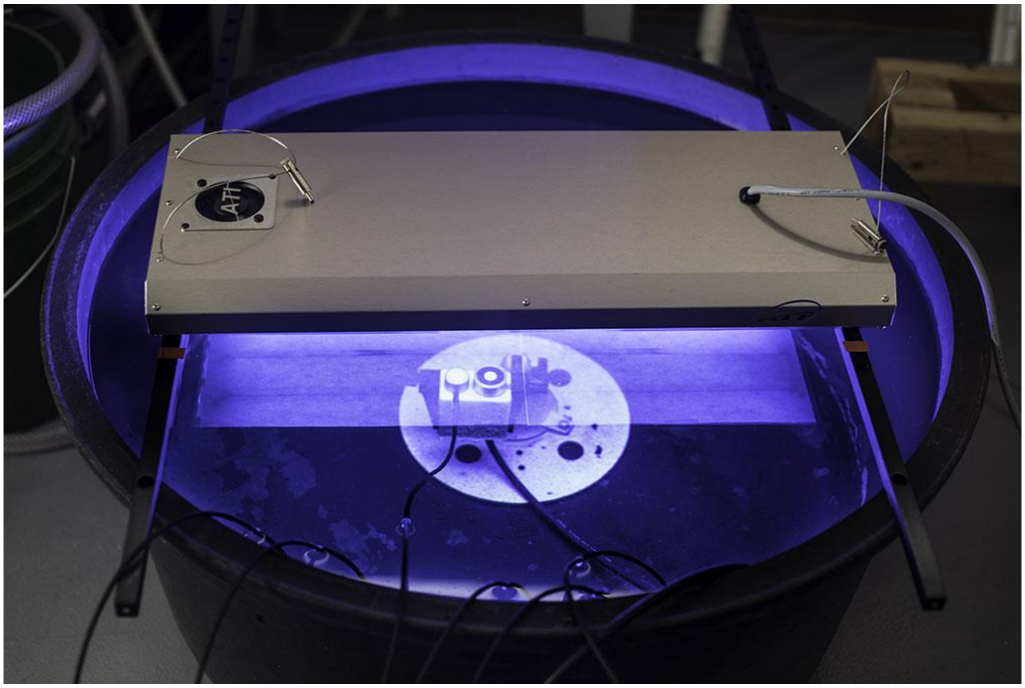

Figure 3: Apogee (model MQ-510, left side; the MQ-510 is a model SQ-500 quantum sensor connected to a handheld meter) and LI-COR (model LI-192, right side) quantum sensors deployed underwater. A plastic tub with flat black walls was used to minimize reflection. Water depth above the quantum sensors was 17.5 cm. Distance between the light fixture and water surface was 4.8 cm. In this photo all four fluorescent tubes mounted in the fixture (ATI model SunPower T5 UNI 4x24W) are blue (ATI model Blue Plus).

Underwater Accuracy of Apogee Quantum Sensors

Spectral response data indicate SQ-500 sensors closely match the defined weighing factors for PAR (Figure 4), indicating spectral errors should be relatively small. Sensitivity of SQ-120 sensors is low at wavelengths less than 450 nm and declines rapidly to zero between 650 and 660 nm (Figure 5). This suggests SQ-120 sensors underweight violet and blue radiation, resulting in errors under radiation sources that have high proportions of violet and blue. SQ-120 sensors are not sensitive to radiation at wavelengths greater than 660 nm, indicating errors will be large for radiation sources that have a high proportion of deep red radiation, but photon flux density from the radiation sources tested in this study is minimal at wavelengths greater than 660 nm (Figure 1). Thus, errors for the SQ-120 for the six radiation sources tested is largely influenced by low sensitivity at wavelengths less than 450 nm.

