3

Micro-meteorological Observation

3.1 Radiation

All objects that are at a temperature higher than 0 K emit energy in the form of electromagnetic waves. The amount of emitted energy is proportional to the fourth power of the absolute temperature of the object (Stefan-Boltzmann Law). The amount of solar radiation emitted by the sun is close to the theoretical value of the radiation from a black body at a temperature of approximately 5,800 K. The spectral peak of the solar radiation is observed around the wavelength of 0.5 μm. Ninety-nine percent of the total solar energy occurs at wavelengths from 0.15 to 3 μm. In contrast, the temperature of the Earth's atmosphere is approximately 300 K. The spectral peak of radiation emitted by the Earth's atmosphere is observed around the wavelength of 10 μm. Most of the radiated energy from the atmosphere occurs at wavelengths from 3 to 100 μm. At the Earth's surface, radiation that originated from both the sun and the Earth's atmosphere is observed. In this section, methods for measuring the radiation originating from these two sources will be discussed.

3.1.1 Solar radiation

Solar radiation is the energy released by the sun. After this radiation enters the atmosphere, it is partially absorbed and scattered by air molecules, water vapor, and dust. Solar radiation that reaches the Earth surface is called shortwave radiation because the wavelengths of the solar radiation range between 0.3 and 3 μm (or between 0.29 and 3 μm).

Solar radiation is classified into direct and diffuse radiation. The direct and diffuse radiation combined together is referred to as global solar radiation.

Types of measuring instruments

The calibration framework for radiation sensors has been established on the basis of the absolute radiometers that are maintained and managed by the World Radiation Center. In addition, the performance standard for radiation sensors is maintained by the International Organization for Standardization (ISO).

The two main types of radiation sensors are thermopile type sensors and photodiode quantum type sensors. The former are commonly used sensors while the latter are simplified sensors. Thermopile sensors can be further classified into heat-sink type and black-and-white type, depending on how the temperature, which is proportional to the solar radiation energy, is evaluated (Ohtani, 1999b). Most of the thermopile sensors distributed currently are of the heat-sink type.

Pyranometers

Various types of pyranometers are commercially available (Table 3.1-1 and Photo 3.1-1). Thermopile pyranometers are equipped with a hemispheric glass dome to cover the heat plate. A frost protection fan can be installed to eliminate the influence of frost and to mitigate the zero-offset problem. The adverse influence of snow accretion can also be mitigated if the snow is not wet.

Pyranometers of various grades are commercially available: ISO secondary standard pyranometers (the highest accuracy available); ISO first class pyranometers, ISO second class pyranometers; and simplified pyranometers.

Table 3.1-1 Characteristics of commonly used pyranometers.

Model	Manufacturer	Sensitivity [mV(kWm^{-2})$^{-1}$]	Spectral range [nm]	ISO classification
MS-802	EKO	7	305 ~ 2800	Secondary Standard
PSP	EPPLEY	approx. 9	285 ~ 2800	Secondary Standard
CMP 21	Kipp & Zonen	7 ~ 14	310 ~ 2800	Secondary Standard
MS-402	EKO	7	305 ~ 2800	First Class
SR11	Hukseflux	15	305 ~ 2800	First Class
CMP 6	Kipp & Zonen	5 ~ 16	310 ~ 2800	First Class
MS-601	EKO	7	300 ~ 2800	Second Class
LP02	Hukseflux	15	305 ~ 2800	Second Class
CMP 3	Kipp & Zonen	5 ~ 15	310 ~ 2800	Second Class
ML020VM	EKO	approx. 7	400 ~ 1100	-
SP Lite2	Kipp & Zonen	60 ~ 100	400 ~ 1100	-
PCM-01	PREDE	7 or 10	305 ~ 2800	-

Photo 3.1-1 Examples of commonly used pyranometers.

Left: MS-402, EKO. (Photograph: courtesy of EKO INSTRUMENTS CO., LTD.)

