CHAPTER 7. MEASUREMENT OF RADIATION

7.1 GENERAL

The various fluxes of radiation to and from the Earth's surface are among the most important variables in the heat economy of the Earth as a whole and at any individual place at the Earth's surface or in the atmosphere. Radiation measurements are used for the following purposes:

(a) To study the transformation of energy within the Earth–atmosphere system and its variation in time and space;

(b) To analyse the properties and distribution of the atmosphere with regard to its constituents, such as aerosols, water vapour, ozone, and so on;

(c) To study the distribution and variations of incoming, outgoing and net radiation;

(d) To satisfy the needs of biological, medical, agricultural, architectural and industrial activities with respect to radiation;

(e) To verify satellite radiation measurements and algorithms.

Such applications require a widely distributed regular series of records of solar and terrestrial surface radiation components and the derivation of representative measures of the net radiation. In addition to the publication of serial values for individual observing stations, an essential objective must be the production of comprehensive radiation climatologies, whereby the daily and seasonal variations of the various radiation constituents of the general thermal budget may be more precisely evaluated and their relationships with other meteorological elements better understood.

A very useful account of the operation and design of networks of radiation stations is contained in WMO (1986). Part IVVolume V of this CIMO Guide describes the scientific principles of the measurements and gives advice on quality assurance, which is most important for radiation measurements. The *Baseline Surface Radiation Network (BSRN) Operations Manual* (WMO, 1998) gives an overview of the latest state of radiation measurements.

Following normal practice in this field, errors and uncertainties are expressed in this chapter as a 66 % confidence interval of the difference from the true quantity, which is similar to a standard deviation of the population of values. Where needed, specific uncertainty confidence intervals are indicated, and uncertainties are estimated using the International Organization for Standardization method (ISO/IEC, 2008 / JCGM, 2008). For example, 95 % uncertainty implies that the stated uncertainty is for a confidence interval of 95 %.

7.1.1 Definitions

Annex 7.A contains the nomenclature of radiometric and photometric quantities. It is based on definitions recommended by the International Radiation Commission of the International Association of Meteorology and Atmospheric Sciences and by the International Commission on Illumination (CIE). Annex 7.B gives the meteorological radiation quantities, symbols and definitions.

Radiation quantities may be classified into two groups according to their origin, namely solar and terrestrial radiation. In the context of this chapter, "radiation" can imply a process or apply to multiple quantities. For example, "solar radiation" could mean solar energy, solar exposure or solar irradiance (see Annex 7.B).

Solar energy is the electromagnetic energy emitted by the sun. The solar radiation incident on the top of the terrestrial atmosphere is called extraterrestrial solar radiation; 97 % of which is confined to the spectral range 290 to 3 000 nm is called solar (or sometimes short-wave) radiation. Part of the extra-terrestrial solar radiation penetrates through the atmosphere to the Earth's surface, while part of it is scattered and/or absorbed by the gas molecules, aerosol particles, cloud droplets and cloud crystals in the atmosphere.

Terrestrial radiation is the long-wave electromagnetic energy emitted by the Earth's surface and by the gases, aerosols and clouds of the atmosphere; it is also partly absorbed within the atmosphere. For a temperature of 300 K, 99.99 % of the power of the terrestrial radiation has a wavelength longer than 3 000 nm and about 99 % longer than 5 000 nm. For lower temperatures, the spectrum is shifted to longer wavelengths.

Since the spectral distributions of solar and terrestrial radiation overlap very little, they can very often be treated separately in measurements and computations. In meteorology, the sum of both types is called total radiation.

Light is the radiation visible to the human eye. The spectral range of visible radiation is defined by the spectral luminous efficiency for the standard observer. The lower limit is taken to be between 360 and 400 nm, and the upper limit between 760 and 830 nm (CIE, 1987). The radiation of wavelengths shorter than about 400 nm is called ultraviolet (UV), and longer than about 800 nm, infrared radiation. The UV range is sometimes divided into three sub-ranges (IEC, 1987):

    UV-A: 315–400 nm
    UV-B: 280–315 nm
    UV-C: 100–280 nm

7.1.2   Units and scales

7.1.2.1   *Units*

The International System of Units (SI) is to be preferred for meteorological radiation variables. A general list of the units is given in Annexes 7.A and 7.B.

7.1.2.2   *Standardization*

The responsibility for the calibration of radiometric instruments rests with the World, Regional and National Radiation Centres, the specifications for which are given in Annex 7.C. Furthermore, the World Radiation Centre (WRC) at Davos is responsible for maintaining the basic reference, the World Standard Group (WSG) of instruments, which is used to establish the World Radiometric Reference (WRR). During international comparisons, organized every five years, the standards of the regional centres are compared with the WSG, and their calibration factors are adjusted to the WRR. They, in turn, are used to transmit the WRR periodically to the national centres, which calibrate their network instruments using their own standards.

Definition of the World Radiometric Reference

In the past, several radiation references or scales have been used in meteorology, namely the Ångström scale of 1905, the Smithsonian scale of 1913, and the international pyrheliometric scale of 1956 (IPS 1956). The developments in absolute radiometry in recent years have very much reduced the uncertainty of radiation measurements. With the results of many comparisons of 15 individual absolute pyrheliometers of 10 different types, a WRR has been defined. The old scales can be transferred into the WRR using the following factors:

$$\frac{\text{WRR}}{\text{Angstrom scale 1905}} = 1.026$$

$$\frac{\text{WRR}}{\text{Smithsonian scale 1913}} = 0.977$$

$$\frac{\text{WRR}}{\text{IPS 1956}} = 1.022$$

The WRR is accepted as representing the physical units of total irradiance within 0.3 % (99 % uncertainty of the measured value).

Realization of the World Radiometric Reference: World Standard Group

~~In order to~~To guarantee the long-term stability of the new reference, a group of at least four absolute pyrheliometers of different design is used as the WSG. At the time of incorporation into this group, the instruments are given a reduction factor to correct their readings to the WRR. To qualify for membership of this group, a radiometer must fulfil the following specifications:

(a) Stability must be better than 0.2 % of the measured value over timescales of decades;

(b) The 95 % uncertainty of the series of measurements with the instrument must lie within the limits of the uncertainty of the WRR;

(c) The instrument has to have a different design from the other WSG instruments.

To meet the stability criteria, the instruments of the WSG are the subjects of an intercomparison at least once a year, and, for this reason, WSG is kept at the WRC Davos.

Computation of world radiometric reference values

~~In order to~~To calibrate radiometric instruments, the reading of a WSG instrument, or one that is directly traceable to the WSG, should be used. During international pyrheliometer comparisons (IPCs), the WRR value is calculated from the mean of at least three participating instruments of the WSG. To yield WRR values, the readings of the WSG instruments are always corrected with the individual reduction factor, which is determined at the time of their incorporation into the WSG. ~~Since the~~The calculation of the mean value of the WSG, serving as the reference, may be jeopardized by the failure of one or more radiometers ~~belonging to the WSG,~~. To address this issue the Commission for Instruments and Methods of Observation resolved[1] that at each IPC an ad hoc group should be established comprising the Rapporteur on Meteorological Radiation Instruments (or designate) and at least five members, including the chairperson. This group assesses the stability of the WSG instruments, and selects instruments to be used in the calculation of the WRR. The director of the comparison must participate in the group's meetings as an expert. The group should discuss the preliminary results of the comparison, based on criteria defined by the WRC, evaluate the reference and recommend the updating of the calibration factors.

7.1.3 Meteorological requirements

7.1.3.1 Data to be reported

Irradiance and radiant exposure are the quantities most commonly recorded and archived, with averages and totals of over 1 h. There are also many requirements for data over shorter periods, down to 1 min or even tens of seconds (for some energy applications). Daily totals of radiant exposure are frequently used, but these are expressed as a mean daily irradiance. Measurements of atmospheric extinction must be made with very short response times to reduce the uncertainties arising from variations in the air mass.

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[1] Recommended by the Commission for Instruments and Methods of Observation at its eleventh session (1994).

For radiation measurements, it is particularly important to record and make available information about the circumstances of the observations. This includes the type and traceability of the instrument, its calibration history, and its location in space and time, spatial exposure and maintenance record.

7.1.3.2   Uncertainty

There are no formally agreed statements of required uncertainty for most radiation quantities, but uncertainty is discussed in the sections of this chapter dealing with the various types of measurements, and best practice uncertainties are stated for the Global Climate Observing System's Baseline Surface Radiation Network (see WMO, 1998). It may be said generally that good quality measurements are difficult to achieve in practice, and for routine operations they can be achieved only with modern equipment and redundant measurements. Some systems still in use fall short of best practice, the lesser performance having has been acceptable for many applications. However, data of the highest quality are increasingly in demand.

Statements of uncertainty for net radiation and radiant exposure are given in Part Volume I, Chapter 1, Annex 1.EA. The required 95 % uncertainty for radiant exposure for a day, stated by WMO for international exchange, is 0.4 MJ m^{-2} for ≤ 8 MJ m^{-2} and 5% for > 8 MJ m^{-2}.

7.1.3.3   Sampling and recording

The uncertainty requirements can best be satisfied by making observations at a sampling period less than the $1/e$ time constant of the instrument, even when the data to be finally recorded are integrated totals for periods of up to 1 h, or more. The data points may be integrated totals or an average flux calculated from individual samples. Digital data systems are greatly to be preferred. Chart recorders and other types of integrators are much less convenient, and the resultant quantities are difficult to maintain at adequate levels of uncertainty.

7.1.3.4   Times of observation

In a worldwide network of radiation measurements, it is important that the data be homogeneous not only for calibration, but also for the times of observation. Therefore, all radiation measurements should be referred to what is known in some countries as local apparent time, and in others as true solar time. However, standard or universal time is attractive for automatic systems because it is easier to use, but is acceptable only if a reduction of the data to true solar time does not introduce a significant loss of information (that is to say, if the sampling and storage rates are high enough, as indicated in section 7.1.3.3 above). See Annex 7.D for useful formulae for the conversion from standard to solar time.

7.1.4   Measurement methods

Meteorological radiation instruments are classified using various criteria, namely the type of variable to be measured, the field of view, the spectral response, the main use, and the like. The most important types of classifications are listed in Table 7.1. The quality of the instruments is characterized by items (a) to (h) below. The instruments and their operation are described in sections 7.2 to 7.4 below. WMO (1986) provides a detailed account of instruments and the principles according to which they operate.

ELEMENT 1: Floating object (Automatic)

Table 7.1. Meteorological radiation instruments

TABLE: Table horizontal lines

Instrument classification	Parameter to be measured	Main use	Viewing angle (sr) (see Figure 7.1)
Absolute pyrheliometer	Direct solar radiation	Primary standard	5 x 10^{-3} (approx. 2.5° half angle)

Pyrheliometer	Direct solar radiation	(a) Secondary standard for calibrations (b) Network	5×10^{-3} to 2.5×10^{-2}
Spectral pyrheliometer	Direct solar radiation in broad spectral bands (e.g. with OG 530, RG 630, etc. filters)	Network	5×10^{-3} to 2.5×10^{-2}
Sunphotometer	Direct solar radiation in narrow spectral bands (e.g. at 500 ±2.5 nm, 368 ± 2.5 nm)	(a) Standard (b) Network	1×10^{-3} to 1×10^{-2} (approx. 2.3° full angle)
Pyranometer	(a) Global (solar) radiation (b) Diffuse sky (solar) radiation (c) Reflected solar radiation	(a) Working standard (b) Network	2π
Spectral pyranometer	Global (solar) radiation in broadband spectral ranges (e.g. with OG 530, RG 630, etc. filters)	Network	2π
Net pyranometer	Net global (solar) radiation	(a) Working standard (b) Network	4π
Pyrgeometer	(a) Upward long-wave radiation (downward-looking) (b) Downward long-wave radiation (upward-looking)	Network	2π
Pyrradiometer	Total radiation	Working standard	2π
Net pyrradiometer	Net total radiation	Network	4π

END ELEMENT

Absolute radiometers are self-calibrating, meaning that the irradiance falling on the sensor is replaced by electrical power, which can be accurately measured. The substitution, however, cannot be perfect; the deviation from the ideal case determines the uncertainty of the radiation measurement.

Most radiation sensors, however, are not absolute and must be calibrated against an absolute instrument. The uncertainty of the measured value, therefore, depends on the following factors, all of which should be known for a well-characterized instrument:

(a) Resolution, namely, the smallest change in the radiation quantity which can be detected by the instrument;

(b) Drifts of sensitivity (the ratio of electrical output signal to the irradiance applied) over time;

(c) Changes in sensitivity owing to changes of environmental variables, such as temperature, humidity, pressure and wind;

(d) Non-linearity of response, namely, changes in sensitivity associated with variations in irradiance;

(e) Deviation of the spectral response from that postulated, namely the blackness of the receiving surface, the effect of the aperture window, and so on;

(f) Deviation of the directional response from that postulated, namely cosine response and azimuth response;

(g) Time constant of the instrument or the measuring system;

(h) Uncertainties in the auxiliary equipment.

Instruments should be selected according to their end-use and the required uncertainty of the derived quantity. Certain instruments perform better for particular climates, irradiances and solar positions.

7.2   MEASUREMENT OF DIRECT SOLAR RADIATION

Direct solar radiation is measured by means ofusing pyrheliometers, the receiving surfaces of which are arranged to be normal to the solar direction. By means ofUsing apertures, only the radiation from the sun and a narrow annulus of the sky is measured, the latter radiation component is sometimes referred to as circumsolar radiation or aureole radiation. In modern instruments, this extends out to a half-angle of about 2.5° on some models, and to about 5° from the sun's centre (corresponding, respectively, to $6 \cdot 10^{-3}$ and $2.4 \cdot 10^{-2}$ sr). The pyrheliometer mount must allow for the rapid and smooth adjustment of the azimuth and elevation angles. A sighting device is usually included in which a small spot of light or solar image falls upon a mark in the centre of the target when the receiving surface is exactly normal to the direct solar beam. For continuous recording, it is advisable to use automatic sun-following equipment (sun tracker).

For all new designs of direct solar radiation instruments, it is recommended that the opening half-angle be 2.5° ($6 \cdot 10^{-3}$ sr) and the slope angle 1°. For the definition of these angles refer to Figure 7.1.

ELEMENT 2: Floating object (Bottom)
ELEMENT 3: Picture inline fixed size NO space
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END ELEMENT

Figure 7.1. View-limiting geometry: The opening half-angle is arctan R/d; the slope angle is arctan $(R-r)/d$.

END ELEMENT

During the comparison of instruments with different view-limiting geometries, the aureole radiation influences the readings more significantly for larger slope and aperture angles. The difference can be as great as 2 % between the two apertures mentioned above for an air mass of 1.0. In order to enable climatological comparison of direct solar radiation data during different seasons, it may be necessary to reduce all data to a mean Sun–Earth distance:

$$E_N = E / R^2 \qquad\qquad (7.1)$$

where E_N is the solar radiation, normalized to the mean Sun–Earth distance, which is defined to be one astronomical unit (AU) (see Annex 7.D); E is the measured direct solar radiation;, and R is the Sun–Earth distance in astronomical units.

