CHAPTER 8

MEASUREMENT OF SUNSHINE DURATION

8.1 GENERAL

The term “sunshine” is associated with the brightness of the solar disc exceeding the background of diffuse sky light, or, as is better observed by the human eye, with the appearance of shadows behind illuminated objects. As such, the term is related more to visual radiation than to energy radiated at other wavelengths, although both aspects are inseparable. In practice, however, the first definition was established directly by the relatively simple Campbell-Stokes sunshine recorder (see section 8.2.3), which detects sunshine if the beam of solar energy concentrated by a special lens is able to burn a special dark paper card. This recorder was already introduced in meteorological stations in 1880 and is still used in many networks. Since no international regulations on the dimensions and quality of the special parts were established, applying different laws of the principle gave different sunshine duration values.

In order to homogenize the data of the worldwide network for sunshine duration, a special design of the Campbell-Stokes sunshine recorder, the so-called interim reference sunshine recorder (IRSR), was recommended as the reference (WMO, 1962). The improvement made by this “hardware definition” was effective only during the interim period needed for finding a precise physical definition allowing for both designing automatic sunshine recorders and approximating the “scale” represented by the IRSR as near as possible. With regard to the latter, the settlement of a direct solar threshold irradiance corresponding to the burning threshold of the Campbell-Stokes recorders was strongly advised. Investigations at different stations showed that the threshold irradiance for burning the card varied between 70 and 280 W m^{-2} (Bider, 1958; Baumgartner, 1979). However, further investigations, especially performed with the IRSR in France, resulted in a mean value of 120 W m^{-2}, which was finally proposed as the threshold of direct solar irradiance to distinguish bright sunshine.[1] With regard to the spread of test results, a threshold accuracy of 20 per cent in instrument specifications is accepted. A pyrheliometer was recommended as the reference sensor for the detection of the threshold irradiance. For future refinement of the reference, the settlement of the field-of-view angle of the pyrheliometer seems to be necessary (see Part I, Chapter 7, sections 7.2 and 7.2.1.3).

8.1.1 Definition

According to WMO (2003),[2] sunshine duration during a given period is defined as the sum of that sub-period for which the direct solar irradiance exceeds 120 W m^{-2}.

8.1.2 Units and scales

The physical quantity of sunshine duration (*SD*) is, evidently, time. The units used are seconds or hours. For climatological purposes, derived terms such as “hours per day” or “daily sunshine hours” are used, as well as percentage quantities, such as “relative daily sunshine duration”, where *SD* may be related to the extra-terrestrial possible, or to the maximum possible, sunshine duration (SD_0 and SD_{max}, respectively). The measurement period (day, decade, month, year, and so on) is an important addendum to the unit.

8.1.3 Meteorological requirements

Performance requirements are given in Part I, Chapter 1. Hours of sunshine should be measured with an uncertainty of ±0.1 h and a resolution of 0.1 h.

Since the number and steepness of the threshold transitions of direct solar radiation determine the possible uncertainty of sunshine duration, the meteorological requirements on sunshine recorders are essentially correlated with the climatological cloudiness conditions (WMO, 1985).

In the case of a cloudless sky, only the hourly values at sunrise or sunset constellations can (depending on the amount of dust) be erroneous because of an imperfectly adjusted threshold or spectral dependencies.

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[1] Recommended by the Commission for Instruments and Methods of Observation at its eighth session (1981) through Recommendation 10 (CIMO-VIII).

[2] Recommended by the Commission for Instruments and Methods of Observation at its tenth session (1989) through Recommendation 16 (CIMO-X).

In the case of scattered clouds (cumulus, stratocumulus), the steepness of the transition is high and the irradiance measured from the cloudy sky with a pyrheliometer is generally lower than 80 W m^{-2}; that means low requirements on the threshold adjustment. But the field-of-view angle of the recorder can influence the result if bright cloud clusters are near the sun.

The highest precision is required if high cloud layers (cirrus, altostratus) with small variations of the optical thickness attenuate the direct solar irradiance around the level of about 120 W m^{-2}. The field-of-view angle is effective as well as the precision of the threshold adjustment.

The requirements on sunshine recorders vary, depending on site and season, according to the dominant cloud formation. The latter can be roughly described by three ranges of relative daily sunshine duration SD/SD_0 (see section 8.1.2), namely “cloudy sky” by ($0 \leq SD/SD_0 < 0.3$), “scattered clouds” by ($0.3 \leq SD/SD_0 < 0.7$) and “fair weather” by ($0.7 \leq SD/SD_0 \leq 1.0$). The results for dominant clouded sky generally show the highest percentage of deviations from the reference.

