# Chapter 7 Measurement of Sunshine Duration and Solar Radiation

CONTENTS


7.1 Measurement of Sunshine Duration ..... 1
7.1.1 Definition ..... 1
7.1.2 Sunshine Duration Measuring Instruments ..... 1
7.1.2.1 Campbell-Stokes Sunshine Recorders ..... 1
(1) Principles and Structure ..... 1
(2) Reading of Recording Paper ..... 2
7.1.2.2 Jordan Sunshine Recorders ..... 2
7.1.2.3 Other Sunshine Recorders ..... 3
(1) Rotating Mirror Sunshine Recorders ..... 3
(2) Solar-cell-type Sunshine Recorders ..... 4
7.2 Measurement of Solar Radiation ..... 5
7.2.1 Definitions and Units ..... 5
(1) Definitions ..... 5
(2) Units ..... 6
7.2.2 Solar Radiation Measuring Instruments (Radiometers) ..... 6
7.2.2.1 Pyrheliometers ..... 6
7.2.2.2 Pyranometers ..... 9
7.3 Sources of Errors ..... 12
7.4 Siting and Exposure ..... 13
7.5 Maintenance ..... 13
7.6 Correlation between Sunshine Duration and Global Solar Radiation ..... 14

# Chapter 7 Measurement of Sunshine Duration and Solar Radiation

## 7.1 Measurement of Sunshine Duration

### 7.1.1 Definition

Sunshine duration is the length of time that the ground surface is irradiated by direct solar radiation (i.e., sunlight reaching the earth's surface directly from the sun). In 2003, WMO defined sunshine duration as the period during which direct solar irradiance exceeds a threshold value of 120 watts per square meter ($W/m^2$). This value is equivalent to the level of solar irradiance shortly after sunrise or shortly before sunset in cloud-free conditions. It was determined by comparing the sunshine duration recorded using a Campbell-Stokes sunshine recorder with the actual direct solar irradiance.

### 7.1.2 Sunshine Duration Measuring Instruments

Campbell-Stokes sunshine recorders and Jordan sunshine recorders have long been used as instruments to measure sunshine duration, and are advantageous in that they have no moving parts and require no electric power. Their disadvantages are that the characteristics of the recording paper or photosensitized paper used in them affect measurement accuracy, differences between observers may arise in determining the occurrence of sunshine, and the recording paper must be replaced after sunset.

As sunshine is defined quantitatively at present, a variety of photoelectric sunshine recorders have been developed and are used in place of these instruments. As the threshold value for the occurrence of sunshine is defined in terms of direct solar irradiance, it is also possible to observe sunshine duration with a pyrheliometer.

#### 7.1.2.1 Campbell-Stokes Sunshine Recorders

(1) Principles and Structure

A Campbell-Stokes sunshine recorder concentrates sunlight through a glass sphere onto a recording card placed at its focal point. The length of the burn trace left on the card represents the sunshine duration.

The device's structure is shown in Figure 7.1 (a). A homogeneous transparent glass sphere L is supported on an arc XY, and is focused so that an image of the sun is formed on recording paper placed in a metal bowl FF' attached to the arc. The glass sphere is concentric to this bowl, which has three partially overlapping grooves into which recording cards for use in the summer, winter or spring and autumn are set (Figure 7.1 (b)). Three different recording cards (Figure 7.1 (c)) are used depending on the season. The focus shifts as the sun moves, and a burn trace is left on the recording card at the focal point. A burn trace at a particular point indicates the presence of sunshine at that time, and the recording card is scaled with hour marks so that the exact time of sunshine occurrence can be ascertained. Measuring the overall length of burn traces reveals the sunshine duration for that day. For exact measurement, the sunshine recorder must be accurately adjusted for planar leveling, meridional direction and latitude. Campbell-Stokes and Jordan sunshine recorders mark the occurrence of sunshine on recording paper at a position corresponding to the azimuth of the sun at the site, and the time of sunshine occurrence is expressed in local apparent time.

Exchange and reading of the recording paper are performed after sunset.