7.2.1   Direct solar radiation

Some of the characteristics of operational pyrheliometers (other than primary standards) are given in Table 7.2 (adapted from ISO, 1990a), with indicative estimates of the uncertainties of measurements made with them if they are used with appropriate expertise and quality control. Cheaper pyrheliometers are available (see ISO, 1990a), but without effort to characterize their response, the resulting uncertainties reduce the quality of the data, and, given that a sun tracker is required, in most cases the incremental cost for a good pyrheliometer is minor. The estimated uncertainties are based on the following assumptions:

(a)   Instruments are well-maintained, correctly aligned and clean;

(b)   1 min and 1 h figures are for clear-sky irradiances at solar noon;

(c)   Daily exposure values are for clear days at mid-latitudes.

ELEMENT 4: Floating object (Automatic)

Table 7.2. Characteristics of operational pyrheliometers

TABLE: Table horizontal lines

Characteristic	High quality[a]	Good quality[b]
Response time (95 % response)	< 15 s	< 30 s
Zero offset (response to 5 K h^{-1} change in ambient temperature)	2 W m^{-2}	4 W m^{-2}
Resolution (smallest detectable change in W m^{-2})	0.51	1
Stability (percentage of full scale, change/year)	0.1	0.5
Temperature response (percentage maximum error due to change of ambient temperature within an interval of 50 K)	1	2
Non-linearity (percentage deviation from the responsivity at 500 W m^{-2} due to the change of irradiance within 100 W m^{-2} to 1 100 W m^{-2})	0.2	0.5
Spectral sensitivity (percentage deviation of the product of spectral absorptance and spectral transmittance from the corresponding mean within the range 300 to 3 000 nm)	0.5	1.0
Tilt response (percentage deviation from the responsivity at 0° tilt (horizontal) due to change in tilt from 0° to 90° at 1 000 W m^{-2})	0.2	0.5
Achievable uncertainty, 95 % confidence level (see above)		
1 min totals %	0.9	1.8
kJ m^{-2}	0.56	1
1 h totals %	0.7	1.5
kJ m^{-2}	21	54
Daily totals %	0.5	1.0
kJ m^{-2}	200	400

Notes:
a Near state of the art; suitable for use as a working standard; maintainable only at stations with special facilities and staff.
b Acceptable for network operations.

END ELEMENT

7.2.1.1 Primary standard pyrheliometers

An absolute pyrheliometer can define the scale of total irradiance without resorting to reference sources or radiators. The limits of uncertainty of the definition must be known; the quality of this knowledge determines the reliability of an absolute pyrheliometer. Only specialized laboratories should operate and maintain primary standards. Details of their construction and operation are given in WMO (1986). However, for the sake of completeness, a brief account is given here.

All absolute pyrheliometers of modern design use cavities as receivers and electrically calibrated, differential heat-flux meters as sensors. At present, this combination has proved to yield the lowest uncertainty possible for the radiation levels encountered in solar radiation measurements (namely, up to 1.5 kW m^{-2}).

Normally, the electrical calibration is performed by replacing the radiative power by electrical power, which is dissipated in a heater winding as close as possible to where the absorption of solar radiation takes place.

The uncertainties of such an instrument's measurements are determined by a close examination of the physical properties of the instrument and by performing laboratory measurements and/or model calculations to determine the deviations from ideal behaviour, that is, how perfectly the electrical substitution can be achieved. This procedure is called characterization of the instrument.

The following specification should be met by an absolute pyrheliometer (an individual instrument, not a type) to be designated and used as a primary standard:

(a) At least one instrument out of a series of manufactured radiometers has to be fully characterized. The 95 % uncertainty of this characterization should be less than 2 W m^{-2} under the clear-sky conditions suitable for calibration (see ISO, 1990*a*). The 95 % uncertainty (for all components of the uncertainty) for a series of measurements should not exceed 4 W m^{-2} for any measured value;

(b) Each individual instrument of the series must be compared with the one which has been characterized, and no individual instrument should deviate from this instrument by more than the characterization uncertainty as determined in (a) above;

(c) A detailed description of the results of such comparisons and of the characterization of the instrument should be made available upon request;

(d) Traceability to the WRR by comparison with the WSG or some carefully established reference with traceability to the WSG is needed in order to prove that the design is within the state of the art. The latter is fulfilled if the 95 % uncertainty for a series of measurements traceable to the WRR is less than 1 W m^{-2}.

7.2.1.2   *Secondary standard pyrheliometers*

An absolute pyrheliometer which does not meet the specification for a primary standard or which is not fully characterized can be used as a secondary standard if it is calibrated by comparison with the WSG with a 95 % uncertainty for a series of measurements less than 1 W m^{-2}.

Other types of instruments with measurement uncertainties similar or approaching those for primary standards may be used as secondary standards.

The Ångström compensation pyrheliometer has been, and still is, used as a convenient secondary standard instrument for the calibration of pyranometers and other pyrheliometers. It was designed by K. Ångström as an absolute instrument, and the Ångström scale of 1905 was based on it; now it is used as a secondary standard and must be calibrated against a standard instrument.

The sensor consists of two platinized manganin strips, each of which is about 18 mm long, 2 mm wide and about 0.02 mm thick. They are blackened with a coating of candle soot or with an optical matt black paint. A thermo-junction of copper-constantan is attached to the back of each strip so that the temperature difference between the strips can be indicated by a sensitive galvanometer or an electrical micro-voltmeter. The dimensions of the strip and front diaphragm yield opening half-angles and slope angles as listed in Table 7.3.

ELEMENT 5: Floating object (Automatic)

Table 7.3. View-limiting geometry of Ångström pyrheliometers

TABLE: Table horizontal lines

Angle	Vertical	Horizontal
Opening half-angle	5° – 8°	~2°
Slope angle	0.7° – 1.0°	1.2° – 1.6°

END ELEMENT

The measurement set consists of three or more cycles, during which the left- or right-hand strip is alternately shaded from or exposed to the direct solar beam. The shaded strip is heated by an electric current, which is adjusted in such a way that the thermal electromagnetic force of the thermocouple and, hence, the temperature difference between the two strips approximate zero. Before and after a measuring sequence, the zero is checked either by shading or by exposing both strips simultaneously. Depending on which of these methods is used and on the operating instructions of the manufacturer, the irradiance calculation differs slightly. The method adopted for the IPCs uses the following formula:

$$E = K \cdot i_L \cdot i_R \qquad (7.2)$$

where E is the irradiance in W m^{-2}; K is the calibration constant determined by comparison with a primary standard (W m^{-2} A^{-2}); and i_L i_R is the current in amperes measured with the left- or right-hand strip exposed to the direct solar beam, respectively.

Before and after each series of measurements, the zero of the system is adjusted electrically by using either of the foregoing methods, the zeros being called "cold" (shaded) or "hot" (exposed), as appropriate. Normally, the first reading, say i_R, is excluded and only the following $i_L - i_R$ pairs are used to calculate the irradiance. When comparing such a pyrheliometer with other instruments, the irradiance derived from the currents corresponds to the geometric mean of the solar irradiances at the times of the readings of i_L and i_R.

The auxiliary instrumentation consists of a power supply, a current-regulating device, a nullmeter and a current monitor.

The sensitivity of the nullmeter should be about $0.05 \cdot 10^{-6}$ A per scale division for a low-input impedance (< 10 Ω), or about 0.5 μV with a high-input impedance (> 10 kΩ). Under these conditions, a temperature difference of about 0.05 K between the junction of the copper-constantan thermocouple causes a deflection of one scale division, which indicates that one of the strips is receiving an excess heat supply amounting to about 0.3 %.

The uncertainty of the derived direct solar irradiance is highly dependent on the qualities of the current-measuring device, whether a moving-coil milliammeter or a digital multimeter which measures the voltage across a standard resistor, and on the operator's skill. The fractional error in the output value of irradiance is twice as large as the fractional error in the reading of the electric current. The heating current is directed to either strip by means of a switch and is normally controlled by separate rheostats in each circuit. The switch can also cut the current off so that the zero can be determined. The resolution of the rheostats should be sufficient to allow the nullmeter to be adjusted to within one half of a scale division.

7.2.1.3   *Field and network pyrheliometers*

These pyrheliometers generally make use of a thermopile as the detector. They have similar view-limiting geometry as standard pyrheliometers. Older models tend to have larger fields of view and slope angles. These design features were primarily designed to reduce the need for accurate sun tracking. However, the larger the slope (and opening) angle, the larger the amount of aureole radiation sensed by the detector; this amount may reach several % for high optical depths and large limiting angles. With new designs of sun trackers, including computer-assisted trackers in both passive and active (sun-seeking) configurations, the need for larger slope angles is unnecessary. However, a slope angle of 1° is still required to ensure that the energy from the direct solar beam is distributed evenly on the detector; and allows for minor sun tracker pointing errors of the order of 0.1°.

The intended use of the pyrheliometer may dictate the selection of a particular type of instrument. Some manually oriented models, such as the Linke Fuessner Actinometer, are used mainly for spot measurements, while others such as the EKO, Eppley, Kipp and Zonen, and Middleton types are designed specifically for the long-term monitoring of direct irradiance. Before deploying an instrument, the user must consider the significant differences found among operational pyrheliometers as follows:

(a)   The field of view of the instrument;

(b)   Whether the instrument measures both the long-wave and short-wave portion of the spectrum (namely, whether the aperture is open or covered with a glass or quartz window);

(c)   The temperature compensation or correction methods;

(d)   The magnitude and variation of the zero irradiance signal;

(e)   If the instrument can be installed on an automated tracking system for long-term monitoring;

(f)   If, for the calibration of other operational pyrheliometers, differences (a) to (c) above are the same, and if the pyrheliometer is of the quality required to calibrate other network instruments.

7.2.1.4   *Calibration of pyrheliometers*

All pyrheliometers, other than absolute pyrheliometers, must be calibrated by comparison using the sun as the source with a pyrheliometer that has traceability to the WSG and a likely uncertainty of calibration equal to or better than the pyrheliometer being calibrated.

As all solar radiation data must be referred to the WRR, absolute pyrheliometers also use a factor determined by comparison with the WSG and not their individually determined one. After such a comparison (for example, during the periodically organized IPCs) such a pyrheliometer can be used as a standard to calibrate, again by comparison with the sun as a source, secondary standards and field pyrheliometers. Secondary standards can also be used to calibrate field instruments, but with increased uncertainty.

The quality of sun-source calibrations may depend on the aureole influence if instruments with different view-limiting geometries are compared. Also, the quality of the results will depend on the variability of the solar irradiance, if the time constants and zero irradiance signals of the pyrheliometers are significantly different. Lastly, environmental conditions, such as temperature, pressure and net long-wave irradiance, can influence the results. If a very high quality of calibration is required, only data taken during very clear and stable days should be used.

The procedures for the calibration of field pyrheliometers are given in an ISO standard (ISO, 1990*b*).

From recent experience at IPCs, a period of five years between traceable calibrations to the WSG should suffice for primary and secondary standards. Field pyrheliometers should be calibrated every one to two years; the more prolonged the use and the more rigorous the conditions, the more often they should be calibrated.

7.2.2   **Exposure**

For continuous recording and reduced uncertainties, an accurate sun tracker that is not influenced by environmental conditions is essential. Sun tracking to within 0.2° is required, and the instruments should be inspected at least once a day, and more frequently if weather conditions so demand (with protection against adverse conditions).

The principal exposure requirement for monitoring direct solar radiation is freedom from obstructions to the solar beam at all times and seasons of the year. Furthermore, the site should be chosen so that the incidence of fog, smoke and airborne pollution is as typical as possible of the surrounding area.

For continuous observations, typically a window is used to protect the sensor and optical elements against rain, snow, and so forth. Care must be taken to ensure that such a window is kept clean and that condensation does not appear on the inside.

7.3   MEASUREMENT OF GLOBAL AND DIFFUSE SKY RADIATION

The solar radiation received from a solid angle of 2π sr on a horizontal surface is referred to as global radiation. This includes radiation received directly from the solid angle of the sun's disc, as well as diffuse sky radiation that has been scattered in traversing the atmosphere.

The instrument needed for measuring solar radiation from a solid angle of 2π sr into a plane surface and a spectral range from 300 to 3 000 nm is the pyranometer. The pyranometer is sometimes used to measure solar radiation on surfaces inclined in the horizontal and in the inverted position to measure reflected global radiation. When measuring the diffuse sky component of solar radiation, the direct solar component is screened from the pyranometer by a shading device (see ~~section~~ 7.3.3.3).

Pyranometers normally use thermo-electric, photoelectric, pyro-electric or bimetallic elements as sensors. Since pyranometers are exposed continually in all weather conditions they must be robust in design and resist the corrosive effects of humid air (especially near the sea). The receiver should be hermetically sealed inside its casing, or the casing must be easy to take off so that any condensed moisture can be removed. Where the receiver is not permanently sealed, a desiccator is usually fitted in the base of the instrument. The properties of pyranometers which are of concern when evaluating the uncertainty and quality of radiation measurement are: sensitivity, stability, response time, cosine response, azimuth response, linearity, temperature response, thermal offset, zero irradiance signal and spectral response. Further advice on the use of pyranometers is given in ISO (1990*c*) and WMO (1998).

Table 7.4 (adapted from ISO, 1990*a*) describes the characteristics of pyranometers of various levels of performance, with the uncertainties that may be achieved with appropriate facilities, well-trained staff and good quality control under the sky conditions outlined in 7.2.1.

7.3.1   Calibration of pyranometers

The calibration of a pyranometer consists of the determination of one or more calibration factors and the dependence of these on environmental conditions, such as:

(a)   Angular distribution of irradiance;

(b)   Calibration methods;

(c)   Directional response of the instrument;

(d)   Inclination of instrument;

(e)   Irradiance level;

(f)   Net long-wave irradiance for thermal offset correction;

(g)   Spectral distribution of irradiance;

(h)   Temperature;

(i)   Temporal variation.

The users of pyranometers must recognize that the uncertainty of observations will increase when the sensor exposure conditions deviate from the conditions in which the pyranometer was calibrated.

Normally, it is necessary to specify the test environmental conditions, which can be quite different for different applications. The method and conditions must also be given in some detail in the calibration certificate.

