MEASUREMENT OF SOLAR RADIATION—I.
RADIATION INSTRUMENTS

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1. INTRODUCTION
In order to assess the availability of solar energy arriving on the earth, measurement of solar radiation at some locations is essential. From measurements, empirical models are developed to predict the availability of solar energy at other locations. Different instruments and their utilities are as follows.

A pyrheliometer is an instrument for measurement of the direct solar radiation flux at normal incidence. The instrument is usually attached to an electrically driven equatorial mount which tracks the sun.

A pyranometer is an instrument for measurement of the direct and diffuse irradiance arriving from the whole hemisphere. This hemisphere is usually the complete sky dome. A pyranometer can be used in a tilted position as well in which case it will also receive ground reflected radiation.

A pyranometer with a shading device is an instrument that measures diffuse solar irradiance within a solid angle of $2\pi S_r^2$, with the exception of the solid angle subtended by the sun’s disk.

The heart of a radiometer (an instrument that measures radiant energy, whether from the sun or from any other source) is its sensor or detector. We begin with a discussion of radiation sensors.

2. DETECTORS FOR RADIATION MEASUREMENT

Detectors [1−4] of the various instruments can be classified as calorimetric, thermomechanical, thermo-electric or photoelectric.

(A) Calorimetric sensors

In the calorimetric instruments, radiant energy is incident on a high-conductivity metal coated with a nonselective black paint of high absorptance. The radiant energy is converted into heat that can be measured by a variety of means, described below.

1) The heat can be carried away by a flowing fluid whose change of enthalpy is measured. The change of enthalpy is an indication of the incident radiant flux.

2) The heat gives rise to a change in the enthalpy of the absorbing metal (sensor). Again, this increase in enthalpy (or increase in temperature) can be easily measured.

3) In modern cavity-type instruments, the temperature difference across a transducer is maintained constant by additional electrical heating required between shielded and exposed phases. The irradiance is then proportional to the difference in cavity electrical heating in the two phases.

(B) Thermomechanical sensors

In instruments based on the thermomechanical principle, the radiant flux is measured through bending of a bimetallic strip. In this system, two metal strips with different thermal expansion properties are rigidly held together. One end is fastened and the other is free to move. One strip is coated with a highly absorbent black paint and the other given a highly reflective coat. The blackened strip is exposed to solar radiation and the other is shielded from it. The two strips are insulated from each other to prevent heat flow from one to the other. The unequal temperatures and unequal coefficients of thermal expansion cause bending of the plates into a curve. The distortion is transmitted optically or mechanically to an indicator.

(C) Thermoelectric sensors

A thermoelectric device consists of two dissimilar metallic wires with their ends connected. An electromotive force (e.m.f.) is developed when the two junctions are at different temperatures [Fig. 1(a)]. The e.m.f. developed is proportional to the temperature difference, and depends on the material of the two metals. A copper-constantan pair is a popular com-
Combination for low-temperature applications. This device is applied in radiometry by exposing one junction to the incident radiation while the other is shielded from it.

The e.m.f. developed by a single thermocouple is very low. It can be increased by connecting a number of thermocouple junctions in series [Fig. 1(b)]. An arrangement in which several thermocouple junctions are utilized is called a thermopile. In a number of solar radiation measuring instruments, the thermopile is arranged in a star-shaped flat grid [Fig. 1(c)]. The hot junctions are coated with black paint, and the cold junctions are painted white to “shield” them from solar radiation.

In order to obtain stable conditions (usually called zero drift) it is necessary to maintain cold junctions at constant temperature. To achieve this objective, Moll devised a thermopile in which the cold junctions are thermally attached to, but electrically insulated from a massive brass plate [Fig. 1(d)]. The thermal inertia of the plate absorbs short-period temperature variations forced by air currents. In the Moll thermopile, the thermocouples are made of very thin Manganin-Constantan strips corrected to copper pins. The pins are in thermal contact with, but electrically insulated from the brass plate.

3. MEASUREMENT OF DIRECT IRRADIANCE

Direct radiation is measured by a pyrheliometer, a telescopic type of instrument with a narrow aperture. This instrument faces the sun and follows its motion. Interest in establishing the value of the solar constant has been the main force behind the development of this instrument. The Smithsonian Institute, from the beginning of the 20th century, has played a leading role in this area. In 1905, Dr Charles Greely Abbot of this institution developed a water flow pyrheliometer for the determination of solar radiation. Prior to this, in 1893, Knut Angström, of Sweden had developed the Angström electrical compensation pyrheliometer which has proved to be a very stable instrument. But these days, more accurate cavity-type pyrheliometers are employed for direct irradiance measurement. Before describing pyrheliometers, let us describe the standard radiation scale, determined by the pyrheliometer itself and the classification of pyrheliometers.

3.1. Standard radiation scales

Before 1956, two standard scales of radiation were in use, namely, the Angström scale and the Smithsonian scale. The Angström scale (AS-1905) was
based on the electrical compensation pyrheliometer of K. Angström and it was adopted in 1905. The Smithsonian scale (SC-1913) was based on the water flow pyrheliometer of C. G. Abbot of the Smithsonian Institution, Washington, and it was adopted in 1913. For about half a century, the two scales were used independently.