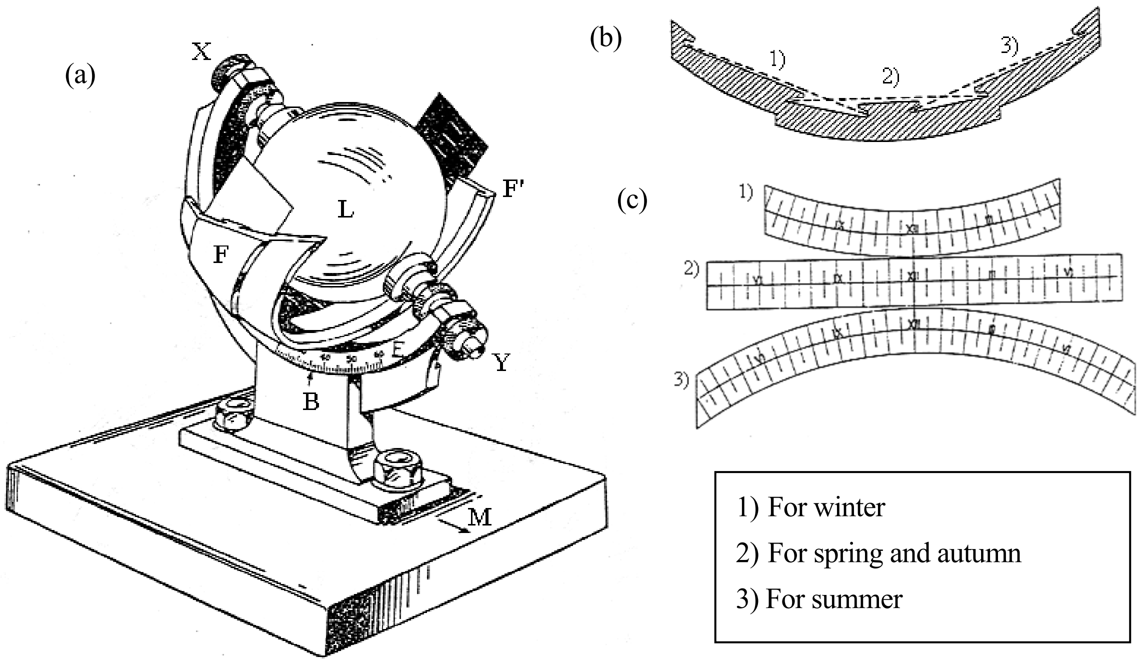



**Figure 7.1 Campbell-Stokes sunshine recorder**

**(a) Structure**

**(b) Cross section of bowl and grooves**

**(c) Recording cards**

(2) Reading of Recording Paper

To obtain uniform results for observation of sunshine duration with a Campbell-Stokes sunshine recorder, the following points should be noted when reading records:

(a) If the burn trace is distinct and rounded at the ends, subtract half of the curvature radius of the trace's ends from the trace length at both ends. Usually, this is equivalent to subtracting 0.1 hours from the length of each burn trace.

(b) If the burn trace has a circular form, take the radius as its length. If there are multiple circular burns, count two or three as a sunshine duration of 0.1 hours, and four, five or six as 0.2 hours. Count sunshine duration this way in increments of 0.1 hours.

(c) If the burn trace is narrow, or if the recording card is only slightly discolored, measure its entire length.

(d) If a distinct burn trace diminishes in width by a third or more, subtract 0.1 hours from the entire length for each place of diminishing width. However, the subtraction should not exceed half the total length of the burn trace.

### 7.1.2.2 Jordan Sunshine Recorders

A Jordan sunshine recorder lets in sunlight through a small hole in a cylinder or a semicylinder onto photosensitized paper set inside the cylinder on which traces are recorded. One common type has two hollow semicylinders arranged back to back with their flat surfaces facing east and west (Figure 7.2 (a)). Each flat surface has a small hole in it. The Jordan sunshine recorder used by JMA is the same in principle, but consists of a hollow cylinder with two holes as shown in Figure 7.2 (b). The instrument has its cylinders inclined to the relevant latitude and their axes set in the meridional direction. Photosensitized paper with a time scale printed on it is set in the cylinders in close contact with the inner surface. When direct solar radiation enters through the hole, the paper records the movement of the sun as a line. Sunshine duration is ascertained by measuring the length of time the paper was exposed to sunlight.

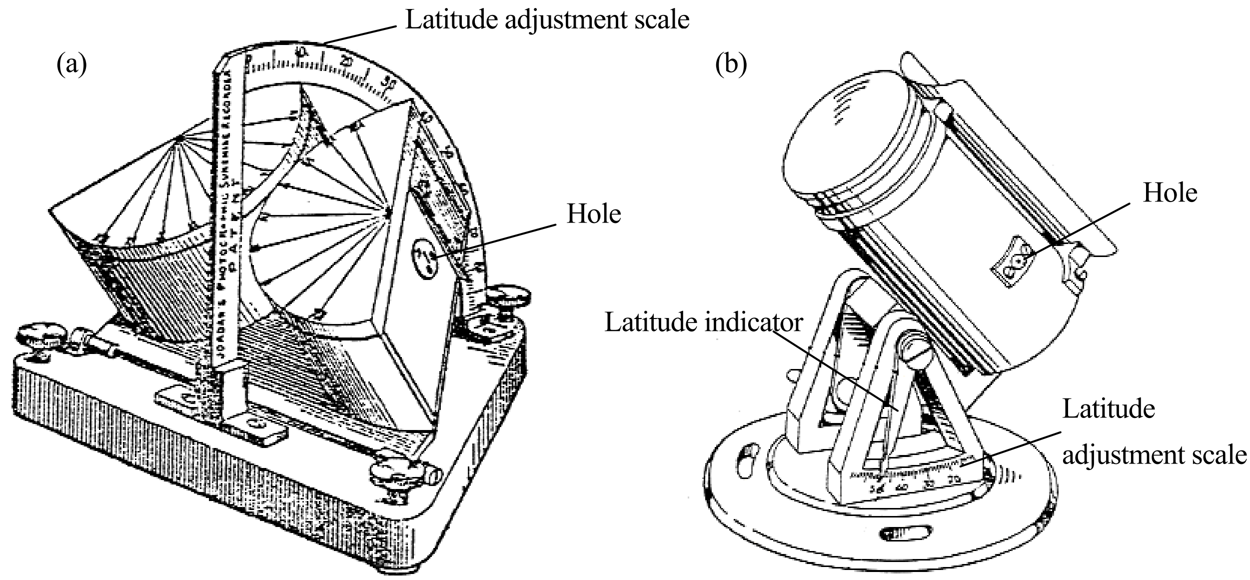



**Figure 7.2 Jordan sunshine recorders**

**(a) Common type**

**(b) JMA type**

### 7.1.2.3 Other Sunshine Recorders

Since the threshold value for the definition of sunshine is set as a direct solar irradiance of 120 W/m$^2$, sunshine recorders using photosensors as radiation detectors have been developed. By way of example, rotating mirror and solar-cell-type sunshine recorders are described below.

