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短 報（Note）

Comparison of the characteristics of five quantum sensors

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Abstract

Five quantum sensors were tested and compared to evaluate their individual characteristics and their degradation due to aging by using an artificial light source and natural sunlight. The results confirm that the accuracy and stability of each sensor are within the manufacturer-specified range. However, some sensors produce erroneous readings when solar elevation angle is low. The outputs from the various types of sensors differ from each other, and the differences between some sensor types may be greater than the individual differences between the same type of sensors. These results suggest the necessity of examining the instrumental differences when comparing measurements of photosynthetically active radiation conducted with sensors of different types.

Key words : aging degradation, azimuthal angle, incident angle, instrument difference, quantum sensor, wavelength

Introduction

Photosynthetically active radiation (PAR), which ranges from 400 to 700 nm, is one of the principal factors in photosynthetic carbon fixation, and photosynthesis is one of the most important components of the carbon cycle in terrestrial ecosystems. Synthetic analysis and comparative research on carbon budgets of terrestrial ecosystems (see, e.g., Hirata *et al*., 2008) have been actively promoted worldwide. Thus, an accurate and consistent method to measure PAR is required for an accurate evaluation of carbon assimilation. Several types of quantum sensors are available to measure PAR, but there is no global standard for quantum sensors in terms of accuracy, inherent characteristics, and degradation through aging.

The most frequently used quantum sensor is the LI-190 (LI-COR) (Mizoguchi *et al*., 2009) because it is a vanguard of PAR sensor and provides a wealth of technical information, and Fluxnet-Canada recommends this model in their measurement protocols (Fluxnet-Canada, 2003). However, AmeriFlux is adopting PAR Lite (Kipp & Zonen, Netherlands) as their standard system (AmeriFlux, 2009). Thus, at the present time a standard sensor does not exist because of the lack of universal standards, such as those existing for pyranometers. In such a situation, the only source of information regarding the reliability of these sensors is the documentation provided by the manufacturers.

In this study, five commonly used quantum sensors are compared, and the inherent characteristics, instrument differences, and degradation through aging of each sensor are evaluated using an artificial light source (i.e., solar simulator) and tested for degradation due to exposure in the field. This study should supply basic information for the development of a standard sensor and for calibration of data measured using different types of quantum sensors.

Methods

Types of quantum sensors

Although there are several manufacturers of quantum sensors worldwide, the basic elements of the devices are essentially the same. Typically, a sensor consists of a diffuser panel for diffusing light, an optical filter for blocking light outside the 400- to 700-nm range, and a silicon photodetector. In this study, we compare five different sensors: the ML-020P (EKO, Japan), the PAR Lite (Kipp & Zonen, the Netherlands), the IKS-27 (KOITO, Japan), the PAR-01 (PREDE, Japan), and the most commonly used sensor, the LI-190 (LI-COR, USA). The bottom of the LI-190 was coated by sealant to waterproof it before the experiments. All sensors used in this study are commercial products and individual differences among sensors of same type were not considered prior to the experiments.

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Laboratory tests

For the laboratory tests, a solar simulator (model ESS-80, EKO, Japan) with a 300-W xenon arc lamp was used as an artificial light source. The irradiation power ranges from 700 to 1000 Wm^{-2} and the stability has a margin of error of ±3%. The available irradiation area is 80 mm × 80 mm and the irradiation distribution has a margin of error of ±5%. The instrument covers the spectral range from 350 to 1100 nm. The performance of the solar simulator is classified as class A in Japanese Industrial Standards. The sensors were placed 20 cm from the light source, and the irradiation power was set at 1000 Wm^{-2} which is the maximum power for this simulator because solar radiation in summer reaches 1000 Wm^{-2} or more. Four measurements were carried out to evaluate the inherent characteristics and instrument differences.

The first set of measurements gives the output of the sensors relative to the incident angle of illumination, which means the zenith angle. The output of the sensors was recorded twice for each 10-degree increment of the incident angle α (see Fig. 1). The second set of measurements gives the output of the sensors relative to the azimuthal angle for a fixed incident angle of 60° (see Fig. 2). The cable-installation position for each sensor was set to the zero-degree point of the azimuthal angle. The sensors were rotated around their vertical axis and the output was recorded twice for each 10-degree increment of the azimuthal angle. The third set of measurements was to check the sensitivity characteristic as a function of incident wavelength by placing a glass filter between the sensor and the light source, with the light at normal incidence (Fig. 3). Output from the sensors was recorded once for each filter. The filters used were RG695, RG715, and RG780 (SCHOTT, Germany) and their thicknesses were 2, 2, and 1 mm, respectively. Fig. 4 shows the filter transmittance spectra quoted by the specification sheets of the glass filters. The filter model number indicates the minimum wavelength that is transmitted through the filter, although light at shorter wavelengths is weakly transmitted. The fourth set of measurement compares each sensor before and after a field experiment with a reference sensor from EKO Instruments Co. Both before and after the field experiments, sensor outputs were recorded three times.