However, it was felt long ago that both the scales suffered from serious errors and needed modification. The Smithsonian scale was found to be about 3.5% higher than the Angström scale. Therefore, in 1956, at Davos, Switzerland, the International Radiation Commission [5] proposed a new scale, known as the International Pyrheliometer scale of 1956 (IPS-1956). This scale is a compromise between AS-1905 and SC-1913. It is 1.5% higher than the Angström scale and 2% lower than the Smithsonian scale. IPS-1956 was based upon the Angström electrical compensation pyrheliometer (new version). In 1975, at the International Pyrheliometer Commission, Davos, it was found that the set of Angström electrical compensation pyrheliometers which maintain the IPS-1956, differ among themselves. Also by 1975, a new generation of absolute pyrheliometers, known as absolute cavity radiometers, had been developed. These instruments have an accuracy better than 0.3%. Therefore, in 1975, a new scale known as the World Radiometric Reference (WRR), based on the absolute cavity radiometer, was adopted. The new scale is 2.2% higher than IPS-1956. Radiation values measured on IPS-1956 have to be multiplied by 1.22 to convert the same to WRR. The new scale is guaranteed by a World Standard Group of five absolute cavity Radiometers, maintained at the World Radiation Center, Davos, Switzerland. These are:

ACR-310 (Wilson, JPL, U.S.A.);
ACR-311 (Wilson, JPL, U.S.A.);
PACKED-III (Kendall, JPL, U.S.A.);
PMO-2 (Frohlich, Davos, Switzerland);
CROM (Crommelynck, Brussels, Belgium).

3.2. Classification of pyrheliometers

Following the Commission for Instruments and Methods of Observation of the World Meteorological Organisation (1965), we classify pyrheliometers as standard, first class, and second class in accordance with the criteria given in Table 1.

Based on this criteria the commercially available pyrheliometers are classified as one of the following.

(i) Standard pyrheliometers. The absolute cavity radiometer; the Angström electrical compensation pyrheliometer; and the Abbot silver-disk pyrheliometer.

(ii) First-class pyrheliometers. The Michelson bimetallic pyrheliometer; the Linke–Feussner iron-chad pyrheliometer; the New Eppley pyrheliometer (temperature compensated); and the Yanishevsky thermoelectric pyrheliometer.

(iii) Second-class pyrheliometers: the Moll–Gorczyński pyrheliometer; and the Old Eppley pyrheliometer (not temperature compensated).

The Smithsonian water-flow pyrheliometer was omitted from the list of standard instruments, but it has been one of the primary standards in the U.S.A., against which silver-disk pyrheliometers and in some cases Angström pyrheliometers, were calibrated. The various types of instruments are discussed individually in the sections which follow.

3.3. Cavity-type absolute pyrheliometer

Since the mid-1960s, a second generation of absolute pyrheliometers has been developed for the accurate measurement of solar radiation. These are elec-

<table>
<thead>
<tr>
<th>Table 1. Classification of pyrheliometers</th>
<th>Standard</th>
<th>First class</th>
<th>Second class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity (mW cm⁻²)</td>
<td>±0.2</td>
<td>±0.4</td>
<td>±0.5</td>
</tr>
<tr>
<td>Stability (percent change per year)</td>
<td>±0.2</td>
<td>±1</td>
<td>±2</td>
</tr>
<tr>
<td>Temperature (maximum error due to changes of ambient temperature, %)</td>
<td>±0.2</td>
<td>±1</td>
<td>±2</td>
</tr>
<tr>
<td>Selectivity (maximum error due to departure from assumed spectral response, %)</td>
<td>±1</td>
<td>±1</td>
<td>±2</td>
</tr>
<tr>
<td>Linearity (maximum error due to non-linearity not accounted for, %)</td>
<td>±0.5</td>
<td>±1</td>
<td>±2</td>
</tr>
<tr>
<td>Time constant (maximum)</td>
<td>25 sec</td>
<td>25 sec</td>
<td>1 min</td>
</tr>
</tbody>
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trically self-calibrated blackened cavity radiometers, developed in the U.S.A. and Europe. Kendall, Wilson and Geist in the U.S.A. [6] and Bross and Frohlich in Europe, are looking after their design and development. These are the instruments upon which the present day value of the solar constant, 1367 W m$^{-2}$, and the absolute radiation scale, World Radiometric Reference (WRR), are based. Through the last two decades, cavity pyrheliometers have undergone a great deal of improvement and the Active Cavity Radiometer [7], type IV (ACR-IV, see Fig. 3), is capable of measuring solar radiation with an accuracy of $\pm 0.1\%$. Different companies manufacture cavity-type pyrheliometers under different brand names: the latest model of Eppley Laboratory, U.S.A., is the 4+F Absolute Cavity Pyrheliometer. Technical Measurements (TMJ) of the U.S.A. is making its product under the name TMJ pyrheliometer.

In the 1960s, absolute cavity pyrheliometers were designed to measure the solar constant from satellite flights. These were called spacecraft cavity radiometers and were designed and manufactured at the Jet Propulsion Laboratory (JPL) of the California Institute of Technology and at Eppley Laboratory, U.S.A.

