# Field View of Underwater Quantum Sensors: Impact on PAR Measurements

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## Introduction

Corals rely on symbiotic relationships with photosynthetic microorganisms for energy. Incident photosynthetically active radiation (PAR) stimulates photosynthesis in coral symbionts, but excessive PAR can be detrimental, causing photoinhibition and coral bleaching. Coral bleaching is a breakdown of the symbiotic relationship between corals and photosynthetic microorganisms. The high sensitivity of corals and their symbionts to PAR means accurate underwater PAR measurements are essential for creating and maintaining healthy coral ecosystems.

## Radiometer Field of View

Radiometer field of view is the solid angle from which the detector can receive and measure radiation. For example, a 180° field of view, sometimes called two pi field of view, means the radiometer is sensitive to radiation emanating from the hemisphere above the detector, and a 360° field of view, sometimes called four pi field of view, means the radiometer is sensitive to radiation emanating from the sphere surrounding the detector. A field of view less than 180° means the radiometer is only sensitive to radiation emanating from the cone above the detector, specified by the angle of the cone. In simple terms, radiometer field of view is the area surrounding the radiometer that the detector can 'see'.

Field of view of quantum sensors used to measure PAR incident on corals is an important sensor property because at any given position within the aquarium PAR may be incident from multiple angles (Figure 1). PAR incident from any angle can contribute to photosynthesis and coral growth, or photoinhibition and bleaching, thus accurate measurement of PAR requires a sensor that captures radiation incident from any angle. There are multiple models of quantum sensors available for measuring underwater PAR, which is almost universally quantified as photosynthetic photon flux density (PPFD), the sum of photons between 400 and 700 nm in units of micromoles per square meter of area per second [$\mu mol\ m^{-2}\ s^{-1}$]. Two lower cost and easy to use quantum sensor models often used to measure PAR in aquariums are the Apogee model MQ-510 and Seneye Reef. The purpose of this work is to determine the impact of field of view on underwater PAR measurements with these two quantum sensors under radiation sources commonly used to illuminate corals in aquariums.

