CHAPTER 7 — MEASUREMENT OF RADIATION

CHAPTER 7

MEASUREMENT OF RADIATION

7.1 General

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

(*a*) The study of the transformation of energy within the Earth-atmosphere system and of its variation in time and space;
(*b*) The analysis of the properties and distribution of the atmosphere with regard to its constituents, such as aerosols, water vapour, ozone, etc.;
(*c*) The study of the distribution and the variations of incoming, outgoing, and net radiation;
(*d*) The satisfaction of the needs of biological, medical, agricultural, architectural and industrial activities with respect to radiation;
(*e*) The verification of 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 object 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 radiation measurements and the operation and design of networks of radiation stations is contained in WMO (1986*b*). It describes the scientific principles of the measurements and gives advice on the quality assurance which is most important for radiation measurements.

Following normal practice in this field, errors and uncertainties are expressed in this chapter as root-mean-square (RMS) quantities.

7.1.1 *Definitions*

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

Radiation quantities may be classified into two groups according to origin: solar radiation and terrestrial radiation.

Solar radiation is the energy emitted by the Sun. The solar radiation incident on the top of the terrestrial atmosphere is called extraterrestrial solar radiation; that 97 per cent of it which is confined to the spectral range 0.29 to 3.0 μm is called short-wave radiation. Part of the extraterrestrial 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 per cent of the power of the terrestrial radiation has a wavelength longer than 3 000 nm and about 99 per cent 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 to be between 760 and 830 nm (ICI, 1987*a*). Thus, 99 per cent of the visible radiation lies between 400 and 730 nm. Radiation of wavelengths shorter than about 400 nm is called ultraviolet, and longer than about 800 nm, infrared radiation. The ultraviolet range is sometimes divided into three subranges (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 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 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 (WRR)

In the past, several radiation references or scales have been used in meteorology: the Ångström Scale 1905, the Smithsonian Scale 1913, and the International Pyrheliometric Scale 1956 (IPS). The developments in absolute radiometry in recent years have very much improved the accuracy 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 WRR by using the following factors:

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

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

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

The WRR is accepted as representing the physical units of total irradiance with an uncertainty less than ±0.3 per cent (RMS) of the measured value.

REALIZATION OF WRR: WORLD STANDARD GROUP (WSG)

In order 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 WRR. To qualify for membership in this group, a radiometer must fulfil the following specifications:

(*a*) The long-term stability must be better than ±0.2 per cent of the measured value;

(*b*) The accuracy and precision of the instrument must lie within the limits of the uncertainty of WRR (±0.3 per cent);

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

To ensure the stability criteria, the instruments of the WSG are intercompared at least once a year and, for this reason, the WSG is kept at the World Radiation Centre at Davos.

COMPUTATION OF WRR VALUES

In order to calibrate radiometric instruments, the reading of an instrument of the WSG or of one which is directly traceable to the WSG should be used. During international comparisons, 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.

7.1.3 *Meteorological requirements*

7.1.3.1 DATA TO BE RECORDED

Irradiance and radiant exposure are the quantities most commonly recorded and archived, with averages and totals of over one hour. There are also many requirements for data over shorter periods, down to one minute or even tens of seconds (for some energy applications), and daily totals are frequently used. For climatological purposes, measurements of direct solar radiation are needed at fixed true solar hours, or at fixed air-mass values. Measurements of turbidity must be made with very short response times to reduce the uncertainties arising from variations in air mass.

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, exposure and maintenance record.

7.1.3.2 ACCURACY

Statements of accuracy for net radiation are given in Chapter 1, Part I. The required accuracy for radiant exposure, stated by WMO for international exchange, is ±0.4 MJ m^{-2} d^{-1} for ≤ 8 MJ m^{-2} d^{-1} and ±5 per cent for > 8 MJ m^{-2} d^{-1}. The achievable accuracy is stated to be ±5 per cent.

There are no formally agreed statements of required accuracy for other radiation quantities, but accuracy is discussed in the sections of this chapter dealing with the various types of measurements. 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. Some systems still in use fall short of best practice, the lesser performance having been acceptable for many applications. However, data of the highest quality are increasingly in demand.

7.1.3.3 SAMPLING AND RECORDING

The accuracy requirements can best be satisfied by making observations every minute, even when the data to be finally recorded are integrated totals for periods of up to one hour, or more. The one-minute data points may be integrated totals or an average flux calculated from six or more individual samples. Digital data systems are greatly to be preferred. Chart recorders and other types of integrators are much less convenient, and they are difficult to maintain at an adequate level of accuracy.

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 rate is high enough, as indicated in section 7.1.3.3). See Annex 7.D for useful formulae for the conversion from Standard to Solar Time.

7.1.4 *Methods of measurement*

Meteorological radiation instruments are classified by using various criteria: the type of variable to be measured, the field of view, the spectral response, the main use, etc. The most important types of classification 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. WMO (1986*b*) provides a detailed account of instruments and the principles on which they operate.

Absolute radiometers are self-calibrating, i.e. the radiation falling on the sensor is replaced by electrical power, which can be accurately measured. The substitution, however, cannot be absolutely 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 accuracy of the measured value, then, depends on the following factors, all of which should be known for a well-characterized instrument:

(*a*) Resolution, i.e. the smallest change in the radiation quantity which can be detected by the instrument;

(*b*) Long-term drifts of sensitivity (the ratio of electrical output signal to the irradiance applied), i.e. the maximum possible change over, say, a year;

TABLE 7.1
Meteorological radiation instruments

Instrument classification	*Parameter to be measured*	*Main use*	*Viewing angle (steradians) (see Figure 7.1)*
Absolute pyrheliometer	Direct solar radiation	Primary standard	5×10^{-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 radiation (*b*) Sky radiation (*c*) Reflected solar radiation	(*a*) Working standard (*b*) Network	2π
Spectral pyranometer	Global radiation in broadband spectral ranges (e.g. with OG 530, RG 630, etc. filters)	Network	2π
Net pyranometer	Net global 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

(*c*) Changes in sensitivity due to changes of environmental variables, such as temperature, humidity, pressure, wind, etc.;

(*d*) Non-linearity of response, i.e. changes in sensitivity associated with variations in irradiance;

(*e*) Deviation of the spectral response from that postulated, i.e. the blackness of the receiving surface, the effect of the aperture window, etc.;

(*f*) Deviation of the directional response from that postulated, i.e. 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. 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 of pyrheliometers, the receiving surfaces of which are arranged to be normal to the solar direction. By means of apertures, only the radiation from the Sun and a narrow annulus of sky is measured. In modern instruments, this extends out to a half-angle of about 2.5° on some models, such as the Linke Fuessner Actinometer, and to about 5° from the Sun's centre, such as the AT-50 (corresponding, respectively, to $5 \cdot 10^{-3}$ and to $5 \cdot 10^{-2}$ steradians (sr)). The construction of the pyrheliometer mounting 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 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.

As to the view-limiting geometry, it is recommended that the opening half-angle be 2.5° ($5 \cdot 10^{-3}$ sr) and the slope angle be 1° for all new designs of direct solar radiation instruments. For the definition of these angles refer to Figure 7.1. During comparison of instruments with different view-limiting geometries, it should be kept in mind that the aureole intensity influences the readings more significantly for larger aperture angles. The difference can be as great as 2 per cent between the two apertures mentioned above for an air mass of 1.0.

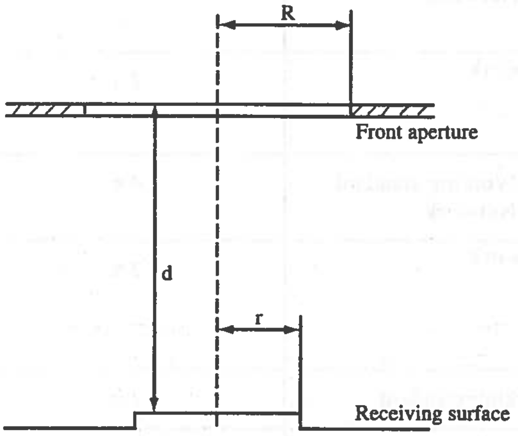

Figure 7.1 — View-limiting geometry. The opening half-angle is arctan R/d. The slope angle is arctan (R- r)/d.