8.1.3.1 Application of sunshine duration data

One of the first applications of *SD* data was to characterize the climate of sites, especially of health resorts. This also takes into account the psychological effect of strong solar light on human well-being. It is still used by some local authorities to promote tourist destinations.

The description of past weather conditions, for instance of a month, usually contains the course of daily *SD* data.

For these fields of application, an uncertainty of about 10 per cent of mean *SD* values seemed to be acceptable over many decades.

8.1.3.2 Correlations to other meteorological variables

The most important correlation between sunshine duration and global solar radiation *G* is described by the so-called Ångström formula:

$$G/G_0 = a + b \cdot (SD/SD_0) \qquad (8.1)$$

where G/G_0 is the so-called clearness index (related to the extra-terrestrial global irradiation), SD/SD_0 is the corresponding sunshine duration (related to the extra-terrestrial possible *SD* value), and *a* and *b* are constants which have to be determined monthly. The uncertainty of the monthly means of daily global irradiation derived in this way from Campbell-Stokes data was found to be lower than 10 per cent in summer, and rose up to 30 per cent in winter, as reported for German stations (Golchert, 1981).

The Ångström formula implies the inverse correlation between cloud amount and sunshine duration. This relationship is not fulfilled for high and thin cloudiness and obviously not for cloud fields which do not cover the sun, so that the degree of inverse correlation depends first of all on the magnitude of the statistical data collected (Stanghellini, 1981; Angell, 1990). The improvement of the accuracy of *SD* data should reduce the scattering of the statistical results, but even perfect data can generate sufficient results only on a statistical basis.

8.1.3.3 Requirement of automated records

Since electrical power is available in an increasing number of places, the advantage of the Campbell-Stokes recorder of being self-sufficient is of decreasing importance. Furthermore, the required daily maintenance requirement of replacing the burn card makes the use of Campbell-Stokes recorders problematic at either automatic weather stations or stations with reduced numbers of personnel. Another essential reason to replace Campbell-Stokes recorders by new automated measurement procedures is to avoid the expense of visual evaluations and to obtain more precise results on data carriers permitting direct computerized data processing.

8.1.4 Measurement methods

The principles used for measuring sunshine duration and the pertinent types of instruments are briefly listed in the following methods:

(a) Pyrheliometric method: Pyrheliometric detection of the transition of direct solar irradiance through the 120 W m^{-2} threshold (according to Recommendation 10 (CIMO-VIII)). Duration values are readable from time counters triggered by the appropriate upward and downward transitions.

Type of instrument: pyrheliometer combined with an electronic or computerized threshold discriminator and a time-counting device.

(b) Pyranometric method:
   (i) Pyranometric measurement of global (*G*) and diffuse (*D*) solar irradiance to derive the direct solar irradiance as the WMO threshold discriminator value and further as in (a) above.

   Type of instrument: Radiometer systems of two fitted pyranometers and one sunshade device combined with an electronic or computerized threshold discriminator and a time-counting device.

   (ii) Pyranometric measurement of global (*G*) solar irradiance to roughly estimate sunshine duration.

   Type of instrument: a pyranometer combined with an electronic or computerized device which is able to deliver 10 min means as well as minimum and maximum global (*G*) solar irradiance within those 10 min.

(c) Burn method: Threshold effect of burning paper caused by focused direct solar radiation (heat effect of absorbed solar energy). The duration is read from the total burn length.

   Type of instrument: Campbell-Stokes sunshine recorders, especially the recommended version, namely the IRSR (see section 8.2).

(d) Contrast method: Discrimination of the insolation contrasts between some sensors in different positions to the sun with the aid of a specific difference of the sensor output signals which corresponds to an equivalent of the WMO recommended threshold (determined by comparisons with reference *SD* values) and further as in (b) above.

   Type of instrument: Specially designed multisensor detectors (mostly equipped with photovoltaic cells) combined with an electronic discriminator and a time counter.

(e) Scanning method: Discrimination of the irradiance received from continuously scanned, small sky sectors with regard to an equivalent of the WMO recommended irradiance threshold (determined by comparisons with reference *SD* values).

   Type of instrument: One-sensor receivers equipped with a special scanning device (rotating diaphragm or mirror, for instance) and combined with an electronic discriminator and a time-counting device.

The sunshine duration measurement methods described in the following paragraphs are examples of ways to achieve the above-mentioned principles. Instruments using these methods, with the exception of the Foster switch recorder, participated in the WMO Automatic Sunshine Duration Measurement Comparison in Hamburg from 1988 to 1989 and in the comparison of pyranometers and electronic sunshine duration recorders of Regional Association VI in Budapest in 1984 (WMO, 1986).

The description of the Campbell-Stokes sunshine recorder in section 8.2.3 is relatively detailed since this instrument is still widely used in national networks, and the specifications and evaluation rules recommended by WMO should be considered (however, note that this method is no longer recommended,[3] since the duration of bright sunshine is not recorded with sufficient consistency).