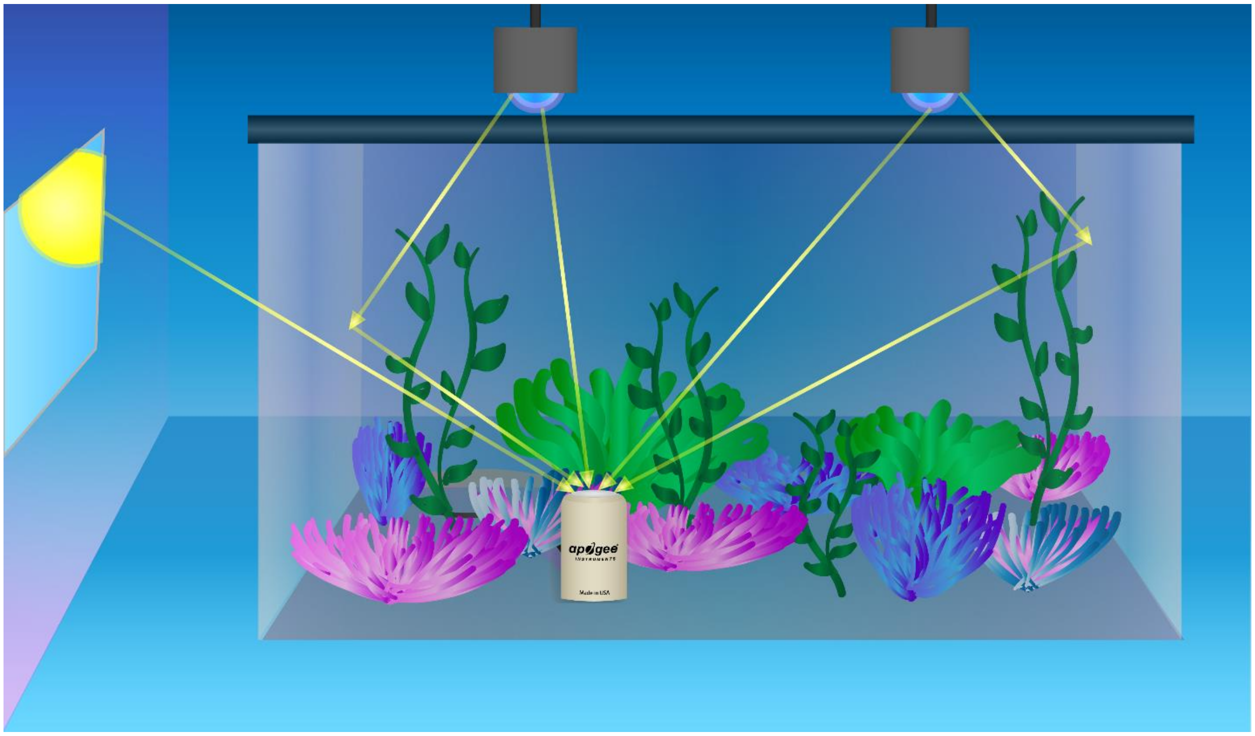


**Figure 1:** Example of the light environment in an aquarium. At any given location photosynthetically active radiation (PAR) can be incident from multiple angles, and a change in location may change the distribution of incidence angles. This example only depicts downwelling PAR (radiation emanating from the hemisphere above the sensor) because the sensor is positioned at the bottom of the aquarium, but reflected PAR from objects at the bottom of the aquarium can be upwelling (radiation emanating from the hemisphere below the sensor) if the sensor is not positioned at the bottom of the aquarium.

**Comparison of PAR Measurements in Aquariums**

Measurements of PAR were made in two separate aquariums, one with actively growing corals illuminated by blue LEDs and the other with water only (no corals) illuminated by blue fluorescent tubes. In the aquarium with corals two LED fixtures (Kessil model A360W E-Series Tuna Blue) were mounted 24 inches from each other and 7.5 inches above the water surface. Both were directed straight down (zenith angle of 0°). PAR measurements were made at two positions: nearly directly underneath one of the LED fixtures where the zenith angle between the LED fixture and the position of the sensors was 10° and between the two LED fixtures where the zenith angle between both LED fixtures and the position of the sensors was 40° (Figure 2). Both measurements were made at positions where corals were actively growing. PAR measurements nearly directly underneath one of the LED fixtures were similar for the Apogee MQ-510 and Seneye Reef. The difference was 2 $\mu$mol m$^{-2}$ s$^{-1}$, or 1.1 % (Figure 2). Measurements of PAR between the two LED fixtures were different for the Apogee MQ-510 and Seneye Reef. The Seneye Reef measured 57 $\mu$mol m$^{-2}$ s$^{-1}$, or 40.4 %, lower than the MQ-510 (Figure 2).