For climatological purposes, instantaneous values of direct solar radiation are needed at fixed true solar hours, or at fixed air-mass values, from routine solar radiation network data.

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:

$$S_N = S/R^2 \qquad (7.1)$$

where S_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), S is the measured solar radiation, and R is the Sun-Earth distance in astronomical units.

7.2.1 *Direct total solar radiation*

Some of the characteristics of operational pyrheliometers (other than primary standards) are given in Table 7.2 (adapted from ISO 1990*c*), with indicative estimates of the uncertainties of measurements made with them if they are used with appropriate staff and quality control. Cheaper instruments are available (see ISO 1990*c*), but they are not much used because the cost of a Sun-tracker, which is necessary for practical direct-beam measurements, would not be warranted. The estimated uncertainties are based on the following assumptions:

(*a*) The instruments are well-maintained, correctly aligned, and clean;

(*b*) The one-minute and one-hour figures are for clear-sky irradiances at solar noon;

(*c*) The daily figures are for clear days at mid-latitudes.

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 accuracy 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*b*) but, for completeness sake, 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 highest accuracy possible for the radiation levels encountered in solar radiation measurements (i.e. 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 accuracy of such an instrument is determined by a close examination of the physical properties of the

TABLE 7.2

Characteristics of operational pyrheliometers

Characteristic	*High quality*[1]	*Good quality*[2]
Response time (95 per cent response)	<15s	<30s
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})	±0.5	±1
Stability (percentage of full scale, change/year)	±1.0	±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 0.3 to 3 μm)	±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} irradiance)	±0.2	±0.5
Achievable uncertainty, 95 per cent confidence level (see above)		
1 minute totals, per cent	±0.9	±1.8
kJ m^{-2}	±0.56	±1
1 hour totals, per cent	±0.7	±1.5
kJ m^{-2}	±21	±54
daily totals, per cent	±0.5	±1.0
kJ m^{-2}	±200	±400

NOTES:

(1) Near state-of-the-art; suitable for use as a working standard; maintainable only at stations with special facilities and staff.

(2) Acceptable for network operations.

instrument and by performing laboratory measurements and/or model calculations to determine the deviations from ideal behaviour, i.e., 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 RMS uncertainty of this characterization should be less than ±0.25 per cent under the clear sky conditions suitable for calibration (see ISO 1990*c*). The uncertainty (simple addition of all the components of the uncertainty) should not exceed ±0.5 per cent (RMS) of 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 RMS uncertainty determined under (*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 World Radiometric Reference by comparison with the World Standard Group or some carefully established and recognized equivalent is needed in order to prove that the design is within the state-of-the-art. The latter is fulfilled if the World Radiometric Reference lies within the RMS uncertainty as determined by (*a*) above.

7.2.1.2 SECONDARY STANDARD PYRHELIOMETERS

An absolute pyrheliometer which does not meet the above specification or which is not fully characterized can be used as a secondary standard if it is calibrated by comparison with the Working Standard Group.

Alternatively, other types of instruments 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 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 thermojunction 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.

TABLE 7.3

View-limiting geometry of Ångström pyrheliometers

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

The measurement consists of three or more cycles, during which the left- or right-hand strip is shaded or irradiated alternately. 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 becomes zero. Before and after a measuring sequence, the zero is checked either by shading or by irradiating both strips. 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 international pyrheliometer comparisons uses the following formula:

$$S = K \cdot i_L \cdot i_R \tag{7.2}$$

where S is the irradiance in W m^{-2} (geometric mean of the irradiances at the time of the left and right measurements, respectively), 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 irradiated, 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" or "hot", 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 intensity. When comparing such a pyrheliometer with other instruments, the intensity 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 $0.05 \cdot 10^{-6}$ amperes 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 per cent.

The accuracy of the measured value of the Sun's irradiance greatly depends on the qualities of the current-measuring device, whether a moving-coil milliammeter or a digital voltmeter which measures the voltage across a standard resistor. 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 PYRHELIOMETERS

Pyrheliometers generally make use of a thermopile as the detector. They have similar view-limiting geometry as standard pyrheliometers, varying from 2.5° to 5.5° opening half-angles and from 1° to 2° slope angles. Older models tend to have larger fields of view and slope angles. These design features were primarily designed to aid in tracking the Sun. However, the larger the opening angle the larger the amount of aureole radiation sensed by the detector; this amount may reach several per cent for high turbidities and large opening angles. With new designs in solar trackers, including computer-assisted trackers in both passive and active configurations, the need for larger apertures is unnecessary.

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

(*a*) The field of view of the instrument;
(*b*) Whether the instrument measures both the long-wave and short-wave portion of the spectrum (i.e. whether the aperture is open or covered with a glass or quartz window);
(*c*) The temperature compensation or correction methods;
(*d*) If the instrument can be installed on an automated tracking system for long-term monitoring;
(*e*) If, for calibration of other operational pyrheliometers, differences (*a*) to (*c*) above are the same, and the pyrheliometer is of the quality necessary to calibrate other network instruments.

7.2.1.4 CALIBRATION OF PYRHELIOMETERS

All pyrheliometers, other than absolute pyrheliometers, need to be calibrated by comparison with an absolute pyrheliometer, using the Sun as a source.

As all solar radiation instruments must be referred to the World Radiometric Reference, absolute pyrheliometers also use a factor determined by comparison with the World Standard Group and not their individually-determined one. After such a comparison (e.g. during the periodically-organized International Pyrheliometer Comparisons) such a pyrheliometer can be used as a primary 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. The quality of such 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 radiation, if the time constants are significantly different. Finally, environmental conditions, such as temperature or pressure, can influence the results. If a very high quality of calibration is required, the only data taken during very clear and stable days should be used, preferably at high-altitude stations.

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

From recent IPCs experience, a period of five years between calibrations 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 *Spectral direct solar radiation and measurement of turbidity*

Spectral measurements of the direct solar radiation are used in meteorology mainly to determine turbidity and the optical depth of aerosols in the atmosphere. They are used also for medical, biological, agricultural, and solar-energy applications.

The aerosol optical depth, or atmospheric turbidity, represents the total extinction, i.e. scattering and absorption by aerosols in the size range 0.1 to 10 μm radius, for the column of the atmosphere equivalent to unit optical air mass. Particulate matter, however, is not the only influencing factor. Other atmospheric constituents such as air molecules (Rayleigh scatterers), ozone, water vapour, nitrogen dioxide, and carbon dioxide also contribute to the total extinction of the beam. Most optical depth measurements are made to understand better the loading of the atmosphere by aerosols. However, optical depth measurements of other constituents, such as water vapour, ozone and nitrogen dioxide, can be obtained if appropriate wavebands are selected.

The vertical aerosol optical depth $\delta_a(\lambda)$ at a specific wavelength λ is based on the Bouguer-Lambert law (or Beer's law for monochromatic radiation) and can be determined by:

$$\delta_a(\lambda) = \frac{\ln\left(S_o(\lambda)/S(\lambda)\right) - \Sigma(\delta_i(\lambda)\cdot m_i)}{m_a} \qquad (7.3)$$

where $\delta_a(\lambda)$ is the aerosol optical depth at a waveband centred at wavelength λ, m_a is the air mass for aerosols (unity for the vertical beam), δ_i is the optical depth for species i, other than aerosols at a waveband centred at wavelength λ, m_i is the air mass for extinction species i, other than aerosols, $S_o(\lambda)$ is the spectral irradiance outside the atmosphere at wavelength λ, and $S(\lambda)$ is the spectral irradiance at the surface at wavelength λ.