From the construction point of view, these radiometers consist of two detectors in the form of conical cavities. Each cavity is connected to the heat sink through a thermal impedance. Cavities and their thermal impedances are made of pure silver (99.99% pure) by the deposition technique. The interior of each cavity is coated with special black paint. A low temperature coefficient electrical winding is bonded to the back of each cavity in the region where it is irradiated by the solar flux. At the top of each thermal impedance and near the aperture, a resistance temperature sensor is provided. The primary cavity has a very accurately known aperture and this is the cavity which is irradiated. The heat sink is insulated from the outer case. Operation of the radiometer is as follows.

Dissipation of radiant energy or electrical power in either cavity will produce a temperature difference across its thermal impedance. This temperature difference is sensed by the resistance sensors, which by means of a servo system, controls the voltage across the heater winding so that the cavity temperature is always higher (about 1°C) than the sink temperature.

The primary cavity is alternatively shaded and exposed to solar radiation by means of a shutter. When the cavity is shaded, the electrical heating maintains the cavity at about 1°C higher temperature than the heat sink. When the shutter is open, direct radiation impinges on the primary cavity. A servo system automatically decreases the electrical heating of the primary cavity by the amount so that it is still at about 1°C higher temperature than the heat sink. Then from energy conservation, the decrease in electrical heating is proportional to the radiant energy falling on the primary cavity, i.e.

$$H = K(P_1 - P_2).$$

Where $P_1$ is the electrical power when the cavity is shaded from solar radiation. $P_2$ is the electrical power when the cavity is exposed to irradiation. $K$ is a constant determined from such instrument parameters as detector area, absorptance of the cavity, heater resistance, etc.

The function of the secondary cavity is to minimize any error due to heat sink temperature drift, i.e. if during the measurement time, the temperature of the heat sink changes, it will introduce errors in $P_1$ and $P_2$ and hence in the irradiance measurement. This is

![Diagram](Fig. 3. Active radiometer, model ACR IV.)
eliminated in the following way. The secondary cavity is always heated with a constant power so that its temperature is about 1°C higher than the heat sink. The primary cavity is also heated with electrical power (variable) so that, when it is shaded, its temperature is the same as that of the secondary cavity. Four temperature sensors are connected, two at the two ends of the thermal impedance of the primary cavity and two at the two ends of the thermal impedance of the secondary cavity. These four thermometers form the four branches of a bridge whose output is proportional to the temperature difference of the two cavities. Bridge output controls the voltage across the heater winding of the primary cavity. Hence, if the temperature of the heat sink changes, it will not produce any output signal across the bridge.

3.4. Smithsonian water-flow pyrheliometer

A schematic diagram of one of the single chamber versions [8] of the water-flow pyrheliometer is shown in Fig. 4. The collimating tube is composed of two sections, AA and BB. The walls of the lower part, section AA, are coated with a highly absorbent black paint. Direct solar radiation from the sun is absorbed by the cone-shaped receiver E. Distilled water flows over the exterior walls of the thin metallic collimating tube, first over section AA and then over section BB. Inlet and outlet temperatures are measured at points D₁ and D₂. The exterior of the water channel is encased in a Dewar vacuum wall. Under stable conditions, accurate measurement of the water-flow rate and of the temperature differences between inlet and outlet yield a measure of the incident radiative flux.

Before the double-chamber water-flow pyrheliometer described in the next section was built, a water-stir instrument was designed in which the principle of calorimetry by the method of mixtures was utilized. In this single-chamber instrument, the sun’s radiant heat is absorbed in a blackened conical cavity at the base of a collimating tube. An electric heater is used to simulate the solar radiant heat. A water tank insulated from the outside protects the calorimeter from ambient temperature variations. The water surrounding the absorption chamber is vigorously stirred by a stirrer mechanism. Solar radiant heat is equated to the electrical heat by balancing the temperatures.

In 1932, Abbott and Aldrich improved the single-chamber water-flow pyrheliometer by utilizing two identical collimating chambers insulated from each other. Both chambers are equipped with an electrical heating system so that the role of the chambers can be easily interchanged. Each chamber has its own cooling water stream. When the instrument faces the sun, one chamber is exposed to sunlight and the other is shielded and heated by an electric current. Under identical water-flow and temperature difference conditions the electrical power consumed represents the amount of solar irradiance. In practice the thermocouples of the two chambers are differentially connected to each other’s absorbers, thereby eliminating the necessity of measuring temperature or flow rate. This technique significantly increased the accuracy of measurement compared to the single-chamber water-flow pyrheliometer.

For the three water-flow pyrheliometers mentioned above, solar irradiance is calculated in true heat units from physical parameters of the instrument. For this reason they are called absolute pyrheliometers. Unfortunately, these instruments are difficult to operate and are therefore no longer manufactured.