Right: CMP 6, Kipp & Zonen. (Photograph: courtesy of Kipp & Zonen B.V.)

Pyrheliometers

Commercially available pyrheliometers include the MS-56 (EKO INSTRUMENTS CO., LTD., Japan), the CHP 1 (Kipp & Zonen B.V., Netherlands) and NIP (THE EPPLEY LABORATORY, INC., US). In order to eliminate the influence of circumsolar radiation, a cylinder is mounted on the instrument. The cylinder has a small opening and has been treated to control internal reflection. For continuous measurements, an automatic solar tracker (e.g., STR-21, EKO; SOLYS 2, Kipp & Zonen; and SMT-3, EPPLEY) can be employed (Photo 3.1-2).

Photo 3.1-2 Pyrheliometer MS-56, EKO equipped with Solar tracker STR-21, EKO.
(Photograph: courtesy of EKO INSTRUMENTS CO., LTD.)

Diffuse radiometers

In order to measure diffuse solar radiation by eliminating direct sunlight, a shadow band, plate or ball (e.g., PSB-100, PREDE CO., LTD, Japan; CM 121B, Kipp & Zonen; and SBS, EPPLEY) is mounted on a pyranometer. For continuous measurements, a sun tracker (e.g., SOLYS 2, Kipp & Zonen and STR-22, EKO) can be used so that the position of the shadow plate changes automatically according to the position of the sun (Photo 3.1-3).

Photo 3.1-3 Measurement of diffuse solar radiation.
Left: SOLYS 2, Kipp & Zonen. (Photograph: courtesy of Kipp & Zonen B.V.)
Right: STR-22, EKO. (Photograph: courtesy of EKO INSTRUMENTS CO., LTD.)

Tips!

The World Radiation Center in Davos, Switzerland, maintains the absolute reference radiometers. In individual districts of the World Meteorological Organization (WMO), a WMO Regional Radiation Center has also been designated. Regional Radiation Centers maintain standard radiometers, intercompare radiometers within a region, and calibrate the standard radiometers against the World Radiometric Reference at the International Pyrheliometer Comparison, a meeting that takes place every five years. The Regional Radiation Centers in the Asia district are located in Japan and India.

Tips 3.1-1

Measuring method

For measuring global solar radiation, a measuring instrument should be deployed horizontally in a location at which the instrument does not get shielded from radiation in any direction. In order to measure the terrestrial energy balance or albedo, two pyranometers with identical characteristics are set up, one facing upward and the other facing downward. Albedometers equipped with a combination of upward and downward facing pyranometers are also commercially available. As measurement errors may occur when the glass dome is not clean, the dome should be cleaned regularly with Kimwipes (Kimberly-Clark Corporation, US) or cotton soaked in alcohol.

In general, the output of a pyranometer is approximately 7 mV$(kWm^{-2})^{-1}$ and small. When data are transmitted over a long distance, the use of thick shielded signal wires is recommended to avoid externally generated noise. For long-term observations, it is desirable to install an arrester on the terminal board to prevent instrument damage due to lightning.

Tips!

A digital multimeter (tester) with a resolution of 0.01 mV, if one is available, is useful for checking the output of a radiometer with small output values.

Tips 3.1-2

Calibration

Because the amount of solar radiation is a key element for studying the terrestrial energy balance, meticulous care is necessary to maintain the sensor accuracy. A radiation sensor can be calibrated by comparing the measurement values from the sensor to those from a highly reliable radiometer around solar noon (Appendix 3.1-1).

Because of the deterioration of the heat-plate coating, the accuracy of radiation sensors used to drift significantly with time, and it was recommended earlier that radiation sensors be inspected every two or three years. The accuracy drift of radiation sensors distributed currently is smaller than that of older sensors.

3.1.2 Longwave radiation

The radiation emitted by the atmosphere or the Earth's surface is called longwave radiation or infrared radiation. The wavelengths of the radiation are 3 ~ 100 μm, longer than those of solar radiation.