Turbidity τ is the same quantity, as originally defined, using base 10 rather than base e in Beer's Law:

$$\tau(\lambda)m = \log\left(S_o(\lambda)/S(\lambda)\right) \qquad (7.4)$$

so:

$$\tau(\lambda) = 2.301\ \delta(\lambda) \qquad (7.5)$$

In meteorology, two types of measurement are performed: broad-band pyrheliometry and sun-photometry (in which narrow-band filters are used). Since the aerosol optical depth is defined only for monochromatic radiation or for a very narrow wavelength range, it can be applied directly to the evaluation of sunphotometer data, but not to broadband pyrheliometer data.

Turbidity observations should be made only when no visible clouds are in the line of sight from the observer to the Sun. When sky conditions permit, as many observations as possible should be made in a day and a maximum range of air masses should be covered, preferably in steps of $\Delta m = 0.2$.

Only instantaneous values can be used for the determination of turbidity.

7.2.2.1 BROAD-BAND PYRHELIOMETRY

Broad-band pyrheliometry makes use of a carefully calibrated pyrheliometer with broad-band glass filters in front of it to select the spectral bands of interest. The specifications of the classical filters used are summarized in Table 7.4.

The cut-off wavelengths depend on temperature, and some correction of the measured data may be needed. The filters must be properly cleaned before use. In operational applications, they should be checked daily and cleaned if necessary.

The derivation of aerosol optical depth from broad-band data is very complex, and there is no standard procedure. Use may be made both of tables which are calculated from typical filter data and of some assumptions on the state of the atmosphere. The reliability of the results depends on how well the filter used corresponds to the filter in the calculations and how good the atmospheric assumptions are. Details of the evaluation and the corresponding tables can be found in WMO (1978). A discussion of the techniques is given by Kuhn (1972) and Lal (1972).

7.2.2.2 SUNPHOTOMETRY AND TURBIDITY

A sunphotometer consists of a narrow-band interference filter and a photovoltaic detector, usually a silicon photodiode. The full field of view of the instrument is 2.5° with a slope angle of 1° (see Figure 1). Although the

TABLE 7.4
Specification of glass filters

Schott type	*Typical 50% cut-off wavelength (nm)*		*Mean transmission (3 mm thickness)*	*Approximate temperature coefficient of short-wave cut-off (nm K^{-1})*
	Short	*Long*		
OG 530	526 ± 2	2 900	0.92	0.12
RG 630	630 ± 2	2 900	0.92	0.17
RG 700	702 ± 2	2 900	0.92	0.18

The temperature coefficients for Schott filters are as given by the manufacturer. The short-wave cut-offs are adjusted to the standard filters used for calibration.

measurement of optical depth using sunphotometers is conceptually simple many early measurements have not produced useful results. The main reasons for this have been the shifting of the instrument response because of changing filter transmissivities and detector characteristics over short-time periods, and poor operator training. Accurate results can be obtained, however, with careful operating procedures and frequent checks of the stability of the instrument. The instrument should be calibrated every six months, either at, or in, consultation with qualified radiation centres.

Detailed advice on sunphotometers and network operations is given in WMO (1993*b*).

To calculate aerosol optical depth from sunphotometer data with good accuracy, the station pressure, the temperature, and an accurate time of measurement must be known. The most accurate calculation of the total and aerosol optical depth from sunphotometer data at wavelength λ (the centre wavelength of its filter) makes use of:

$$\delta_a(\lambda) = \frac{\ln\left(\frac{J_o(\lambda)}{J(\lambda)R^2}\right) - \frac{p}{p_o}\,\delta_R(\lambda)\,m_R - \delta_{O_3}(\lambda)m_{O_3} \cdots}{m_a} \tag{7.6}$$

where $J(\lambda)$ is the instrument reading (e.g. in volts), $J_o(\lambda)$ is the hypothetical reading corresponding to $S_o(\lambda)$. This can be established by extrapolation to air-mass zero by the Langley method, or from the radiation centre which calibrated the instrument, R is the Sun-Earth distance (in astronomical units, see Annex 7.D), p is the atmospheric pressure, and p_o is the standard atmospheric pressure, and the second, third and subsequent terms in the top line are the contributions of Rayleigh, ozone and other extinctions. This can be simplified for less accurate work by assuming that the relative air masses for each of the components are equal.

For all sunphotometer wavelengths, Rayleigh extinction must be considered. Ozone optical depth must be considered at wavelengths less than 340 nm and throughout the Chapuis band. Nitrogen dioxide optical depths should be considered for all sunphotometer wavelengths less than 650 nm, especially if measurements are made in areas that have urban influences. Although there are weak water vapour absorption bands even within the 500 nm spectral region, water vapour absorption can be neglected for wavelengths less than 650 nm. Further references on wavelength selection can be found in WMO (1986*a*).

Rayleigh scattering optical depths should be calculated following the procedure outlined by Fröhlich and Shaw (1980), but using Young's (1981) correction. Both ozone and nitrogen dioxide follow Beer's law of absorption. The WMO World Ozone Data Centre recommends the ozone absorption coefficients of Bass and Paur (1985) in the ultraviolet and Vigroux (1953) in the visible. Nitrogen dioxide absorption coefficients can be obtained from Schneider, *et al.* (1987). For the reduction of wavelengths influenced by water vapour, the work of Frouin, Deschamps and Lecomte (1990) may be considered. Because of the complexity of water vapour absorption, bands that are influenced significantly should be avoided for all but the most accurate work and for the determination of water vapour amount by sunphotometry.

7.2.3 *Exposure*

For continuous recording, an equatorial mounting or an automatic tracker is required which should be protected against prevailing environmental influences. For equatorial mounts, the principal axis must be kept parallel to the axis of the Earth's rotation, the adjustments in both azimuth and elevation being correct to within 0.25°. The instruments should be inspected at least once a day and more frequently if weather conditions demand it (with protection against adverse conditions), since these measurements call for great care.

The principal exposure requirement for a recording instrument is the same as that for an ordinary sunshine recorder; that 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 recording with pyrheliometers or sunphotometers, protection is needed against rain, snow, etc. The optical window, for instance, must be protected as it is usually made of quartz and is located in front of the instrument. Care must be taken to ensure that such window is kept clean and that condensation does not appear on the inside.

7.3 Measurement of global and diffuse radiation

The solar radiation received from a solid angle of 2π steradian on a horizontal surface is referred to as global radiation. This includes radiation received directly from the solid angle of the Sun's disk 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 steradians into a plane surface and a spectral range from 0.3 to 3.0 μm 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 component of solar radiation alone, the direct solar component may he screened from the pyranometer by a masking device (see section 7.3.3.3).

Pyranometers normally use thermoelectric, photoelectric, pyroelectric, 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 easily removable 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 accuracy and quality of radiation measurement are: sensitivity, stability, response time, cosine response, azimuth response, linearity, temperature response, and spectral response. Further advice on the use of pyranometers is given in the ISO (1990*b*).

Table 7.5 (adapted from ISO 1990*c*) 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.

7.3.1 *Calibration of pyranometers*

The calibration of a pyranometer consists of the determination of its calibration factor and the dependence of this on environmental conditions, such as:

(*a*) Temperature;
(*b*) Irradiance level;
(*c*) Spectral distribution of irradiance;
(*d*) Temporal variation;
(*e*) Angular distribution of irradiance;
(*f*) Inclination of instrument.

Normally, one must specify the test environmental conditions, which can be quite different for different applications. Hence, the method and conditions should also be given in some detail in the calibration certificate.

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

(*a*) By comparison with a standard pyrheliometer for the direct solar beam and a shaded pyranometer for the diffuse part;
(*b*) By comparison with a standard pyrheliometer using the Sun as a source, with a removable shading disk for the pyranometer;

TABLE 7.5

Characteristics of operational pyranometers

Characteristic	*High quality*[1]	*Good quality*[2]	*Moderate quality*[3]
Response time (95 per cent response)	< 15s	< 30s	< 60s
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 absoptance and spectral transmittance from the corresponding mean within the range 0.3 to 3 μm)	±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} irradiance)	±0.5	±2	±5
Achievable uncertainty, 95 per cent confidence level:			
Hourly totals	3%	8%	20%
Daily totals	2%	5%	10%

NOTES: (1) Near state-of-the-art; suitable for use as a working standard; maintainable only at stations with special facilities and staff.
(2) Acceptable for network operations.
(3) Suitable for low-cost networks where moderate to low performance is acceptable.