Table 7.4. Characteristics of operational pyranometers

Characteristic	High quality[a]	Good quality[b]	Moderate quality[c]
Response time (95 % response)	< 15 s	< 30 s	< 60 s
Zero offset:			
(a) Response to 200 W m^{-2} net thermal radiation (ventilated)	7 W m^{-2}	15 W m^{-2}	30 W m^{-2}
(b) Response to 5 K h^{-1} change in ambient temperature	2 W m^{-2}	4 W m^{-2}	8 W m^{-2}
Resolution (smallest detectable change)	1 W m^{-2}	5 W m^{-2}	10 W m^{-2}
Stability (change per year, percentage of full scale)	0.8	1.5	3.0
Directional response for beam radiation (the range of errors caused by assuming that the normal incidence responsivity is valid for all directions when measuring, from any direction, a beam radiation whose normal incidence irradiance is 1 000 W m^{-2})	10 W m^{-2}	20 W m^{-2}	30 W m^{-2}
Temperature response (percentage maximum error due to any change of ambient temperature within an interval of 50 K)	2	4	8
Non-linearity (percentage deviation from the responsivity at 500 W m^{-2} due to any change of irradiance within the range 100 to 1 000 W m^{-2})	0.5	1	3
Spectral sensitivity (percentage deviation of the product of spectral absorptance and spectral transmittance from the corresponding mean within the range 300 to 3 000 nm)	2	5	10
Tilt response (percentage deviation from the responsivity at 0° tilt (horizontal) due to change in tilt from 0° to 90° at 1 000 W m^{-2})	0.5	2	5
Achievable uncertainty (95% confidence level):			
Hourly totals	3 %	8 %	20 %
Daily totals	2 %	5 %	10 %

Notes:
a   Near state of the art; suitable for use as a working standard; maintainable only at stations with special facilities and staff.
b   Acceptable for network operations.
c   Suitable for low-cost networks where moderate to low performance is acceptable.

There are a variety of methods for calibrating pyranometers using the sun or laboratory sources. These include the following:

(a)   By comparison with a standard pyrheliometer for the direct solar irradiance and a calibrated shaded pyranometer for the diffuse sky irradiance;

(b)   By comparison with a standard pyrheliometer using the sun as a source, with a removable shading disc for the pyranometer;

(c)   With a standard pyrheliometer using the sun as a source and two pyranometers to be calibrated alternately measuring global and diffuse irradiance;

(d)   By comparison with a standard pyranometer using the sun as a source, under other natural conditions of exposure (for example, a uniform cloudy sky and direct solar irradiance not statistically different from zero);

(e) In the laboratory, on an optical bench with an artificial source, either normal incidence or at some specified azimuth and elevation, by comparison with a similar pyranometer previously calibrated outdoors;

(f) In the laboratory, with the aid of an integrating chamber simulating diffuse sky radiation, by comparison with a similar type of pyranometer previously calibrated outdoors.

These are not the only methods; (a), (b) and (c) and (d) are commonly used. However, it is essential that, except for (b), either the zero irradiance signals for all instruments are known or pairs of identical model pyranometers in identical configurations are used. Ignoring these offsets and differences can bias the results significantly.

Method (c) is considered to give very good results without the need for a calibrated pyranometer.

It is difficult to determine a specific number of measurements on which to base the calculation of the pyranometer calibration factor. However, the standard error of the mean can be calculated and should be less than the desired limit when sufficient readings have been taken under the desired conditions. The principal variations (apart from fluctuations due to atmospheric conditions and observing limitations) in the derived calibration factor are due to the following:

(a) Departures from the cosine law response, particularly at solar elevations of less than 10° (for this reason it is better to restrict calibration work to occasions when the solar elevation exceeds 30°);

(b) The ambient temperature;

(c) Imperfect levelling of the receiver surface;

(d) Non-linearity of instrument response;

(e) The net long-wave irradiance between the detector and the sky.

The pyranometer should be calibrated only in the position of use.

When using the sun as the source, the apparent solar elevation should be measured or computed (to the nearest 0.01°) for this period from solar time (see Annex 7.D). The mean instrument or ambient temperature should also be noted.

7.3.1.1   By reference to a standard pyrheliometer and a shaded reference pyranometer

In this method, described in ISO (1993), the pyranometer's response to global irradiance is calibrated against the sum of separate measurements of the direct and diffuse components. Periods with clear skies and steady radiation (as judged from the record) should be selected. The vertical component of the direct solar irradiance is determined from the pyrheliometer output, and the diffuse sky irradiance is measured with a second pyranometer that is continuously shaded from the sun. The direct component is eliminated from the diffuse sky pyranometer by shading the whole outer dome of the instrument with a disc of sufficient size mounted on a slender rod and held some distance away. The diameter of the disc and its distance from the receiver surface should be chosen in such a way that the screened angle approximately equals the aperture angles of the pyrheliometer. Rather than using the radius of the pyranometer sensor, the radius of the outer dome should be used to calculate the slope angle of the shading disc and pyranometer combination. This shading arrangement occludes a close approximation of both the direct solar beam and the circumsolar sky irradiance as sensed by the pyrheliometer.

On a clear day, the diffuse sky irradiance is less than 15 % of the global irradiance; hence, the calibration factor of the reference pyranometer does not need to be known very accurately. However, care must be taken to ensure that the zero irradiance signals from both pyranometers are accounted for, given that for some pyranometers under clear sky conditions the zero irradiance signal can be as high as 15 % of the diffuse sky irradiance.

The calibration factor is then calculated according to:

$$E \cdot \sin h + V_s k_s = V \cdot k \qquad (7.3)$$

or:

$$k = (E \sin h + V_s k_s) / V \qquad (7.4)$$

where E is the direct solar irradiance measured with the pyrheliometer (W m^{-2}), V is the global irradiance output of the pyranometer to be calibrated (μV); V_s is the diffuse sky irradiance output of the shaded reference pyranometer (μV), h is the apparent solar elevation at the time of reading; k is the calibration factor of the pyranometer to be calibrated (W m^{-2} μV^{-1}); and k_s is the calibration factor of the shaded reference pyranometer (W m^{-2} μV^{-1}), and all the signal measurements are taken simultaneously.

The direct, diffuse and global components will change during the comparison, and care must be taken with the appropriate sampling and averaging to ensure that representative values are used.

7.3.1.2   By reference to a standard pyrheliometer

This method, described in ISO (1993), is similar to the method of the preceding paragraph, except that the diffuse sky irradiance signal is measured by the same pyranometer. The direct component is eliminated temporarily from the pyranometer by shading the whole outer dome of the instrument as described in ~~section~~ 7.3.1.1. The period required for occulting depends on the steadiness of the radiation flux and the response time of the pyranometer, including the time interval needed to bring the temperature and long-wave emission of the glass dome to equilibrium; 10 times the thermopile $1/e$ time constant of the pyranometer should generally be sufficient.

The difference between the representative shaded and unshaded outputs from the pyranometer is due to the vertical component of direct solar irradiance E measured by the pyrheliometer. Thus:

$$E \cdot \sin h = (V_{un} - V_s) \cdot k \qquad (7.5)$$

or:

$$k = (E \cdot \sin h) / (V_{un} - V_s) \qquad (7.6)$$

where E is the representative direct solar irradiance at normal incidence measured by the pyrheliometer (W m^{-2}); V_{un} is the representative output signal of the pyranometer (μV) when in unshaded (or global) irradiance mode; V_s is the representative output signal of the pyranometer (μV) when in shaded (or diffuse sky) irradiance mode; h is the apparent solar elevation, and k is the calibration factor (W m^{-2} μV^{-1}), which is the inverse of the sensitivity (μV W^{-1} m^2).

Both the direct and diffuse components will change during the comparison, and care must be taken with the appropriate sampling and averaging to ensure that representative values of the shaded and unshaded outputs are used for the calculation. To reduce uncertainties associated with representative signals, a continuous series of shade and un-shade cycles should be performed and time-interpolated values used to reduce temporal changes in global and diffuse sky irradiance. Since the same pyranometer is being used in differential mode, and the difference in zero irradiance signals for global and diffuse sky irradiance is negligible, there is no need to account for zero irradiances in equation 7.6.

7.3.1.3   Alternate calibration using a pyrheliometer

This method uses the same instrumental set-up as the method described in ~~section~~ 7.3.1.1, but only requires the pyrheliometer to provide calibrated irradiance data (E), and the two pyranometers are assumed to be un-calibrated (Forgan, 1996). The method calibrates both pyranometers by solving a pair of simultaneous equations analogous to equation 7.3. Irradiance signal data are initially collected with the pyrheliometer and one pyranometer (pyranometer A) measures global irradiance signals (V_{gA}) and the other pyranometer (pyranometer B) measures diffuse irradiance signals (V_{dB}) over a range of solar zenith angles in clear sky conditions. After sufficient data have been collected in the initial configuration, the pyranometers are exchanged so

that pyranometer A, which initially measured the global irradiance signal, now measures the diffuse irradiance signal (V_{dA}), and vice versa with regard to pyranometer B. The assumption is made that for each pyranometer the diffuse (k_d) and global (k_g) calibration coefficients are equal, and the calibration coefficient for pyranometer A is given by:

$$k_A = k_{gA} = k_{dA} \qquad (7.7)$$

with an identical assumption for pyranometer B coefficients. Then for a time t_0 in the initial period a modified version of equation 7.3 is:

$$E(t_0)\sin(h(t_0)) = k_A V_{gA}(t_0) - k_B V_{dB}(t_0) \qquad (7.8)$$

For time t_1 in the alternate period when the pyranometers are exchanged:

$$E(t_1)\sin(h(t_1)) = k_B V_{gB}(t_1) - k_A V_{dA}(t_1) \qquad (7.9)$$

As the only unknowns in equations 7.8 and 7.9 are k_A and k_B, these can be solved for any pair of times (t_0, t_1). Pairs covering a range of solar elevations provide an indication of the directional response. The resultant calibration information for both pyranometers is representative of the global calibration coefficients and produces almost identical information to method 7.3.1.1, but without the need for a calibrated pyranometer.

As with method 7.3.1.1, to produce coefficients with minimum uncertainty this alternate method requires that the irradiance signals from the pyranometers be adjusted to remove any estimated zero irradiance offset. To reduce uncertainties due to changing directional response it is recommended to use a pair of pyranometers of the same model and observation pairs when $\sin h (t_0) \sim \sin h (t_1)$.

The method is ideally suited to automatic field monitoring situations where three solar irradiance components (direct, diffuse and global) are monitored continuously. Experience suggests that the data collection necessary for the application of this method may be conducted during as little as one day with the exchange of instruments taking place around solar noon. However, at a field site, the extended periods and days either side of the instrument change may be used for data selection, provided that the pyrheliometer has a valid calibration.

7.3.1.4   By comparison with a reference pyranometer

As described in ISO (1992), this method entails the simultaneous operation of two pyranometers mounted horizontally, side by side, outdoors for a sufficiently long period to acquire representative results. If the instruments are of the same model and monitoring configuration, only one or two days of comparison should be sufficient. The more pronounced the difference between the types of pyranometer configurations, the longer the period of comparison required. A long period, however, could be replaced by several shorter periods covering typical conditions (clear, cloudy, overcast, rainfall, snowfall, and so on). The derivation of the instrument factor is straightforward, but, in the case of different pyranometer models, the resultant uncertainty is more likely to be a reflection of the difference in model, rather than the stability of the instrument being calibrated. Data selection should be carried out when irradiances are relatively high and varying slowly. Each mean value of the ratio R of the response of the test instrument to that of the reference instrument may be used to calculate $k = R \cdot k_r$, where k_r is the calibration factor of the reference, and k is the calibration factor being derived. During a sampling period, provided that the time between measurements is less than the $1/e$ time constant of the pyranometers, data collection can occur during times of fluctuating irradiance.

The mean temperature of the instruments or the ambient temperature should be recorded during all outdoor calibration work to allow for any temperature effects.

7.3.1.5   By comparison in the laboratory

There are two methods which involve laboratory-maintained artificial light sources providing either direct or diffuse irradiance. In both cases, the test pyranometer and a reference standard pyranometer are exposed under the same conditions.

In one method, the pyranometers are exposed to a stabilized tungsten-filament lamp installed at the end of an optical bench. A practical source for this type of work is a 0.5 to 1.0 kW halogen lamp mounted in a water-cooled housing with forced ventilation and with its emission limited to the solar spectrum by a quartz window. This kind of lamp can be used if the standard and the instrument to be calibrated have the same spectral response. For general calibrations, a high-pressure xenon lamp with filters to give an approximate solar spectrum should be used. When calibrating pyranometers in this way, reflection effects should be excluded from the instruments by using black screens. The usual procedure is to install the reference instrument and measure the radiant flux. The reference is then removed and the measurement repeated using the test instrument. The reference is then replaced and another determination is made. Repeated alternation with the reference should produce a set of measurement data of good precision (about 0.5 %).

In the other method, the calibration procedure uses an integrating light system, such as a sphere or hemisphere illuminated by tungsten lamps, with the inner surface coated with highly reflective diffuse-white paint. This offers the advantage of simultaneous exposure of the reference pyranometer and the instrument to be calibrated. Since the sphere or hemisphere simulates a sky with an approximately uniform radiance, the angle errors of the instrument at 45° dominate. As the cosine error at these angles is normally low, the repeatability of integrating-sphere measurements is generally within 0.5 %. As for the source used to illuminate the sphere, the same considerations apply as for the first method.

7.3.1.6   Routine checks on calibration factors

There are several methods for checking the constancy of pyranometer calibration, depending upon the equipment available at a particular station. Every opportunity to check the performance of pyranometers in the field must be seized.

At field stations where carefully preserved standards (either pyrheliometers or pyranometers) are available, the basic calibration procedures described above may be employed. Where standards are not available, other techniques can be used. If there is a simultaneous record of direct solar radiation, the two records can be examined for consistency by the method used for direct standardization, as explained in s̶e̶c̶t̶i̶o̶n̶ 7.3.1.2. This simple check should be applied frequently.

If there are simultaneous records of global and diffuse sky radiation, the two records should be frequently examined for consistency. In periods of total cloud, the global and diffuse sky radiation should be identical, and these periods can be used when a shading disc is used for monitoring diffuse sky radiation. When using shading bands, it is recommended that the band be removed so that the diffuse sky pyranometer is measuring global radiation and its data can be compared to simultaneous data from the global pyranometer.

The record may be verified with the aid of a travelling working standard sent from the central station of the network or from a nearby station. Lastly, if calibrations are not performed at the site, the pyranometer can be exchanged for a similar one sent from the calibration facility. Either of the last two methods should be used at least once a year. Pyranometers used for measuring reflected solar radiation should be moved into an upright position and checked using the methods described above.

7.3.2   Performance of pyranometers

Considerable care and attention to details are required to attain the desirable standard of uncertainty. A number of properties of pyranometers and measurement systems should be evaluated so that the uncertainty of the resultant data can be estimated. For example, it has been demonstrated that, for a continuous record of global radiation without ancillary measurements of diffuse sky and direct radiation, an uncertainty better than 5 % in daily totals represents the result of good and careful work. Similarly, when a protocol similar to that proposed by WMO (1998) is used, uncertainties for daily total can be of the order of 2 %.

7.3.2.1 Sensor levelling

For accurate global radiation measurements with a pyranometer it is essential that the spirit level indicate when the plane of the thermopile is horizontal. This can be tested in the laboratory on an optical levelling table using a collimated lamp beam at about a 20° elevation. The levelling screws of the instrument are adjusted until the response is as constant as possible during rotation of the sensor in the azimuth. The spirit-level is then readjusted, if necessary, to indicate the horizontal plane. This is called radiometric levelling and should be the same as physical levelling of the thermopile. However, this may not be true if the quality of the thermopile surface is not uniform.