A historical review of sunshine recorders is given in Coulson (1975), Hameed and Pittalwala (1989) and Sonntag and Behrens (1992).

8.2 INSTRUMENTS AND SENSORS

8.2.1 Pyrheliometric method

8.2.1.1 General

This method, which represents a direct consequence of the WMO definition of sunshine (see section 8.1.1) and is, therefore, recommended to obtain reference values of sunshine duration, requires a weatherproof pyrheliometer and a reliable solar tracker to point the radiometer automatically or at least semi-automatically to the position of the sun. The method can be modified by the choice of pyrheliometer, the field-of-view angle of which influences the irradiance measured when clouds surround the sun.

The sunshine threshold can be monitored by the continuous comparison of the pyrheliometer output with the threshold equivalent voltage $V_{th} = 120\ \text{W m}^{-2} \cdot R\ \mu V\ \text{W}^{-1}\ \text{m}^2$, which is calculatable

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[3] See Recommendation 10 (CIMO-VIII).

from the responsivity R of the pyrheliometer. A threshold transition is detected if $\Delta V = V - V_{th}$ changes its sign. The connected time counter is running when $\Delta V > 0$.

8.2.1.2 Sources of error

The field-of-view angle is not yet settled by agreed definitions (see Part I, Chapter 7, sections 7.2 and 7.2.1.3). Greater differences between the results of two pyrheliometers with different field-of-view angles are possible, especially if the sun is surrounded by clouds. Furthermore, typical errors of pyrheliometers, namely tilt effect, temperature dependence, non-linearity and zero-offset, depend on the class of the pyrheliometer. Larger errors appear if the alignment to the sun is not precise or if the entrance window is covered by rain or snow.

8.2.2 Pyranometric method

8.2.2.1 General

The pyranometric method to derive sunshine duration data is based on the fundamental relationship between the direct solar radiation (I) and the global (G) and diffuse (D) solar radiation:

$$I \cdot \cos \zeta = G - D \qquad (8.2)$$

where ζ is the solar zenith angle and $I \cdot \cos \zeta$ is the horizontal component of I. To fulfil equation 8.2 exactly, the shaded field-of-view angle of the pyranometer for measuring D must be equal to the field-of-view angle of the pyrheliometer (see Part I, Chapter 7). Furthermore, the spectral ranges, as well as the time-constants of the pyrheliometers and pyranometers, should be as similar as possible.

In the absence of a sun-tracking pyrheliometer, but where computer-assisted pyranometric measurements of G and D are available, the WMO sunshine criterion can be expressed according to equation 8.2 by:

$$(G–D)/\cos \zeta > 120 \text{ W m}^{-2} \qquad (8.3)$$

which is applicable to instantaneous readings.

The modifications of this method in different stations concern first of all:

(a) The choice of pyranometer;
(b) The shading device applied (shade ring or shade disc with solar tracker) and its shade geometry (shade angle);
(c) The correction of shade-ring losses.

As a special modification, the replacement of the criterion in equation 8.3 by a statistically derived parameterization formula (to avoid the determination of the solar zenith angle) for applications in more simple data-acquisition systems should be mentioned (Sonntag and Behrens, 1992).

The pyranometric method using only one pyranometer to estimate sunshine duration is based on two assumptions on the relation between irradiance and cloudiness as follows:

(a) A rather accurate calculation of the potential global irradiance at the Earth's surface based on the calculated value of the extraterrestrial irradiation (G_0) by taking into account diminishing due to scattering in the atmosphere. The diminishing factor depends on the solar elevation h and the turbidity T of the atmosphere. The ratio between the measured global irradiance and this calculated value of the clear sky global irradiance is a good measure for the presence of clouds;
(b) An evident difference between the minimum and maximum value of the global irradiance, measured during a 10 min interval, presumes a temporary eclipse of the sun by clouds. On the other hand, in the case of no such difference, there is no sunshine or sunshine only during the 10 min interval (namely, $SD = 0$ or $SD = 10$ min).

Based on these assumptions, an algorithm can be used (Slob and Monna, 1991) to calculate the daily SD from the sum of 10 min SD. Within this algorithm, SD is determined for succeeding 10 min intervals (namely, $SD_{10'} = f \cdot 10$ min, where f is the fraction of the interval with sunshine, $0 \le f \le 1$). The diminishing factor largely depends on the optical path of the sunlight travelling through the atmosphere. Because this path is related to the elevation of the sun, $h = 90° - z$, the algorithm discriminates between three time zones. Although usually $f = 0$ or $f = 1$, special attention is given to $0 < f < 1$. This algorithm is given in the annex. The uncertainty is about 0.6 h for daily sums.