(1) Rotating mirror sunshine recorder (Figure 7.3)

A rotating mirror sunshine recorder is an application of the scanning method presented in the CIMO Guide. A rotating mirror is used to reflect sunlight onto the photosensor, and the occurrence of sunshine is detected by measuring the intensity of the light received. The rotating mirror sunshine recorder used by JMA has a mirror that rotates once every 30 seconds and a photosensor to receive the reflected sunlight. Once the instrument is set to an angle corresponding to the latitude at the site by adjusting the scale on the body at installation, the double-surfaced mirror reflects sunlight as required throughout the year regardless of changes in the sun's elevation. Although the radiation received by the photosensor contains both direct solar radiation and diffuse sky radiation, the latter is removed by differentiating the output signal for time electrically, and only direct solar radiation can be detected at the peak of the maximum differential coefficient. The instrument emits a pulse when the signal exceeds the threshold value of 120 W/$m^2$ corresponding to the definition of direct solar irradiance, and the processing unit counts two minutes of sunshine for every four pulses.

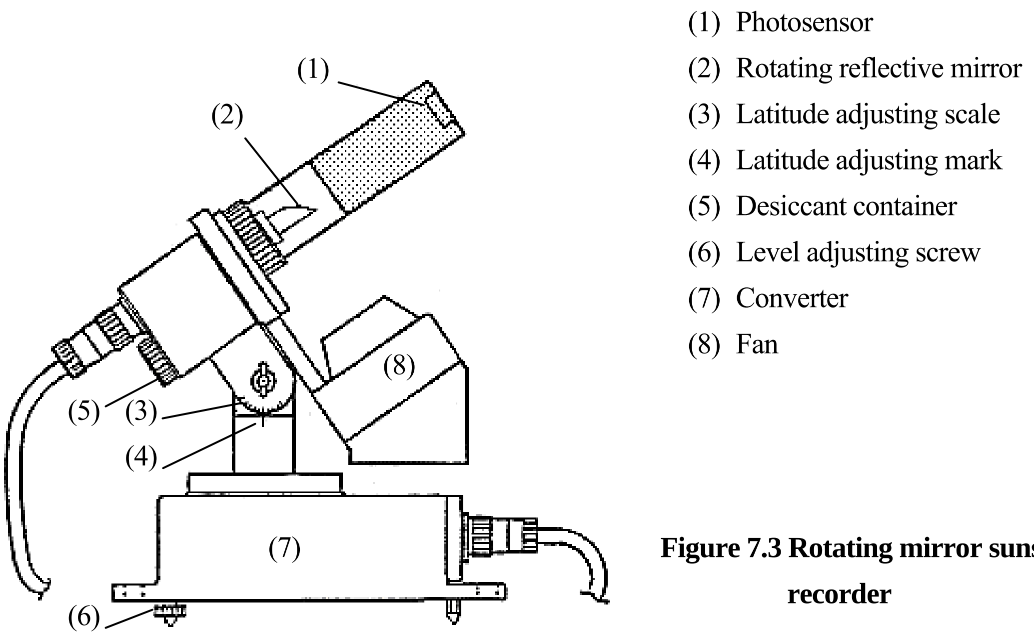



**Figure 7.3 Rotating mirror sunshine recorder**

(2) Solar-cell-type sunshine recorder (Figure 7.4)

A solar-cell-type sunshine recorder is an application of the contrast method presented in the CIMO Guide. It uses solar cells and determines the occurrence of sunshine from the intensity of their output. The device is equipped with three solar cells on a triangular prism oriented toward the celestial north pole – one on top and one on each of the southeast and southwest faces.

The output of the solar cells on each of the southeast and southwest faces includes direct solar irradiance and diffuse sky radiation. As the solar cell on the top is shaded from direct sunlight, its output can be considered equivalent to the level of diffuse sky radiation. By taking the difference between these outputs, an output value equivalent to the level of direct solar irradiance can be obtained. Solar-cell-type sunshine recorders are somewhat inferior in terms of accuracy to rotating mirror sunshine recorders; they are known to underestimate the sunshine duration in the morning and evening, during cloudy weather, and in the summer season when the sun's elevation is high.

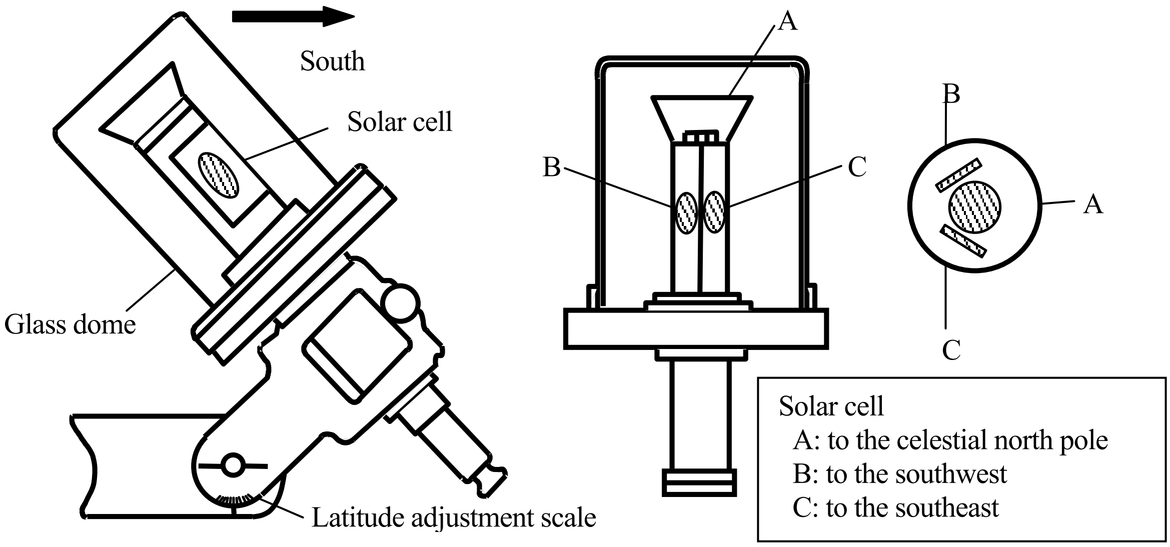



**Figure 7.4 Solar-cell-type sunshine recorder**

# 7.2 Measurement of Solar Radiation

## 7.2.1 Definitions and Units

(1) Definitions

Everything in nature emits electromagnetic energy, and solar radiation is energy emitted by the sun. The energy of extraterrestrial solar radiation is distributed over a wide continuous spectrum ranging from ultraviolet to infrared rays. In this spectrum, solar radiation in short wavelengths (0.29 to 3.0 μm) accounts for about 97 percent of the total energy. Figure 7.5 shows the spectrum distribution of solar radiation.