7.3.2.2 Change of sensitivity due to ambient temperature variation

Thermopile instruments exhibit changes in sensitivity with variations in instrument temperature. Some instruments are equipped with integrated temperature compensation circuits in an effort to maintain a constant response over a large range of temperatures. The temperature coefficient of sensitivity may be measured in a temperature-controlled chamber. The temperature in the chamber is varied over a suitable range in 10 °C steps and held steady at each step until the response of the pyranometers has stabilized. The data are then fitted with a smooth curve. If the maximum percentage difference due to temperature response over the operational ambient range is 2 % or more, a correction should be applied on the basis of the fit of the data.

If no temperature chamber is available, the standardization method with pyrheliometers (see ~~section~~ 7.3.1.1, 7.3.1.2 or 7.3.1.3) can be used at different ambient temperatures. Attention should be paid to the fact that not only the temperature, but also, for example, the cosine response (namely, the effect of solar elevation) and non-linearity (namely, variations of solar irradiance) can change the sensitivity.

7.3.2.3 Variation of response with orientation

The calibration factor of a pyranometer may very well be different when the instrument is used in an orientation other than that in which it was calibrated. Inclination testing of pyranometers can be conducted in the laboratory or with the standardization method described in ~~section~~ 7.3.1.1 or 7.3.1.2. It is recommended that the pyranometer ~~be~~is calibrated in the orientation in which it will be used. A correction for tilting is not recommended unless the instrument's response has been characterized for a variety of conditions.

7.3.2.4 Variation of response with angle of incidence

The dependence of the directional response of the sensor upon solar elevation and azimuth is usually known as the Lambert cosine response and the azimuth response, respectively. Ideally, the solar irradiance response of the receiver should be proportional to the cosine of the zenith angle of the solar beam, and constant for all azimuth angles. For pyranometers, it is recommended that the cosine error (or percentage difference from ideal cosine response) be specified for at least two solar elevation angles, preferably 30° and 10°. A better way of prescribing the directional response is given in Table 7.4, which specifies the permissible error for all angles.

Only lamp sources should be used to determine the variation of response with the angle of incidence~~,~~ because the spectral distribution of the sun changes with the angle of elevation. Using the sun as a source, an apparent variation of response with solar elevation angle could be observed which, in fact, is a variation due to non-homogeneous spectral response.

7.3.2.5 Uncertainties in hourly and daily totals

As most pyranometers in a network are used to determine hourly or daily exposures (or exposures expressed as mean irradiances), it is evident that the uncertainties in these values are important.

Table 7.4 lists the expected maximum deviation from the true value, excluding calibration errors. The types of pyranometers in the third column of Table 7.4 (namely, those of moderate quality)

are not suitable for hourly or daily totals, although they may be suitable for monthly and yearly totals.

7.3.3   Installation and maintenance of pyranometers

The site selected to expose a pyranometer should be free from any obstruction above the plane of the sensing element and, at the same time, should be readily accessible. If it is impracticable to obtain such an exposure, the site must be as free as possible of obstructions that may shadow it at any time in the year. The pyranometer should not be close to light-coloured walls or other objects likely to reflect solar energy onto it; nor should it be exposed to artificial radiation sources.

In most places, a flat roof provides a good location for mounting the radiometer stand. If such a site cannot be obtained, a stand placed some distance from buildings or other obstructions should be used. If practicable, the site should be chosen so that no obstruction, in particular within the azimuth range of sunrise and sunset over the year, should have an elevation exceeding 5°. Other obstructions should not reduce the total solar angle by more than 0.5 sr. At stations where this is not possible, complete details of the horizon and the solid angle subtended should be included in the description of the station.

A site survey should be carried out before the initial installation of a pyranometer whenever its location is changed or if a significant change occurs with regard to any surrounding obstructions. An excellent method of doing this is to use a survey camera that provides azimuthal and elevation grid lines on the negative. A series of exposures should be made to identify the angular elevation above the plane of the receiving surface of the pyranometer and the angular range in azimuth of all obstructions throughout the full 360° around the pyranometer. If a survey camera is not available, the angular outline of obscuring objects may be mapped out by means of a theodolite or a compass and clinometer combination.

The description of the station should include the altitude of the pyranometer above sea level (that is, the altitude of the station plus the height of pyranometer above the ground), together with its geographical longitude and latitude. It is also most useful to have a site plan, drawn to scale, showing the position of the recorder, the pyranometer, and all connecting cables.

The accessibility of instrumentation for frequent inspection is probably the most important single consideration when choosing a site. It is most desirable that pyranometers and recorders be inspected at least daily, and preferably more often.

The foregoing remarks apply equally to the exposure of pyranometers on ships, towers and buoys. The exposure of pyranometers on these platforms is a very difficult and sometimes hazardous undertaking. Seldom can an instrument be mounted where it is not affected by at least one significant obstruction (for example, a tower). Because of platform motion, pyranometers are subject to wave motion and vibration. Precautions should be taken, therefore, to ensure that the plane of the sensor is kept horizontal and that severe vibration is minimized. This usually requires the pyranometer to be mounted on suitably designed gimbals.

7.3.3.1   Correction for obstructions to a free horizon

If the direct solar beam is obstructed (which is readily detected on cloudless days), the record should be corrected wherever possible to reduce uncertainty.

Only when there are separate records of global and diffuse sky radiation can the diffuse sky component of the record be corrected for obstructions. The procedure requires first that the diffuse sky record be corrected, and the global record subsequently adjusted. The fraction of the sky itself which is obscured should not be computed, but rather the fraction of the irradiance coming from that part of the sky which is obscured. Since the diffuse sky radiation from elevations below 5° contributes less than 1 % to the diffuse sky radiation, it can normally be neglected. Attention should be concentrated on objects subtending angles of 10° or more, as well as those which might intercept the solar beam at any time. In addition, it must be borne in mind that light-coloured objects can reflect solar radiation onto the receiver.

Strictly speaking, when determining corrections for the loss of diffuse sky radiation due to obstacles, the variance in sky radiance over the hemisphere should be taken into account. However, the only practical procedure is to assume that the radiance is isotropic, that is, the same from all parts of the sky. In order to determine the relative reduction in diffuse sky irradiance for obscuring objects of finite size, the following expression may be used:

$$\Delta E_{\mathrm{sky}} = \pi^{-1} \int_{\phi} \int_{\Theta} \sin\theta \cos\theta d\,\theta d\,\varphi \qquad (7.10)$$

where θ is the angle of elevation; φ is the azimuth angle, Θ is the extent in elevation of the object; and ϕ is the extent in azimuth of the object.

The expression is valid only for obstructions with a black surface facing the pyranometer. For other objects, the correction has to be multiplied by a reduction factor depending on the reflectivity of the object. Snow glare from a low sun may even lead to an opposite sign for the correction.

7.3.3.2 Installation of pyranometers for measuring global radiation

A pyranometer should be securely attached to whatever mounting stand is available, using the holes provided in the tripod legs or in the baseplate. Precautions should always be taken to avoid subjecting the instrument to mechanical shocks or vibration during installation. This operation is best effected as follows. First, the pyranometer should be oriented so that the emerging leads or the connector are located poleward of the receiving surface. This minimizes heating of the electrical connections by the sun. Instruments with Moll-Gorcynski thermopiles should be oriented so that the line of thermo-junctions (the long side of the rectangular thermopile) points east-west. This constraint sometimes conflicts with the first, depending on the type of instrument, and should have priority since the connector could be shaded, if necessary. When towers are nearby, the instrument should be situated on the side of the tower towards the Equator, and as far away from the tower as practical.

Radiation reflected from the ground or the base should not be allowed to irradiate the instrument body from underneath. A cylindrical shading device can be used, but care should be taken to ensure that natural ventilation still occurs and is sufficient to maintain the instrument body at ambient temperature.

The pyranometer should then be secured lightly with screws or bolts and levelled with the aid of the levelling screws and spirit-level provided. After this, the retaining screws should be tightened, taking care that the setting is not disturbed so that, when properly exposed, the receiving surface is horizontal, as indicated by the spirit-level.

The stand or platform should be sufficiently rigid so that the instrument is protected from severe shocks and the horizontal position of the receiver surface is not changed, especially during periods of high winds and strong solar energy.

The cable connecting the pyranometer to its recorder should have twin conductors and be waterproof. The cable should be firmly secured to the mounting stand to minimize rupture or intermittent disconnection in windy weather. Wherever possible, the cable should be properly buried and protected underground if the recorder is located at a distance. The use of shielded cable is recommended; the pyranometer, cable and recorder being connected by a very low resistance conductor to a common ground. As with other types of thermo-electric devices, care must be exercised to obtain a permanent copper-to-copper junction between all connections prior to soldering. All exposed junctions must be weatherproof and protected from physical damage. After identification of the circuit polarity, the other extremity of the cable may be connected to the data-collection system in accordance with the relevant instructions.

7.3.3.3 Installation of pyranometers for measuring diffuse sky radiation

For measuring or recording separate diffuse sky radiation, the direct solar radiation must be screened from the sensor by a shading device. Where continuous records are required, the pyranometer is usually shaded either by a small metal disc held in the sun's beam by a sun tracker, or by a shadow band mounted on a polar axis.

The first method entails the rotation of a slender arm synchronized with the sun's apparent motion. If tracking is based on sun-synchronous motors or solar almanacs, frequent inspection is essential to ensure proper operation and adjustment, since spurious records are otherwise difficult to detect. Sun trackers with sun-seeking systems minimize the likelihood of such problems. The second method involves frequent personal attention at the site and significant corrections to the record on account of the appreciable screening of diffuse sky radiation by the shading arrangement. Assumptions about the sky radiance distribution and band dimensions are required to correct for the band and increase the uncertainty of the derived diffuse sky radiation compared to that using a sun-seeking disc system. Annex 7.E provides details on the construction of a shading ring and the necessary corrections to be applied.

A significant error source for diffuse sky radiation data is the zero irradiance signal. In clear sky conditions the zero irradiance signal is the equivalent of 5 to 10 W m^{-2} depending on the pyranometer model, and could approach 15 % of the diffuse sky irradiance. The *Baseline Surface Radiation Network (BSRN) Operations Manual* (WMO, 1998) provides methods to minimize the influence of the zero irradiance signal.

The installation of a diffuse sky pyranometer is similar to that of a pyranometer which measures global radiation. However, there is the complication of an equatorial mount or shadow-band stand. The distance to a neighbouring pyranometer should be sufficient to guarantee that the shading ring or disc never shadows it. This may be more important at high latitudes where the sun angle can be very low.

Since the diffuse sky radiation from a cloudless sky may be less than one tenth of the global radiation, careful attention should be given to the sensitivity of the recording system.

7.3.3.4   *Installation of pyranometers for measuring reflected radiation*

The height above the surface should be 1 to 2 m. In summer timesummertime, the ground should be covered by grass that is kept short. For regions with snow in winter, a mechanism should be available to adjust the height of the pyranometer in order to maintain a constant separation between the snow and the instrument. Although the mounting device is within the field of view of the instrument, it should be designed to cause less than 2 % error in the measurement. Access to the pyranometer for levelling should be possible without disturbing the surface beneath, especially if it is snow.

7.3.3.5   *Maintenance of pyranometers*

Pyranometers in continuous operation should be inspected at least once a day and perhaps more frequently, for example when meteorological observations are being made. During these inspections, the glass dome of the instrument should be wiped clean and dry (care should be taken not to disturb routine measurements during the daytime). If frozen snow, glazed frost, hoar frost or rime is present, an attempt should be made to remove the deposit very gently (at least temporarily), with the sparing use of a de-icing fluid, before wiping the glass clean. A daily check should also ensure that the instrument is level, that there is no condensation inside the dome, and that the sensing surfaces are still black.

In some networks, the exposed dome of the pyranometer is ventilated continuously by a blower to avoid or minimize deposits in cold weather, and to minimize the temperature difference between the dome and the case. The temperature difference between the ventilating air and the ambient air should not be more than about 1 K. If local pollution or sanddust forms a deposit on the dome, it should be wiped very gently, preferably after blowing off most of the loose material or after wetting it a little, in order to prevent the surface from being scratched. Such abrasive action can appreciably alter the original transmission properties of the material. Desiccators should be kept charged with active material (usually a colour-indicating silica gel).

7.3.3.6   *Installation and maintenance of pyranometers on special platforms*

Very special care should be taken when installing equipment on such diverse platforms as ships, buoys, towers and aircraft. Radiation sensors mounted on ships should be provided with gimbals because of the substantial motion of the platform.

If a tower is employed exclusively for radiation equipment, it may be capped by a rigid platform on which the sensors can be mounted. Obstructions to the horizon should be kept to the side of the platform farthest from the Equator, and booms for holding albedometers should extend towards the Equator.

Radiation sensors should be mounted as high as is practicable above the water surface on ships, buoys and towers, in order to keep the effects of water spray to a minimum.

Radiation measurements have been taken successfully from aircraft for a number of years. Care must be exercised, however, in selecting the correct pyranometer and proper exposure.

Particular attention must be paid during installation, especially for systems that are difficult to access, to ensure the reliability of the observations. It may be desirable, therefore, to provide a certain amount of redundancy by installing duplicate measuring systems at certain critical sites.

7.4   MEASUREMENT OF TOTAL AND LONG-WAVE RADIATION

The measurement of total radiation includes both short wavelengths of solar origin (300 to 3 000 nm) and longer wavelengths of terrestrial and atmospheric origin (3 000 to 100 000 nm). The instruments used for this purpose are pyrradiometers. They may be used for measuring either upward or downward radiation flux components, and a pair of them may be used to measure the differences between the two, which is the net radiation. Single-sensor pyrradiometers, with an active surface on both sides, are also used for measuring net radiation. Pyrradiometer sensors must have a constant sensitivity across the whole wavelength range from 300 to 100 000 nm.

The measurement of long-wave radiation can be accomplished either directly using pyrgeometers, or indirectly by subtracting the measured global radiation from the total radiation measured. Most pyrgeometers eliminate the short wavelengths by means of filters which have approximately constant transparency to long wavelengths while being almost opaque to the shorter wavelengths (300 to 3 000 nm). Some pyrgeometers – either without filters or filters that do not eliminate radiation below 3 000 nm – can be used only during the night.

The long-wave flux L^- measured by a pyrgeometer or a pyrradiometer has two components, the black-body flux from the surface temperature of the sensing element and the net radiative flux measured by the receiver:

$$L^- = L^* + \sigma T_s^4 \qquad (7.11)$$

σ is the Stefan-Boltzmann constant ($5.670\ 4 \cdot 10^{-8}$ W m^{-2} K^{-1}); T_s is the underlying surface temperature (K); L^- is the irradiance measured either by a reference pyrgeometer or calculated from the temperature of the black-body cavity capping the upper receiver (W m^{-2}); $L*$ is the net radiative flux at the receiver (W m^{-2}). Measuring the short-wave component measured by a pyrradiometer follows the description in 7.3.

7.4.1   Instruments for the measurement of long-wave radiation

Over the last decade, significant advances have been made in the measurement of terrestrial radiation by pyrgeometers particularly with the advent of the silicon domed pyrgeometer, and as a result pyrgeometers provide the highest accuracy measurements of terrestrial radiation. Nevertheless, the measurement of terrestrial radiation is still more difficult and less understood than the measurement of solar irradiance, Table 7.5 provides an analysis of the sources of errors.