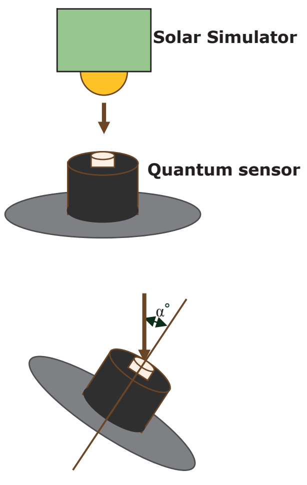

Fig. 1. Diagram of the incident angle test.

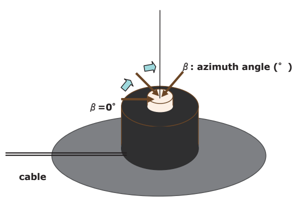

Fig. 2. Diagram of azimuthal angle test.
Incident angle (α) is 60°.

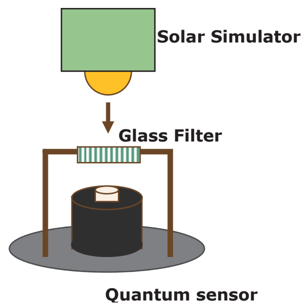

Fig. 3. Diagram of spectral sensitivity test.

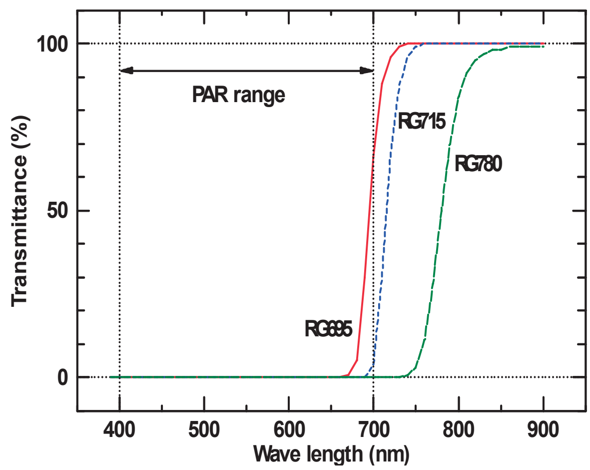

Fig. 4. Manufacturer-specified transmittance of glass filters.

Field experiments

After laboratory tests, the five sensors described above and the optional sensor LI-190 (LI-COR, USA), which was used as a benchmark (hereinafter referred to as LI-190BM) for degradation due to aging, were placed atop a 32-m tower at Fujiyoshida forest meteorology research site for comparison (lat. 35.45°N, long. 138.77°E, 1030-m elevation) (Ohtani *et al.*, 2001). Measurements were taken continuously over two weeks in September 2006, after which LI-190BM was withdrawn and kept in completely dark conditions to serve as a benchmark for degradation through aging. It was put back on the tower 12 months later to compare its output with that of the other sensors. The diffusion panels of the five sensors were cleaned every three weeks for the duration of the exposure. Precipitation and mean air temperature for this period was 1910 mm and 9.9 °C, respectively.

In addition to the experiment just described, two field experiments were conducted using LI-190s. These experiments consisted of exposure experiments using a non-coated LI-190 sensor for 30 months at Fujiyoshida, and a comparative test of eight LI-190s on a rooftop in Tsukuba (lat. 36.00°N, long. 140.12°E, 24-m elevation).