3.5. Ångström compensation pyrheliometer

The Ångström electrical compensation pyrheliometer is still one of the most accurate and convenient instruments for measuring solar radiation. A schematic of the Ångström pyrheliometer is shown in Fig. 5. Its receiver consists of two strips (L and M) of manganese foil of approximately 20 × 2 × 0.01 mm coated on one side with Parsons optical black lacquer. The strips are mounted side by side across the opening of the strip holder. A thermojunction is attached to the back of each strip and electrical leads from the strips and the thermojunctions are attached to external binding posts on the base of the holder. P and N
form a reversible switch. The holder is fixed at the bottom of a circular tube, which has a rectangular aperture in front having an opening angle $6 \times 3^\circ$. The tube is mounted on a tripod so that it can be pointed accurately towards the sun's disc. A reversible shutter at the front end of the tube shades one strip from the sun and exposes the other strip to solar radiation. The shaded strip is heated by a controlled electric current. The electric current is adjusted so that the two strips show exactly the same temperature. The radiation energy absorbed in one strip is then equal to the electrical energy dissipated in the other strip. If the length of the strips is $l$, the width $b$, the absorption coefficient $a$, and the intensity of direct radiation is $I$, then the radiant energy absorbed is $albI$. The electrical energy dissipated is $RI^2$, where $R$ is the resistance of strip and $I$, the current. The intensity of the direct solar radiation $I$ is then given by

$$I = \frac{CRi^2}{ab}$$

where $C$ is a constant determined by the units employed. For an absolute measurement of radiation the instrumental factors $a, l, b$ and $R$ must be determined by some means. Since the determination of $a, l, b$ and $R$ to the required accuracy is a difficult procedure, a constant $K$ given by

$$K = \frac{CR}{ab}$$

is normally determined by the manufacturer of the instrument via reference to a primary standard. Thus knowing the value of $K$ the incident radiation flux can be determined by the relation $I = KR^2$. The stability of the Angstrom pyrheliometer has been demonstrated to be extremely high, of the order of two parts in one thousand, over periods of years and this justifies its use as a reference standard.

In the most modern models (developed by the Swedish and by Eppley), errors caused by the so-called edge effect and the inability to heat the shaded strip in the same manner as the exposed one and from differences in the thermal conductances of the strips, are minimized. Marsh has recently introduced a zero-operated electronic system in which the current to the heated strip is controlled automatically, thereby rendering the operation more convenient and reducing personnel errors in the measurements.

The IGY instruction manual [5] specifies that for instruments calibrated according to the uncorrected Angstrom Scale before 1 January 1957, measured radiation values should be multiplied by the factor 1.015 to convert them to the IPS. Pyrheliometers which have been standardized since 1957 have this correction included in the instrument constants.

3.6. Abbot silver-disc pyrheliometer

This instrument was designed by Abbot in 1902 at the Smithsonian Institution and was used as a secondary standard for radiation measurements. A schematic diagram of the silver-disc pyrheliometer is shown in Fig. 6. The sensitive element of the instrument is a blackened silver disc, $D$, which is 3.8 cm in diameter and 0.7 cm thick. The disc has a hole bored radially into its edge, into which is inserted the bulb of a sensitive mercury-in-glass thermometer $T$. A good thermal contact between the silver disc and thermometer bulb is maintained by using mercury. The disc is suspended by three fine steel wires inside a copper box, $B$, which is enclosed in a wooden box to protect the instrument from the temperature changes of the surroundings. The thermometer stem is bent through a right angle to make this instrument more

![Fig. 5. Circuit of the Angstrom compensation pyrheliometer.](image)

![Fig. 6. Abbot's silver disc pyrheliometer.](image)
compact and easier to use. In order to facilitate temperature readings, a slot is cut into the tube supporting and protecting the thermometer, which is graduated in steps of 0.1°C between −15 and +50°C. The field of view of the instrument is limited, by appropriate diaphragms inside the collimator tube, to a circular cone whose aperture angle is 5.7°. A three-wafer shutter of polished metal plates is rotated in and out of the field of view to alternately shade and expose the silver disc to solar radiation in specified and carefully timed sequences. Solar radiation which enters the instrument through the collimator tube labelled C, are absorbed by the blackened silver disc, D, and causes a rise in the temperature of the disc. The rate of change of temperature of the disc is monitored by careful readings of the thermometer in a series of 2 min cycles. The instrument may be made to follow the sun by means of an equatorial mounting. Several comparisons of the silver-disc pyrheliometer were made and it was observed that it remains extremely stable with time, as shown by Hoover and Froiland in Table 2. It can be seen from the table that the variations are within the error of observation.

3.7. Linke–Feussner pyrheliometer (actinometer)

This is one of the most convenient instruments used for the measurement of direct radiation at normal incidence with and without filters. A schematic diagram of the Linke–Feussner pyrheliometer is shown in Fig. 7. The main body of the instrument consists of six massive copper rings which are contoured on the inside of a tube to produce a set of radiation diaphragms for decreasing internal reflections, for defining the acceptance angle of the instrument, and for limiting turbulent air currents inside the instrument, thus securing a high stability and good sensitivity. A rotating disc with filters is positioned in the upper end of the tube. At the upper extremity of the tube is a special screening head which eliminates unwanted reflection in filter measurements.

This pyrheliometer employs a specially designed Moll thermopile receiver consisting of 40 manganese–constantan thermocouples (of tenths of micro-ohm sensitivity), arranged in a circle of 1 cm diameter.

The thermocouples (blackened with Parsons optical lacquer) are in two equal sectional arrays, which are connected in opposition. One section is exposed to the radiation being measured and the other is shaded. Thus the sections tend to compensate each other for short period temperature fluctuations of the environment and for thermal effects caused by quasi-adiabatic pressure changes near the thermopile surface which occur in fluctuating air currents. The aperture angle is approximately 10°, the sensitivity of the thermopile is about 11 mV/cal cm−2 min−1, the impedance of the thermopile is about 65 ohm and the temperature sensitivity coefficient is −0.2%/°C−1.