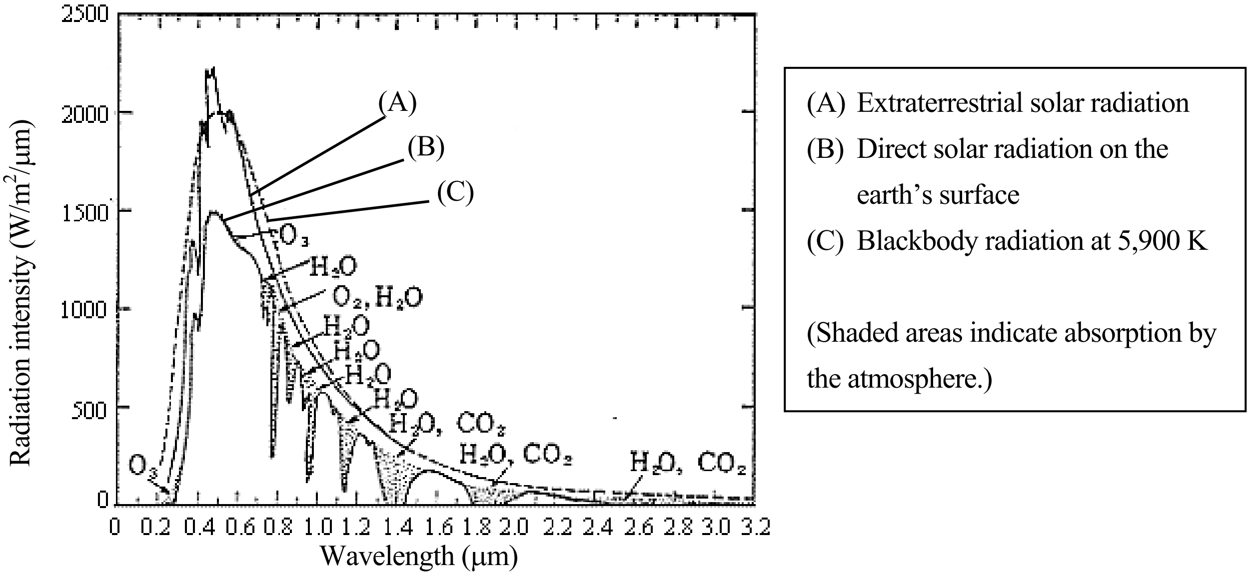



**Figure 7.5 Spectrum distribution of solar radiation**

Solar radiation is partly absorbed, scattered and reflected by molecules, aerosols, water vapor and clouds as it passes through the atmosphere. The direct solar beam arriving directly at the earth's surface is called direct solar radiation. The total amount of solar radiation falling on a horizontal surface (i.e. the direct solar beam plus diffuse solar radiation on a horizontal surface) is referred as global solar radiation.

Direct solar radiation is observed from sunrise to sunset, while global solar radiation is observed in the twilight before sunrise and after sunset, despite its diminished intensity at these times.

(2) Units

The solar irradiance is expressed in watts per square meter ($W/m^2$) and the total amount in joules per square meter ($J/m^2$). Conversion between the currently used unit (SI) and the former unit (calories) can be performed using the following formulae:

Solar irradiance: $1\ kW/m^2 = 1.433\ cal/cm^2/min$

Total amount of solar radiation: $1\ MJ/m^2 = 23.89\ cal/cm^2$

In Japan, the total amount of global solar radiation per day is about 20 $MJ/m^2$ in the summer in Okinawa and about 5 $MJ/m^2$ in the winter along the Sea of Japan. The value of direct solar irradiance is about 120 $W/m^2$ at around sunrise and sunset, and about 800 $W/m^2$ at around noon on a clear day in summer. Being aware of mean solar radiation levels in clear conditions for each season is useful for checking normal operation of instruments.

### 7.2.2 Solar Radiation Measuring Instruments (Radiometers)

A radiometer absorbs solar radiation at its sensor, transforms it into heat and measures the resulting amount of heat to ascertain the level of solar radiation. Methods of measuring heat include taking out heat flux as a temperature change (using a water flow pyrheliometer, a silver-disk pyrheliometer or a bimetallic pyranograph) or as a thermoelectromotive force (using a thermoelectric pyrheliometer or a thermoelectric pyranometer). In current operation, types using a thermopile are generally used.

The radiometers used for ordinary observation are pyrheliometers and pyranometers that measure direct solar radiation and global solar radiation, respectively, and these instruments are described in this section. For details of other radiometers such as measuring instruments for diffuse sky radiation and net radiation, refer to "Guide to Meteorological Instruments and Observation Methods" and "Compendium of Lecture Notes on Meteorological Instruments for Training Class III and Class IV Meteorological Personnel" published by WMO.

#### 7.2.2.1 Pyrheliometers

A pyrheliometer is used to measure direct solar radiation from the sun and its marginal periphery. To measure direct solar radiation correctly, its receiving surface must be arranged to be normal to the solar direction. For this reason, the instrument is usually mounted on a sun-tracking device called an equatorial mount.