Pyrgeometers have developed in two forms. In the first form, the thermopile receiving surface is covered with a hemispheric dome inside which an interference filter is deposited. In the second form, the thermopile is covered with a flat plate on which the interference filter is deposited. In both cases, the surface on which the interference filter is deposited is made of silicon. The first style of instrument provides a full hemispheric field of view, while for the second a 150° field of view is typical and the hemispheric flux is modelled using the manufacturer's procedures. The argument used for the latter method is that the deposition of filters on the inside of a hemisphere has greater imprecision than the modelling of the flux below 30° elevations. Both types of instruments are operated on the principle that the measured output signal is the difference between the irradiance emitted from the source and the black-body radiative temperature of the instrument. In general, pyrgeometer derived terrestrial radiation can be approximated by a modification to equation 7.11:

$$L^- = L^* + k_2 \sigma T_s^4 + k_3 \sigma \left(T_d^4 - T_s^4 \right) \qquad (7.12)$$

where k_2 takes into account the emission properties of the thermopile and uncertainties of the temperature measurement of the cold surface of the thermopile; k_3 is the instrument dome sensitivity to infrared irradiance (μV/(W m^{-2})); and T_d is the detector temperature (K).

The net radiative flux measured by the receiver, L^*, is defined as:

$$L^* = U/C \left(1 + k_1 \sigma T_s^4 \right) \qquad (7.13)$$

where C is the sensitivity of the receiver (μV/(W m^{-2})), and k_1 is a residual temperature coefficient of the receiver. While state-of-the-art pyrgeometers have a temperature correction circuitry implemented in their receiver to bring k_1 very close to zero (as described in section 7.3.2.2), it is still recommended to determine k_1 by a laboratory characterization as described in section 7.4.3.

Several recent comparisons have been made using instruments of similar manufacture in a variety of measurement configurations. These studies have indicated that, following careful calibration, fluxes measured at night agree to within ±1 W m^{-2}, but in periods of high solar energy the difference between unshaded instruments can be significant. The reason for the differences is that the silicon dome and the associated interference filter may transmit solar radiation and is not a perfect reflector of solar energy. Thus, a solar contribution may reach the sensor, and solar heating of the dome occurs. By shading the instrument similarly to that used for diffuse solar measurements, ventilating it as recommended by ISO (1990a), and measuring the temperature of the dome and the instrument case, this discrepancy can be reduced to ±2 W m^{-2}. Based upon these and other comparisons, the following recommendations should be followed for the measurement of long-wave radiation:

(a) When using pyrgeometers that have a built-in battery circuit to emulate the black-body condition of the instrument, extreme care must be taken to ensure that the battery is well maintained. Even a small change in the battery voltage will significantly increase the measurement error. If at all possible, the battery should be removed from the instrument, and the case and dome temperatures of the instrument should be measured according to the manufacturer's instructions;

(b) Where possible, both the case and dome temperatures of the instrument should be measured and used in the determination of irradiance;

(c) The instrument should be ventilated;

(d) For best results, the instrument should be shaded from direct solar irradiance by a small sun-tracking disc as used for diffuse sky radiation measurement.

These instruments should be calibrated at national or regional calibration centres by using reference pyrgeometers traceable to the World Infrared Standard Group of Pyrgeometers (WISG) of the WRC Davos.

7.4.2 Instruments for the measurement of total radiation

One problem with instruments for measuring total radiation is that there are no absorbers which have a completely constant sensitivity over the extended range of wavelengths concerned. Similarly, it is difficult to find suitable filters that have constant transmission between 300 and 100 000 nm. Therefore, the recommended practice for measuring total radiation is to perform simultaneous separate measurements of short- and long-wave radiation using a pyranometer and a pyrgeometer, respectively.

The use of thermally sensitive sensors requires a good knowledge of the heat budget of the sensor. Otherwise, it is necessary to reduce sensor convective heat losses to near zero by protecting the sensor from the direct influence of the wind. The technical difficulties linked with such heat losses are largely responsible for the fact that net radiative fluxes are determined less precisely than global radiation fluxes. In fact, different laboratories have developed their own pyrradiometers on technical bases which they consider to be the most effective for reducing the convective heat transfer in the sensor. During the last few decades, pyrradiometers have been built which, although not perfect, embody good measurement principles. Thus, there is a great variety of pyrradiometers employing different methods for eliminating, or allowing for, wind effects, as follows:

(a) No protection, in which case empirical formulae are used to correct for wind effects;

(b) Determination of wind effects by the use of electrical heating;

(c) Stabilization of wind effects through artificial ventilation;

(d) Elimination of wind effects by protecting the sensor from the wind.

The long-wave component of a pyrradiometer is described in equation 7.11.

Table 7.5 provides an analysis of the sources of error arising in pyrradiometric measurements and proposes methods for determining these errors.

Table 7.5. Sources of error in pyrradiometric measurements

TABLE: Table horizontal lines

Elements influencing the measurements	Nature of influence on pyrradiometers		Effects on the precision of measurements	Methods for determining these characteristics
	with domes	without domes		
Screening properties	Spectral characteristics of transmission	None	(a) Spectral variations in calibration coefficient (b) The effect of reduced incident radiation on the detector due to short-wave diffusion in the domes (depends on thickness) (c) Ageing and other variations in the sensors	(a) Determine spectrally the extinction in the screen (b) Measure the effect of diffuse sky radiation or measure the effect with a varying angle of incidence (c) Spectral analysis: compare with a new dome; determine the extinction of the dome

Convection effects	Changes due to non-radiative energy exchanges: sensor-dome environment (thermal resistance)	Changes due to non-radiative energy exchanges: sensor-air (variation in areal exchange coefficient)	Uncontrolled changes due to wind gusts are critical in computing the radiative flux divergence in the lowest layer of the atmosphere	Study the dynamic behaviour of the instrument as a function of temperature and speed in a wind tunnel
Effects of hydrometeors (rain, snow, fog, dew, frost) and dust	Variation of the spectral transmission plus the non-radiative heat exchange by conduction and change	Variation of the spectral character of the sensor and of the dissipation of heat by evaporation	Changes due to variations in the spectral characteristics of the sensor and to non-radiative energy transfers	Study the influence of forced ventilation on the effects
Properties of the sensor surface (emissivity)	Depends on the spectral absorption of the blackening substance on the sensor		Changes in calibration coefficient (a) As a function of spectral response (b) As a function of intensity and azimuth of incident radiation (c) As a function of temperature effects	(a) Spectrophoto-metric analysis of the calibration of the absorbing surfaces (b) Measure the sensor's sensitivity variability with the angle of incidence
Temperature effects	Non-linearity of the sensor as a function of temperature		A temperature coefficient is required	Study the influence of forced ventilation on these effects
Asymmetry effects	(a) Differences between the thermal capacities and resistance of the upward- and downward-facing sensors (b) Differences in ventilation of the upward- and downward-facing sensors (c) Control and regulation of sensor levelling		(a) Influence on the time constant of the instrument (b) Error in the determination of the calibration factors for the two sensors	(a) Control the thermal capacity of the two sensor surfaces (b) Control the time constant over a narrow temperature range

It is difficult to determine the uncertainty likely to be obtained in practice. In situ comparisons at different sites between different designs of pyrradiometer yield results manifesting differences of up to 5 % to 10 % under the best conditions. In order to improve such results, an exhaustive laboratory study should precede the in situ comparison in order to determine the different effects separately.

Deriving total radiation by independently measuring the short-wave and long-wave components achieves the highest accuracies and is recommended over the pyrradiometer measurements. Short-wave radiation can be measured using the methods outlined in 7.2 and 7.3, while long-wave radiation can be measured with pyrgeometers.

Table 7.6 lists the characteristics of pyrradiometers of various levels of performance, and the uncertainties to be expected in the measurements obtained from them.

ELEMENT 6: Floating object (Automatic)

Table 7.6. Characteristics of operational pyrradiometers

TABLE: Table horizontal lines

Characteristic	High quality[a]	Good quality[b]	Moderate quality[c]
Resolution (W m^{-2})	1	5	10
Stability (annual change; % of full scale)	2_%	5_%	10_%
Cosine response error at 10° elevation	3_%	7_%	15_%
Azimuth error at 10° elevation (additional to cosine error) (deviation from mean)	3_%	5_%	10_%
Temperature dependence (−20 °C to 40 °C) (deviation from mean)	1_%	2_%	5_%
Non-linearity (deviation from mean)	0.5_%	2_%	5_%
Variation in spectral sensitivity integrated over 200 nm intervals from 300 to 75 000 nm	2_%	5_%	10_%

Notes:
a Near state of the art; maintainable only at stations with special facilities and specialist staff.
b Acceptable for network operations.
c Suitable for low-cost networks where moderate to low performance.

END ELEMENT

7.4.3   Calibration of pyrgeometers

Pyrradiometers and net pyrradiometers can be calibrated for short-wave radiation using the same methods as those used for pyranometers (see ~~section~~ 7.3.1) using the sun and sky as the source. In the case of one-sensor net pyrradiometers, the downward-looking side must be covered by a cavity of known and steady temperature.

Long-wave radiation calibration of reference radiometers is best done in the laboratory with black-body cavities, but night-time comparison to reference instruments is preferred for network measurements. In the case of calibration of the sensor the downward flux L^- is measured separately by using a pyrgeometer or provided by a black-body cavity. In which case, signal V from the net radiative flux received by the instrument (via equation 7.11) amounts to:

$$V = L^* \cdot K \text{ or } K = V / L^* \qquad (7.14)$$

where V is the output of the instrument (μV); and K is sensitivity (μV/(W m^{-2})).

The instrument sensitivities should be checked periodically in situ by careful selection of well-described environmental conditions with slowly varying fluxes. Pyrgeometers should also be checked periodically to ensure that the transmission of short-wave radiation has not changed.

The symmetry of net pyrradiometers requires regular checking. This is done by inverting the instrument, or the pair of instruments, in situ and noting any difference in output. Differences of greater than 2_% of the likely full scale between the two directions demand instrument recalibration because either the ventilation rates or absorption factors have become significantly different for the two sensors. Such tests should also be carried out during calibration or installation.

7.4.4   Installation of pyrradiometers and pyrgeometers

Pyrradiometers and pyrgeometers are generally installed at a site which is free from obstructions, or at least has no obstruction with an angular size greater than 5° in any direction, and which has a low sun angle at all times during the year.

A daily check of the instruments should ensure that:

(a) The instrument is level;

(b)   Each sensor and its protection devices are kept clean and free from dew, frost, snow and rain;

(c)   The domes do not retain water (any internal condensation should be dried up);

(d)   The black receiver surfaces have emissivities very close to 1.

Since it is not generally possible to directly measure the reflected solar radiation and the upward long-wave radiation exactly at the surface level, it is necessary to place the pyrradiometers, or pyranometers and pyrgeometers at a suitable distance from the ground to measure these upward components. Such measurements integrate the radiation emitted by the surface beneath the sensor. For those instruments which have an angle of view of 2π sr and are installed 2 m above the surface, 90 % of all the radiation measured is emitted by a circular surface underneath having a diameter of 12 m (this figure is 95 % for a diameter of 17.5 m and 99 % for one of 39.8 m), assuming that the sensor uses a cosine detector.

This characteristic of integrating the input over a relatively large circular surface is advantageous when the terrain has large local variations in emittance, provided that the net pyrradiometer can be installed far enough from the surface to achieve a field of view which is representative of the local terrain. The output of a sensor located too close to the surface will show large effects caused by its own shadow, in addition to the observation of an unrepresentative portion of the terrain. On the other hand, the readings from a net pyrradiometer located too far from the surface can be rendered unrepresentative of the fluxes near that surface because of the existence of undetected radiative flux divergences. Usually, a height of 2 m above short homogeneous vegetation is adopted, while in the case of tall vegetation, such as a forest, the height should be sufficient to eliminate local surface heterogeneities adequately.

7.4.5   Recording and data reduction

In general, the text in section 7.1.3 applies to pyrradiometers and pyrgeometers. Furthermore, the following effects can specifically influence the readings of these radiometers, and they should be recorded:

(a)   The effect of hydrometeors on non-protected and non-ventilated instruments (rain, snow, dew, frost);

(b)   The effect of wind and air temperature;

(c)   The drift of zero of the data system. This is much more important for pyrradiometers, which can yield negative values, than for pyranometers, where the zero irradiance signal is itself a property of the net irradiance at the sensor surface.

Special attention should be paid to the position of instruments if the derived long-wave radiation requires subtraction of the solar irradiance component measured by a pyranometer; the pyrradiometer and pyranometer should be positioned within 5 m of each other and in such a way that they are essentially influenced in the same way by their environment.

7.5   MEASUREMENT OF SPECIAL RADIATION QUANTITIES

7.5.1   Measurement of daylight

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Figure 7.2. Relative luminous sensitivity $V(\lambda)$ of the human eye for photopic vision

END ELEMENT

Illuminance is the incident flux of radiant energy that emanates from a source with wavelengths between 380 and 780 nm and is weighted by the response of the human eye to energy in this wavelength region. The CIE has defined the response of the human eye to photons with a peak responsivity at 555 nm. Figure 7.2 and Table 7.7 provide the relative response of the human eye normalized to this frequency. Luminous efficacy is defined as the relationship between radiant emittance (W m^{-2}) and luminous emittance (lm). It is a function of the relative luminous sensitivity $V(\lambda)$ of the human eye and a normalizing factor K_m (683) describing the number of lumens emitted per watt of electromagnetic radiation from a monochromatic source of 555.19 nm (the freezing point of platinum), as follows:

$$\Phi_v = K_m \int_{380}^{780} \Phi(\lambda)V(\lambda)d\lambda \qquad (7.15)$$

where Φ_v is the luminous flux (lm m^{-2} or lx); $\Phi(\lambda)$ is the spectral radiant flux (W m^{-2} nm^{-1}); $V(\lambda)$ is the sensitivity of the human eye; and K_m is the normalizing constant relating luminous to radiation quantities. Thus, 99 % of the visible radiation lies between 400 and 730 nm.

Quantities and units for luminous variables are given in Annex 7.A.

ELEMENT 9: Floating object (Top)

**Table 7.7. Photopic spectral luminous efficiency values
(unity at wavelength of maximum efficacy)**

TABLE: Table horizontal lines

Wavelength (nm)	Photopic $V(\lambda)$	Wavelength (nm)	Photopic $V(\lambda)$
380	0.000 04	590	0.757
390	0.000 12	600	0.631
400	0.000 4	610	0.503
410	0.001 2	620	0.381
420	0.004 0	630	0.265
430	0.011 6	640	0.175
440	0.023	650	0.107
450	0.038	660	0.061
460	0.060	670	0.032
470	0.091	680	0.017
480	0.139	690	0.008 2
490	0.208	700	0.004 1
500	0.323	710	0.002 1
510	0.503	720	0.001 05
520	0.710	730	0.000 52
530	0.862	740	0.000 25
540	0.954	750	0.000 12
550	0.995	760	0.000 06
560	0.995	770	0.000 03
570	0.952	780	0.000 015

Wavelength (nm)	Photopic $V(\lambda)$	Wavelength (nm)	Photopic $V(\lambda)$
580	0.870		

END ELEMENT

7.5.1.1   Instruments

Illuminance meters comprise a photovoltaic detector, one or more filters to yield sensitivity according to the $V(\lambda)$ curve, and often a temperature control circuit to maintain signal stability. The CIE has developed a detailed guide to the measurement of daylight (CIE, 1994) which describes expected practices in the installation of equipment, instrument characterization, data-acquisition procedures and initial quality control.