(*c*) By comparison with a standard pyranometer using the Sun as a source, under other natural conditions of exposure (e.g. a uniform cloudy sky);

(*d*) 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;

(*e*) 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, but (*a*), (*b*) and (*c*) are commonly used. Method (*a*) is preferred over (*b*) because the sensitivity of some pyranometers can be different in normal and in shaded conditions.

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 of accuracy when sufficient readings have been taken. The principal variations (apart from fluctuations due to atmospheric conditions and observing limitations) are due to:

(*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.

In every case, the pyranometer should be calibrated in the normal position of use.

The solar elevation should be measured (during the shading operation for method (*b*) above), or computed (to the nearest 0.1°) 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 PYRANOMETER

In this method, the pyranometer's response to global radiation is calibrated against the sum of separate measurements of the direct and diffuse components. Occasions should be selected with clear skies and steady radiation (as judged from the record). The vertical component of the direct solar radiation is determined from the pyrheliometer output and the diffuse radiation is measured with a second pyranometer which is continuously shaded from the Sun. As during a clear day, the diffuse irradiance is less than 15 per cent of the global radiation; the calibration factor of the second pyranometer does not need to be known very accurately. The calibration factor is then calculated according to:

$$S \cdot \sin h + V_s k_s = V \cdot k \qquad (7.7)$$

or:

$$k = (S \sin h + V_s k_s)/V \qquad (7.8)$$

where S is the direct solar irradiance measured with the pyrheliometer (W m^{-2}), V is the output of the pyranometer to be calibrated (μV), V_s is the output of the shaded pyranometer (μV), h is the 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 pyranometer (W m^{-2} μV^{-1}).

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

7.3.1.2 BY REFERENCE TO A STANDARD PYRHELIOMETER

This method is similar to the method of the preceding paragraph except that the diffuse radiation is measured by the same pyranometer. The direct component is eliminated temporarily from the pyranometer by shading the whole outer dome of the instrument with a disk of sufficient size mounted on a slender rod and held some distance away. The diameter of the disk and its distance to the receiver surface should be chosen in such a way that the screened angle approximately equals the aperture angle of the pyrheliometer used (e.g. a disk of about 90 mm diameter at a distance of 1 m corresponds to a half-angle of 2.5°). This arrangement occludes both the direct solar beam and the circumsolar sky radiation, both of which fall on the pyrheliometer sensing element. 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 an equilibrium; three to 10 minutes should generally be sufficient.

The difference between the shaded and unshaded pyranometer outputs is due to the vertical component of direct solar radiation S measured by the pyrheliometer, i.e. its projection on the horizontal surface. Thus:

$$S \cdot \sin h = V \cdot k \qquad (7.9)$$

or:

$$k = (S \cdot \sin h)/V \qquad (7.10)$$

where S is the direct solar irradiance at normal incidence measured by the pyrheliometer (W m^{-2}), V is the output signal of the pyranometer (μV) due to the direct solar beam (i.e. the difference between the shaded and unshaded outputs), h is the 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 appropriate sampling and averaging to ensure that representative values of the shaded and unshaded outputs are used for the calculation.

7.3.1.3 BY COMPARISON WITH A REFERENCE PYRANOMETER

Comparison 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 type, only a day or two should be sufficient. The more pronounced the difference between the types, the longer the period of comparison must be. A long period, however, could be replaced by several shorter periods covering typical conditions (clear, cloudy, overcast, rainfall, snowfall, etc.). The derivation of the instrument factor is straightforward. If chart recorders are used, the selection should be made, from the two sets of records, of occasions when the traces are sufficiently high and reasonably smooth. 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. If voltage integrators or fast-scanning data loggers are used, then conditions of fluctuating radiation can also be used.

The mean temperature of the instruments or the ambient temperature should be recorded during all outdoor calibration work so that any temperature effects can be allowed for.

7.3.1.4 By comparison in the laboratory

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

In one method, exposure is 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 to 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 per cent.

In the other method, calibration is by use of 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 low, the difference between the calibration factors gained by this method and with normal incidence should be small. The repeatability of integrating-sphere measurements is generally within ±0.5 per cent. As for the source used to illuminate the sphere, the same considerations apply as for the first method.

7.3.1.5 Routine checks on calibration factors

There are several methods for checking the constancy of calibration of pyranometers, depending upon the equipment available at a particular station. It cannot be stressed too strongly that every opportunity to check the performance of pyranometers in the field should be used to advantage.

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 section 7.3.1.2. This simple check should be applied frequently. If there is a simultaneous record of diffuse radiation, the two records should be frequently examined for consistency by removing the shadow disk or band. The record may be verified with the aid of a travelling working standard sent out from the central station of the network or from a nearby station. Finally, the pyranometer can be exchanged for a similar one sent out from the central station, to which the original one is returned for calibration. Either of the last two methods should be used at least once a year. Pyranometers normally 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 accuracy. A number of properties of pyranometers should be evaluated so that the accuracy of the results can be estimated. Both the type of pyranometer and the nature of the measurement are concerned. For example, it has been demonstrated that for a continuous record of global radiation an accuracy of better than ±5 per cent in daily totals represents the result of good and careful work.

7.3.2.1 Sensor levelling

It is essential for accurate measurement with a pyranometer 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 thermopile surface is not uniform in quality.

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 built-in 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 (–40 to 40°C) in 10° steps, and held steady at each step until the response of the pyranometers has stabilized. The data are then plotted and a smooth curve drawn through the points. If the maximum percentage error due to temperature response is two per cent or more, a correction should be applied on the basis of the best straight-line fit of the data over the temperature range of interest — for example, with the temperature coefficient $(Y_{T2}/Y_{T1} - 1)/(T_2 - T_1)$, where Y_{T1} and Y_{T2} are, respectively, the pyranometer outputs at temperatures T_1 and T_2.

If no temperature chamber is available, then the standardization method with pyrheliometers (section 7.3.1.1 or 7.3.1.2) 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 (i.e. the effect of solar elevation) and the nonlinearity (i.e. variations of solar irradiance) can change the sensitivity.

7.3.2.3 VARIATION OF RESPONSE WITH ALTITUDE

The calibration factor of a pyranometer may very well be different when the instrument is used in an altitude other than that in which it was calibrated. Inclination testing of pyranometers can be done in the laboratory or with the standardization method described in section 7.3.1.1 or 7.3.1.2. In every case, it is recommended that the pyranometer be calibrated in the altitude where it will be used. A correction for tilting is not recommended.

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 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 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 7.5, where the permissible error for all angles is specified.

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 too much with the angle of elevation. Thus, an apparent variation 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 totals, it is evident that the uncertainties in these values are most important. However, some response variations cancel each other out if the integration period is long enough.

Table 7.5 lists the expected maximum deviation from the true value, excluding calibration errors. The types of pyranometers in the third column of Table 7.5 are not suitable for hourly or daily totals, although they are used for monthly totals.

7.3.3 *Installation and care of pyranometers*

The site selected for exposing 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 from obstructions which may shadow it at any time in the year. The pyranometer should not be near to light-coloured walls or other objects likely to reflect sunlight onto it, nor should it be exposed to artificial radiation sources.

In most places, a flat roof provides a good location for mounting the stand for the radiometer. If such a site cannot be obtained, then 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 steradians. 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 made before the initial installation of a pyranometer whenever its location is changed or if a significant change occurs in regard to any surrounding obstructions. An excellent method of doing this makes use of a survey camera which exposes 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, then the angular outline of obscuring objects may be mapped out by means of a theodolite or a combination of compass and clinometer.

The description of the station should include the altitude of the pyranometer above sea level (i.e. altitude of station plus height of pyranometer above 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.

Probably the most important single consideration in choosing a site is the accessibility of instrumentation for frequent inspection. 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 (e.g. 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 there is obstruction to the direct solar beam (readily detected on cloudless days), then the record should be corrected wherever this can be done with reasonable confidence.