The structure of an **Angstrom electrical compensation pyrheliometer** is shown in Figure 7.6 (a). This is a reliable instrument used to observe direct solar radiation, and has long been accepted as a working standard. However, its manual operation requires experience.

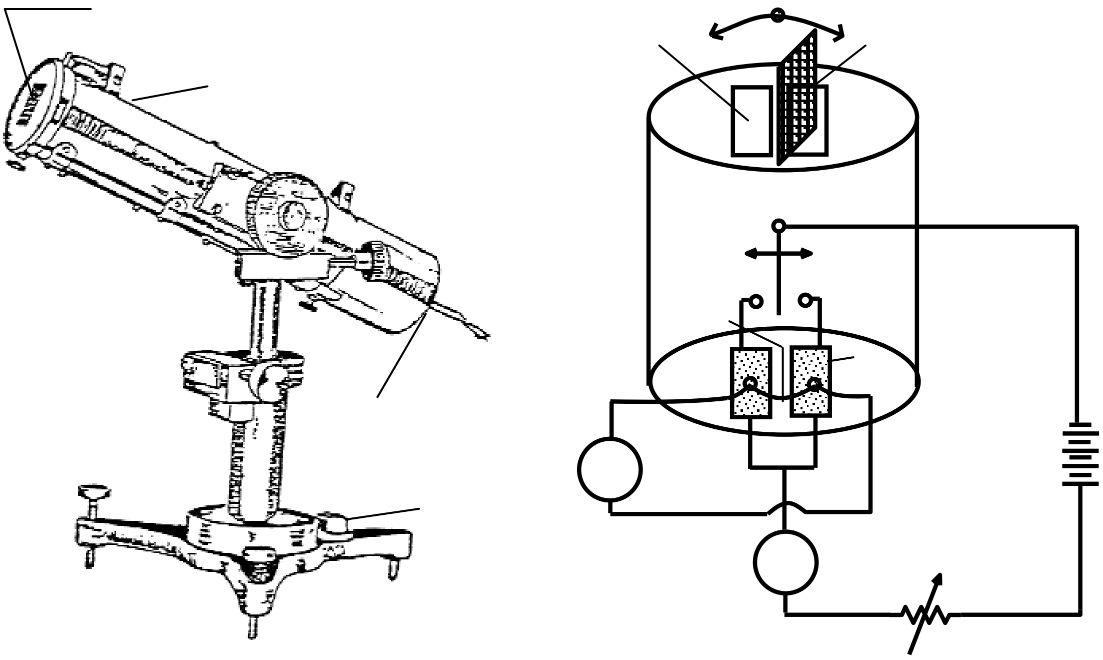


**Figure 7.6 Angstrom electrical compensation pyrheliometer**

**(a) Structure**

**(b) Circuit**

**A: Aperture B: Battery C: Sensor surface D: Cylinder**

**P: Switch R: Variable resistor S: Shutter**

**T: Thermocouple G: Galvanometer mA: Ammeter**

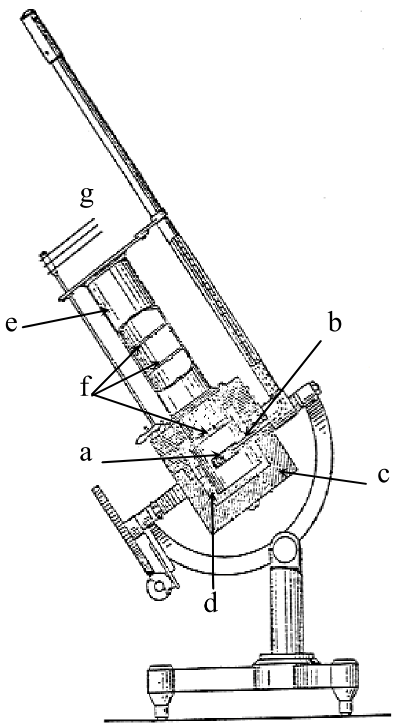
This pyrheliometer has a rectangular aperture, two manganin-strip sensors (20.0 mm × 2.0 mm × 0.02 mm) and several diaphragms to let only direct sunlight reach the sensor. The diaphragms are the same as those in the silver-disk pyrheliometer in Figure 7.7 and in the thermoelectric pyrheliometer in Figure 7.8. The sensor surface is painted optical black and has uniform absorption characteristics for short-wave radiation. A copper-constantan thermocouple is attached to the rear of each sensor strip, and the thermocouple is connected to a galvanometer. The sensor strips also work as electric resistors and generate heat when a current flows across them (see the principle drawing in Figure 7.6 (b)).

When solar irradiance is measured with this type of pyrheliometer, the small shutter on the front face of the cylinder shields one sensor strip from sunlight, allowing it to reach only the other sensor. A temperature difference is therefore produced between the two sensor strips because one absorbs solar radiation and the other does not, and a thermoelectromotive force proportional to this difference induces current flow through the galvanometer. Then, a current is supplied to the cooler sensor strip (the one shaded from solar radiation) until the pointer in the galvanometer indicates zero, at which point the temperature raised by solar radiation is compensated by Joule heat. A value for direct solar irradiance is obtained by converting the compensated current at this time. If S is the intensity of direct solar irradiance and i is the current, then

$$S = Ki^2,$$

where K is a constant intrinsic to the instrument and is determined from the size and electric resistance of the sensor strips and the absorption coefficient of their surfaces. The value of K is usually determined through comparison with an upper-class standard pyrheliometer.