Measuring instruments

As with a heat-sink type pyranometer, an infrared radiometer measures the temperature difference between the light-receiving surface and the heat sink with a thermopile. The protective dome of an infrared radiometer is made of silicon rather than glass. The silicon dome (window) reflects solar radiation and allows only longwave radiation to pass through. As the sensing element emits radiative energy according to the

Stefan-Boltzmann law, the infrared radiation that passes through the dome, R_d [Wm^{-2}], can be expressed as follows:

$$R_d = \frac{\Delta E}{k} + \sigma T_b^4 \qquad (3.1\text{-}1)$$

where ΔE: thermopile output voltage [mV], k: thermopile sensitivity [$mV(Wm^{-2})^{-1}$], σ: Stefan-Boltzmann constant (5.67051×10^{-8} $Wm^{-2}K^{-4}$) and T_b: sensor body temperature [K].

The use of a silicon dome mitigates dome heating caused by the solar radiation absorbed by the dome. However, dome heating cannot be completely eliminated, and accurate measurements sometimes require corrections for the effect of the heated dome. The most commonly used correction formula was proposed by Albrecht *et al*. (1974) and can be expressed as:

$$R_d = \frac{\Delta E}{k} + \sigma T_b^4 + k_d \sigma \left(T_b^4 - T_d^4\right) \qquad (3.1\text{-}2)$$

where k_d: dome coefficient and T_d: dome temperature [K]

Furthermore, Hirose and Shibata (2000) proposed the following equation for evaluating the infrared radiation passing though the dome:

$$R_d = \frac{\Delta E}{k}\left(1 + k_1 \sigma T_b^3\right) + k_2 \sigma T_b^4 + k_3 \sigma \left(T_b^4 - T_d^4\right) \qquad (3.1\text{-}3)$$

where k_1, k_2, k_3: coefficients associated with the temperature of the infrared radiometer.

The values of infrared radiation calculated with Equation 3.1-3 agreed well with the values observed according to the global standard instituted in 2006 (Ohkawara and Takano, 2008). However, because the performance of individual infrared radiometers cannot be easily checked against the infrared radiometer certifying device owned by the Aerological Observatory of Japan, either Equation 3.1-1 or Equation 3.1-2 is frequently employed.

Table 3.1-2 lists the commercially available infrared radiometers that are commonly in use and some of their images are shown in Photo 3.1-4.

Table 3.1-2 Properties of major infrared radiometers.

Model	**Manufacturer**	**Sensitivity** [$mV(kWm^{-2})^{-1}$]	**Spectral range** [nm]	**Window heating offset** [Wm^{-2}]	**Temperature dependency** [%°C^{-1}]	**Measurement of dome temperature**
MS-202	EKO	approx. 4	3,000 ~ 50,000	-	-	yes
PIR	EPPLEY	approx. 4	3,500 ~ 50,000	-	1 (–20 ~ 40°C)	yes
CGR 4	Kipp & Zonen	5 ~ 10	4,500 ~ 42,000	less than 4	1 (–20 ~ 50°C)	no
CGR 3	Kipp & Zonen	5 or 7	4,500 ~ 42,000	less than 15	5 (–10 ~ 40°C)	no

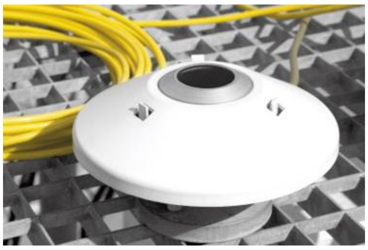


Photo 3.1-4 Infrared radiometers.
Left: CGR 4, Kipp & Zonen. (Photograph: courtesy of Kipp & Zonen B.V.)
Right: PIR, EPPLEY.