In this instrument five filters are usually provided fitted in the rotating disc. For the exclusion of the longwave terrestrial radiation, a filter of ultrasil (quartz) is provided, and the absorption filters OGI (transparent from 0.525 to 2.80 μm) and RGB (0.70–2.80 μm) are normally used. The filter mount is as well fitted with a double walled opaque disc for use in zeroing the instrument. This instrument is installed on a manually operated azimuth-elevation mount by which it can be oriented in any direction.

3.8. Eppley normal incidence (NI) pyrheliometer

The Eppley normal incidence pyrheliometer has found wide acceptance in many parts of the world. The latest model of the NI pyrheliometer uses a thin silver disc (9 mm in diameter) as a receiver which is coated with Parsons optical black lacquer. Fifteen junctions of fine bismuth–silver thermocouples are in thermal contact with, but electrically insulated from, the lower surface of the disc. The cold junctions are in contact with the copper tube of the instrument. The

<table>
<thead>
<tr>
<th>Date</th>
<th>Number of values</th>
<th>Mean constant</th>
</tr>
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<tbody>
<tr>
<td>1932</td>
<td>37</td>
<td>0.3625</td>
</tr>
<tr>
<td>1934</td>
<td>42</td>
<td>0.3629</td>
</tr>
<tr>
<td>1947</td>
<td>18</td>
<td>0.3626</td>
</tr>
<tr>
<td>1952</td>
<td>100</td>
<td>0.3622</td>
</tr>
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</table>
unit is mounted at the base of a double walled brass tube which is chromed externally and blackened internally. Recent models incorporate thermistor compensated circuits which eliminate the effect of ambient temperature variations. A series of diaphragms limits the aperture to a circular cone of full angle 5°41'30". A manually rotatable disc, which can accommodate three filters (such as Schott OG1, RG2, and RG8) and leave one aperture for total spectrum measurements, is provided. A diopeter is used to determine the direction of the sun. The tube is sealed with a silica window which is 1 mm thick. The sensitivity of this instrument is about 6 mV/cal cm⁻² min⁻¹, its impedance 180 ohm, and response time (maximum) 20 s.

This instrument is supplied with an electrically driven equatorial mount for solar tracking. The output of the pyrheliometer can be either directly recorded on a strip chart recorder or integrated over an appropriate time period and registered. This instrument is found to be very stable.

During the year 1957–1958, the International Geophysical Year (IGY), this instrument was recommended as one of the instruments for solar radiation measurement.

4. MEASUREMENT OF GLOBAL RADIATION

Global solar irradiance is measured by radiometers with hemispheric fields of view, called pyranometers. The sensing element of most common pyranometers are based on thermoelectric, thermo-mechanical or photovoltaic principles. Unlike the conical absorber of some of the pyrheliometers, the sensing element of the pyranometers are flat surfaces. In routine meteorological measurements, pyranometers are always placed in a horizontal position.

4.1. Classification of pyranometers

Based on sensitivity, stability and accuracy, the WMO (1965) has classified pyranometers as first class, second class and third class. All the pyranometers which have been developed require calibration with respect to a primary radiation standard, so none can be classed as a standard pyranometer. The basis for the classification is given in Table 3.

The ratings of pyranometers, according to these criteria, are as follows.

(i) First-class pyranometers: Eppley Precision Spectral Pyranometer; and Kipp and Zonen pyranometer, CM-11.

(ii) Second-class pyranometers: Moll–Gorczynski (Kipp) pyranometer; Eppley pyranometer (also called 180° pyrheliometer); Volacine thermopile pyranometer; Dirnspahr–Sanberer (star) pyranometer; Yanishevsky thermoelectric pyranometer; and Spherical Bellani pyranometer.

(iii) Third-class pyranometers: Robitsch bimetallic pyranometer.

In general, a pyranometer should have the following characteristics.

(i) The calibration factor must be independent of temperature.

(ii) It should not be wavelength-selective.

4.2. The Moll–Gorczynski pyranometer

The Moll–Gorczynski pyranometer (often called solarimeter) uses a thermopile designed by Dr W. J. Moll of the University of Utrecht. This Moll thermopile was used by Dr L. Gorczynski, Director of the Polish Meteorological Institute for constructing pyrheliometers and pyranometers in the year 1924. The thermopile consists of 14 very thin (0.005 mm) black-