The structure of a **silver-disk pyrheliometer** is shown in Figure 7.7. This instrument was developed as a portable version of a water flow pyrheliometer, which was the former primary standard.




a: Black-painted silver disk
b: Mercury-in-glass thermometer
c: Wooden container
d: Copper case
e: Cylinder
f: Diaphragm
g: Shutter

**Figure 7.7 Silver-disk pyrheliometer**

The sensing element is a silver disk measuring 28 mm in diameter with a thickness of 7 mm that is painted black on its radiation-receiving side. It has a hole from the periphery toward the center to allow insertion of the bulb of a high-precision mercury-in-glass thermometer. To maintain good thermal contact between the disk and the bulb, the hole is filled with a small amount of mercury. It is enclosed outside by a heat-insulating wooden container. The stem of the thermometer is bent in a right angle outside the wooden container and supported in a metallic protective tube. A cylinder with diaphragms inside is fitted in the wooden container to let direct solar radiation fall onto the silver disk. There is a metallic-plate shutter at the top end of the cylinder to block or allow the passage of solar radiation to the disk.

During the measurement phase, the disk is heated by solar radiation and its temperature rises. The intensity of this radiation is ascertained by measuring the temperature change of the disk between the measurement phase and the shading phase with the mercury-in-glass thermometer.

The structure of a **thermoelectric pyrheliometer** is shown in Figure 7.8. This instrument uses a thermopile at its sensor, and continuously delivers a thermoelectromotive force in proportion to the direct solar irradiance. While Angstrom electrical compensation pyrheliometers and silver-disk pyrheliometers have a structure that allows the outer air to come into direct contact with the sensor portion, this type has transparent optical glass in the aperture to make it suitable for use in all weather conditions. It is mounted on a sun-tracking device to enable outdoor installation for automatic operation by JMA.

There are several types of thermoelectric pyrheliometer, but their structures are similar. Figure 7.8 shows the structure of the one used by JMA. Copper-plated constantan wire is used as the thermopile in the sensor portion, which is attached to the bottom of the cylinder at right angles to the cylinder axis. The cylinder is fitted with diaphragms to direct sunlight to the sensor portion. It is made of a metallic block with high heat capacity and good thermal conductivity, and is enclosed in a polished intermediate cylinder and a silver-plated outer brass cylinder with high reflectivity to prevent rapid ambient temperature changes or outer wind from disturbing the heat flux in the radiation-sensing element. The cylinder is kept dry using a desiccant to prevent condensation on the inside of the aperture window.

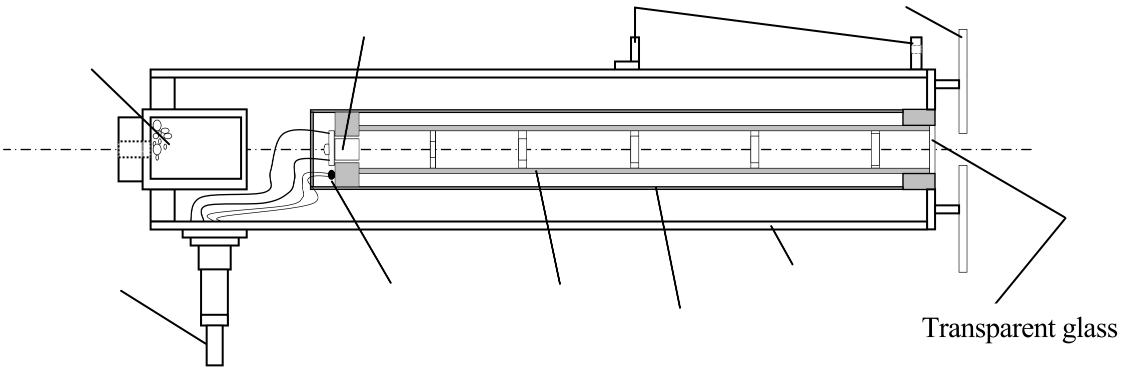



**Figure 7.8 Thermoelectric pyrheliometer**

In this pyrheliometer, a temperature difference is produced between the sensor surface (called the hot junction) and the reference temperature point, i.e., the metallic block of the inner cylinder (called the cold junction). As the temperature difference is proportional to the intensity of the radiation absorbed, the level of solar radiation can be derived by measuring the thermoelectromotive force from the thermopile. Since this type of pyrheliometer is a relative instrument, calibration should be performed to determine the instrumental factor through comparison with a standard instrument. As the thermoelectromotive force output depends on the unit’s temperature, the temperature inside the cylinder should be monitored to enable correction.

### 7.2.2.2 Pyranometers

A pyranometer is used to measure global solar radiation falling on a horizontal surface. Its sensor has a horizontal radiation-sensing surface that absorbs solar radiation energy from the whole sky (i.e. a solid angle of 2π sr) and transforms this energy into heat. Global solar radiation can be ascertained by measuring this heat energy. Most pyranometers in general use are now the thermopile type, although bimetallic pyranometers are occasionally found.

**Thermoelectric pyranometers** are shown in Figure 7.9. The instrument's radiation-sensing element has basically the same structure as that of a thermoelectric pyrheliometer. Another similarity is that the temperature difference derived between the radiation-sensing element (the hot junction) and the reflecting surface (the cold junction) that serves as a temperature reference point is expressed by a thermopile as an thermoelectromotive force. In the case of a pyranometer, methods of ascertaining the temperature difference are as follows:

1) Several pairs of thermocouples are connected in series to make a thermopile that detects the temperature difference between the black and white radiation-sensing surfaces (Figures 7.9 (a) and (c)).
2) The temperature difference between two black radiation-sensing surfaces with differing areas is detected by a thermopile.
3) The temperature difference between a radiation-sensing surface painted solid black and a metallic block with high heat capacity is detected by a thermopile (Figure 7.9 (b)).