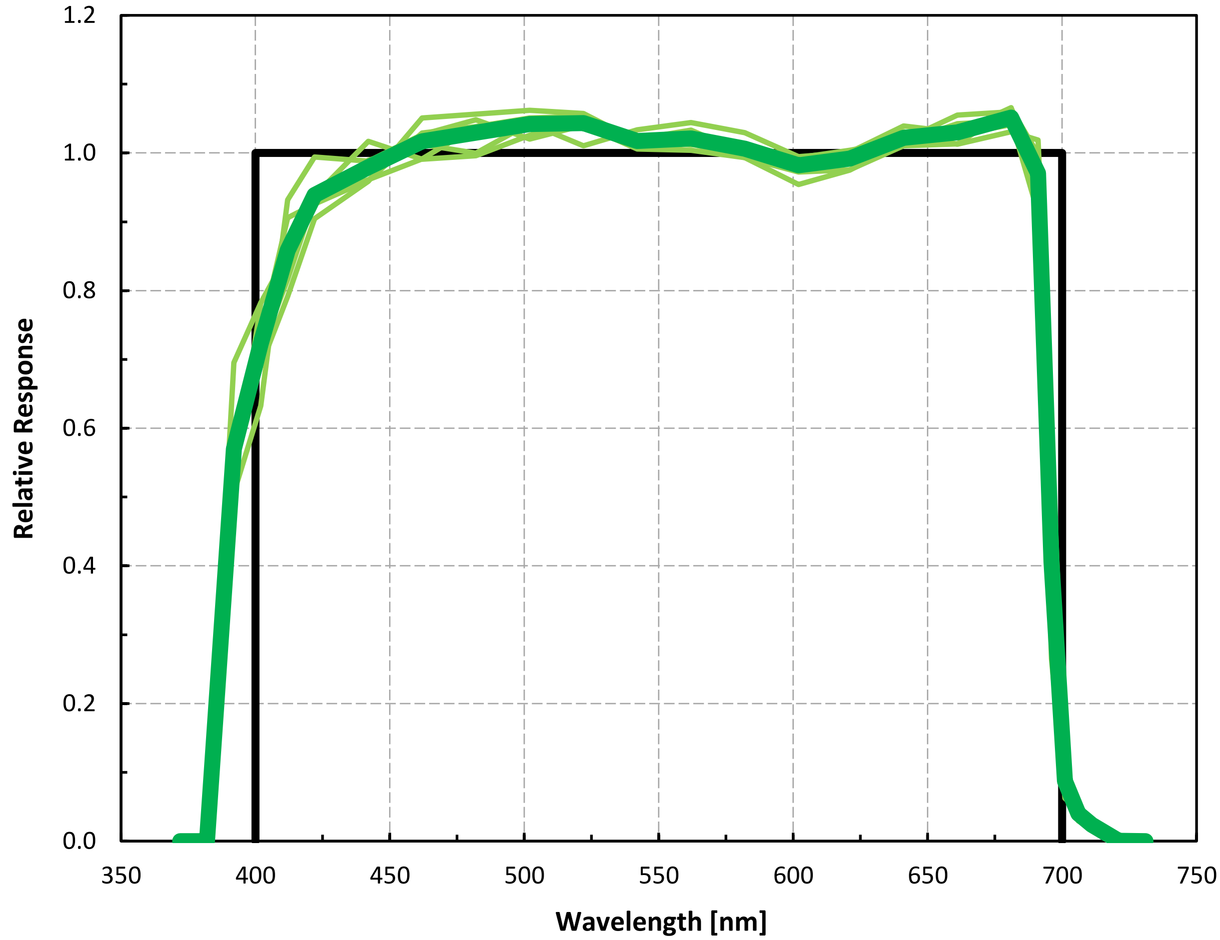

Figure 4: Measured spectral response of six replicate Apogee model SQ-500 quantum sensors. Thin light green lines are data from individual sensors, and the thick dark green line is the mean response calculated from the six replicates. Spectral responses were measured with a monochromator at Apogee Instruments. After spectral responses were measured, the mean response was input into Equation 1 to calculate spectral errors (Table 1) for six radiation sources commonly used to illuminate corals in aquariums (Figure 1). The sensors were also attached to handheld meters and compared to a LI-COR model LI-192 underwater quantum sensor under the same six radiation sources (see next section).