<table>
<thead>
<tr>
<th>Table 3. Classification of pyranometers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitive (mW cm⁻²)</td>
</tr>
<tr>
<td>Stability (per cent change per year)</td>
</tr>
<tr>
<td>Temperature (maximum error due to changes of ambient temperature, %)</td>
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<tr>
<td>Selectivity (maximum error due to departure from assumed spectral response, %)</td>
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<tr>
<td>Linearity (maximum error due to non-linearity not accounted for, %)</td>
</tr>
<tr>
<td>Time constant (maximum)</td>
</tr>
<tr>
<td>Cosine response (deviation from that assumed, taken at sun elevation 10° on clear day, %)</td>
</tr>
<tr>
<td>Azimuth response (deviation from that assumed, taken on clear day, %)</td>
</tr>
</tbody>
</table>
ened strips of manganese–constantan junctions, half of which are exposed to the sun while the other half are completely shaded. The narrow metallic ribbons which form the thermopile are arranged in the form of a rectangle, approximately 12 × 11 mm in extent. The exposed junctions are coated with dull black lacquer and protected from the weather by two hemispherical glass domes (Fig. 8), which can be removed for inspection and cleaning. Condensation of moisture on the inside of the domes is prevented by the enclosed spaces being connected through a tube to a bottle of desiccant, such as silica gel. In later models, the outer dome can be exchanged with filter domes. The 30 cm diameter radiation shield surrounding the outer dome, and coplanar with this sensitive element, prevents direct solar radiation from heating the base of the instrument. The domes have uniformly high transmission characteristics throughout the spectral range, 0.32 μm–2.5 μm. Sensitivity of the instrument is 8–9 mV/cal cm⁻² min⁻¹, and the internal resistance of the thermopile is 10 ohm. The temperature coefficient is about 0.0015–0.0020 (°C)⁻¹ in the sense of decreasing sensitivity with increasing temperature.

In the Moll–Gorczyński pyranometer (old version) the cosine error caused by change of angle of incidence of radiation and azimuth of the incident radiation is a source of considerable error.

4.3. The Eppley 180° pyranometer

The pyranometer manufactured by Eppley Laboratories, has been by far the most widely used solar radiation instrument in the United States.

The instrument was first developed in 1923 by Kimberly and Hobbs of the U.S. Weather Bureau and is known as the Eppley pyranometer. The receiver surface of the Eppley pyranometer consists of two concentric silver rings; the inner one is coated with Parsons optical black lacquer and the outer one with white magnesium oxide. The temperature difference between the two rings is measured with a thermopile of gold–palladium and platinum–rhodium alloys. The whole assembly is hermetically sealed inside a specially blown spherical lamp bulb, 76 mm in diameter, and made of soda lime glass of about 0.6 mm thickness, filled with dry air. The time required for about 98% response to a sudden change is about 30 s.

This pyranometer is available in two models, one of them having 10 junctions and the other 50 junctions. The temperature difference between the rings gives rise to a thermal e.m.f. of the order of 2 mV/cal cm⁻² min⁻¹ in the 10-junction model, and 7–8 mV in the 50-junction model. The internal resistances of the two models are 35 and 100 ohms, respectively. The upper surface of the receiver lies in the plane passing through the centre of the glass bulb.

In 1951, MacDonald observed and reported some systematic errors in this pyranometer. He showed that with increase of ambient temperature the response of the instrument decreased by approximately 0.1% °C⁻¹.

Moreover, when the detector is kept in a vertical plane, because of the convection effects within the glass enclosure, errors as high as 5% were observed.

Recently, the older 10- and 50-junction pyranometers, discussed above, have been replaced by the “black and white” pyranometer. In this new instrument the detector is a wire wound thermopile made by electropolishing copper on constantan. The hot and cold junctions are painted with Parsons optical black lacquer and barium sulphate, respectively. There is a built-in temperature compensation device which provides a signal which is independent of ambient temperature within ±1.5% from −20 to 40 °C. The sensitivity is about 7.5 mV/cal cm⁻² min⁻¹, and the deviation from a true cosine response is within ±2% for incident angles of 0–80°. In this new system there is an optically ground Schott W.G.7 glass envelope, in place of the blown glass bulb used previously.

A number of improvements to this instrument have been recently introduced by the Eppley Laboratories. The latest model (Model PSP) uses a thermistor-compensated electrical circuit which reduces the temperature dependence to ±1.0% constancy from −20 to 40 °C. The cosine response is ±1% for a 0–70° angle of incidence and ±3% for a 70–80° angle of incidence. The output of the thermopile is unaffected.
by detector orientation. The outer glass hemisphere can be either optically clear glass or one of several filter glasses. The detector is much smaller in size and utilizes a thermopile of copper electroplated on constantan wire over one half of each turn of a wire wound thermopile. The sensitivity of the instrument is about 5 mV/cal cm$^{-2}$ min$^{-1}$. The impedance is 300 ohm and the response time is 1 s.

4.4. Photovoltaic silicon pyranometer

The invention of the silicon photovoltaic cell at the Bell Laboratories in 1954 made available a new and powerful transducer capable of producing an electrical signal which is proportional to the intensity of the solar radiation. These solar cells can be used for the measurement of solar radiation. Instruments based on solar cells have, essentially, an instantaneous response (about 10 µs), high current output, proportionality between current and incident radiation, overall stability with time and exposure to weather, and are of simple design and low expense. The major disadvantage is the high spectral dependence of the cell output. The spectral response is such that it is more sensitive to the red, and near infrared, portion of the solar spectrum. Also, the calibration varies with the angle of incidence of the radiation. Several models are produced all over the world. One particularly interesting instrument uses four solar cells to power an amper-hour meter to give an integrated value of the total horizontal radiant energy in the 0.4–1.1 µm spectral region. From the milliammeter readings, the integrated solar radiation can be determined after applying a correction factor. Various types of diffusers have been placed over the cells to improve their cosine response or to make the instrument weatherproof. These pyranometers are not recommended for use by WMO.