A **bimetallic pyranograph** is shown in Figure 7.10. The radiation-sensing element (in the upper right of the figure) consists of two pairs of bimetals, one painted black and the other painted white, placed in opposite directions (face up and face down) and attached to a common metal plate at one end. At the other end, the white bimetallic strips are fixed to the frame of the pyranograph, and the black ones are connected to the recorder section via a transmission shaft. The deflection of the free edge of the black strips is transmitted to the recording pen through a magnifying system. When the air temperature changes, the black and white strips attached to the common plate at one end both bend by the same amount but in opposite directions. As a result, only the temperature difference attributed to solar radiation is transmitted to the recording pen.

Thermoelectric pyranometers and bimetallic pyranographs are both hermetically sealed in a glass dome to protect the sensor portion from wind and rain and prevent the sensor surface temperature from being disturbed by wind. A desiccant is placed in the dome to prevent condensation from forming on the inner surface. The glass allows the passage of solar radiation in wavelengths from about 0.3 to 3.0 μm – a range that covers most of the sun's radiation energy. Some models are equipped with a fan to prevent dust or frost, which greatly affect the amount of light received, from collecting on the dome's outer surface. It is necessary to check and clean the glass surface at regular intervals to ensure that the dome wall constantly allows the passage of solar radiation.

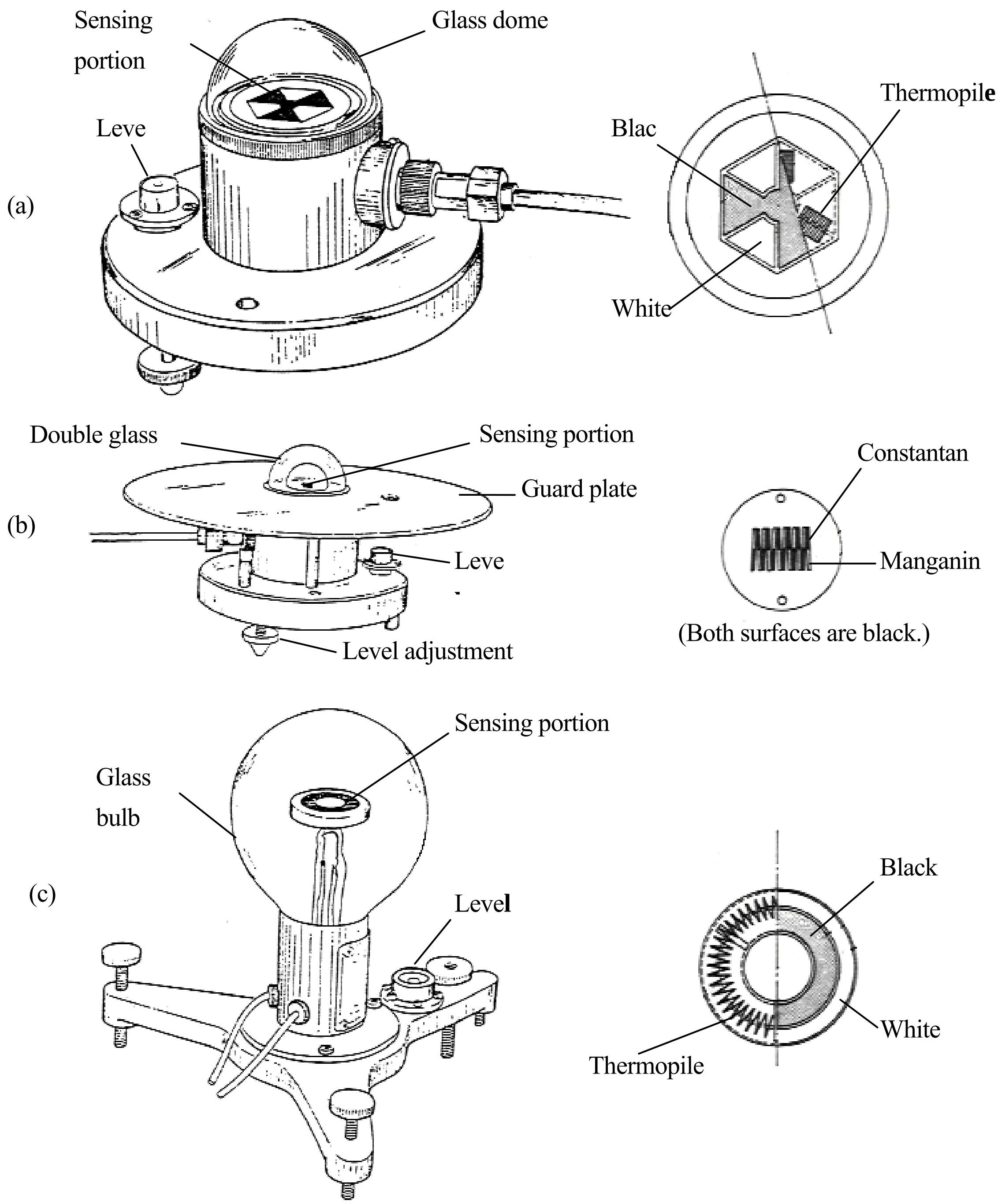



**Figure 7.9 Thermoelectric pyranometer and sensing**

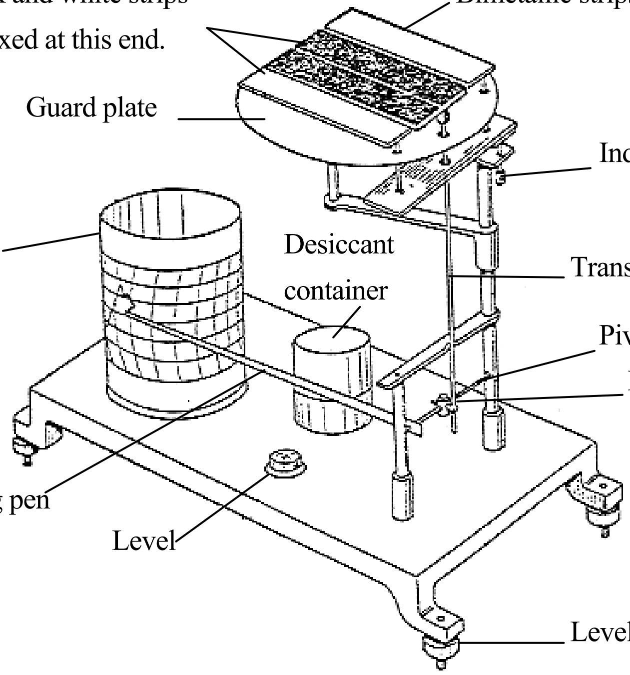



**Figure 7.10 Bimetallic pyranograph**

## 7.3 Sources of Errors

Radiometer measurement errors are attributed to sensitivity, response characteristics and other factors common to ordinary meteorological instruments. In addition to these influences, the following sources of measurement errors are also peculiar to radiometers:

(1) Wavelength Characteristics (for pyrheliometers and pyranometers)

The absorption coefficient of the radiation sensor surface and the transmission coefficient of the glass cover or glass dome of a radiometer should be constant for all wavelengths of solar radiation. In reality, however, these coefficients vary with wavelength. Since this wavelength characteristic differs slightly from radiometer to radiometer, observation errors occur when the energy distribution of solar radiation against wavelength varies with the sun's elevation or atmospheric conditions.

(2) Temperature Characteristics (for pyrheliometers and pyranometers)

As the thermoelectromotive force of a thermopile is nonlinear and the heat conductivity inside a radiometer depends on temperature, the sensitivity of these instruments varies and an error occurs when the ambient temperature and the temperature of the radiometer change.

(3) Characteristics against Elevation and Azimuth (for pyranometers)

The output of the ideal pyranometer decreases with lower sun elevation angles in proportion to cosZ (Z: zenith angle). In reality, however, output varies with the sun's elevation or azimuth due to the uneven absorption coefficient and with the shape of the radiation sensor surface. The characteristic may also deviate and errors may occur because of the uneven thickness, curvature or material of the glass cover. Usually, sensitivity rapidly decreases at an elevation angle of around 20 degrees or lower.

(4) Field of View (for pyrheliometers)

The field of view of a pyrheliometer is somewhat larger than the viewing angle of the sun. If the field of view differs, the extent of influence from diffuse sky radiation near the sun also differs. Pyrheliometers with different fields of view may make different observations depending on the turbidity of the atmosphere. (WMO recommends a total opening angle of five degrees.)