Results and discussions

Incident-angle characteristics

Fig. 5 shows the result of the incident-angle test. It shows the ratio of the output at each incident angle α to the output at zero incident angle. For each target sensor, both measurements yield equivalent values except for PAR Lite at α = 60°. The value reported for PAR Lite at 60° is the average, and thus there is a possibility of measurement error at this point. For each sensor, the output ratio decreases as α increases for α ≤ 50°. We find that the influence of the incident angle for ML-020P and PAR-Light is similar to the cosine response described in the manufacturer's specifications (the cosine response for ML-020P, PAR-Light, and LI-190 was provided). The influence of the incident angle for LI-190 was slightly larger than given graphically in the catalogue. The output ratios of PAR-01 (0.9 at α = 40° and 0.8 at α = 60°) and IKS-27 (0.9 at α = 40°), in particular, are less than those of the other sensors for α ≥ 40°. The output ratio of IKS-27 is considerably greater than unity at α = 85°, whereas the output ratios of the other sensors are less than 0.5. Therefore, the cosine-correction method of the IKS-27 may be different from the method used by the other sensors. When the solar altitude is low, such as in the morning or evening and during the winter, the PAR measured with PAR-01 and IKS-27 may be lower or higher than that measured with the other sensors.

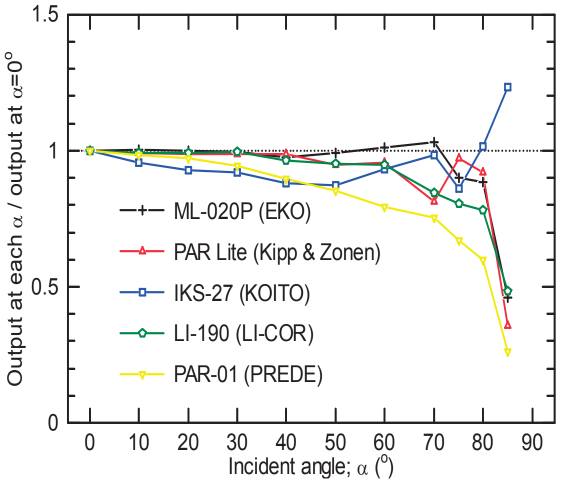

Fig. 5. Dependence of output on incident angle for each sensor.

Azimuthal angle characteristics

The ratio of the sensor outputs to the average of all outputs (0° to 180º) is shown in Fig. 6 as a function of azimuthal angle β. The outputs vary as a function of β for each sensor except for the outputs of ML-020P and LI-190, which vary less than 1%. The photodiode shape and the filter installed in the sensor may cause this β-dependent variation. Although a large variation in β may cause a detection error with a diurnal alteration, the variation was less than 5% for α = 60° for all sensors. Overall, the results of this test indicate that the influence on the sensor output of the azimuthal angle β is not as significant as the influence of the incident angle α.

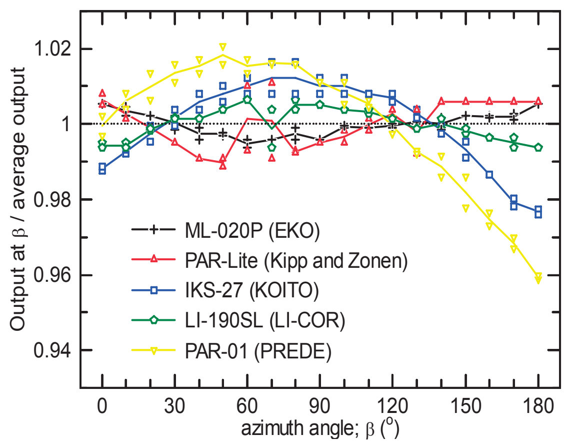

Fig. 6. Dependence of output on azimuthal angle for each sensor.

The symbols indicate measured values, and the lines represent the averages of two easurements.

Sensitivity characteristic as a function of avelength

The wavelength of PAR ranges from 400 to 700 nm. Thus, the ideal situation would be for the quantum sensor to measure only wavelengths in this range. Fig. 7 shows the ratio of the readout due to filtered light to the readout due to unfiltered light (the filter transmittance). When using the RG780 filter, the sensor output should be zero because this filter blocks all PAR wavelengths. However, the actual situation is different because all sensors detect small amounts of light with this filter in place. When using the RG695 filter, which should transmit a small band of light with wavelengths less than 700 nm (see Fig. 1), LI-190 produces the smallest output. This result indicates that the response of LI-190 to wavelengths just below 700 nm is less than that of the other sensors.

