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# Quantum sensors for accurate and stable long-term photosynthetically active radiation observations

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ABSTRACT

Long-term accurate data of photosynthetically active radiation (PAR) are needed because PAR is one of the standard environmental statistics needed to evaluate plant photosynthesis. Therefore, PAR observation sites are globally distributed, particularly in flux observation sites. Quantum sensors have been used for half a century to observe PAR; however, their accuracy is still uncertain. This study evaluates the accuracies of nine quantum sensor products by examining their spectral and cosine responses. On the basis of these data as well as reference spectrum data provided by our standard spectrometric measurement, we performed the following analyses: (1) a simulation of errors caused by the sensors' non-ideal spectral response in three types of radiation inputs (open sky, forest canopy transmission, and forest canopy reflection), (2) a simulation of the errors caused by a complex combination of the sensors' non-ideal spectral and cosine responses in three diurnal variation types of incident radiation (clear sky, partial clouds, and an overcast sky), and (3) an observation of the sensors' long-term sensitivity degradation outdoors. Based on the results, we recommend two quantum sensors with minimal errors, LI-COR LI-190 encased in a weather-proof external housing with a glass dome and PREDE PAR-02D. The findings of this study contribute in establishing a long-term PAR observation protocol and should become a basis for quality checks and controls of PAR observation values that have previously been obtained worldwide.


## 1. Introduction

Photosynthetically active radiation (PAR) is the energy source for photosynthesis and largely controls vegetation productivity. Therefore, PAR is required in modeling and predicting the gross primary production (GPP) of ecosystems (e.g., Running et al., 2004; Sasai et al., 2005; Xiao et al., 2004). In particular, global studies of plant productivity and the carbon cycle require global wall-to-wall datasets of PAR, which are currently derived using numerical climate data and/or satellite remote sensing (e.g., Eck and Dye, 1991; Frouin and Murakami, 2007; Frouin and Pinker, 1995; Kobayashi, 2004; Nasahara, 2009). Its ground validation requires long-term accurate PAR data derived from multiple observation sites. In recent years, world-wide long-term PAR observation data have been collected at ground sites, such as those of FLUXNET (e.g., Baldocchi et al., 2001; Saigusa et al., 2013; http://fluxnet.ornl.gov/).

To observe PAR, commercially available quantum sensors are commonly used. However, it has been pointed out that quantum sensors have problems with spectral errors caused by non-ideal spectral responses, cosine errors caused by non-ideal incident angle responses, and long-term sensitivity degradation caused by exposure to rain and UV radiation in field observations (e.g., Michalsky et al., 1995; Mizoguchi et al., 2010; Ross and Sulev, 2000).

The spectral error is a serious problem, especially when observing radiation with various spectral patterns, such as sky light, canopy reflection, and canopy transmission. If the spectral response is non-ideal, the quantum sensor yields different values, even if the actual PAR is the same for the different spectral patterns. However, there are more than 10 commercial quantum sensor products that have never been tested for their spectral errors with realistic radiation data. In actuality, several researchers have worked on this issue for specific products under limited conditions. For example, Pearcy (1989) simulated spectral errors for two types of sensors (a GaAsP

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photodiode and a quantum sensor using a Si photodiode) using their inherent spectral response curves and two types of observed spectral radiation curves (under a clear sky and in the understory of a Costa Rican rainforest). According to his reports, even though the spectral response in the GaAsP photodiode was non-ideal and had potential problems, its output errors were likely within a tolerable range. Nevertheless, the spectral radiation curves used in the simulation were not described in his paper or in the paper being cited (Chazdon and Fetcher, 1984). Ross and Sulev (2000) also simulated spectral errors in two Si quantum sensors using their spectral response curves and various spectral radiation curves. However, the quality of their spectral radiation curves is not clear in light of recent advances in spectral measurements (Akitsu et al., 2015).

The cosine error is another serious problem, especially when observing radiation coming from various directions. For example, the direction of the direct solar radiation varies diurnally and seasonally. Moreover, under thick clouds and/or aerosols, the radiation comes from all directions roughly homogeneously. If the cosine response is poor, the quantum sensor yields different values even if the actual PAR values are the same for different solar zenith angle, cloud, and aerosol conditions.

In combination, the cosine error and spectral error can influence a quantum sensor's output in a complex manner. As mentioned above, if the cosine response is poor, the change in the direction of the direct solar radiation causes a cosine error. Meanwhile, the change in the direction of the sun (especially the solar zenith angle) causes a change in the spectral patterns in both direct and diffuse radiation (Kume et al., 2016). Moreover, the spectral patterns in direct and diffuse radiation are substantially different from one another (Kume et al., 2016). If the spectral response is poor, such varying spectral patterns could also cause spectral errors. However, such complex and combined errors in quantum sensors have not been investigated.