Measuring method

An infrared radiometer needs to be deployed in a location at which it does not get shielded from radiation in any direction. For downward radiation measurements, the radiometer is deployed horizontally with the sensor side facing upward. Similarly, for upward radiation measurements, the radiometer is deployed horizontally with the sensor side facing downward. When upward radiation is measured, the measurement height needs to be selected by taking the following factors into consideration: if the measurement height is too high, the measurement may include the influence of objects other than the target of observation; if the measurement height is too low, the measurement may be highly affected by the radiometer itself.

Tips!

The thermal converter IRI-01 (PREDE) for the PIR instrument amplifies the thermopile voltage by a factor of 1000 with an amplifier and outputs the amplified voltage. The use of an amplifier often produces noise and sometimes induces errors due to the amplification process. The output from the amplifier needs to be checked with a DC reference voltage generator (e.g., 3K02, NEC Avio Infrared Technologies Co., Ltd., Japan).

Tips 3.1-3

Calibration

Sensors need to be inspected regularly as their sensitivity changes with time. The difference between upward and downward longwave radiation is not as large as the difference between upward and downward solar radiation. Therefore, in order to avoid the influence of difference among radiometers on the radiation measurements, difference among the radiometers need to be examined in advance.

3.1.3 Net radiation

Radiation over the entire wavelength range, combining both solar radiation and longwave radiation, is called all-wave radiation. The difference between the downward and upward all-wave radiation is called net radiation.

Types of measuring instruments

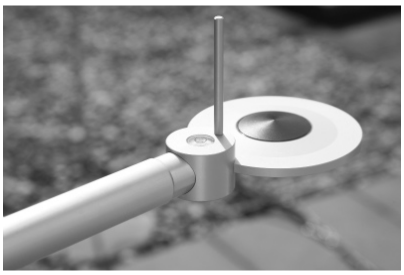
There are two types of net radiometers: net pyrradiometers and four-component radiometers. The former output net radiation directly. The latter physically combines downward/upward shortwave radiometers and downward/upward infrared radiometers.

Net pyrradiometers

A net pyrradiometer includes upward and downward-facing light-receiving surfaces, and the temperature difference between the two light-receiving surfaces is measured with a thermopile (Table 3.1-3, Photo 3.1-5). For protection from the wind, the light-receiving surfaces are covered by domes made of polyethylene that allows radiation of all wavelengths to pass through. Because conventional polyethylene is soft, domes made of this material (e.g., MF-11, EKO) are pressurized with dry air. On the other hand, the Q*7 (Radiation and Energy Balance Systems, Inc., REBS, US) is equipped with rigid polyethylene domes, which require no internal pressurization. Finally, the light-receiving surfaces of the NR Lite2 (Kipp & Zonen) are Teflon-coated instead of being covered by polyethylene domes. This design reduces maintenance work.

Table 3.1-3 Commonly used net pyrradiometers.

Model	**Manufacturer**	**Spectral range** [μm]
MF-11	EKO	0.3 ~ 30
NR Lite2	Kipp & Zonen	0.2 ~ 100
Q*7	REBS	0.25 ~ 60



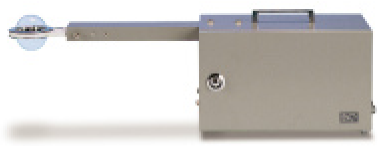


Photo 3.1-5 Net pyrradiometers.

Left: NR Lite2, Kipp & Zonen. (Photograph: courtesy of Kipp & Zonen B.V.)

Right: MF-11, EKO. (Photograph: courtesy of EKO INSTRUMENTS CO., LTD.)

Tips!

Radiometers can be damaged by crows and other birds. Particularly when net pyrradiometers with polyethylene domes are used, protective measures need to be implemented. For example, several wires may be installed around the sensor or fishing lines may be set up at locations on which birds will likely land.