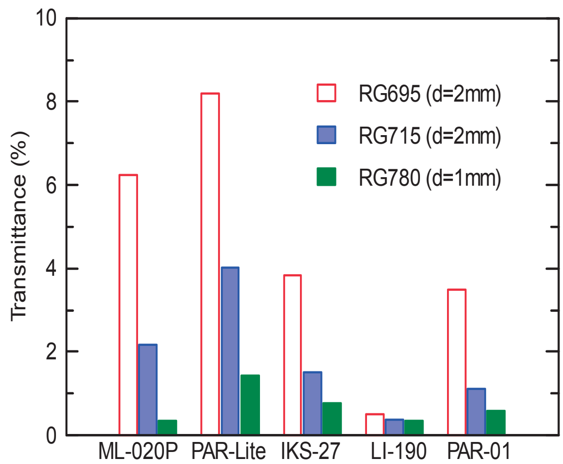

Fig. 7. Transmittance of filters measured by each sensor. Transmittance is defined as the ratio of the sensor output for the filtered light to the output for the unfiltered light.

Although the documentation for all sensors state that the measurement range is between 400 and 700 nm, high-pass filters installed in the sensor cause differing outputs among the sensors near the upper PAR wavelength range. It is possible that a similar effect occurs at the lower PAR wavelength range, so similar experiments should be performed near 400 nm.

Instrument differences

To judge instrument differences, Tables 1 and 2 show the ratio of the output from test sensors to the output of a benchmark sensor under artificial and natural light sources, respectively. The results for the laboratory tests are averages of three measurements at the incident angle α = 0°, and the benchmark sensor was the EKO reference sensor. The LI-190BM sensor was not checked under an artificial light source before the field experiment. The numbers in parentheses in Table 1 result from assuming that the relation between the EKO reference sensor and LI-190BM is maintained over the entire 12-month period of this experiment. The standard deviation for each sensor is less than 0.4 and the variability between three measurements for each sensor is small. For the field experiment, values averaged over two hours centered on the culmination time were used, because the incident-angle effect is smallest at the culmination time, and LI-190BM was adopted as the benchmark for judging instrument differences. Table 3 shows the results of comparison tests for eight LI-190s. The values are normalized by the output of sensor "e," and the letters in the left-hand column of the table identify each instrument.

The maximum instrument difference between sensors is approximately 8% for the solar simulator and 17% for sunlight, and the maximum instrument difference for the eight LI-190s

Table 1. Outputs from five sensor types illuminated by solar simulator and differences in the outputs before and after the field experiment.

Model	Manufacturer	EKO reference sensor			LI−190BM		
		Jul.25,2006	Oct.25,2007	Differences	Jul.25,2006	Oct.25,2007	Differences
ML−020P	EKO	99.67	96.72	−2.95	(98.39)	95.48	−2.91
PAR−Lite	Kipp & Zonen	106.70	105.86	−0.84	(105.33)	104.50	−0.83
IKS−27	KOITO	100.45	90.88	−9.57	(99.16)	89.71	−9.45
LI−190	LI−COR	102.51	92.49	−10.02	(101.20)	91.31	−9.89
LI−190BM	LI−COR	(101.30)	101.30	−	−	−	−
PAR−01	PREDE	99.45	91.64	−7.81	(98.17)	90.47	−7.71

The values listed are normalized by the outputs of EKO reference sensor and LI190BM. The numbers in parentheses result from assuming that the relation between the EKO reference sensor and the LI-190BM is maintained.

Table 2. Ratios of sensor outputs to the output of the benchmark sensor LI-190BM and differences in the average outputs before and after the field experiment.

Model	Manufacturer	Sep. 22 to Oct. 01, 2006		Sep. 20 to Sep. 29, 2007		Differences of averages
		Average	Standard deviation	Average	Standard deviation	
ML-020P	EKO	99.450	3.652	96.838	2.848	−2.611
PAR-LITE	Kipp & Zonen	96.172	1.630	93.963	1.624	−2.208
IKS-27	KOITO	82.532	0.855	85.970	1.041	3.437
LI-190	LI-COR	95.784	0.766	93.346	0.977	−2.439
PAR-01	PREDE	85.000	1.123	83.793	0.783	−1.207

The results listed represent an average over two hours centered on the culmination time for 10 days.

Table 3. Individual differences between several LI-190 sensors.

Sensor	Average	Standard Deviation
a	99.84	0.235
b	97.84	0.369
c	99.72	0.367
d	100.44	0.245
e	100.00	-
f	101.82	0.286
g	101.47	0.253
h	100.53	0.292

Measurement period is from April 7 to 12, 2009. Data among two hours that centered at the culmination time are used.

is less than 5% (Table 3) for sunlight, which is within the manufacturer-specified range. Instrument differences for the five sensors are large, when the individual difference of each type sensor is similar to that of LI-190. In addition, the instrument differences measured using the artificial light source are smaller than those measured using natural sunlight.