The measurement of global illuminance parallels the measurement of global irradiance. However, the standard illuminance meter must be temperature controlled or corrected from at least −10 °C to 40 °C. Furthermore, it must be ventilated to prevent condensation and/or frost from coating the outer surface of the sensing element. Illuminance meters should normally be able to measure fluxes over the range 1 to 20 000 lx. Within this range, uncertainties should remain within the limits of Table 7.8. These values are based upon CIE recommendations (CIE, 1987), but only for uncertainties associated with high-quality illuminance meters specifically intended for external daylight measurements.

ELEMENT 10: Floating object (Automatic)

Table 7.8. Specification of illuminance meters

TABLE: Table horizontal lines

Specification	Uncertainty percentage
$V(\lambda)$ match	2.5
UV response	0.2
IR response	0.2
Cosine response	1.5
Fatigue at 10 klx	0.1
Temperature coefficient	0.1 K^{-1}
Linearity	0.2
Settling time	0.1 s

END ELEMENT

Diffuse sky illuminance can be measured following the same principles used for the measurement of diffuse sky irradiance. Direct illuminance measurements should be taken with instruments having a field of view whose open half-angle is no greater than 2.85° and whose slope angle is less than 1.76°.

7.5.1.2   Calibration

Calibrations should be traceable to a Standard Illuminant A following the procedures outlined in CIE (1987). Such equipment is normally available only at national standards laboratories. The calibration and tests of specification should be performed yearly. These should also include tests to determine ageing, zero setting drift, mechanical stability and climatic stability. It is also recommended that a field standard be used to check calibrations at each measurement site between laboratory calibrations.

7.5.1.3 Recording and data reduction

The CIE has recommended that the following climatological variables be recorded:

(a) Global and diffuse sky daylight illuminance on horizontal and vertical surfaces;

(b) Illuminance of the direct solar beam;

(c) Sky luminance for 0.08 sr intervals (about 10° · 10°) all over the hemisphere;

(d) Photopic albedo of characteristic surfaces such as grass, earth and snow.

Hourly or daily integrated values are usually needed. The hourly values should be referenced to true solar time. For the presentation of sky luminance data, stereographic maps depicting isolines of equal luminance are most useful.

7.6   MEASUREMENT OF UV RADIATION

Measurements of solar UV radiation are in demand because of its effects on the environment and human health, and because of the enhancement of radiation at the Earth's surface as a result of ozone depletion (Kerr and McElroy, 1993) and changes in other parameters like clouds and aerosols. The UV spectrum is conventionally divided into three parts, as follows:

(a) UV-A is the band with wavelengths of 315 to 400 nm, namely, just outside the visible spectrum. It is usually[2] less biologically active, and its intensity at the Earth's surface does not vary significantly with atmospheric ozone content;

(b) UV-B is defined as radiation in the 280 to 315 nm band. It is biologically active and its intensity at the Earth's surface depends on the atmospheric ozone column, depending on wavelength. A frequently used expression of its biological activity is its erythemal effect, which is the extent to which it causes the reddening of human skin;

(c) UV-C, in wavelengths of 100 to 280 nm, is completely absorbed in the atmosphere and does not occur naturally at the Earth's surface.

UV-B is the band on which most interest is centred for measurements of UV radiation. An alternative, but now non-standard, definition of the boundary between UV-A and UV-B is 320 nm rather than 315 nm.

Measuring UV radiation is difficult because of the small amount of energy reaching the Earth's surface, the variability due to changes in stratospheric ozone levels, and the rapid increase in the magnitude of the flux with increasing wavelength. Figure 7.3 illustrates changes in the spectral irradiance between 290 and 325 nm at the top of the atmosphere and at the surface in W m^{-2} nm^{-1}. Global UV irradiance is strongly affected by atmospheric phenomena such as clouds, and to a lesser extent by atmospheric aerosols.

The influence of surrounding surfaces is also significant because of multiple scattering. This is especially the case in snow-covered areas.

Difficulties in the standardization of UV radiation measurement stem from the variety of uses to which the measurements are put (WMO, 2003, 2011). Unlike most meteorological measurements, standards based upon global needs have not yet been reached. In many countries, measurements of UV radiation are not taken by Meteorological Services, but by health or environmental protection authorities. This leads to further difficulties in the standardization of instruments and methods of observation. Standards are necessary for compatible observations, quality assurance

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[2] The phytoplankton photosynthesis action spectrum, for example, has an important component in the UV-A.

and quality control of measurements, and data archiving, as well as for connecting measurements with the user communities (WMO, 2003).

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Figure 7.3. Model results illustrating the effect of increasing ozone levels on the transmission of UV-B radiation through the atmosphere

Guidelines and standard procedures have been developed on how to characterize and calibrate UV broadband instruments, spectroradiometers and filter radiometers used to measure solar UV irradiance (see WMO, 1996, 1999*a*, 1999*b*, 2001, 2008, 2010*a*). Although not available commercially yet, guides and standard procedures have also been developed for array spectroradiometers (WMO, 2010*b*). Application of the recommended procedures for data quality assurance performed at sites operating instruments for solar UV radiation measurements will ensure a valuable UV radiation database. This is needed to derive a climatology of solar UV irradiance in space and time for studies of the Earth's climate. Recommendations for measuring sites and instrument specifications are also provided in these documents. Requirements for UV-B measurements were put forward in the WMO GAW Programme (WMO, 1993, 2001, 2003, 2010*a*, 2010*b*, 2011, 2014). For UV-B global spectral irradiance, requirements depend on the objective. Specifications for less demanding objectives are reproduced in Table 7.9 (WMO, 2001).

ELEMENT 12: Floating object (Automatic)

Table 7.9. GAW Programme requirements for UV-B global spectral irradiance measurements

TABLE: Table horizontal lines

Characteristic	Requirements
Cosine error[a]	(a) < ±10 % for incidence angles < 60° (b) < ±10 % for integrated isotropic radiance
Minimum spectral range	290–325 nm[b]
Bandwidth (FWHM)	< 1 nm
Wavelength precision	< ±0.05 nm
Wavelength accuracy	< ±0.1 nm
Slit function	< 10^{-3} of maximum at 2.5 FWHM away from centre
Sampling wavelength interval	< FWHM
Maximum irradiance	> 1 W m^{-2} nm^{-1} at 325 nm and, if applicable, 2 W m^{-2} nm^{-1} at 400 nm (noon maximum)
Detection threshold	< 5 · 10^{-5} W m^{-2} nm^{-1} (for signal-to-noise ratio (SNR) = 1 at 1 nm FWHM)
Stray light	< 5 · 10^{-4} W m^{-2} nm^{-1} when the instrument is exposed to the sun at minimum solar zenith angle
Instrument temperature	Monitored and sufficiently stable to maintain overall instrument stability
Scanning duration	< 10 min per spectrum, e.g. for ease of comparison with models
Overall calibration uncertainty[c]	< ±10 % (unless limited by detection threshold)
Scan date and time	Recorded with each spectrum such that timing is known to within 10 s at each wavelength
Ancillary measurements required	Direct normal spectral irradiance or diffuse spectral irradiance Total ozone column, e.g. derived from measurements of direct normal spectral irradiance Erythemally weighted irradiance, measured with a broadband radiometer Atmospheric pressure Cloud amount Illuminance, measured with a luxmeter Direct irradiance at normal incidence measured with a pyrheliometer Visibility
Data frequency	At least one scan per hour and additionally a scan at local solar noon

Notes:
a Smaller cosine errors would be desirable, but are unrealistic for the majority of the instruments that are currently in use.

b The overall calibration uncertainty is expressed at 95 % confidence level and includes all uncertainties associated with the irradiance calibration (for example, uncertainty of the standard lamps, transfer uncertainties, alignment errors during calibration, and drift of the instrument between calibrations). For more details, see Bernhard and Seckmeyer (1999), Cordero et al. (2008), and Cordero et al. (2013).

c An extension to longer wavelengths is desirable for the establishment of a UV climatology with respect to biological applications, see WMO (2001, 2010*b*).

END ELEMENT

The following instrument descriptions are provided for general information and for assistance in selecting appropriate instrumentation.

7.6.1   Instruments

Three general types of instruments are available commercially for the measurement of UV radiation. The first class of instruments use broadband filters. These instruments integrate over either the UV-B or UV-A spectrum or the entire broadband UV region responsible for affecting human health. The second class of instruments use one or more interference filters to integrate over discrete portions of the UV-A and/or UV-B spectrum. The third class of instruments are spectroradiometers that measure across a pre-defined portion of the spectrum sequentially, or simultaneously, using a fixed passband.

7.6.1.1   Broadband sensors

Most, but not all, broadband sensors are designed to measure a UV spectrum that is weighted by the erythemal function proposed by McKinlay and Diffey (1987) and reproduced in Figure 7.4. Another action spectrum found in some instruments is that of Parrish et al. (1982). Two methods (and their variations) are used to accomplish this hardware weighting.

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Figure 7.4. Erythemal curves

Source: Parrish et al. (1982) and McKinlay and Diffey (1987)

END ELEMENT

One of the means of obtaining erythemal weighting is to first filter out nearly all visible wavelength light using UV-transmitting, black-glass blocking filters. The remaining radiation then strikes a UV-sensitive phosphor. In turn, the green light emitted by the phosphor is filtered again by using coloured glass to remove any non-green visible light before impinging on a gallium arsenic or a gallium arsenic phosphorus photodiode. The quality of the instrument is dependent on such items as the quality of the outside protective quartz dome, the cosine response of the instrument, the temperature stability, and the ability of the manufacturer to match the erythemal curve with a combination of glass and diode characteristics. Instrument temperature stability is crucial, both with respect to the electronics and the response of the phosphor to incident UV radiation. Phosphor efficiency decreases by approximately 0.5 % K^{-1} and its wavelength response curve is shifted by approximately 1 nm longer every 10 K. This latter effect is particularly important because of the steepness of the radiation curve at these wavelengths.

More recently, instruments have been developed to measure erythemally weighted UV irradiance using thin film metal interference filter technology and specially developed silicon photodiodes. These overcome many problems associated with phosphor technology, but must contend with very low photodiode signal levels and filter stability.

Other broadband instruments use one or the other measurement technology to measure the complete spectra by using either a combination of glass filters or interference filters. The bandpass is as narrow as 20 nm full-width half-maximum (FWHM) to as wide as 80 nm FWHM for instruments measuring a combination of UV-A and UV-B radiation. Some manufacturers of these

instruments provide simple algorithms to approximate erythemal dosage from the unweighted measurements.

The basic maintenance of these instruments consists of ensuring that the domes are cleaned, the instrument is levelled, the desiccant (if provided) is active, and the heating/cooling system is working correctly, if so equipped. Quality control and quality assurance as well as detailed maintenance should be done by well-experienced staff.

7.6.1.2   *Narrowband sensors*

The definition of narrowband for this classification of instrument is vague. The widest bandwidth for instruments in this category is 10 nm FWHM. The narrowest bandwidth at present for commercial instruments is of the order of 2 nm FWHM (WMO, 2010*a*).

These sensors use one or more interference filters to obtain information about a portion of the UV spectra. The simplest instruments consist of a single filter, usually at a wavelength that can be measured by a good-quality, UV enhanced photodiode, although more than one filter is desirable. Specifications required for this type of instrument (WMO, 2010*a*) are given in Table 7.10. Wavelengths near 305 nm are typical for such instruments. The out-of-band rejection of such filters should be equal to, or greater than, 10^{-6} throughout the sensitive region of the detector. Higher quality instruments of this type either use Peltier cooling to maintain a constant temperature near 20 °C or heaters to increase the instrument filter and diode temperatures to above normal ambient temperatures, usually 40 °C. However, the latter alternative markedly reduces the life of interference filters. A modification of this type of instrument uses a photomultiplier tube instead of the photodiode. This allows the accurate measurement of energy from shorter wavelengths and lower intensities at all measured wavelengths.

ELEMENT 15: Floating object (Top)

Table 7.10. Requirements for UV-B global narrowband irradiance measurements

TABLE: Table horizontal lines

Characteristic	*Requirements*
Stray light including sensitivity to visible and infrared radiation	< 1 % contribution to the signal of wavelengths outside 2.5 FWHM for a solar zenith angle less than 70°
Stability over time on timescales up to a year	Signal change: Currently in use: better than 5 % Desired: 2 %
Minimum number of channels	At least one channel with centre wavelength < 310 nm and at least one with centre wavelength > 330 nm
Maximum irradiance	Signal of the instruments must not saturate at radiation levels encountered on the Earth's surface
Detection threshold	SNR = 3 for irradiance at solar zenith angle of 80° and total ozone column of 300 Dobson units
Instrument temperature	Monitored and sufficiently stable to maintain overall instrument stability
Response time	< 1 s
Multiplexing time	< 1 s
Accuracy of time	Better than ±10 s
Sampling frequency	≤ 1 min
Levelling	< 0.2°
Calibration uncertainty	< 10% (unless limited by detection threshold)

END ELEMENT

Manufacturers of instruments that use more than a single filter often provide a means of reconstructing the complete UV spectrum and determining biologically effective doses for a variety of action spectra, the total column ozone amount and cloud attenuation, through modelled relationships developed around the measured wavelengths (WMO, 2010*a*). Single wavelength instruments are used similarly to supplement the temporal and spatial resolution of more sophisticated spectrometer networks or for long-term accurate monitoring of specific bands to detect trends in the radiation environment.

The construction of the instruments must be such that the radiation passes through the filter close to normal incidence so that wavelength shifting to shorter wavelengths is avoided. For example, a 10° departure from normal incidence may cause a wavelength shift of 1.5 nm, depending on the refractive index of the filter. The effect of temperature can also be significant in altering the central wavelength by about 0.012 nm K^{-1} on very narrow filters (< 1 nm).

Maintenance for simple one-filter instruments is similar to that of the broadband instruments. For instruments that have multiple filters in a moving wheel assembly, maintenance will include determining whether or not the filter wheel is properly aligned. Regular testing of the high-voltage power supply for photomultiplier-equipped instruments and checking the quality of the filters are also recommended.