8.2.2.2 Sources of error

According to equation 8.3, the measuring errors in global and diffuse solar irradiance are propagated by the calculation of direct solar irradiance and are strongly amplified with increasing solar zenith angles. Therefore, the accuracy of corrections for losses of diffuse solar energy by the use of shade rings (WMO, 1984*a*) and the choice of pyranometer quality is of importance to reduce the uncertainty level of the results.

8.2.3 The Campbell-Stokes sunshine recorder (burn method)

The Campbell-Stokes sunshine recorder consists essentially of a glass sphere mounted concentrically in a section of a spherical bowl, the diameter of which is such that the sun's rays are focused sharply on a card held in grooves in the bowl. The method of supporting the sphere differs according to whether the instrument is operated in polar, temperate or tropical latitudes. To obtain useful results, both the spherical segment and the sphere should be made with great precision, the mounting being so designed that the sphere can be accurately centred therein. Three overlapping pairs of grooves are provided in the spherical segment so that the cards can be suitable for different seasons of the year (one pair for both equinoxes), their length and shape being selected to suit the geometrical optics of the system. It should be noted that the aforementioned problem of burns obtained under variable cloud conditions indicates that this instrument, and indeed any instrument using this method, does not provide accurate data of sunshine duration.

The table below summarizes the main specifications and requirements for a Campbell-Stokes sunshine recorder of the IRSR grade. A recorder to be used as an IRSR should comply with the detailed specifications issued by the UK Met Office, and IRSR record cards should comply with the detailed specifications issued by Météo-France.

8.2.3.1 Adjustments

In installing the recorder, the following adjustments are necessary:

(a) The base must be levelled;

(b) The spherical segment should be adjusted so that the centre line of the equinoctial card lies in the celestial Equator (the scale of latitude marked on the bowl support facilitates this task);

(c) The vertical plan through the centre of the sphere and the noon mark on the spherical segment must be in the plane of the geographic meridian (north-south adjustment).

Campbell-Stokes recorder (IRSR grade) specifications

Glass sphere		*Spherical segment*		*Record cards*	
Shape:	Uniform	Material:	Gunmetal or equivalent durability	Material:	Good quality pasteboard not affected appreciably by moisture
Diameter:	10 cm	Radius:	73 mm	Width:	Accurate to within 0.3 mm
Colour:	Very pale or colourless	Additional specifications:	(a) Central noon line engraved transversely across inner surface	Thickness:	0.4 ± 0.05 mm
Refractive index:	1.52 ± 0.02			Moisture effect:	Within 2 per cent
Focal length:	75 mm for sodium "D" light		(b) Adjustment for inclination of segment to horizontal according to latitude	Colour:	Dark, homogeneous, no difference detected in diffuse daylight
				Graduations:	Hour-lines printed in black
			(c) Double base with provision for levelling and azimuth setting		

A recorder is best tested for (c) above by observing the image of the sun at the local apparent noon; if the instrument is correctly adjusted, the image should fall on the noon mark of the spherical segment or card.

8.2.3.2 Evaluation

In order to obtain uniform results from Campbell-Stokes recorders, it is especially important to conform closely to the following directions for measuring the IRSR records. The daily total duration of bright sunshine should be determined by marking off on the edge of a card of the same curvature the lengths corresponding to each mark and by measuring the total length obtained along the card at the level of the recording to the nearest tenth of an hour. The evaluation of the record should be made as follows:

(a) In the case of a clear burn with round ends, the length should be reduced at each end by an amount equal to half the radius of curvature of the end of the burn; this will normally correspond to a reduction of the overall length of each burn by 0.1 h;

(b) In the case of circular burns, the length measured should be equal to half the diameter of the burn. If more than one circular burn occurs on the daily record, it is sufficient to consider two or three burns as equivalent to 0.1 h of sunshine; four, five, six burns as equivalent to 0.2 h of sunshine; and so on in steps of 0.1 h;

(c) Where the mark is only a narrow line, the whole length of this mark should be measured, even when the card is only slightly discoloured;

(d) Where a clear burn is temporarily reduced in width by at least a third, an amount of 0.1 h should be subtracted from the total length for each such reduction in width, but the maximum subtracted should not exceed one half of the total length of the burn.

In order to assess the random and systematic errors made while evaluating the records and to ensure the objectivity of the results of the comparison, it is recommended that the evaluations corresponding to each one of the instruments compared be made successively and independently by two or more persons trained in this type of work.

8.2.3.3 Special versions

Since the standard Campbell-Stokes sunshine recorder does not record all the sunshine received during the summer months at stations with latitudes higher than about 65°, some countries use modified versions.