Tips 3.1-4

Four-component radiometers

A four-component radiometer is equipped with relatively small pyranometers and pyrgeometers (Table 3.1-4 and Photo 3.1-6). One pair of sensors faces upward and the other pair of sensors faces downward. Net radiation can easily be evaluated by adding the four radiation components. For this reason, four-component radiometers are currently more often used than the above-mentioned net pyrradiometers.

Table 3.1-4 Commonly used four-component radiometers.

Model	**Manufacturer**	**Spectral range** [μm]		**Temperature sensor of pyrgeometer**
		Pyranometer	**Pyrgeometer**	
MR-60	EKO	0.305 ~ 2.8	5 ~ 50	Body
CNR 1(previous model)	Kipp & Zonen	0.305 ~ 2.8	5 ~ 42	Body
CNR 2	Kipp & Zonen	0.310 ~ 2.8	4.5 ~ 42	None
CNR 4	Kipp & Zonen	0.300 ~ 2.8	4.5 ~ 42	Body
NR01	Hukseflux	0.305 ~ 2.8	4.5 ~ 50	Body

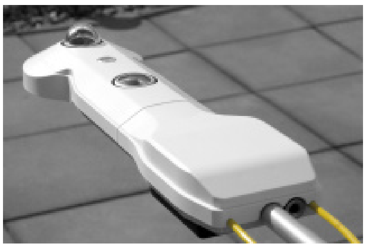


Photo 3.1-6 Four-component radiometers.

Left: CNR 4, Kipp & Zonen. (Photograph: courtesy of Kipp & Zonen B.V.)

Right: MR-60, EKO. (Photograph: courtesy of EKO INSTRUMENTS CO., LTD.)

Measuring method

As with other measurements of radiation components, four-component radiometers are deployed horizontally at a location at which the radiometers are not shielded from radiation in any direction. As measurement errors may occur when the polyethylene domes or sensor protective covers are not clean, the domes and covers should be cleaned regularly with alcohol and Kimwipes. Because polyethylene domes deteriorate quickly, they need to be replaced frequently.

Data processing

A net pyrradiometer evaluates the net radiation from the output voltage and the sensitivity coefficient of the sensor.

When a four-component radiometer is used or when the individual components of downward/upward shortwave radiation and downward/upward longwave radiation are measured, the following equation is used for calculating the net radiation:

$$R_{net} = S\downarrow - S\uparrow + L\downarrow - L\uparrow \qquad (3.1\text{-}4)$$

Where R_{net}: net radiation [Wm^{-2}], $S\downarrow$: downward shortwave radiation (global solar radiation) [Wm^{-2}], $S\uparrow$: upward shortwave radiation (reflected solar radiation) [Wm^{-2}], $L\downarrow$: downward longwave radiation [Wm^{-2}] and $L\uparrow$: upward longwave radiation [Wm^{-2}].

3.1.4 Photosynthetically active radiation (photosynthetic photon flux density)

Photosynthetically active radiation (PAR) refers to radiation with a wavelength between 400 and 700 nm, which are the wavelengths that chlorophyll can absorb. It is synonymous with photosynthetic photon flux density (PPFD). Its basic unit is $\mu molm^{-2}s^{-1}$, which can be converted into Wm^{-2} (Appendix 3.1-2).

Types of instruments

Instruments for measuring PAR include spectroradiometers that are capable of measuring irradiance according to wavelength and quantum sensors that selectively sense light between 400 and 700 nm.

Spectroradiometers

One all-weather spectroradiometer is the MS-700, EKO which is of the diffraction-grating type and it measures wavelengths between 350 and 1050 nm. For use of the MS-700, a personal computer (PC) or a logger with a digital I/O port (e.g., CR1000, Campbell Scientific, Inc., US) is necessary to control measurements and save data.

Spectroradiometers are also able to figure out the normalized difference vegetation index (NDVI) which is commonly used in remote-sensing research to indicate the wavelength properties of plant leaves. This particular subject is not addressed in this handbook.