## 7.4 Siting and Exposure

Sunshine recorders and radiometers should be installed in a location where solar radiation is not shaded by trees or buildings in any season from sunrise to sunset and where there are no smoke emission sources. Pyranometers in particular should be installed at a site where the instrument is not influenced by intense reflected light from the wall surfaces of buildings. Usually, such instruments are installed on rooftops or towers, but the convenience of routine maintenance and checking tasks such as cleaning of the sensor part should be taken into consideration.

When installing a sunshine duration or solar radiation instrument, it must be set properly using a spirit level. It must also be oriented in the prescribed direction using the meridional plane as reference (for methods of determining the meridional direction, refer to Chapter 1) with its elevation angle set to the latitude of the site. It should be checked that the pyranometer's output does not fluctuate when the sensor rotates in clear weather.

## 7.5 Maintenance

Any dust, condensation, frost, ice or snow deposited on the windshield glass should be removed with a feather duster or soft cloth. Wash away any stubborn soiling with water while taking care not to damage the glass surface. As pyrheliometers have a small field of view, they are particularly sensitive to windshield glass soiling.

The desiccant in the sunshine recorder and the radiometer should be checked at regular intervals and replaced immediately once its function has deteriorated (the silica gel will turn pink). Any condensation forming on the inner surface of the windshield glass should be wiped off after detaching the glass, and the desiccant should be replaced. This maintenance should be carried out according to the indications of the instruction manual. However, if care is difficult (as in the case of a sealed instrument filled with dry air), contact the manufacturer to request repair.

If the paint on the radiation-sensing element of the radiometer has discolored or peeled, it should be repainted immediately.

As the indication from a radiometer fluctuates even in clear weather depending on the season and the time of day, it is difficult to determine whether the instrument is operating normally from the output value alone. Rough values of radiometer output in clear weather should be kept in mind, and the radiometer should be monitored to ensure that it is delivering the expected output value so that abnormalities can be detected at an early stage.

The sensor parts and the equatorial mount of a pyrheliometer are designed for all-weather usage, and continuous operation is usually possible. If potential damage from a severe storm is foreseen, operation should be stopped and the instrument should be brought indoors or protected with a cover.

## 7.6 Correlation between Sunshine Duration and Global Solar Radiation

The empirical correlation between sunshine duration and the amount of global solar radiation is as follows:

$$Q/Q_0 = a + bN/N_0,$$

where Q is the daily total amount of global solar radiation at the ground surface, $Q_0$ is the daily total amount of global solar radiation outside the atmosphere, N is the sunshine duration, $N_0$ is the possible sunshine duration, and a and b are constants.

The empirically obtained values of a and b vary depending on the location and month of observation. According to annual mean values obtained using Jordan sunshine recorders and pyranometers at five stations in Japan, the value of a ranges from 0.16 to 0.25, that of b ranges from 0.44 to 0.60, and the mean averaged values of a and b at the five stations are 0.22 and 0.52 respectively. These values may be affected by air pollution stemming from urban activity and factory operation. As the daily total amount of global solar radiation and the sunshine duration vary widely from day to day, daily totals averaged over a month are used to derive the values of a and b.

Although it is not possible to estimate the daily total amount of global solar radiation on a particular day from the sunshine duration using this method, it does enable rough estimation of a monthly value.