Long-term sensitivity degradation is another significant issue, especially in the monitoring of seasonal and annual variations of PAR. As mentioned above, sensor degradation is caused by UV radiation and water vapor; the speed and extent of the degradation depends on how the sensor is installed and exposed to sunlight as well as rain and dew. This can lead to additional complications, e.g., in measurements of the PAR albedo with a pair of sensors where a quantum sensor observing the sky (which is installed upward) may degrade more rapidly than a quantum sensor observing the ground surface (which is installed downward), resulting in a differing sensitivity between the pair. This can cause the over-estimation of the albedo over long periods, even if the pair was calibrated with each other carefully at the initiation of the monitoring. Therefore, researchers need to check their quantum sensors' sensitivity before and after observations. For example, Mizoguchi et al. (2010) detected degradation in five quantum sensors over a 1-year field observation by checking their sensitivity before and after exposure. However, their study could not give a clear profile of the degradation because they did not verify the sensor sensitivity continuously with a reliable standard. Fielder and Comeau (2000) also detected degradation in two types of quantum sensors (their handmade original sensor and LI-190; LI-COR, Inc., Lincoln, NB, U.S.A) installed on a forest floor by checking their sensitivity before and after exposure. They tried but failed to observe the degradation process continuously because the degradation happened in both types of sensors so that neither sensor could work as a standard with sufficient stability and reliability. Therefore, a reliable profile of the sensitivity degradation was difficult to obtain.

Above all, the fundamental problem is lack of a measurement system of PAR with sufficient accuracy and stability that can work as a standard reference for quantum sensors to test their accuracy and stability under actual and varying light conditions (including a variety of spectra as well as a variety of solar directions) over long periods. Under the assumption of the sufficient reliability and stability of a specific quantum sensor as a standard reference, several other quantum sensors' performances have been evaluated (e.g., Fielder and Comeau, 2000; Pearcy, 1989). However, the stability and accuracy of such "standard" quantum sensors have not been carefully evaluated. Alternatively, several studies have carried out calibrations of quantum sensors using standard lamps in laboratories; however, this is not sufficient because such a test can only provide limited light conditions (e.g., Fielder and Comeau, 2000; Hu et al., 2007). Several studies conducted calibrations of quantum sensors using a secondary standard pyranometer outdoors in natural sky conditions (e.g., Howell et al., 1983); however, this is also not sufficient because differences in the spectral responses between the pyranometer and the quantum sensors make evaluations difficult in natural sunlight with various spectral patterns, as mentioned earlier.

Therefore, this study aims to establish an accurate and stable PAR observation protocol over long periods, eliminating the above problems as much as possible.

To achieve this aim, the spectral and cosine responses of nine quantum sensors (including a GaAsP sensor) were inspected in laboratories. Even though some data for these responses are available from the manufacturers' specification sheets, we inspected each sensor's responses in a unified method to achieve a dispassionate evaluation. Furthermore, we observed reference spectral radiation (such as open sky, forest canopy transmission, and forest canopy reflection) using a highly calibrated spectrometric measurement system (Akitsu et al., 2015). Then, PAR was obtained by integrating the spectral photon flux in the PAR wavelength range from 400 nm to 700 nm in each spectral pattern. We defined these spectral radiations and the PAR as the reference standard.

Using these data, we simulated each quantum sensor's spectral error and a combined error of its spectral error and cosine error. By modifying this simulation method, we also simulated how the quantum sensors were evaluated in the conventional approach, adopting the LI-190 quantum sensor as a "reference standard." Furthermore, a long-term weathering test was conducted in the field to evaluate the sensors' long-term sensitivity degradations.

## 2. Materials and methods

### 2.1. Inspection of the quantum sensors' characteristics

#### 2.1.1. The quantum sensors used in this study

We inspected the characteristics of nine quantum sensors, of which eight were out-of-the-box products (Table 1 and left side of Fig. 1a) and one was an LI-190 encased in a weather-proof external housing with a glass dome (Hukseflux, Delft, The Netherlands), which we call Encased LI-190 (right side of Fig. 1a).

#### 2.1.2. The quantum sensors' spectral responses

The spectral response [$R(\lambda)$; unitless] for wavelengths of 380 nm to 720 nm was inspected using the spectra of light from a 150 W halogen lamp (7157XHP; PHILIPS) dispersed with a subtractive double monochromator (CT-25CD; JASCO), whose wavelength accuracy is 0.2 nm, at the Japan Aerospace Exploration Agency (JAXA). The monochromator's inherent energy-based spectral value [$L^{E}(\lambda)$; with no defined unit] was converted into a photon-based spectral value [$L^{P}(\lambda)$; with no defined unit], according to the Planck relation $E = h\,c/\lambda$, as follows:

$$L^{P}(\lambda) = \frac{L^{E}(\lambda) \times \lambda}{h \times c \times N_A}, \tag{1}$$

where $h$ is the Planck constant ($6.626 \times 10^{-34}$ J s), $c$ is the speed of light ($2.998 \times 10^{8}$ m s$^{-1}$), $N_A$ is the Avogadro constant