4.5. Bimetallic pyranograph

This instrument is also called a bimetallic actinograph or Robitzch bimetallic pyranometer. It uses bimetallic strips as sensors. It is not recommended for general use because of its large temperature coefficient and equally large azimuth and cosine errors and long response time. It is suitable only for daily totals of radiation in which accuracies of ±10% are adequate. However, it is used for observing the daily total irradiance because it is a simple and sturdy instrument and requires no electric power supply for its operation, and thus it is particularly suitable for remote areas.

Various models of pyranograph are available, but basically they are of the same type. The receiver is a blackened bimetallic strip (nickel–iron) of dimensions about 8.5 × 1.5 cm which simply acts as a bimetallic thermometer. One end is free to move as changes of temperature cause a distortion of the strip. The change, which is a function of solar irradiance, is recorded on a recorder chart mounted on a clock-driven drum. The main sensor is covered by a hemispherical glass dome and the other mechanism is enclosed in a sealed metal case. Because of the relatively large mass of the bimetallic strip, the response time of the instrument is large (10–15 min for 98% response). There are several improved models available but the errors are still much greater than those of electrical pyranometer types.

4.6. Yanishevsky pyranometer

This is the main instrument for measuring global, diffuse and surface albedo in Russia. The sensor is constructed either in a square checker-board pattern of alternate black and white squares and rectangles, or in a radial pattern of alternate black and white segments. The thermocouple is composed of alternate strips of manganese and constantan. The hot junctions are sooted black, and the cold are whitened with magnesia. A hemispherical glass cover prevents wind effects. The pyranometer is used as a relative instrument and, therefore, requires calibration against a standard. Deviation of the response with solar angle from the ideal cosine law is considerable, and a correction is applied for this cosine effect. An additional correction is also applied for wavelength selectivity of the instrument when it is used for measuring only the diffuse radiation. A recent model of the Yanishevsky pyranometer has a receiving surface of 30 × 30 mm, a sensitivity of 7–10 mV/cal cm$^{-2}$ min$^{-1}$, internal resistance of 28–32 ohm, an insignificant temperature coefficient, and a good agreement with the cosine law.

4.7. The Dirmhirt–Sauberer pyranometer

This pyranometer is also known as the star pyranometer and it was developed at the Zentralanstalt für Meteorologie und Geodynamik, Vienna. The star pyranometer is used all over the world and is recommended as a suitable instrument for the measurement of global and sky radiation by a Commission of the World Meteorological Organisation. The receiver consists of 32 small copper plates which are 0.05 mm thick, half of which are blackened and half of which are covered with a highly reflecting white paint. The two sets of plates are mounted as alternate black and white segments radiating as a star from a central point thus forming a flat circular disc of about 5 cm in diameter. The two types of plates are thermally isolated from each other by being mounted on poorly
conducting concentric rings which are themselves thermally isolated from the main base plate of the instrument. The thermopile consists of manganese-constantan or copper-constantan junctions which are soldered to a plate. The receiver is covered by a polished glass hemisphere which is 2–3 mm thick and 70 mm in diameter.

The 32-junction thermopile gives a sensitivity of 1.8 mV/cal cm⁻² min⁻¹; the internal resistance is 5 ohm; the 98% response time to a sudden change is about 20–30 s; and the temperature coefficient is negligible.

5. SPECTRAL MEASUREMENTS

The radiant energy contained within specific wavelength regions of the solar radiation can be measured either by using spectrophotographs and monochromators or thermal radiation detectors. Monochromators are used in laboratories where high quality and precision is required, while in the field both solid and liquid filters (which are broad band filters) are used to measure the radiation in different spectral regions ranging from the ultraviolet to the infrared. In solar radiation measurements, however, the solid type of filter is preferred. Glass filters, especially the Schott filters of different types are preferred since they are not affected by outside conditions and a simple manipulation will do the job. Considerable work has been done in recent years on the investigation of the optical properties of narrow and broad bandpass filters; and typical broad bandpass filters of the type used in meteorological research have been very thoroughly investigated.

The International Radiation Commission recommends the following standard Schott filters, as shown in Table 4.

An essential peculiarity of the Schott filters is that they have wide radiation transmission ranges. To narrow the transmission range one uses a combination of different filters.

Precision spectral pyranometers measure the global radiation in various spectral regions, with ground and polished hemispheres of yellow OG 14, orange OG 1, red RG 2, or dark red RG 8 filter glasses.

If only flat filters are available it is possible to use a photometersphere (the sensing aperture of which is covered with a flat filter) as the radiation receiver.

For distinguishing ultraviolet radiation, special glass filters may be used. To this end, thin coatings of silver pulverized over a quartz lamina are often used. A filter of this kind has a narrow transmission band, with the centre at about 0.32 μm, and is employed in instruments for spectroscopic determination of the total ozone content in the atmosphere.

Recently, much progress has been made in constructing filters for the infrared spectral region. Crystalline germanium filters are very conveniently used to filter infrared radiation. These filters are totally non-transparent for visible radiation and transmit infrared radiation in the range from 1.5–2 μm to 50–60 μm. Also used for this purpose are KRS five filters (a crystal mixture of gallium bromide iodide), with a transmission range approximately from 0.6 to 30–40 μm. Also available at present are glass filters that are transparent to infrared radiation in different intervals, up to 21 μm.