These comparison tests, which were conducted under identical conditions, may suggest that the cause of instrument differences is the spectral characterization of each sensor. Therefore, it is necessary to compare the sensors as a function of illumination wavelength to clarify the origin of the differences for each sensor.

Degradation due to aging

The outputs of a new LI-190 and an LI-190 that was used for 30 months were compared over a 10-day period from December 25, 2001 to January 3, 2002. The latter one (old sensor) was not waterproofed by sealant. The output of the old sensor was significantly less than that of the new sensor (see Fig. 8). The average output over a 10-day period from two-hour measurements that were centered on the culmination time of the old sensor are about 75% of that of the new sensor. This degradation due to aging is large even if individual differences are considered because these two sensors were not compared with each other before the old sensor was put in use 30 months ago.

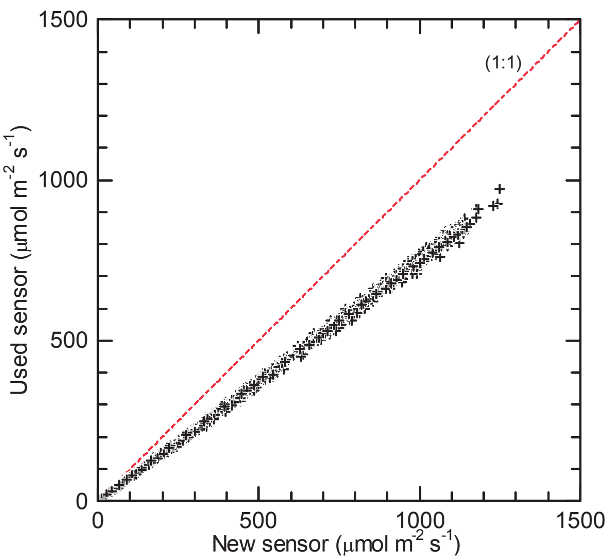

Fig. 8. Comparison between a new LI-190 and a used LI-190. The used LI-190 was not waterproofed by sealant, and the measurement period spanned from December 25, 2001 to January 3, 2002.

Tables 1 and 2 also show sensor outputs compared to the benchmark sensor LI-190BM after a 12-month field experiment, and at the end of the experiments under artificial and natural light sources, respectively. The LI-190BM sensor was exposed only briefly to sunlight, so it is assumed not to have degraded. The two LI-190s used in this experiment were waterproofed by sealant before the experiment. In the laboratory experiments, the sensor outputs decreased from 1% to 10% after 12 months. In the field experiments, the sensor outputs decreased from 1% to 3%, except for IKS-27, for which the output increased by about 3%. The difference in the results of the field experiment and the laboratory experiment may suggest that calibrating the sensor with an artificial light source will not a guarantee the accuracy of the sensor output. For each sensor, degradation after 12 months in the field experiment falls within the manufacturer-specified range, but the extent of degradation over a longer period is still unknown. If sensors are to be used for over 12 months, regular testing of their output may be necessary.

Conclusion

Quantum sensors have no global standards, such as is the case for other radiation sensors (e.g., pyranometers). Thus, the specifications published by manufacturers are the only verification of the sensor output. Through experimentation, the accuracy and stability of several different sensors were confirmed to lie within the manufacturer-specified range. However, each sensor has different characteristics with regards to the incident angle, azimuthal angle, and wavelength. The instrument differences among the target sensors may be larger than the individual differences between different individual sensors of the same type. Additional strict examination is required to evaluate the instrument difference between sensors definitely, because the number of target sensors was insufficient in this study. Furthermore, the degradation due to aging after 12 months is unknown, and we observe severe degradation of LI-190 by moisture (before waterproofing treatment), requiring additional waterproofing of the sensor. Humid areas are widespread in Asia and durability in terms of water resistance is required. Therefore, degradation due to aging longer than 12 months and durability under severe conditions are issues to be addressed in the future.

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各種光量子センサの特性比較

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要 旨

5 種類の光量子センサを対象に、人工光源を使用した室内実験および屋外での比較測定を行い、それぞれのセンサの特性と出力の経時変化を測定した。その結果、各センサの精度は仕様書に示された範囲内に収まっていることが確認された。ただし、一部の測器に太陽高度の低いときに誤差が生じやすいことがわかった。各センサ間の器差は、同タイプの個体差以上の差を生じる可能性があり、タイプの異なるセンサを使用した光合成有効放射量の比較の際には、器差補正が必要なことが示された。

キーワード：経年変化、方位角、入射角、器差、光量子センサ、波長

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