Correction for obstruction to the diffuse component of the record can be attempted only when there are separate records of global and diffuse radiation. The procedure requires first that the diffuse record be corrected and then that the global record be adjusted. What should be computed is not the fraction of the sky itself which is obscured, but rather the fraction of the total vertical flux coming from that part of the sky which is obscured. It will be apparent, therefore, that radiation incident at angles less than 5° makes only a very small contribution to the total. Since the sky radiation limited to an elevation of 5° contributes less than one per cent to the global solar radiation, such an effect 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 radiation due to obstacles, account should be taken of the variation in intensity of the diffuse radiation over the hemisphere. However, the only practical procedure is to assume that the radiation is the same from all parts of the sky. In order to determine the reduction in solid angle for obscuring objects of finite size, the following expression may be used:

$$\Delta A = \int_{\Phi}\int_{\Theta} \sin\theta \cos\theta \, d\theta \, d\varphi \qquad (7.11)$$

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 integration may be done graphically or numerically. If done graphically, then the outline of obscuring objects is drawn on a $\theta - \varphi$ diagram. Their projections on this diagram should then be divided into suitable component areas over which a mean value of $\sin\theta \cos\theta$ may be assigned and the fractional additive correction may be obtained by summation.

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 albedo 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 thermojunctions (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 permitted to irradiate the instrument body from underneath. A cylindrical shading device can be used, but care should be taken 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.

The cable connecting the pyranometer to its recorder should have twin conductors and should 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 under ground 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 thermoelectric device, 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 could be connected to the recorder in accordance with the relevant instructions.

7.3.3.3 INSTALLATION OF PYRANOMETERS FOR MEASURING DIFFUSE RADIATION

For measuring or recording separate 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 disk held in the Sun's beam by a power-driven equatorial device, or by a shadow band mounted on a polar axis. In the first method, which entails the rotation of a slender arm synchronized with the Sun's apparent motion, frequent inspection is essential to ensure proper operation and adjustment, since spurious records are otherwise difficult to detect. The second method involves less personal attention at the site, but necessitates corrections to the record on account of the appreciable screening of diffuse radiation by the shading arrangement. Reference is made to Annex 7.E for details of the construction of a shading ring and the necessary corrections to be applied.

The installation of a sky pyranometer is similar to that of a pyranometer for the measurement of 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 disk never shadows it. This may be more important at high latitudes where the Sun-angle can be very low.

Since the 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 1–2 m. In summer-time, the ground should be covered by grass which is kept short. For regions with snow in winter, a mechanism should be available to adjust the height of the pyranometer above the snow in order to maintain a constant separation. The mounting device is within the field of view of the instrument, but it should be designed to cause less than 2 per cent error in the measurement. Access to the pyranometer for levelling should be provided without disturbing the surface beneath, especially if it is of snow.

7.3.3.5 CARE OF PYRANOMETERS

Pyranometers in continuous operation should be inspected at least once a day and perhaps more frequently, say when meteorological observations are being made. During these inspections, the glass dome of the instrument should be wiped clear and dry. 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, and subsequently wipe 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 cool the dome in calm weather situations. The temperature difference between the ventilating air and the ambient air should not be more than about 1 K. If local pollution or sand forms a deposit on the dome, the wiping process should be carried out very gently, preferably after blowing off most of the loose material or after wetting it a little, in order to prevent scratching the surface. 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 CARE OF PYRANOMETERS ON SPECIAL PLATFORMS

Very special care should be directed towards the installation of 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 made successfully from aircraft for a number of years. Care must be exercised, however, in the proper selection of the pyranometer and in its exposure.

Particular attention must be paid during installation, especially to systems difficult of access, so as to ensure 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 (0.3 to 3.0 μm) and longer wavelengths of terrestrial and atmospheric origin (3.0 to 100 μm). 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 flat sensitivity characteristic across the whole wavelength range from 0.3 to 100 μm.

The measurement of long-wave radiation can be accomplished either indirectly, by subtracting the measured global radiation from the total radiation measured, or directly, by using pyrgeometers. Most pyrgeometers eliminate the short wavelengths by means of filters having a constant transparency to long wavelengths while being almost opaque to the shorter wavelengths (0.3 to 3.0 μm).

There also exist pyrgeometers for night-time use only; however, no means for eliminating short-wave radiation is provided.

7.4.1 *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.

The use of thermally-sensitive sensors, which are still the only ones used for total radiation-flux measurements, requires a good knowledge of the heat budget of the sensor. Otherwise, one is forced 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 appear to them 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 exist a great variety of pyrradiometers employing different methods for eliminating, or allowing for, wind effect, as follows:

(*a*) No protection. Empirical formulae are used to correct for wind effects;

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

(*c*) Stabilizing the wind effects through artificial ventilation;

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

Table 7.6 provides an analysis of the sources of error arising in pyrradiometric measurement and proposes methods for determining these errors.

It is difficult to determine the precision likely to be obtained in practice. *In situ* comparisons at different sites between different designs of pyrradiometer yield results manifesting differences of up to five to 10 per cent 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.

Table 7.7 lists the characteristics of pyrradiometers of various levels of performance, and the uncertainties to be expected in the measurements obtained from them.

7.4.2 *Calibration of pyrradiometers and net pyrradiometers*

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 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 is best done in the laboratory with black body cavities. However, it is possible to perform field calibrations. In the case of a net pyrradiometer, the downward flux, $L{\downarrow}$, is measured separately by using a pyrgeometer; or the upper receiver may be covered as above with a cavity, and the temperature of the snow or water surface T_s, is measured directly. Then, the radiative flux received by the instrument amounts to:

$$L^* = L{\downarrow} - \varepsilon \sigma T_s^4 \qquad (7.12)$$

and:

$$V = L^* \cdot K \text{ or } K = V/L^* \qquad (7.13)$$

where ε is the emittance of the water or snow surface (normally taken as 1), σ is the Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}$ W m^{-2} K^{-1}), T_s is the underlying surface temperature (K), $L{\downarrow}$ is the irradiance measured by the pyrgeometer or calculated from the temperature of the cavity capping the upper receiver (W m^{-2}), L^* is the radiative flux at the receiver (W m^{-2}), 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*.

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 greater than two per cent of 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.

TABLE 7.6

Sources of error in pyrradiometric measurements

Effects 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 extinction in the screen (*b*) Measure the effect of diffuse radiation or measure the effect with 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 changes in the spectral characteristics of the sensor and to non-radiative energy transfers	Study the influence of forced ventilation on these 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*) Spectrophotometric 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

TABLE 7.7
Characteristics of operational pyrradiometers

Characteristic	*High quality*[1]	*Good quality*[2]	*Moderate quality*[3]
Resolution (W m^{-2})	±1	±5	±10
Stability (annual change, per cent 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 to 40°C) (deviation from mean)	±1%	±2%	± 5%
Non-linearity (deviation from mean)	±0.5%	±2%	± 5%
Spectral sensitivity integrated over 0.2 μm intervals from 0.3 to 75 μm (deviation from mean)	±2%	±5%	±10%

NOTES: (1) Near state-of-the-art; maintainable only at stations with special facilities and staff.
(2) Acceptable for network operations.
(3) Suitable for low-cost networks where moderate to low performance is acceptable.

7.4.3 *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, which block out solar radiation. Early instruments of this type had significant problems with premature ageing of the materials used in blocking the short-wave portion of the spectrum, while being transparent to the long-wave portion. However, with the advent of the silicon domed pyrgeometer this stability problem has been greatly reduced. Nevertheless, the measurement of terrestrial radiation is still more difficult and less understood than the measurement of solar irradiance. Pyrgeometers are subject to the same errors as pyrradiometers (Table 7.6).