The so-called neutral filters of non-selective transmission for both short-wave and long-wave radiation present a considerable interest to actinometry. For neutral filters, films of polyethylene, which is transparent to radiation of wavelengths from 0.3 to 50 μm (except narrow intervals near 3, 5, 7 and 14 μm where absorption bands are observed), have been found practicable.

Attempts are being made to develop types of filters with a very narrow transmission band so as to enable them to compete with spectral instruments. It appears that metallic filters, known as interferential filters, possess such properties. Recent years have also brought interferential nullilayer dielectrical filters.

High resolution spectral measurements are required for the study of fine structure over a broad range of wavelengths. Complex instruments called spectro-radiometers are available for this purpose. The spectroradiometer built under the directions of SERI is a highly sophisticated instrument. This radiometer can complete a spectral scan from 0.3 to 2.5 μm with less than 1 nm resolution in 2.5 min. Here, visible and infrared channels are used to simultaneously view an integrating sphere. This spectrometer has unique properties like continuous spectral solar radiation calibration, continuous monitoring of broadband (0.3–1.1 μm) solar radiation stability, and self-correction for changes in the response at each wavelength.

<table>
<thead>
<tr>
<th>Filter mark</th>
<th>Transmission region (μm)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OG 1</td>
<td>525–2800</td>
<td>2.4</td>
</tr>
<tr>
<td>RG 2</td>
<td>630–2800</td>
<td>1.5</td>
</tr>
<tr>
<td>RG 8</td>
<td>710–2700</td>
<td>3.0</td>
</tr>
<tr>
<td>Glass</td>
<td>350–2800</td>
<td>—</td>
</tr>
<tr>
<td>Quartz</td>
<td>250–4000</td>
<td>—</td>
</tr>
</tbody>
</table>
6. MEASUREMENT OF DIFFUSE RADIATION

The same instrument which is used for the measurement of total or global radiation (a pyranometer) can be employed for the measurement of diffuse radiation, provided that a suitable device is used to prevent direct solar radiation from reaching the receiver. Shading of the pyranometer from direct solar radiation is done either by a disc which is made to move with the sun so as always to cast its shadow on the pyranometer, or by means of a shadow ring. Because a shading disc needs constant supervision and maintenance and an equatorial mount is expensive, the shadow ring is the more popular of the two devices. In the latter case a small correction factor (9) is applied for the part of the diffuse radiation which is cut off from the sensor by the shadow ring. This correction can either be computed or determined experimentally. Some of the factors affecting the accuracy are:

(i) multiple reflection within the glass cover which affects the accuracy of the measurement;
(ii) in calculating the correction factor, it is assumed that the sky is isotropic;
(iii) a part of the circumsolar radiation is also prevented from reaching the receiver by the shading device;
(iv) the dimensions of the receivers are not adequately standardized.

The correction factor can be experimentally obtained by successive measurements with a ring and disc of suitable diameter. The amount of diffuse radiation which is cut off is added to the results obtained with the ring above.

7. DURATION OF SUNSHINE HOURS

A knowledge of the daily and hourly records of the amount of sunshine is necessary for estimating solar radiation values using regression equations and also for optimizing the design of a particular solar collector. This measurement is simpler and far less expensive than solar radiation measuring equipment. Sunshine hours are extensively measured all over the world using Campbell–Stokes sunshine recorders.

7.1. The Campbell–Stokes sunshine recorder

This instrument was invented in the U.K. by Campbell in 1853, and was modified by Stokes in 1879. It consists, essentially, of a glass sphere about 10 cm in diameter mounted in a section of a spherical bowl. The axis of the glass sphere is parallel to that of the earth, and its diameter is such that the sun’s rays are focussed sharply on a card held in grooves in the bowl. The sphere acts as a lens and the focussed image moves along a specially prepared paper bearing a time scale. Bright sunshine burns a path along this paper. The method of supporting the sphere differs according to whether the instrument is required for operation in polar, temperate or tropical latitudes. Three overlapping pairs of grooves are provided in the spherical segment to accommodate cards suitable for different seasons of the year. The chief requirements of the sphere are that it should be uniform, well annealed and made of colourless glass.

In 1962, the World Meteorological Organisation adopted the Campbell–Stokes sunshine recorder as a standard of reference known as the “Interim reference sunshine recorder (IRSR)” and recommended that all future values of the duration sunshine be reduced to the IRSR.

7.2. Photoelectric sunshine recorder

This photoelectric recorder, known as the Foster sunshine switch, was developed by the U.S. Weather Bureau [10] and became operational in the year 1953. This is basically a differential instrument, sensing radiation by means of a shaded and an unshaded selenium barrier-layer photovoltaic cell, both mounted inside a transparent tube supported by a simple equatorial mount that allows seasonal adjustment. A shading band, concentric with the tube, protects one cell from direct solar radiation, while the other remains exposed. They are connected in electrical opposition so that their responses to diffuse light results in no electrical signal. The differential output increases during periods of sunshine sufficiently to activate a relay which in turn is used to mark on a recorder the duration of sunshine in one minute units. This instrument is stable and reliable and requires very little maintenance. The lag of the instrument is negligible, and its sensitivity is very high. It is a standard instrument of the U.S. National Weather Service and these days, the conventional sunshine recorder, the Campbell–Stokes sunshine recorder, has been replaced by it.

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