One possibility is to use two Campbell-Stokes recorders operated back to back, one of them being installed in the standard manner, while the other should be installed facing north.

In many climates, it may be necessary to heat the device to prevent the deposition of frost and dew. Comparisons in climates like that of northern Europe between heated and normally operated instruments have shown that the amount of sunshine not measured by a normal version, but recorded by a heat device, is about 1 per cent of the monthly mean in summer and about 5 to 10 per cent of the monthly mean in winter.

8.2.3.4 Sources of error

The errors of this recorder are mainly generated by the dependence on the temperature and humidity of the burn card as well as by the overburning effect, especially in the case of scattered clouds (Ikeda, Aoshima and Miyake, 1986).

The morning values are frequently disturbed by dew or frost at middle and high latitudes.

8.2.4 Contrast-evaluating devices

The Foster sunshine switch is an optical device that was introduced operationally in the network of the United States in 1953 (Foster and Foskett, 1953). It consists of a pair of selenium photocells, one of which is shielded from direct sunshine by a shade ring. The cells are corrected so that in the absence of the direct solar beam no signal is produced. The switch is activated when the direct solar irradiance exceeds about 85 W m^{-2} (Hameed and Pittalwala, 1989). The position of the shade ring requires adjustments only four times a year to allow for seasonal changes in the sun's apparent path across the sky.

8.2.5 Contrast-evaluating and scanning devices

8.2.5.1 General

A number of different opto-electronic sensors, namely contrast-evaluating and scanning devices (see, for example, WMO, 1984*b*), were compared during the WMO Automatic Sunshine Duration Measurement Comparison at the Regional Radiation Centre of Regional Association VI in Hamburg (Germany) from 1988 to 1989. The report of this comparison contains detailed descriptions of all the instruments and sensors that participated in this event.

8.2.5.2 Sources of error

The distribution of cloudiness over the sky or solar radiation reflected by the surroundings can influence the results because of the different procedures to evaluate the contrast and the relatively large field-of-view angles of the cells in the arrays used. Silicon photovoltaic cells without filters typically have the maximum responsivity in the near-infrared, and the results, therefore, depend on the spectrum of the direct solar radiation.

Since the relatively small, slit-shaped, rectangular field-of-view angles of this device differ considerably from the circular-symmetrical one of the reference pyrheliometer, the cloud distribution around the sun can cause deviations from the reference values.

Because of the small field of view, an imperfect glass dome may be a specific source of uncertainty. The spectral responsivity of the sensor should also be considered in addition to solar elevation error. At present, only one of the commercial recorders using a pyroelectric detector is thought to be free of spectral effects.

8.3 EXPOSURE OF SUNSHINE DETECTORS

The three essential aspects for the correct exposure of sunshine detectors are as follows:

(a) The detectors should be firmly fixed to a rigid support. This is not required for the SONI (WMO, 1984*b*) sensors that are designed also for use on buoys;

(b) The detector should provide an uninterrupted view of the sun at all times of the year throughout the whole period when the sun is more than 3° above the horizon. This recommendation can be modified in the following cases:

   (i) Small antennas or other obstructions of small angular width ($\leq 2°$) are acceptable if no alternative site is available. In this case, the position, elevation and angular width of obstructions should be well documented and the potential loss of sunshine hours during particular hours and days should be estimated by the astronomical calculation of the apparent solar path;

   (ii) In mountainous regions (valleys, for instance), natural obstructions are acceptable as a factor of the local climate and should be well documented, as mentioned above;

(c) The site should be free of surrounding surfaces that could reflect a significant amount of direct solar radiation to the detector. Reflected radiation can influence mainly the results of the contrast-measuring devices. To overcome this interference, white paint should be avoided and nearby surfaces should either be kept free of snow or screened.

The adjustment of the detector axis is mentioned above. For some detectors, the manufacturers recommend tilting the axis, depending on the season.

8.4 GENERAL SOURCES OF ERROR

The uncertainty of sunshine duration recorded using different types of instrument and methods was demonstrated as deviations from reference values in WMO for the weather conditions of Hamburg (Germany) in 1988–1989.

The reference values are also somewhat uncertain because of the uncertainty of the calibration factor of the pyrheliometer used and the dimensions of its field-of-view angle (dependency on the aureole). For single values, the time constant should also be considered.

General sources of uncertainty are as follows:

(a) The calibration of the recorder (adjustment of the irradiance threshold equivalent (see section 8.5));

(b) The typical variation of the recorder response due to meteorological conditions (for example, temperature, cloudiness, dust) and the position of the sun (for example, errors of direction, solar spectrum);

(c) The poor adjustment and instability of important parts of the instrument;

(d) The simplified or erroneous evaluation of the values measured;

(e) Erroneous time-counting procedures;

(f) Dirt and moisture on optical and sensing surfaces;

(g) Poor quality of maintenance.