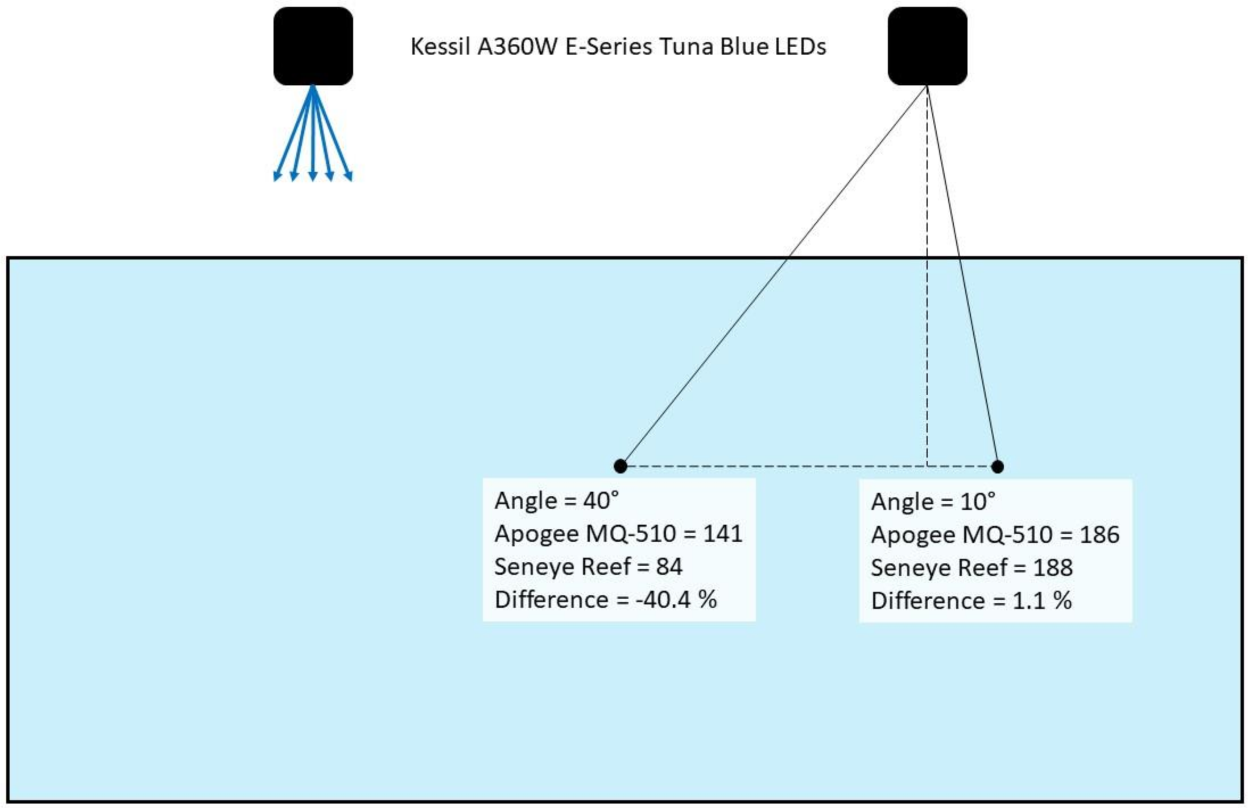


**Figure 2:** Depiction of measurements in an aquarium with actively growing corals illuminated by light emitting diodes (LEDs). The aquarium is 48 inches long, 12.5 inches wide, and 20 inches deep. The two LED fixtures illuminating the aquarium are spaced 24 inches from each other and are 7.5 inches above the water surface. Both are directed straight down (zenith angle of 0°). Measurements of photosynthetically active radiation (PAR) were made with the Apogee MQ-510 and Seneye Reef at the two positions marked with black dots, nearly directly beneath one of the LED fixtures at an angle 10° and between the LED fixtures at an angle of 40°. Each sensor was separately placed in each position and twelve measurements were recorded at each position. The mean of these measurements is listed, where mean values were used because of the variability of individual measurements caused by ripples at the water surface, along with the relative difference between measurements from the Seneye Reef and Apogee MQ-510.

In the aquarium with water only, four fluorescent tubes (ATI model T5 24 W Blue Plus) were mounted in a fixture (ATI model SunPower T5 UNI 4x24W) suspended above the water surface, and sensors were placed in the middle of the aquarium at a depth of 10 inches (Figure 3). Measurements were made with the light fixture initially mounted 9 inches and then 5 inches above the water surface. PAR measurements at both positions were different for the Apogee MQ-510 and Seneye Reef. The difference was 19 $\mu$mol $m^{-2}$ $s^{-1}$, or -8.1 %, when the fixture was 9 inches above the water surface and 67 $\mu$mol $m^{-2}$ $s^{-1}$, or -16.6 %, when the fixture was 5 inches above the water surface (Figure 3).