Quantum sensors

As Table 3.1-5 and Photo 3.1-7 show, there are many types of quantum sensors. Unlike pyranometers, for which the World Radiometric Reference (WRR) was established, quantum sensors have no global standards and therefore observation results of sensors differ between manufacturers. Even among sensors of the same type, instrumental error and age-related changes are significant. For this reason, it is necessary to set up a reference instrument and exercise periodic calibration to correct for instrumental error and age-related changes.

Table 3.1-5 quantum sensors.

Model	**Manufacturer**
LI-190SA	LI-COR
ML-020P	EKO
IKS-27	KOITO
PQS 1	Kipp & Zonen
PAR-01	PREDE
SKP215	Skye

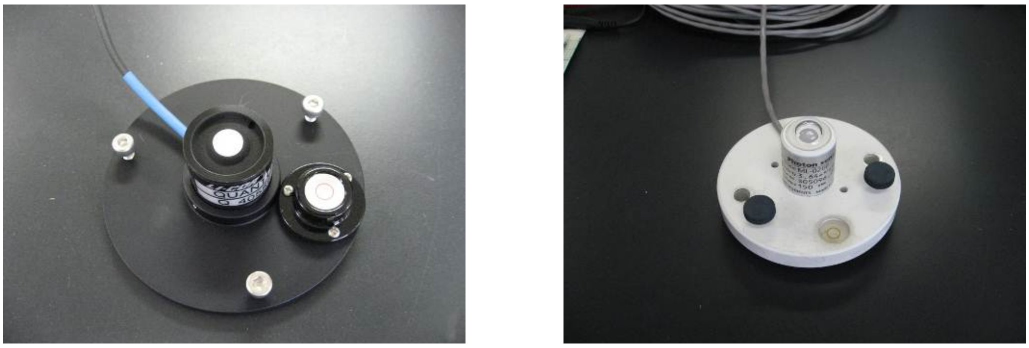


Photo 3.1-7 Quantameters. Left: LI-190, LI-COR. Right: ML020P, EKO.

Measuring method

To measure photosynthetically active radiation incident on a forest canopy, a sensor should be placed horizontally and higher than the canopy.

The amount of radiation absorbed by a forest canopy (absorbed PAR: APAR [$\mu molm^{-2}s^{-1}$]) can be obtained as follows. In remote-sensing research, the balance between downward PAR ($PAR{\downarrow}_{above}$ [$\mu molm^{-2}s^{-1}$]) measured above a forest canopy and reflected PAR ($PAR{\uparrow}_{above}$ [$\mu molm^{-2}s^{-1}$]) is calculated as APAR.

$$APAR = \left|PAR\downarrow\right|_{above} - \left|PAR\uparrow\right|_{above} \qquad (3.1\text{-}5)$$

In research on agriculture/forest meteorology and ecology, more rigorous calculations may be worked out by taking the $PAR{\downarrow}_{below}$ [$\mu molm^{-2}s^{-1}$] and $PAR{\uparrow}_{below}$ [$\mu molm^{-2}s^{-1}$] under a canopy into account.

$$APAR = \left(\left|PAR\downarrow\right|_{above} - \left|PAR\uparrow\right|_{above}\right) - \left(\left|PAR\downarrow\right|_{below} - \left|PAR\uparrow\right|_{below}\right) \qquad (3.1\text{-}6)$$

Generally, as the value of $PAR{\uparrow}_{below}$ in a closed forest during a growing season is small, it may be ignored in some cases.

It is desirable to obtain an average value of measurements from more than one point, because values vary widely from place to place when sensors are placed below a forest canopy.

Two of most commonly used instruments are introduced below. One is the LI-190SA (LI-COR, Inc., US), which has an exposed diffuser panel on the surface, and the other is the ML-020P (EKO), which has a glass dome over a diffuse panel to collect radiation.