7.6.1.3   Spectroradiometers

The most sophisticated commercial instruments are those that use either ruled or holographic gratings to disperse the incident energy into a spectrum. The low energy of the UV radiation compared with that in the visible spectrum necessitates a strong out-of-band rejection. This is achieved by using a double monochromator or by blocking filters, which transmit only UV radiation, in conjunction with a single monochromator. A photomultiplier tube is most commonly used to measure the output from the monochromator (WMO, 2001). Some less expensive instruments use photodiode or charge-coupled detector arrays (WMO, 2010b), enabling the measurement of an entire spectral region of interest at the same time. These instruments are unable to measure energy in the shortest wavelengths of the UV-B radiation and generally have more problems associated with stray light.

Monitoring instruments are now available with several self-checking features. Electronic tests include checking the operation of the photomultiplier and the analogue to digital conversion. Tests to determine whether the optics of the instrument are functioning properly include testing the instrument by using internal mercury lamps and standard quartz halogen lamps. While these do not give absolute calibration data, they provide the operator with information on the stability of the instrument both with respect to spectral alignment and intensity.

Commercially available instruments are constructed to provide measurement capabilities from approximately 290 nm to the mid-visible wavelengths, depending upon the type of construction and configuration. The bandwidth of the measurements is usually between 0.5 and 2.0 nm. The time required to complete a full scan across the grating depends upon both the wavelength resolution and the total spectrum to be measured. Scan times to perform a spectral scan across the UV region and part of the visible region (290 to 450 nm) with small wavelength steps range from less than 1 min per scan with modern fast scanning spectroradiometers to about 10 min for some types of conventional high-quality spectroradiometers.

For routine monitoring of UV radiation it is recommended that the instrument either be environmentally protected or developed in such a manner that the energy incident on a receiver is transmitted to a spectrometer housed in a controlled climate. In both cases, care must be taken in the development of optics so that uniform responsivity is maintained down to low solar elevations.

The maintenance of spectroradiometers designed for monitoring UV-B radiation requires well-trained on-site operators who will care for the instruments. It is crucial to follow the manufacturer's maintenance instructions because of the complexity of this instrument.

7.6.2   Calibration

The calibration of all sensors in the UV-B is both very important and difficult. Guidelines on the calibration of UV spectroradiometers and UV filter radiometers have been given in WMO (1996, 1999a, 1999b, 2001, 2008, 2010a, 2010b) and in the relevant scientific literature. Spectroradiometers must be calibrated against standard lamps, which have to be traceable to national standards laboratories. Many countries do not have laboratories capable of characterizing lamps in the UV. In these countries, lamps are usually traceable to the National Institute of Standards and Technology in the United States or to the Physikalisch-Technische Bundesanstalt in Germany.

It is estimated that a 5% uncertainty in spot measurements at 300 nm can be achieved only under the most rigorous conditions at the present time. The uncertainty of measurements of daily totals is about the same, using best practice. Fast changes in cloud cover and/or cloud optical depths at the measuring site require fast spectral scans and small sampling time steps between subsequent spectral scans, in order to obtain representative daily totals of spectral UV irradiance. Measurements of erythemal irradiance would have uncertainties typically in the range 5 % to 20 %, depending on a number of factors, including the quality of the procedures and the equipment. The sources of error are discussed in the following paragraphs and include:

(a) Uncertainties associated with standard lamps;

(b) The stability of instruments, including the stability of the spectral filter and, in older instruments, temperature coefficients;

(c) Cosine error effects;

(d) The fact that the calibration of an instrument varies with wavelength, and that:

   (i) The spectrum of a standard lamp is not the same as the spectrum being measured;

   (ii) The spectrum of the UV-B irradiance being measured varies greatly with the solar zenith angle.

The use of standard lamps as calibration sources leads to large uncertainties at the shortest wavelengths, even if the transfer of the calibration is perfect. For example, at 350 nm the uncertainty associated with the standard irradiance is of the order of 1.3 %; when transferred to a standard lamp, another 0.7 % uncertainty is added. Uncertainties in calibration decrease with increasing wavelength. Consideration must also be given to the set-up and handling of standard lamps. Even variations as small as 1 % in the current, for example, can lead to errors in the UV flux of 10 % or more at the shortest wavelengths. Inaccurate distance measurements between the lamp and the instrument being calibrated can also lead to errors in the order of 1 % as the inverse square law applies to the calibration. Webb et al. (1994) discuss various aspects of uncertainty as related to the use of standard lamps in the calibration of UV or visible spectroradiometers.

The problems associated with broadband instruments stem from: (a) the complex set of filters used to integrate the incoming radiation into the erythemal signal; and (b) the fact that the spectral nature of the atmosphere changes with air mass and ozone amount. Even if the characterization of the instrument by using calibrated lamp sources is perfect, the difference between the measured solar spectrum and the lamp spectrum affects the uncertainty of the final measurements. The use of high-output deuterium lamps, a double monochromator and careful filter selection will help in the characterization of these instruments, but the number of laboratories capable of calibrating these devices is extremely limited. Different calibration methods for broadband instruments are described in WMO (2008).

Trap detectors could potentially be used effectively for narrowband sensors, but have been used only in research projects to date. In recalibrating these instruments, whether they have a single filter or multiple filters, care must be taken to ensure that the spectral characteristics of the filters have not shifted over time. Different methods for calibrating narrowband sensors, as well as their advantages and disadvantages, are described in WMO (2010a).

Spectroradiometers should be calibrated in the same position as that in which the measurements are to be taken, as many spectroradiometers are adversely affected by changes in orientation. The calibration of a spectroradiometer should also include testing the accuracy of the wavelength positioning of the monochromator, checking for any changes in internal optical alignment and cleanliness, and an overall test of the electronics. The out-of-band rejection needs to be characterized, possibly by scanning a helium cadmium laser (λ = 325 nm), only once, as it usually does not change with time.

Most filter instrument manufacturers indicate a calibration frequency of once a year. Spectroradiometers should be calibrated at least twice a year and more frequently if they do not

have the ability to perform self-checks on the photomultiplier output or the wavelength selection. In all cases, absolute calibrations of the instruments should be performed by qualified technicians at the sites on a regular time schedule. The sources used for calibration must guarantee that the calibration can be traced back to absolute radiation standards kept at national metrological institutes. If the results of quality assurance routines applied at the sites indicate a significant change in an instrument's performance or changes of its calibration level over time, an additional calibration may be needed in between two regular calibrations. All calibrations should be based on expertise and documentation available at the site and on the guidelines and procedures such as those published in WMO (1996, 1999*a*, 1999*b*, 2001, 2008, 2010*a*, 2010*b*). In addition to absolute calibrations of instruments, intercomparisons between the sources used for calibration, for example, calibration lamps, and the measuring instruments are useful to detect and remove inconsistencies or systematic differences between station instruments at different sites.

ANNEX 7.A. NOMENCLATURE OF RADIOMETRIC AND PHOTOMETRIC QUANTITIES[3]

(1) Radiometric quantities

TABLE: Table horizontal lines

Name	Symbol	Unit	Relation	Remarks
Radiant energy	Q, (W)	J = W s	–	–
Radiant flux	Φ, (P)	W	$\Phi = \dfrac{dQ}{dt}$	Power
Radiant flux density	(M), (E)	W m^{-2}	$\dfrac{d\Phi}{dA} = \dfrac{d^2Q}{dA \cdot dt}$	Radiant flux of any origin crossing an area element
Radiant exitance	M	W m^{-2}	$M = \dfrac{d\Phi}{dA}$	Radiant flux of any origin emerging from an area element
Irradiance	E	W m^{-2}	$E = \dfrac{d\Phi}{dA}$	Radiant flux of any origin incident onto an area element
Radiance	L	W m^{-2} sr^{-1}	$L = \dfrac{d^2\Phi}{d\Omega \cdot dA_1 \cos\theta}$	The radiance is a conservative quantity in an optical system
Radiant exposure	H	J m^{-2}	$H = \dfrac{dQ}{dA} = \displaystyle\int_{t_1}^{t_2} E\,dt$	May be used for daily sums of global radiation, etc.
Radiant intensity	I	W sr^{-1}	$I = \dfrac{d\Phi}{d\Omega}$	May be used only for radiation outgoing from "point sources"

(2) Photometric quantities

TABLE: Table horizontal lines

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[3] For further details, please refer to: http://eilv.cie.co.at/.

Name	Symbol	Unit
Quantity of light	Q_v	lm · s
Luminous flux	Φ_v	lm
Luminous exitance	M_v	lm m^{-2}
Illuminance	E_v	lm m^{-2} = lx
Light exposure	H_v	lm m^{-2} s = lx · s
Luminous intensity	I_v	lm sr^{-1} = cd
Luminance	L_v	lm m^{-2} s r^{-1} = cdm^{-2}
Luminous flux density	$(M_v ; E_v)$	lm m^{-2}

(3) Optical characteristics

TABLE: Table horizontal lines

Characteristic	Symbol	Definition	Remarks
Emissivity	ε	$\varepsilon = \dfrac{M_\varepsilon}{M_{\varepsilon=1}}$	$\varepsilon = 1$ for a black-body
Absorptance	α	$\alpha = \dfrac{\Phi_a}{\Phi_i}$	Φ_a and Φ_i are the absorbed and incident radiant flux, respectively
Reflectance	ρ	$\rho = \dfrac{\Phi_r}{\Phi_i}$	Φ_r is the reflected radiant flux
Transmittance	τ	$\tau = \dfrac{\Phi_t}{\Phi_i}$	Φ_t is the radiant flux transmitted through a layer or a surface
Optical depth	δ	$\tau = e^{-\delta}$	In the atmosphere, δ is defined in the vertical. Optical thickness equals $\delta/\cos\theta$, where θ is the apparent zenith angle

ANNEX 7.B. METEOROLOGICAL RADIATION QUANTITIES, SYMBOLS AND DEFINITIONS

TABLE: Table horizontal lines

Quantity	Symbol	Relation	Definitions and remarks	Units
Downward radiation	$\Phi\downarrow$[a] $Q\downarrow$ $M\downarrow$ $E\downarrow$ $L\downarrow$ $H\downarrow$	$\Phi\downarrow = \Phi_g\downarrow + \Phi_l\downarrow$ $Q\downarrow = Q_g\downarrow + Q_l\downarrow$ $M\downarrow = M_g\downarrow + M_l\downarrow$ $E\downarrow = E_g\downarrow + E_l\downarrow$ $L\downarrow = L_g\downarrow + L_l\downarrow$ $H\downarrow = H_g\downarrow + H_l\downarrow$ (g = global) (l = long wave)	Downward radiant flux " radiant energy " radiant exitance[b] " irradiance " radiance " radiant exposure for a specified time interval	W J (W s) W m^{-2} W m^{-2} W m^{-2} sr^{-1} J m^{-2} per time interval
Upward radiation	$\Phi\uparrow$[a] $Q\uparrow$ $M\uparrow$ $E\uparrow$ $L\uparrow$ $H\uparrow$	$\Phi\uparrow = \Phi_r\uparrow + \Phi_l\uparrow$ $Q\uparrow = Q_r\uparrow + Q_l\uparrow$ $M\uparrow = M_r\uparrow + M_l\uparrow$ $E\uparrow = E_r\uparrow + E_l\uparrow$ $L\uparrow = L_r\uparrow + L_l\uparrow$ $H\uparrow = H_r\uparrow + H_l\uparrow$	Upward radiant flux " radiant energy " radiant exitance " irradiance " radiance " radiant energy per unit area for a specified time interval	W J (W s) W m^{-2} W m^{-2} W m^{-2} sr^{-1} J m^{-2} per time interval
Global radiation	$E_g\downarrow$	$E_g\downarrow = E\cos\theta_e + E_d\downarrow$	Hemispherical irradiance on a horizontal surface (θ_e = *apparent solar zenith angle*)[c]	W m^{-2}
Sky radiation: downward diffuse solar radiation	$\Phi_{d\downarrow}$ $Q_{d\downarrow}$ $M_{d\downarrow}$ $E_{d\downarrow}$ $L_{d\downarrow}$ $H_{d\downarrow}$		Subscript d = diffuse	As for downward radiation

Quantity	Symbol	Relation	Definitions and remarks	Units
Upward/downward long-wave radiation	$\Phi_{l\uparrow}$, $\Phi_{l\downarrow}$ $Q_l\uparrow$, $Q_l\downarrow$ $M_l\uparrow$, $M_l\downarrow$ $E_l\uparrow$, $E_l\downarrow$ $H_l\uparrow$, $H_l\downarrow$		Subscript l = long wave. If only atmospheric radiation is considered, the subscript a may be added, e.g., $\Phi_{l,a\uparrow}\sigma\sigma$	As for downward radiation
Reflected solar radiation	$\Phi_r\uparrow$ $Q_r\uparrow$ $M_r\uparrow$ $E_r\uparrow$ $L_r\uparrow$ $H_r\uparrow$		Subscript r = reflected (the subscript s (specular) and d (diffuse) may be used, if a distinction is to be made between these two components)	As for downward radiation
Net radiation	$\Phi*$ $Q*$ $M*$ $E*$ $L*$ $H*$	$\Phi* = \Phi\downarrow - \Phi\uparrow$ $Q* = Q\downarrow - Q\uparrow$ $M* = M\downarrow - M\uparrow$ $E* = E\downarrow - E\uparrow$ $L* = L\downarrow - L\uparrow$ $H* = H\downarrow - H\uparrow$	The subscript g or l is to be added to each of the symbols if only short-wave or long-wave net radiation quantities are considered	As for downward radiation
Direct solar radiation	E	$E = E_0\tau$ $\tau = e^{-\delta/\cos\theta_e}$ $\quad E = E_0\tau$ $\tau = e^{-\delta/\cos\theta_e}$	τ = atmospheric transmittance δ = optical depth (vertical)	W m^{-2}
Solar constant	E_0		Solar irradiance, normalized to mean Sun–Earth distance	W m^{-2}

Notes:

a   The symbols − or + could be used instead of ↓ or ↑ (e.g., $\Phi^+ = \Phi\uparrow$).

b   Exitance is radiant flux emerging from the unit area; irradiance is radiant flux received per unit area. For flux density in general, the symbol M or E can be used. Although not specifically recommended, the symbol F, defined as Φ/area, may also be introduced.

c   In the case of inclined surfaces, θ_e is the angle between the normal to the surface and the direction to the sun.

ANNEX 7.C. SPECIFICATIONS FOR WORLD, REGIONAL AND NATIONAL RADIATION CENTRES

World Radiation Centres

The World Radiation Centres were designated by the Executive Committee at its thirtieth session in 1978 through Resolution 11 (EC-XXX) to serve as centres for the international calibration of meteorological radiation standards within the global network and to maintain the standard instruments for this purpose.