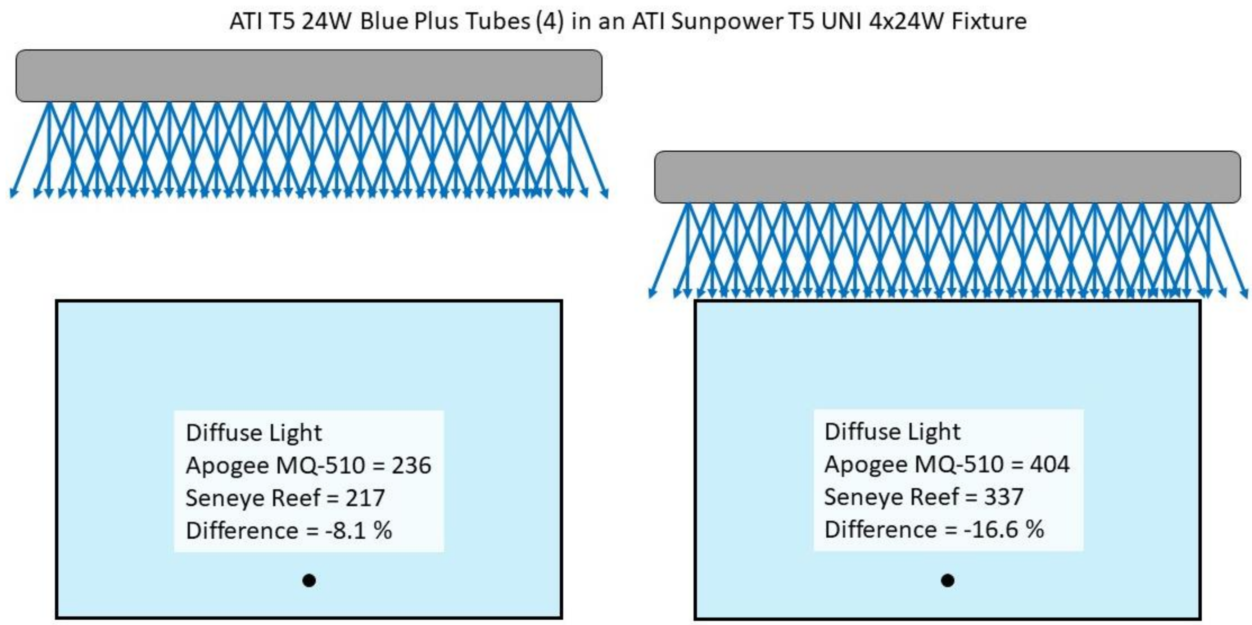


**Figure 3:** Depiction of measurements in an aquarium illuminated with fluorescent tubes (ATI model T5 24 W Blue Plus in an ATI model SunPower T5 UNI 4x24W fixture). The aquarium is 20 inches long, 10 inches wide, and 12 inches deep. The light fixture illuminating the aquarium was mounted 9 inches above the water surface for one set of measurements (left) and 5 inches above the water surface for the other (right). Measurements of PAR were made with the Apogee MQ-510 and Seneye Reef at the position marked by the black dot, in the middle of the aquarium at a depth of 10 inches. Each sensor was separately placed in position, and a measurement was recorded. Measurements from each sensor and the relative difference between measurements from the Seneye Reef and MQ-510 are listed.

**Effect of Field of View on PAR Measurements**

Position had a large effect on PAR measurements from the two sensors in the aquarium illuminated by LED fixtures. When positioned nearly directly beneath one of the fixtures, the Apogee MQ-510 and Seneye Reef sensors measured nearly the same PAR because a large proportion of the radiation output by the LED fixture was incident on the sensors at low angles. The different fields of view of the sensors had little influence on the measurements in this case. When the sensors were positioned between the LED fixtures, the Seneye Reef measured about 40 % lower than the MQ-510 because a large proportion of the radiation output by the LED fixtures was incident on the sensors at high angles. The Seneye Reef detector did not capture some of the higher angle radiation due to the restricted, non-hemispherical field of view.

Illuminating an aquarium with diffuse radiation, where there was a large proportion of radiation incident at high angles, also caused differences in PAR measurements between the Apogee MQ-510 and Seneye Reef. As explained above, the Seneye Reef did not capture some of the radiation incident at higher angles due to the restricted field of view. When the lamps were moved closer to the water surface the difference between the Seneye Reef and MQ-510 increased from about -8 % to about -17 %. This increase was likely due to more PAR reflecting off the aquarium walls resulting in a higher percentage of radiation incident at higher angles and a higher proportion of radiation not captured by the Seneye Reef.

The Seneye Reef is a useful tool for underwater measurements because it measures PAR, water temperature, pH, and ammonia ($NH_3$). The PAR measurements can be used to monitor the output of lights over time. However, it is not the best tool for aquarium light mapping because of the restricted, non-hemispherical field of view. Sensors used for light mapping should be as sensitive as possible to the same PAR that corals would be sensitive to in the position where a measurement is made. Light mapping measurements with the Seneye Reef could potentially be improved under direct (non-diffuse) radiation sources by angling the detector towards the radiation source. However, this method only provides a measurement of PAR incident from the direction in which the detector is angled and neglects PAR from other directions. Therefore, even with this method it is possible to undermeasure PAR incident on corals. Under diffuse radiation sources the Seneye Reef is likely to always undermeasure independent of the angle of the detector with respect to the radiation source. For light mapping in aquariums, sensors with a hemispherical (two pi) field of view provide higher accuracy.

Ultimately, a quantum sensor with a spherical (four pi) field of view should provide the most accurate measurements of incident radiation at a given location in an aquarium because it is sensitive to radiation from all directions. However, spherical sensors tend to be expensive and may not be practical for light mapping in aquariums. In addition, upwelling PAR in aquariums is typically small. Upwelling PAR measured in the two aquariums described above (Figure 2 and Figure 3) was 2 $\mu mol\ m^{-2}\ s^{-1}$ or less at multiple locations in each aquarium. Therefore, in typical aquarium lighting conditions the measurement of upwelling PAR is not essential and a sensor with hemispherical field of view is adequate.

## Conclusions

The results of this work indicate that quantum sensors with a restricted, non-hemispherical field of view can significantly undermeasure PAR incident on corals and are not recommended for aquarium light mapping. Theoretically, quantum sensors with a spherical field of view are the most accurate because they capture radiation from all directions, downwelling and upwelling. However, they are expensive, and in many cases, the upwelling PAR contribution is negligible. In practice, quantum sensors with a hemispherical field of view are recommended for light mapping in aquariums because they are lower cost and provide a measurement of PAR representative of the conditions corals will experience, meaning a PAR measurement that includes downwelling radiation incident from all directions.