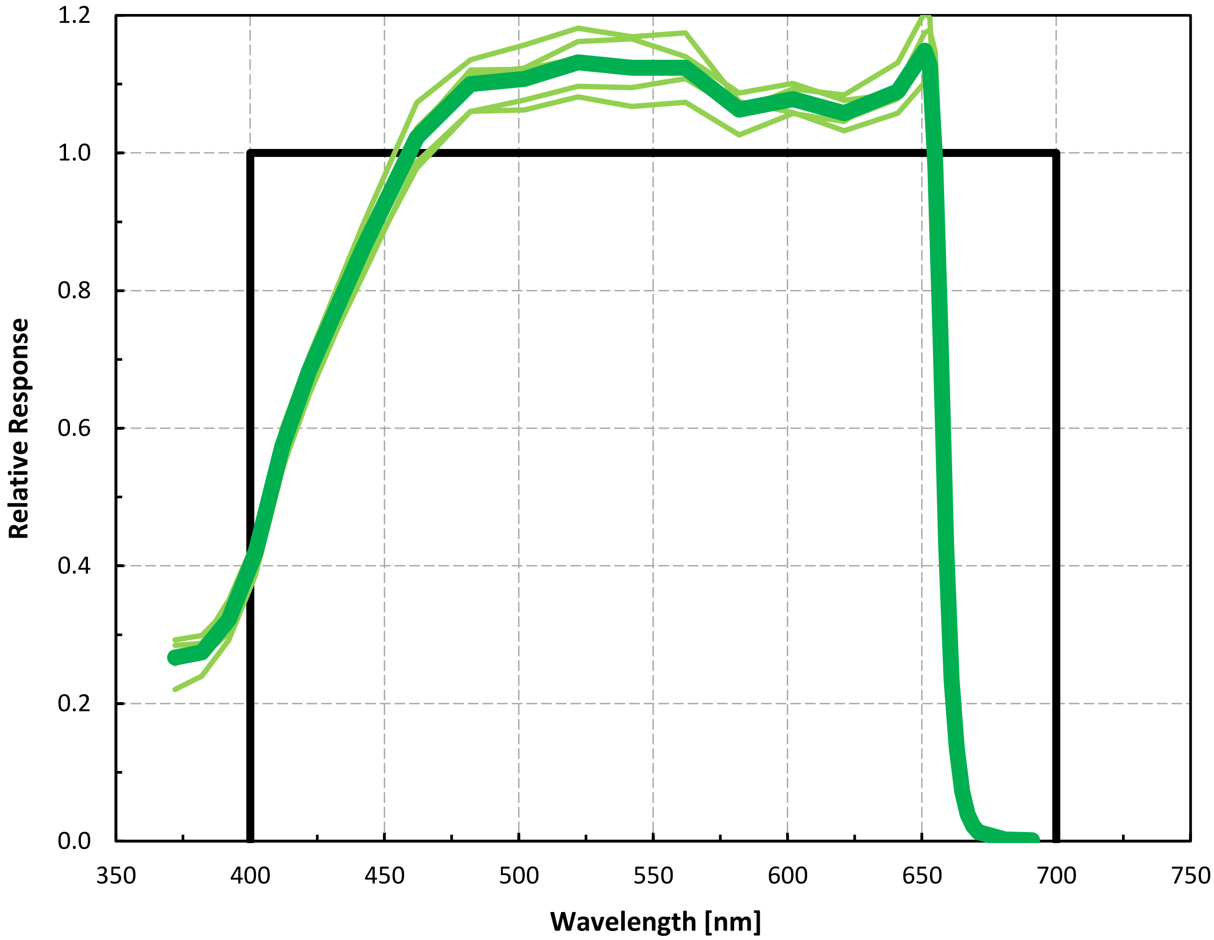

Figure 5: Measured spectral response of six replicate Apogee model SQ-120 quantum sensors. Thin light green lines are data from individual sensors, and the thick dark green line is the mean response calculated from the six replicates. Spectral responses were measured with a monochromator at Apogee Instruments. After spectral responses were measured, the mean response was input into Equation 1 to calculate spectral errors (Table 1) for six radiation sources commonly used to illuminate corals in aquariums (Figure 1). The sensors were also attached to handheld meters and compared to a LI-COR model LI-192 underwater quantum sensor under the same six radiation sources (see next section).

Modeled spectral errors calculated with Equation 1 using sensor spectral responses (Figure 4 and Figure 5) and radiation source photon flux densities (Figure 1) were less than 2 % for the SQ-500 for all radiation sources except violet, which was -3.3 % (Table 1). Modeled spectral errors for the SQ-120 were negative for all radiation sources, except white. The largest error was -18.4 % for violet, which is expected because a large proportion of output from the violet tubes is between 400 and 450 nm where sensitivity of the SQ-120 is less than defined PAR.

The differences of the Apogee quantum sensors from the LI-192 underwater quantum sensor were similar to the modeled spectral errors. Measured differences and modeled errors were within 2 % for the SQ-500 and within 2.5 % for the SQ-120 (Table 1). Direct comparison to an LI-192 quantum sensor assumes the LI-192 is accurate for all six radiation sources. A recently published technical note from LI-COR Biosciences suggests minimal spectral error, typically less than 2 % for the radiation sources used in their study, for the new (model LI-190R) and original (model LI-190) versions of LI-COR quantum sensors (LI-COR Biosciences, 2018).

Table 1: Spectral error and measured difference for Apogee models MQ-510 and MQ-210 underwater quantum meters for six radiation sources (different combinations of fluorescent tubes commonly used to illuminate corals in aquariums). Modeled spectral errors were calculated with Equation 1 using the mean of measured spectral responses for each quantum sensor model (Figure 4 and Figure 5) and measured spectral output of the radiation sources (Figure 1). Measured differences are mean values and were determined by direct comparison of six replicates of each meter to a LI-COR model LI-192 underwater quantum sensor, where measurements were made under each radiation source at a water depth of 17.5 cm (6.9 in).

Fluorescent Tubes	Modeled Error MQ-510	Measured Difference MQ-510	Modeled Error MQ-210	Measured Difference MQ-210
4 White	0.4	2.3	0.6	-1.9
4 Blue	0.1	-0.5	-5.6	-4.6
4 Violet	-3.3	-3.3	-18.4	-16.0
2 White, 2 Blue	0.2	0.4	-2.8	-3.7
2 White, 2 Violet	-1.1	-0.7	-7.0	-8.0
2 Blue, 2 Violet	-1.3	-2.2	-10.8	-9.2

Conclusions

Measured differences (relative to a LI-COR model LI-192 underwater quantum sensor) and modeled spectral errors (from Equation 1) matched within 2 % for Apogee SQ-500 quantum sensors and within 2.5 % for Apogee SQ-120 quantum sensors. These data provide two independent measures of accuracy for underwater measurements with Apogee quantum sensors, and indicate the SQ-500 is accurate within about 3 % for the six radiation sources tested in this study. The SQ-120 is less accurate than the SQ-500, with errors between -8 and -16 % for radiation sources that have a significant proportion of output between 400 and 450 nm (radiation sources that included violet tubes in this study).

References

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