A World Radiation Centre shall fulfil the following requirements. It shall either:

(a)   Possess and maintain a group of at least three stable absolute pyrheliometers, with a traceable 95 % uncertainty of less than 1 W m^{-2} to the World Radiometric Reference, and in stable, clear sun conditions with direct irradiances above 700 W m^{-2}, 95 % of any single measurements of direct solar irradiance will be expected to be within 4 W m^{-2} of the

irradiance. The World Radiation Centre Davos is requested to maintain the World Standard Group for realization of the World Radiometric Reference;

(b) It shall undertake to train specialists in radiation;

(c) The staff of the centre should provide for continuity and include qualified scientists with wide experience in radiation;

(d) It shall take all steps necessary to ensure, at all times, the highest possible quality of its standards and testing equipment;

(e) It shall serve as a centre for the transfer of the World Radiometric Reference to the regional centres;

(f) It shall have the necessary laboratory and outdoor facilities for the simultaneous comparison of large numbers of instruments and for data reduction;

(g) It shall follow closely or initiate developments leading to improved standards and/or methods in meteorological radiometry;

(h) It shall be assessed by an international agency or by CIMO experts, at least every five years, to verify traceability of the direct solar radiation measurements;

or:

(a) Provide and maintain an archive for solar radiation data from all the Member States of WMO;

(b) The staff of the centre should provide for continuity and include qualified scientists with wide experience in radiation;

(c) It shall take all steps necessary to ensure, at all times, the highest possible quality of, and access to, its database;

(d) It shall be assessed by an international agency or by CIMO experts, at least every five years.

Regional Radiation Centres

A Regional Radiation Centre is a centre designated by a regional association to serve as a centre for intraregional comparisons of radiation instruments within the Region and to maintain the standard instrument necessary for this purpose.

A Regional Radiation Centre shall satisfy the following conditions before it is designated as such and shall continue to fulfil them after being designated:

(a) It shall possess and maintain a standard group of at least three stable pyrheliometers, with a traceable 95 % uncertainty of less than 1 W m^{-2} to the World Standard Group, and in stable, clear sun conditions with direct irradiances above 700 W m^{-2}, 95 % of any single measurements of direct solar irradiance will be expected to be within 6 W m^{-2} of the irradiance;

(b) One of the radiometers shall be compared through a WMO/CIMO sanctioned comparison, or calibrated, at least once every five years against the World Standard Group;

(c) The standard radiometers shall be intercompared at least once a year to check the stability of the individual instruments. If the mean ratio, based on at least 100 measurements, and with a 95 % uncertainty less than 0.1 %, has changed by more than 0.2 %, and if the erroneous instrument cannot be identified, a recalibration at one of the World Radiation Centres must be performed prior to further use as a standard;

(d) It shall have, or have access to, the necessary facilities and laboratory equipment for checking and maintaining the accuracy of the auxiliary measuring equipment;

(e) It shall provide the necessary outdoor facilities for simultaneous comparison of national standard radiometers from the Region;

(f) The staff of the centre should provide for continuity and include a qualified scientist with wide experience in radiation;

(g) It shall be assessed by a national or international agency or by CIMO experts, at least every five years, to verify traceability of the direct solar radiation measurements.

National Radiation Centres

A National Radiation Centre is a centre designated at the national level to serve as a centre for the calibration, standardization and checking of the instruments used in the national network of radiation stations and for maintaining the national standard instrument necessary for this purpose.

A National Radiation Centre shall satisfy the following requirements:

(a) It shall possess and maintain at least two pyrheliometers for use as a national reference for the calibration of radiation instruments in the national network of radiation stations with a traceable 95 % uncertainty of less than 4 W m^{-2} to the regional representation of the World Radiometric Reference, and in stable, clear sun conditions with direct irradiances above 700 W m^{-2}, 95 % of any single measurements of direct solar irradiance will be expected to be within 20 W m^{-2} of the irradiance;

(b) One of the national standard radiometers shall be compared with a regional standard at least once every five years;

(c) The national standard radiometers shall be intercompared at least once a year to check the stability of the individual instruments. If the mean ratio, based on at least 100 measurements, and with a 95 % uncertainty less than 0.2 %, has changed by more than 0.6 % and if the erroneous instrument cannot be identified, a recalibration at one of the Regional Radiation Centres must be performed prior to further use as a standard;

(d) It shall have or, have access to, the necessary facilities and equipment for checking the performance of the instruments used in the national network;

(e) The staff of the centre should provide for continuity and include a qualified scientist with experience in radiation.

National Radiation Centres shall be responsible for preparing and keeping up to date all necessary technical information for the operation and maintenance of the national network of radiation stations.

Arrangements should be made for the collection of the results of all radiation measurements taken in the national network of radiation stations, and for the regular scrutiny of these results with a view to ensuring their accuracy and reliability. If this work is done by some other body, the National Radiation Centre shall maintain close liaison with the body in question.

List of World and Regional Radiation Centres

TABLE: Table as text NO space

World Radiation Centres

Davos   (Switzerland)
St Petersburg (see note)   (Russian Federation)

Regional Radiation Centres

Region I (Africa):

Cairo	(Egypt)
Khartoum	(Sudan)
Kinshasa	(Democratic Republic of the Congo)
Lagos	(Nigeria)
Tamanrasset	(Algeria)
Tunis	(Tunisia)

Region II (Asia):

Pune	(India)
Tokyo	(Japan)

Region III (South America):

Buenos Aires	(Argentina)
Santiago	(Chile)
Huayao	(Peru)

Region IV (North America, Central America and the Caribbean):

Toronto	(Canada)
Boulder	(United States)
Mexico City/Colima	(Mexico)

Region V (South-West Pacific):

Melbourne	(Australia)

Region VI (Europe):

Budapest	(Hungary)
Davos	(Switzerland)
St Petersburg	(Russian Federation)
Norrköping	(Sweden)
Toulouse/Carpentras	(France)
Uccle	(Belgium)
Lindenberg	(Germany)

Note: The Centre in St Petersburg is mainly operated as a World Radiation Data Centre ~~under the Global Atmosphere Watch Strategic Plan~~.

ANNEX 7.D. USEFUL FORMULAE

General

All astronomical data can be derived from tables in the nautical almanacs or ephemeris tables. However, approximate formulae are presented for practical use. Michalsky (1988*a*, 1988*b*) compared several sets of approximate formulae and found that the best are the equations presented as convenient approximations in the *Astronomical Almanac* (United States Naval Observatory, 1993). They are reproduced here for convenience.

The position of the sun

To determine the actual location of the sun, the following input values are required:

(a) Year;

(b) Day of year (for example, 1 February is day 32);

(c) Fractional hour in universal time (UT) (for example, hours + minute/60 + number of hours from Greenwich);

(d) Latitude in degrees (north positive);

(e) Longitude in degrees (east positive).

To determine the Julian date (JD), the *Astronomical Almanac* determines the present JD from a prime JD set at noon 1 January 2000 UT. This JD is 2 451 545.0. The JD to be determined can be found from:

$$JD = 2\,432\,917.5 + delta \cdot 365 + leap + day + hour/24$$

where:

delta = year − 1949
leap = integer portion of (delta/4)

The constant 2 432 917.5 is the JD for 0000 1 January 1949 and is simply used for convenience.

Using the above time, the ecliptic coordinates can be calculated according to the following steps (L, g and l are in degrees):

(a) n = JD − 2 451 545;

(b) L (mean longitude) = 280.460 + 0.985 647 4 · n (0 ≤ L < 360°);

(c) g (mean anomaly) = 357.528 + 0.985 600 3 · n (0 ≤ g < 360°);

(d) l (ecliptic longitude) = L + 1.915 · sin (g) + 0.020 · sin (2g) (0 ≤ l < 360°);

(e) ep (obliquity of the ecliptic) = 23.439 − 0.000 000 4 · n (degrees).

It should be noted that the specifications indicate that all multiples of 360° should be added or subtracted until the final value falls within the specified range.

From the above equations, the celestial coordinates can be calculated – the right ascension (ra) and the declination (dec) – by:

$$\tan(ra) = \cos(ep) \cdot \sin(l)/\cos(l)$$

$$\sin(dec) = \sin(ep) \cdot \sin(l)$$

To convert from celestial coordinates to local coordinates, that is, right ascension and declination to azimuth (A) and altitude (a), it is convenient to use the local hour angle (h). This is calculated by first determining the Greenwich mean sidereal time (GMST, in hours) and the local mean sidereal time (LMST, in hours):

$$\text{GMST} = 6.697\,375 + 0.065\,709\,824\,2 \cdot n + \text{hour}(\text{UT})$$

where: $0 \leq \text{GMST} < $ ~~24h~~24 h

$$\text{LMST} = \text{GMST} + (\text{east longitude})/(15°\,\text{h}^{-1})$$

From the LMST, the hour angle (ha) is calculated as (ha and ra are in degrees):

$$ha = 15 \cdot \text{LMST} - ra \qquad (-12 \leq ha < 12h)$$

Before the sun reaches the meridian, the hour angle is negative. Caution should be observed when using this term, because it is opposite to what some solar researchers use.

The calculations of the solar elevation (el) and the solar azimuth (az) follow (az and el are in degrees):

$$\sin(el) = \sin(dec) \cdot \sin(\text{lat}) + \cos(dec) \cdot \cos(\text{lat}) \cdot \cos(ha)$$

and:

$$\sin(az) = -\cos(dec) \cdot \sin(ha)/\cos(el)$$

$$\cos(az) = (\sin(dec) - \sin(el) \cdot \sin(\text{lat}))/(\cos(el) \cdot \cos(\text{lat}))$$

where the azimuth is from 0° north, positive through east.

To take into account atmospheric refraction, and derive the apparent solar elevation (h) or the apparent solar zenith angle, the *Astronomical Almanac* proposes the following equations:

(a) A simple expression for refraction r for zenith angles less than 75°:

$$r = 0°.004\,52\,P\tan z/(273 + T)$$

where z is the zenith distance in degrees; P is the pressure in hectopascals; and T is the temperature in °C.

(b) For zenith angles greater than 75° and altitudes below 15°, the following approximate formula is recommended:

$$r = \frac{P(0.159\,4 + 0.019\,6a + 0.000\,02a^2)}{\left[(273 + T)(1 + 0.505a + 0.084\,5a^2)\right]}$$

where a is the elevation (90° – z) where $h = el + r$ and the apparent solar zenith angle $z_0 = z + r$.

Sun–Earth distance

The present-day eccentricity of the orbit of the Earth around the Sun is small but significant to the extent that the square of the Sun–Earth distance R and, therefore, the solar irradiance at the Earth, varies by 3.3 % from the mean. In astronomical units (AU), to an uncertainty of 10^{-4}:

$$R = 1.000\,14 - 0.016\,71 \cdot \cos(g) - 0.000\,14 \cdot \cos(2g)$$

where g is the mean anomaly and is defined above. The solar eccentricity is defined as the mean Sun–Earth distance (1 AU, R_0) divided by the actual Sun–Earth distance squared:

$$E_0 = (R_0/R)^2$$

Air mass

In calculations of extinction, the path length through the atmosphere, which is called the absolute optical air mass, must be known. The relative air mass for an arbitrary atmospheric constituent, m, is the ratio of the air mass along the slant path to the air mass in the vertical direction; hence, it is a normalizing factor. In a plane parallel, non-refracting atmosphere m is equal to $1/\sin h_0$ or $1/\cos z_0$.

Local apparent time

The mean solar time, on which our civil time is based, is derived from the motion of an imaginary body called the mean sun, which is considered as moving at uniform speed in the celestial equator at a rate equal to the average rate of movement of the true sun. The difference between this fixed time reference and the variable local apparent time is called the equation of time, Eq, which may be positive or negative depending on the relative position of the true mean sun. Thus:

$$LAT = LMT + Eq = CT + LC + Eq$$

where LAT is the local apparent time (also known as TST, true solar time), LMT is the local mean time; CT is the civil time (referred to a standard meridian, thus also called standard time); and LC is the longitude correction (4 min for every degree). LC is positive if the local meridian is east of the standard and vice versa.

For the computation of Eq, in minutes, the following approximation may be used:

$$Eq = 0.017\,2 + 0.428\,1 \cos \Theta_0 - 7.351\,5 \sin \Theta_0 - 3.349\,5 \cos 2\Theta_0 - 9.361\,9 \sin 2\Theta_0$$

where $\Theta_0 = 2\pi d_n/365$ in radians or $\Theta_0 = 360\,d_n/365$ in degrees, and where d_n is the day number ranging from 0 on 1 January to 364 on 31 December for a normal year or to 365 for a leap year. The maximum error of this approximation is 35 s (which is excessive for some purposes, such as air-mass determination).

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ANNEX 7.E. DIFFUSE SKY RADIATION – CORRECTION FOR A SHADING RING

The shading ring is mounted on two rails oriented parallel to the Earth's axis, in such a way that the centre of the ring coincides with the pyranometer during the equinox. The diameter of the ring ranges from 0.5 to 1.5 m and the ratio of the width to the radius b/r ranges from 0.09 to 0.35. The adjustment of the ring to the solar declination is made by sliding the ring along the rails. The length of the shading band and the height of the mounting of the rails relative to the pyranometer are determined from the solar position during the summer solstice; the higher the latitude, the longer the shadow band and the lower the rails.

Several authors, for example, Drummond (1956), Dehne (1980) and Le Baron et al. (1980), have proposed formulae for operational corrections to the sky radiation accounting for the part not

measured due to the shadow band. For a ring with $b/r < 0.2$, the radiation D_v lost during a day can be expressed as:

$$D_{\mathrm{v}} \approx \frac{b}{r}\cos^3\delta \int_{t_{\mathrm{rise}}}^{t_{\mathrm{set}}} L(t)\cdot\sin h_{\mathrm{e}}\,(t)\,dt$$

where δ is the declination of the sun; t is the hour angle of the sun; t_{rise} and t_{set} are the hour angle at sunrise and sunset, respectively, for a mathematical horizon (Φ being the geographic latitude, $t_{\mathrm{rise}}= - t_{\mathrm{set}}$ and $\cos t_{\mathrm{rise}}= - \tan \Phi \cdot \tan \delta$); $L(t)$ is the sky radiance during the day; and h_{e} is the solar elevation.

With this expression and some assumptions on the sky radiance, a correction factor f can be determined:

$$f = \frac{1}{1-\dfrac{D_{\mathrm{v}}}{D}}$$

D being the unobscured sky radiation. In the figure below, an example of this correction factor is given for both a clear and an overcast sky, compared with the corresponding empirical curves. It is evident that the deviations from the theoretical curves depend on climatological factors of the station and should be determined experimentally by comparing the instrument equipped with a shading ring with an instrument shaded by a continuously traced disc. If no experimental data are available for the station, data computed for the overcast case with the corresponding b/r should be used. Thus:

$$\frac{D_{\mathrm{v}}}{D_{\mathrm{overcast}}} = \frac{b}{r}\cos^3\delta\left(t_{\mathrm{set}} - t_{\mathrm{rise}}\right)\cdot\sin\Phi\cdot\sin\delta + \cos\Phi\cdot\cos\delta\cdot\left(\sin t_{\mathrm{set}} - \sin t_{\mathrm{rise}}\right)$$

where δ is the declination of the sun; Φ is the geographic latitude; and t_{rise} and t_{set} are the solar hour angle for set and rise, respectively (for details, see above).

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END ELEMENT

Comparison of calculated and empirically determined correction factors for a shading ring, with b/r = 0.169; f indicates calculated curves and F indicates empirical ones.

Source: Dehne (1980)

SECTION: Chapter_book
Chapter title in running head: CHAPTER 7. MEASUREMENT OF RADIATION
Chapter_ID: 8_I_7_en
Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

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