LI-190SA

1) The sensor outputs the current. In the use of a voltage logger, a precision resistor with a small temperature coefficient (1 kΩ of resistance, 0.1 % accuracy, metal film or wire-wound resistor) is inserted into the logger to convert current to voltage just before the logger (Fig. 3.1-1).
2) If an extension cable is required, a thick coaxial cable (e.g., RG58A/U standard) should be used.
3) Because the BNC connector is not water resistant, waterproofing measures should be taken to protect the connector by treating it with self-bonding tape and then vinyl tape (Photo 3.1-8). It is desirable to encase the device such as to avoid direct contact with water.
4) Regular maintenance is required for the diffuser panel. Alcohol should not be applied.

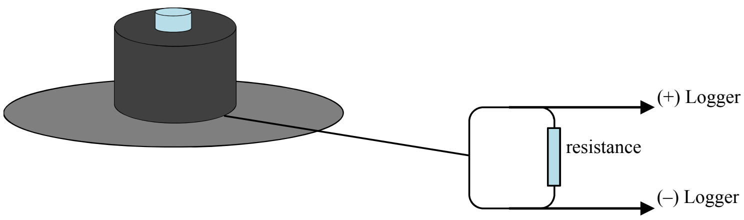


Fig. 3.1-1 LI-190 (current output) and resistance-controlled voltage measurement.

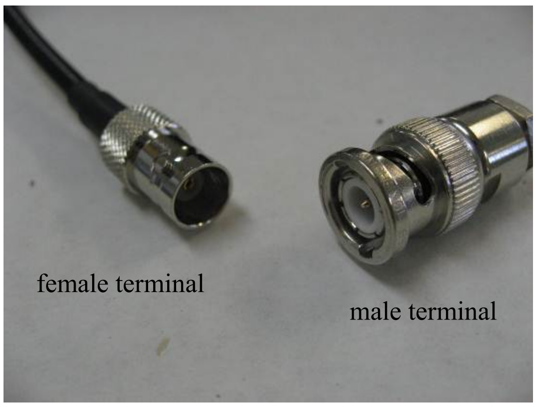


Photo 3.1-8 Cable extended to LI-190.

Left: Wrap self-fusing tape around BNC connecter to waterproof.

Right: Female (cable side) and male (sensor side) connecter.

Tips!

When connecting extension cable to LI-190, attach female terminal of BNC connecter (BNC-R).

Tips 3.1-5

Tips!

The LI-190 has a built-in interference filter to allow light of selected wavelength ranges to enter. It is generally known that inference filters degrade from exposure to water. When the LI-190 is used in a climate of high temperature and high humidity, it needs to be waterproofed by the application of sealant to the sensor bottom, particularly to the cable connection area.

Tips 3.1-6

Tips!

Caution is called for when the temperature of the body case decreases. An ice film may form over the diffuser panel if it is cleansed with Kimwipes (or cotton) that has been soaked in pure water.

Tips 3.1-7

ML-020P

1) The current output from the sensor is converted into the voltage output by the resistor which is inserted in the radiometer. When a long cable is used, a drop in output voltage has to be taken into consideration.
2) The glass dome should be regularly cleansed with Kimwipes or cotton soaked in alcohol.

Tips!

The weight of snow may cause the sensor table to tilt. In a snowy area, an installation table should be reinforced such that it can remain level during the snowfall and snowmelt seasons. It is necessary to confirm that the table is level after the snowmelt season.

Tips 3.1-8

Calibration

Because of large instrument error, the sensor needs to be rechecked before measurement. Because age-related changes are also noticeable, regular instrumental check-ups by the manufacturer or with the reference meter are recommended.

Appendix 3.1-1: Necessary factors to obtain the solar position

The followings are the calculations of factors necessary to obtain the solar position at a given time in a given place.