Pyrgeometers have developed in two forms: the thermopile receiving surface is covered with a hemispheric dome inside which an interference filter is deposited; and 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 the second has a 150° field of view, the hemispheric flux being modelled following 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 imprecisions than the modelling of the flux below 30° elevations. Both types of instrument 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, this is given by the equation:

$$E\downarrow_i = \frac{V}{K} + 5.669\,7 \cdot 10^{-8} \cdot T_d^4 = \beta \qquad (7.14)$$

where $E\downarrow_i$ is the infrared irradiance (W m^{-2}), V is the voltage output from the sensing element (μV), K is the instrument sensitivity to infrared irradiance (μV/(W m^{-2})), T_d is the detector temperature (K), and β is the uncertainty estimate (this may be reduced by correcting for specific sensor characteristics).

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 2 per cent, but in high solar radiation this difference between instruments can reach 13 per cent. The reasons for the differences are that the silicon dome does not have a sharp and reproducible cut-off between solar and terrestrial radiation, and it is not a perfect reflector. Thus, solar heating occurs. By shading the instrument, ventilating the instrument as recommended by ISO (1990*c*), and measuring the temperature of the dome and the case of the instrument, this discrepancy can be reduced to less than 5 per cent (approximately 15 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 temperature of the instrument should be measured directly according to the manufacturer's instructions;

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

(*c*) The instrument should be ventilated;

(*d*) For best results, the instrument should be shaded from direct solar rays by a small tracking shading disk.

The calibration of these instruments should be done at national or regional calibration centres by using absolute black-body calibration units. Experiments using near black-body radiators fashioned from large hollowed blocks of ice have also met with good success. The calibration centre should provide information on the best method of determining the atmospheric irradiance from a pyrgeometer depending upon which of the above recommendations are being followed.

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 angular size greater than 5° in any direction which has a low Sun angle at any time 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 are fully black.

Additionally, where polythene domes are used, it is necessary to check from time to time that ultraviolet effects have not changed the transmission characteristics. A half-yearly exchange of the upper dome is recommended.

Since it is not generally possible to measure directly the reflected short-wave radiation and the upward long-wave radiation exactly at the surface level, it will be necessary to place the pyranometers and pyrradiometers 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 pyranometers and pyrradiometers having an angle of view of 2π steradians, and installed 2 m above the surface, 90 percent of all the radiation measured is emitted by a circular surface underneath having a diameter of 12 m, 95 per cent by one of 17.5 m and 99 per cent by one of 39.8 m, assuming the sensor uses an orthotropic 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 due to 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. Furthermore, the following effects can specifically influence the readings of pyrradiometers, 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 recording system. This is much more important for pyrradiometers, which can yield negative values, than for pyranometers, where the solar input can be assumed to be zero during night-time.

Special attention should be paid to the position of instruments, if the long-wave radiation must be evaluated for day-time conditions by subtracting the output of a pyranometer from the readings of the pyrradiometer; they should be positioned closely together 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*

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 International Commission on Illumination (ICI) has defined the response of the human eye to photons with a peak responsivity at 555 nm. Figure 7.2 and Table 7.8 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

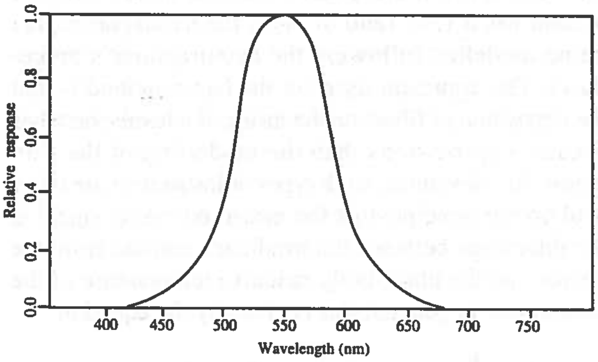

Figure 7.2 — Relative luminous sensitivity $V(\lambda)$ of the human eye for photopic vision.

TABLE 7.8

Photopic spectral luminous efficiency values (unity at wavelength of maximum efficacy)

Wavelength (nm)	*Photopic V(λ)*	*Wavelength (nm)*	*Photopic V(λ)*
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
580	0.870		

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 lux), $\Phi(\lambda)$ 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.

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

7.5.1.1 INSTRUMENTS

Illuminance meters comprise a photovoltaic detector, one or more filters to yield sensitivity according to the V(λ) curve, and often a temperature control circuit to maintain signal stability. The ICI has developed a detailed guide to the measurement of daylight, (ICI, 1993). This *Guide* describes expected practices in the installation of equipment, instrument characterization, data acquisition procedures, and first-level 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 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 7.9. These values are based upon ICI recommendations (ICI, 1987), but only for uncertainties associated with high-quality illuminance meters specifically intended for external daylight measurements.

Diffuse illuminance can be measured following the same principles used for the measurement of diffuse irradiance. Direct illuminance measurements should be made 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°.

TABLE 7.9

Specification of illuminance meters

Specification	*Uncertainty percentage*
V(λ)-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

7.5.1.2 CALIBRATION

Calibrations should be traceable to a Standard Illuminant type A following the procedures outlined in ICI (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 ICI has recommended that the following climatological variables be recorded:

(*a*) Global and diffuse daylight illuminance on horizontal and vertical surfaces;
(*b*) Illuminance of the direct solar beam;
(*c*) Sky luminance for 0.08 steradian intervals (about 10° · 10°) all over the hemisphere;
(*d*) Photopic albedo of characteristic surfaces such as grass, earth, snow, etc.

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 ultraviolet (UV) radiation

Measurements of solar ultraviolet radiation are in demand because of its effects on the environment and human health, and because of the enhancement of UV-B radiation at the Earth's surface caused by ozone depletion (Kerr and McElroy, 1993). The UV spectrum is conventionally divided into three parts, as follows:

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

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

(*c*) UV-C, in the wavelengths 10 to 280 nm, is completely absorbed in the atmosphere and does not occur naturally at the Earth's surface.

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

Measuring of ultraviolet 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 flux between 290 nm and 325 nm at the top of the atmosphere and at the surface in W m^{-2} nm^{-1}. UV irradiance is influenced by such atmospheric properties as cloud and 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 ultraviolet radiation measurement stem from the variety of uses to which the measurements are put. Unlike most meteorological measurements, standards based upon global needs have not yet been reached. In many countries, measurements of UV radiation are not made by Meteorological Services, but by health or environmental protection authorities. This leads to further difficulties in the standardization of instruments and methods of observation.

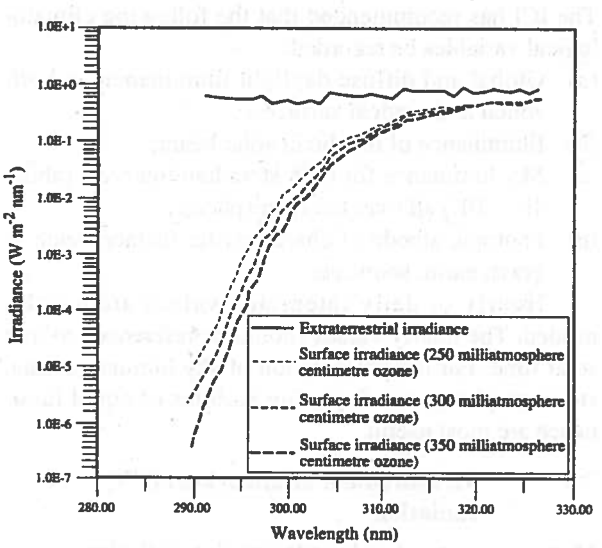

Figure 7.3 — Model results illustrating the effect of increasing ozone levels on the transmission of UV-B radiation through the atmosphere.

At the present time, no standards have been set within WMO to govern the measurement of UV radiation with respect to either instrument characteristics or methods of observation. Requirements for UV-B measurements were put forward in the WMO Global Ozone Research and Monitoring Project (WMO, 1993*a*) and are reproduced in Table 7.10.

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 ultraviolet 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 ultraviolet region responsible for affecting human health. The second class 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 spectrometers that measure across a pre-defined portion of the spectrum sequentially using a fixed passband.