8.5 CALIBRATION

The following general remarks should be made before the various calibration methods are described:

(a) No standardized method to calibrate *SD* detectors is available;

(b) For outdoor calibrations, the pyrheliometric method has to be used to obtain reference data;

(c) Because of the differences between the design of the *SD* detectors and the reference instrument, as well as with regard to the natural variability of the measuring conditions, calibration results must be determined by long-term comparisons (some months);

(d) Generally the calibration of *SD* detectors requires a specific procedure to adjust their threshold value (electronically for opto-electric devices, by software for pyranometric systems);

(e) For opto-electric devices with an analogue output, the duration of the calibration period should be relatively short;

(f) The indoor method (using a lamp) is recommended primarily for regular testing of the stability of field instruments.

8.5.1 Outdoor methods

8.5.1.1 Comparison of sunshine duration data

Reference values SD_{ref} have to be measured simultaneously with the sunshine duration values SD_{cal} of the detector to be calibrated. The reference instrument used should be a pyrheliometer on a solar tracker combined with an irradiance threshold discriminator (see section 8.1.4). Alternatively, a regularly recalibrated sunshine recorder of selected precision may be used. Since the accuracy requirement of the sunshine threshold of a detector varies with the meteorological conditions (see section 8.1.3), the comparison results must be derived statistically from data sets covering long periods.

If the method is applied to the total data set of a period (with typical cloudiness conditions), the first calibration result is the ratio $q_{tot} = \Sigma_{tot}\ SD_{ref}/\Sigma_{tot}\ SD_{cal}$.

For $q > 1$ or $q < 1$, the threshold equivalent voltage has to be adjusted to lower and higher values, respectively. Since the amount of the required adjustment is not strongly correlated to q_{tot}, further comparison periods are necessary to validate iteratively the approach to the ideal threshold by approximation of $q_{tot} = 1$. The duration of a total calibration period may be three to six months at European mid-latitudes. Therefore, the facilities to calibrate network detectors should permit the calibration of several detectors simultaneously. (The use of q_{tot} as a correction factor for the $\Sigma\ SD$ values gives reliable results only if the periods to be evaluated have the same cloud formation as during the calibration period. Therefore, this method is not recommended.)

If the method is applied to data sets which are selected according to specific measurement conditions (for example, cloudiness, solar elevation angle, relative sunshine duration, daytime), it may be possible, for instance, to find factors $q_{sel} = \Sigma_{sel}\ SD_{ref}/\Sigma_{sel}\ SD_{cal}$ statistically for different types of cloudiness. The factors could also be used to correct data sets for which the cloudiness is clearly specified.

On the other hand, an adjustment of the threshold equivalent voltage is recommended, especially if q_{sel} values for worse cloudiness conditions (such as cirrus and altostratus) are considered. An iterative procedure to validate the adjustment is also necessary; depending on the weather, some weeks or months of comparison may be needed.

8.5.1.2 Comparison of analogue signals

This method is restricted to *SD* detectors which have an analogue output that responds linearly to the received direct solar irradiance, at least in the range <500 W m^{-2}. The comparison between the reference irradiance measured by a pyrheliometer and the simultaneously measured analogue output should be performed at cloudless hours or other intervals with slowly variable direct solar irradiance below 500 W m^{-2}.

The linear regression analysis of such a data set generates a best-fit line from which the threshold equivalent voltage at 120 W m^{-2} can be derived. If this calibration result deviates from the certified voltage by more than ±20 per cent, the threshold of the detector should be adjusted to the new value.

For detectors with a pronounced spectral response, the measured data at low solar elevation angles around 120 W m^{-2} should be eliminated because of the stronger non-linearity caused by the spectrum, unless the threshold voltage at sunrise and sunset is of special interest. The threshold equivalent voltage has to be extrapolated from higher irradiance values.

8.5.1.3 Mean effective irradiance threshold method

The so-called mean effective irradiance threshold (MEIT) method is based on the determination of an hourly mean effective irradiance threshold I_m for the detector to be calibrated.

As a first step of this method, *SD* values SD_{ref} (h_k, $I(n)$) have to be determined from computer-controlled pyrheliometric measurements for hours h_k and fictitious threshold irradiances $I(n)$ between 60 and 240 W m^{-2} (this means that $I(n)$ = (60 + n) W m^{-2} with n = 0, 1, 2, ... 180). As a second step, the hourly *SD* value $SD(h_k)$ of the detector must be compared with the $SD_{ref}(h_k, I(n))$ to find the $n = n_k$ for which $SD(h_k)$ equals SD_{ref} (h_k, $I(n_k)$). $I(n_k)$ represents the MEIT value of the hour h_k: $I_m(h_k)$ = (60 + n_k) W m^{-2}. If n_k is not found directly, it has to be interpolated from adjacent values.