Equation of time Ω [h]: the difference between mean solar time (hypothetical hour angle on the assumption that the sun moves over the celestial equator at a constant speed) and true solar time (actual hour angle of the sun). Although there are several estimation equations (Matsumoto, 2005), a simple equation is introduced below.

$$\Omega = \frac{1}{60}\left[0.528276\cos(\omega J) - 3.354103\cos(2\omega J) - 0.086077\cos(3\omega J) - 0.137550\cos(4\omega J) - 7.341887\sin(\omega J) - 9.338832\sin(2\omega J) - 0.304815\sin(3\omega J) - 0.170209\sin(4\omega J)\right] \quad \text{(A3.1-1)}$$

where ω = 2π/365 or 2π/366 and J: the number of days elapsed since 0:00, Jan. 1 (real number, e.g., J = 0.5 for 12:00, Jan. 1) which is calculated based on 8-year (1998 ~ 2005) data from the Chronological Scientific Tables.

Hour angle ζ_a [°]: the angular displacement of the Earth's rotation after the sun culmination. The hour angle at the culmination is 0°. The value is negative before the culmination and positive after the culmination, increasing at a rate of 15° an hour.

$$\varsigma_a = 15(t_s - 12 + \Omega) + \gamma - \gamma_0 \quad \text{(A3.1-2)}$$

where t_s: standard time [h], γ: longitude [°] and γ_0: meridian [°].

Declination of the sun δ [°]: the celestial position of the sun. δ = 0° for the equinox, δ = –23.44° for the summer solstice, and δ = 23.44° for the winter solstice. A simple equation is introduced below.

$$\delta = 0.38145 - 22.95333\cos(\omega J) - 0.38122\cos(2\omega J) - 0.153343\cos(3\omega J) - 3.77859\sin(\omega J) - 0.034839\sin(\omega J) - 0.078079\sin(3\omega J) \quad \text{(A3.1-3)}$$

which is calculated based on data (1992 ~ 2005) from the Chronological Scientific Tables.

Culmination time t_a [h]: the time when the sun passes the meridian over the observation point.

$$t_a = 12 - \frac{(\gamma - \gamma_0)}{15} - \Omega \quad \text{(A3.1-4)}$$

Solar zenith angle β [°]**:** the angle between the zenith and the sun.

$$\cos\beta = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\varsigma_a \quad \text{(A3.1-5)}$$

where φ: latitude [°].

Solar altitude ζ_s [°]: the angle between the sun and the horizon viewed from the observation point.

$$\sin\varsigma_s = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\varsigma_a \quad \text{(A3.1-6)}$$

Appendix 3.1-2: Conversion of measurement units

The relationship between molar photon flux density F_{Q_λ} [molm^{-2}s^{-1}] and radiant flux density F_{E_λ} [Wm^{-2}] of single wavelength can be expressed with Equation A3.1-7.

$$F_{Q_\lambda} = \frac{\lambda \cdot F_{E_\lambda}}{A \cdot h \cdot c_1} \qquad \text{(A3.1-7)}$$

where λ: wavelength [m], A: Avogadro's number (6.023×10^{23} mol^{-1}), h: Planck's constant (6.626×10^{-34} Js) and c_l: velocity of light (2.9979×10^{8} ms^{-1}).

Thus, the relationship between photon flux density F_Q [molm^{-2}s^{-1}] and radiant flux density F_E [Wm^{-2}] integrated in the PAR wavelength range is expressed with Equation A3.1-8.

$$F_Q = 8.36 \times 10^{-9} \int_{400}^{700} \lambda F_{E_\lambda} \, d\lambda \qquad \text{(A3.1-8)}$$

PAR measured by a quantum sensor is limited to the integrated values, and other values for each wavelength are unknown. Accordingly, the conversion into radiant flux density is mostly done with Equation A3.1-9, where a constant α (4.24 ~ 4.57 in the case of natural light) is given on the basis of experimental results of McCree (1972) for the sake of convenience.

$$F_Q = \alpha \times F_E \qquad \text{(A3.1-9)}$$

It should be noted that the constant is not always the same, as the radiant energy at each wavelength changes according to atmospheric and other conditions.