7.6.1.1 BROADBAND SENSORS

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

TABLE 7.10
Requirements for UV-B measurements

UV-B

1. Wavelength resolution — 1.0 nm or better
2. Temporal resolution — 10 minutes or better
3. Directional (angular) — separation into direct and diffuse components or better
4. Meticulous calibration strategy

Ancillary data

(*a*) *Absolutely necessary*
1. Total column ozone (within 100 km)
2. Aerosol optical depth
3. Ground albedo
4. Cloud cover

(*b*) *Highly recommended*
5. Aerosol, lidar profile
6. Vertical ozone distribution
7. Short-wave irradiance (i.e. global solar radiation)
8. Polarization of zenith radiance
9. Water vapour

The most common 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 a 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 per cent 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 erythermally-weighted UV irradiance using thin film metal interference filter technology and specially developed silicon photodiodes. These ove come many problems associated with phosphor technology, but must contend with very low photodiode signal levels.

Other broadband instruments use one or the other measurement technologies to measure the complete spectra by using either a combination of glass filters or interference filters. The passband 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 maintenance of these instruments consists of ensuring that the domes are cleaned, the instrument is level, the desiccant (if provided) is active, and the heating/cooling system is working correctly, if so equipped. Otherwise care is similar to a pyranometer.

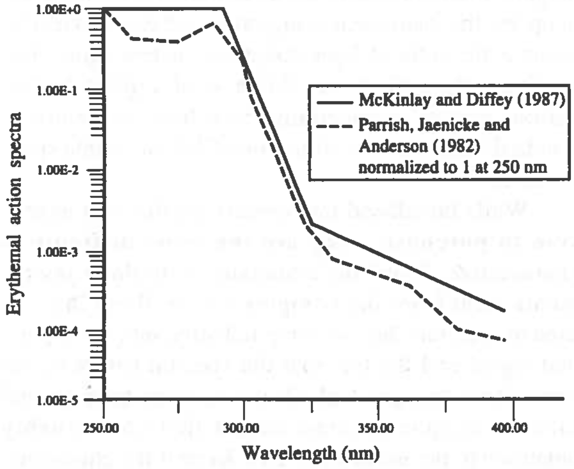

Figure 7.4 — Erythemal curves as presented by Parrish, Jaenicke and Anderson (1982) and McKinlay and Diffey (1987).

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 2 nm FWHM.

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. 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^{-5} or better throughout the sensitive region of the detector. Higher quality of instruments of this type either use peltier cooling to maintain a constant temperature near 20°C or use 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.

Manufacturers of instruments that use more than a single filter often provide a means of reconstructing the complete UV spectrum through modelled relationships developed around the measured wavelengths. 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.

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 the broadband instruments. For those 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 SPECTROMETERS

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 the use of 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. Some less expensive instruments use photodiode or charge-coupled detector arrays. 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 to intensity.

Commercially-available instruments are constructed to provide measurement capabilities from approximately 290 nm to as long as the mid-visible depending upon their construction and configuration. The bandwidth of the measurements is usually between 0.5 nm and 2.0 nm. The time that is required to complete a full scan across the grating depends upon both the wavelength resolution and the total spectrum to be measured, but is in of the order of one to 10 seconds per wavelength step.

The routine monitoring of UV radiation requires that the instrument either be environmentally-protected or be 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.

Normal maintenance on spectrometers designed for monitoring the UV-B radiation takes approximately 15 to 20 minutes per day, excluding calibrations. It is crucial to follow the manufacturer's maintenance instructions because of the complexity of the instrument.

7.6.2 *Calibration*

The calibration of all sensors in the UV-B is difficult. Unlike pyranometers that can be traced back to a standard set of instruments maintained at the World Radiometric Reference, these sensors must be either calibrated against light sources or against trap detectors. The latter, while promising in the long-term calibration of narrow-band filter instruments, are still not readily available. Therefore, the use of standard lamps that are traceable to national standards laboratories remains the most common means of calibrating sensors measuring in the UV-B. Many countries do not have laboratories that are capable of characterizing lamps in the UV. In these countries, lamps are usually traceable to the National Institute for Standards and Technology (NIST) in the United States or to the Physikalisch-Technische Bundesanstalt (PTB) in Germany.

It is estimated that a 5 per cent uncertainty in spot measurements at 300 nm can only be achieved under the most rigorous conditions at the present time. The accuracy of measurements of daily totals is about the same, using best practice. Measurements of erythemal activity would have accuracies typically in the range 5 to 20 per cent, 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 effects;

(*d*) The fact that the calibration of an instrument varies with wavelength, and:
  - (i) The spectrum of a standard lamp is not the same as the spectrum being measured;
  - (ii) The spectrum of the UV-B radiation being measured varies strongly with time.

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 250 nm, the uncertainty associated with the standard irradiance is of the order of 2.2 per cent. When transferred to a standard lamp another 1 per cent uncertainty is added. At 350 nm, these uncertainties decrease to approximately 1.3 and 0.7 per cent, respectively. Consideration must also be made for the set-up and handling of standard lamps. Even variations as small as 1 per cent in current, for example, can lead to errors in the UV flux of 10 per cent 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 per cent 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 spectrometers.

While broadband instruments are the least expensive to purchase, they are the most difficult to characterize. Problems associated with these instruments stem from the complex set of filters that are used to integrate the incoming radiation into the erythemal signal and the fact that the spectral nature of the atmosphere changes with air mass, ozone amount, and other atmospheric constituents that are probably unknown to the instrument user. Even if the characterization of the instrument by using calibrated lamp sources is perfect, the changing spectral properties between the atmosphere and the laboratory would affect the accuracy 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.

Narrowband sensors are easier to characterize than broadband sensors because of the smaller variation in calibrating source intensities over the smaller wavelength passband. Trap detectors could potentially be used effectively for narrowband sensors, but have only been used in research projects to date. In recalibrating these instruments, whether single or multiple filter, care must be taken to ensure that the spectral characteristics of the filters have not shifted over time.

Spectrometer calibration is straightforward, assuming that the instrument has been maintained between calibrations. Once again, it must be emphasized that the transfer from the standard lamp is difficult because of the care that must be taken in setting up the calibration (see above). The instrument should be calibrated in the same position as the measurements are to be made, as many spectrometers are adversely affected by changes in orientation. The calibration of a spectrometer should also include testing of 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. Periodic testing of the out-of-band rejection, possibly by scanning a helium cadmium laser ($\lambda = 325$ nm), is also advisable.

Most filter instrument manufacturers indicate a calibration frequency of once a year. Spectrometers should be calibrated at least semi-annually 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, calibrations should only be performed by qualified technicians in recognized standards laboratories.

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ANNEX 7.A

NOMENCLATURE OF RADIOMETRIC AND PHOTOMETRIC QUANTITIES

(1) Radiometric quantities

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

(2) Photometric quantities

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} sr^{-1} = cd m^{-2}
Luminous flux density	$(M_v; E_v)$	lm m^{-2}