The third step is the adjustment of the threshold equivalent voltage of the recorder if the relative deviation between a MEIT value I_m and the ideal threshold 120 W m^{-2} is larger than ±20 per cent. The mean value should be a monthly average, for instance, because of the large spread of the deviations of hourly MEIT values.

The method is not applicable to hours with dominant fast threshold transitions; the average gradient of an hour should be lower than 5 W m^{-2} s^{-1}. The MEIT values are not representative of the total data set of the calibration period.

8.5.2 Indoor method

Since the simulation of the distribution of direct and diffuse solar fluxes is difficult indoors, only a "spare calibration" can be recommended which is applicable for *SD* detectors with an adjustable threshold equivalent voltage. The laboratory test equipment consists of a stabilized radiation source (preferably with an approximated solar spectrum) and a stand for a precise local adjustment of the *SD* detector as well as of an *SD* detector (carefully calibrated outdoors) which is used as reference. Reference and test detectors should be of the same model.

At the beginning of the test procedure, the reference detector is positioned precisely in the beam of the lamp so that 120 W m^{-2} is indicated by an analogue output or by the usual "sunshine switch". Afterwards, the reference device is replaced precisely by the test device, whose threshold voltage must be adjusted to activate the switch, or to get a 120 W m^{-2} equivalent. The repeatability of the results should be tested by further exchanges of the instruments.

8.6 MAINTENANCE

The required maintenance routine for technicians consists of the following:

(a) Cleaning: The daily cleaning of the respective entrance windows is necessary for all detectors, especially for scanning devices with small field-of-view angles. Instruments without equipment to prevent dew and frost should be cleared more than once on certain days;

(b) Checking: The rotation of special (scanning) parts as well as the data-acquisition system should be checked daily;

(c) Exchange of record: In Campbell-Stokes sunshine recorders, the burn card must be exchanged daily; in other devices, the appropriate data carriers have to be replaced regularly;

(d) Adjustments: Adjustments are required if a seasonal change of the tilt of the detector is recommended by the manufacturer, or possibly after severe storms.

Special parts of the detectors and of the data-acquisition systems used should undergo maintenance by trained technicians or engineers according to the appropriate instruction manuals.

ANNEX

ALGORITHM TO ESTIMATE SUNSHINE DURATION FROM DIRECT GLOBAL IRRADIANCE MEASUREMENTS

(See Slob and Monna, 1991)

The estimation of the daily SD is based on the sum of the fractions f of 10 min intervals, namely, $SD = \Sigma\, SD_{10}$, where $SD_{10} = f \leq 10$ min. In practice $f = 0$ (no sunshine at all, overcast) or 1 (only sunshine, no clouds), but special attention is given to $0 < f < 1$ (partly sunshine, part clouded). Because the correlation between SD and the global irradiation, measured horizontally, depends on the elevation of the sun (h), discrimination is made in the first place in terms of sin (h).

The following variables are applicable:

h	Elevation angle of the sun in degrees
G	Global irradiance on a horizontal surface in W m^{-2}
I	Direct irradiance on a surface perpendicular to the direction of the sun in W m^{-2}
D	Diffuse radiation on a horizontal surface in W m^{-2}
T_L	"Linke"— turbidity (dimensionless)

For the measured values of G it holds that:

G	represents a 10 min average of the measured global irradiance
G_{min}	represents the minimum value of the global irradiance, measured during the 10 min interval
G_{max}	represents the maximum value of the global irradiance, measured during the 10 min interval ($G_{min} \leq G \leq G_{max}$)

Equations used:

$G_0 = I_0 \sin(h)$, $I_0 = 1367$ W m^{-2} (for extra-terrestrial irradiance)

$I = I_0 \exp(-T_L/(0.9 + 9.4 \sin(h))$, $I_0 = 1367$ W m^{-2}

$c = (G - D)/(I \sin(h))$, where
$T_L = 4$ and
$D = 1.2\, G_{min}$ if $(1.2\, G_{min} < 0.4)$ else $D = 0.4$