(3) Radiometric characteristics

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

ANNEX 7.B

METEOROLOGICAL RADIATION QUANTITIES, SYMBOLS, AND DEFINITIONS

Quantity	*Symbol*	*Relation*	*Definitions, remarks*	*Units*
Downward radiation	$\Phi\downarrow$[1] $Q\downarrow$ $M\downarrow$ $E\downarrow$ $L\downarrow$ $H\downarrow$	$\Phi\downarrow=\Phi_g\downarrow+\Phi_l\downarrow$ $Q\downarrow=Q_g\downarrow+Q_l\downarrow$ $M\downarrow=M_g\downarrow+M_l\downarrow$ $E\downarrow=E_g\downarrow+E_l\downarrow$ $L\downarrow=L_g\downarrow+L_l\downarrow$ $H\downarrow=H_g\downarrow+H_l\downarrow$ (g = global) (l = long wave)	Downward radiant flux " radiant energy " radiant exitance[2] " 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	$\Phi\uparrow$[1] $Q\uparrow$ $M\uparrow$ $E\uparrow$ $L\uparrow$ $H\uparrow$	$\Phi\uparrow=\Phi_r\uparrow+\Phi_l\uparrow$ $Q\uparrow=Q_r\uparrow+Q_l\uparrow$ $M\uparrow=M_r\uparrow+M_l\uparrow$ $E\uparrow=E_r\uparrow+E_l\uparrow$ $L\uparrow=L_r\uparrow+L_l\uparrow$ $H\uparrow=H_r\uparrow+H_l\uparrow$	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	$E_g\downarrow$	$E_g\downarrow=S\cdot\cos\theta_{\odot}+E_d\downarrow$	Hemispherical radiation on horizontal surface ($\theta_{\odot}$ = solar zenith-angle)[3]	W m^{-2}
Sky radiation: downward diffuse solar radiation	$\Phi_d\uparrow$[1] $Q_d\uparrow$ $M_d\uparrow$ $E_d\uparrow$ $L_d\uparrow$ $H_d\uparrow$		Subscript d = diffuse	As for downward radiation
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, then the subscript a may be added, e.g. $\Phi_{l,a}\uparrow$	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 subscripts 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	Φ^* 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 subscripts g or l are 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	S	$S=S_o\tau$ $\tau=e^{-\delta/\cos\theta_{\odot}}$	Since this is a special quantity, a separate symbol (S) is used for solar irradiance. τ = atmospheric transmittance δ = optical depth (vertical)	W m^{-2}
Solar constant	S_o		Solar irradiance outside the atmosphere, normalized to mean Sun-Earth distance	W m^{-2}

1. The symbols – or + could be used instead of ↓, ↑ (e.g. $\Phi^+ \equiv \Phi\uparrow$).
2. 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.
3. In the case of inclined surfaces, $\theta_{\odot}$ 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

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

A World Radiation Centre should fulfil the following requirements:

(*a*) It should possess and maintain a group of at least three of the most stable pyrheliometers or absolute radiometers, the calibration of which is directly derived from the World Radiometric Reference. The World Radiation Centre Davos is requested to maintain the World Standard Group for the realization of the World Radiometric Reference;

(*b*) It should take all steps necessary to ensure at all times the highest possible quality of its standards and testing equipment;

(*c*) It should serve as a centre for the calibration of regional standards;

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

(*e*) It should follow closely or initiate developments leading to improved standards and/or methods in meteorological radiometry;

(*f*) It should undertake training of specialists in radiation;

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

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 instruments necessary for this purpose.

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

(*a*) It should possess and maintain a standard group of radiometers, which consists, of either three standard radiometers of the Ångström, silver-disk or absolute radiometer type or of two absolute radiometers;

(*b*) One of the standard radiometers should be compared at least once every five years against the World Standard Group;

(*c*) The standard radiometers should be intercompared at least once a year to check the stability of the individual instruments. If the ratio has changed by more than ±0.2 per cent and if the erroneous instrument cannot be identified, then a recalibration at one of the World Radiation Centres has to be performed prior to further use as standard;

(*d*) It should have the necessary facilities and laboratory equipment for checking and maintain-ing the accuracy of the auxiliary measuring equipment;

(*e*) It should 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 should include a qualified scientist with wide experience in radiation.

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 should satisfy the following requirements:

(*a*) It should possess and maintain at least one standard radiometer of the Ångström, silver-disk or absolute radiometer type for use as a national reference for the calibration or radiation instruments in the national network of radiation stations;

(*b*) The national standard radiometer should be compared with a regional standard at least once every five years;

(*c*) It should have the necessary facilities and equipment for checking the performance of the instruments used in the national network;

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

National Radiation Centres should 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 made 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 should maintain close liaison with that body.

List of World and Regional Radiation Centres

WORLD RADIATION CENTRES

Davos	(Switzerland)
St. Petersburg[1]	(Russia)

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[1] Mainly operated as a World Radiation Data Centre (WRDC).

REGIONAL RADIATION CENTRES

Region I (Africa):

Cairo	(Egypt)
Khartoum	(Sudan)
Kinshasa	(Zaire)
Lagos	(Nigeria)
Tamanrasset	(Algeria)
Tunis	(Tunisia)

Region II (Asia):

Pune	(India)
Tokyo	(Japan)

Region III (South America):

Buenos Aires	(Argentina)
Santiago	(Chile)

Region IV (North and Central America):

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

Region V (South-West Pacific):

Melbourne	(Australia)

Region VI (Europe):

Budapest	(Hungary)
Davos	(Switzerland)
St. Petersburg	(Russia)
Norrköping	(Sweden)
Trappes/Carpentras	(France)
Uccle	(Belgium)
Potsdam	(Germany)

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*, *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 required are:

(1) Year;
(2) Day of year (e.g. February 1 is day 32);
(3) Fractional hour in Universal Time (e.g. hours + minute/60 + number of hours from Greenwich);
(4) Latitude in degrees (north positive);
(5) 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 Universal Time (UT). This JD is 2 451 545.0. The JD to be determined can be found from:

$$\mathrm{JD} = 2\,432\,916.5 + \mathrm{delta} \cdot 365 + \mathrm{leap} + \mathrm{day} + \mathrm{hour}/24$$

where: delta = year – 1949
leap = integer portion of (delta/4)

The constant 2 432 916.5 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:

(1) $n = \mathrm{JD} - 2\,451\,545$;
(2) L (mean longitude) $= 280.460 + 0.985\,647\,4 \cdot n$ $(0 \leq L < 360°)$;
(3) g (mean anomaly) $= 357.528 + 0.985\,600\,3 \cdot n$ $(0 \leq g < 360°)$;
(4) l (ecliptic longitude) $= L + 1.915 \cdot \sin(g) + 0.020 \cdot \sin(2g)$ $(0 \leq l < 360°)$;
(5) ep (obliquity of the ecliptic) $= 23.439 - 0.000\,000\,4 \cdot n$ (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) and the Local Mean Sidereal Time (LMST):

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

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

$$\mathrm{LMST} = \mathrm{GMST} + (\mathrm{east\ longitude})/15$$

From the LMST, the hour angle (*ha*) is calculated as:

$$ha = \mathrm{LMST} - ra \quad (-12 \leq ha < 12\mathrm{h})$$

Before the Sun reaches the meridian, the hour angle is negative. Caution should be used 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:

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

and:

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

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

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 per cent from the mean. In astronomical units (AU), to an accuracy to better than 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, *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 $1/\sin h_0$. To take into account atmospheric refraction, the *Astronomical Almanac* proposes the following equations:

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

$$R = 0^\circ.004\,52\, P \tan z/(273 + T)$$

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°, this approximate formula is recommended:

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

where a is the altitude $(90^\circ - z)$.

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 (four minutes 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:

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

where $\Theta_o = 2\pi d_n/365$ in radians or $\Theta_o = 360\, d_n/365$ 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 seconds (which is not sufficient 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, e.g. Drummond (1956), Dehne (1980), and Le Baron, Peterson and Dirmhirn (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:

$$D_v \sim \frac{b}{r} \cos^3 \delta \int_{t_{rise}}^{t_{set}} L(t) \cdot \sin h_{\odot}(t)\, dt$$

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

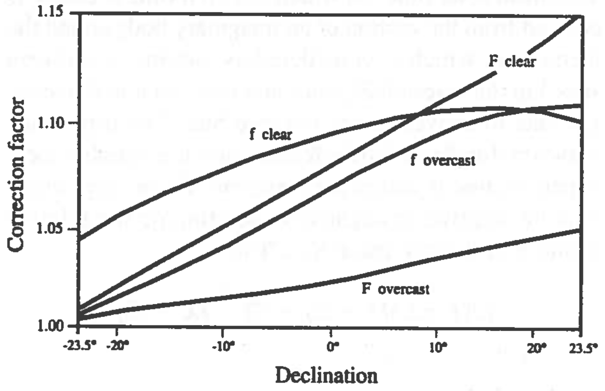
With this expression and some assumptions on the sky radiance, a correction factor f can be determined:

$$f = \frac{1}{\left(1 - \frac{D_v}{D}\right)}$$

D being the unobscured sky radiation. In the figure opposite, 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 having a shading ring with an instrument shaded by a continuously traced disk. If no experimental data are available for the station, data computed for the overcast case with the corresponding b/r should be used. Thus:

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

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



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 (after Dehne, 1980).

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