<table>
<tr><td><i>Sun elevation</i></td><td>sin (h) < 0.1, h < 5.7°</td><td colspan="2">0.1 ≤ sin (h) ≤ 0.3, 5.7° ≤ h ≤ 17.5°</td><td colspan="6">sin (h) ≥ 0.3, h ≥ 17.5°</td></tr>
<tr><td rowspan="7"><i>Other criteria</i></td><td rowspan="7">No further decision criteria</td><td colspan="2" rowspan="3">Is $G/G_0 \leq \{0.2 + \sin(h)/3 + \exp(-T_L/(0.9 + 9.4 \sin(h))\}$ with $T_L = 6$?</td><td colspan="6">Is $G_{max}/G_0 < 0.4$?</td></tr>
<tr><td rowspan="6">If "yes"</td><td colspan="5">If "no"</td></tr>
<tr><td colspan="5">Is $G_{min}/G_0 > \{0.3 + \exp(-T_L/(0.9 + 9.4 \sin(h))\}$ with $T_L = 10$?</td></tr>
<tr><td rowspan="4">If "yes"</td><td rowspan="4">If "no"</td><td rowspan="4">If "yes"</td><td colspan="4">If "no"</td></tr>
<tr><td colspan="4">Is $G_{max}/G_0 > \{0.3 + \exp(-T_L/(0.9 + 9.4 \sin(h))\}$ and $G_{max} - G_{min} < 0.1\, G_0$ with $T_L = 10$?</td></tr>
<tr><td rowspan="2">If "yes"</td><td colspan="3">If "no"</td></tr>
<tr><td>$c < 0$</td><td>$0 \leq c \leq 1$</td><td>$c > 1$</td></tr>
<tr><td><i>Result</i></td><td>$f = 0$</td><td>$f = 0$</td><td>$f = 1$</td><td>$f = 0$</td><td>$f = 1$</td><td>$f = 1$</td><td>$f = 0$</td><td>$f = c$</td><td>$f = 1$</td></tr>
</table>

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CHAPTER 9

MEASUREMENT OF VISIBILITY

9.1 GENERAL

9.1.1 Definitions

Visibility was first defined for meteorological purposes as a quantity to be estimated by a human observer, and observations made in that way are widely used. However, the estimation of visibility is affected by many subjective and physical factors. The essential meteorological quantity, which is the transparency of the atmosphere, can be measured objectively and is represented by the meteorological optical range (MOR).

The *meteorological optical range* is the length of path in the atmosphere required to reduce the luminous flux in a collimated beam from an incandescent lamp, at a colour temperature of 2 700 K, to 5 per cent of its original value, the luminous flux being evaluated by means of the photometric luminosity function of the International Commission on Illumination.

Visibility, meteorological visibility (by day) and meteorological visibility at night[1] are defined as the greatest distance at which a black object of suitable dimensions (located on the ground) can be seen and recognized when observed against the horizon sky during daylight or could be seen and recognized during the night if the general illumination were raised to the normal daylight level (WMO, 1992*a;* 2003).

Visual range (meteorological): Distance at which the contrast of a given object with respect to its background is just equal to the contrast threshold of an observer (WMO, 1992*a*).

Airlight is light from the sun and the sky which is scattered into the eyes of an observer by atmospheric suspensoids (and, to a slight extent, by air molecules) lying in the observer's cone of vision. That is, airlight reaches the eye in the same manner as diffuse sky radiation reaches the Earth's surface. Airlight is the fundamental factor limiting the daytime horizontal visibility for black objects, because its contributions, integrated along the cone of vision from eye to object, raise the apparent luminance of a sufficiently remote black object to a level which is indistinguishable from that of the background sky. Contrary to subjective estimates, most of the airlight entering observers' eyes originates in portions of their cone of vision lying rather close to them.

The following four photometric qualities are defined in detail in various standards, such as by the International Electrotechnical Commission (IEC, 1987):

(a) *Luminous flux* (symbol: F (or Φ); unit: lumen) is a quantity derived from radiant flux by evaluating the radiation according to its action upon the International Commission on Illumination standard photometric observer;
(b) *Luminous intensity* (symbol: I; unit: candela or lm sr^{-1}) is luminous flux per unit solid angle;
(c) *Luminance* (symbol: L; unit: cd m^{-2}) is luminous intensity per unit area;
(d) *Illuminance* (symbol; E, unit; lux or lm m^{-2}) is luminous flux per unit area.

The *extinction coefficient* (symbol σ) is the proportion of luminous flux lost by a collimated beam, emitted by an incandescent source at a colour temperature of 2 700 K, while travelling the length of a unit distance in the atmosphere. The coefficient is a measure of the attenuation due to both absorption and scattering.

The *luminance contrast* (symbol C) is the ratio of the difference between the luminance of an object and its background and the luminance of the background.

The *contrast threshold* (symbol ε) is the minimum value of the luminance contrast that the human eye can detect, namely, the value which allows an object to be distinguished from its background. The contrast threshold varies with the individual.

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[1] To avoid confusion, visibility at night should not be defined in general as "the greatest distance at which lights of specified moderate intensity can be seen and identified" (see the *Abridged Final Report of the Eleventh Session of the Commission for Instruments and Methods of Observation* (WMO-No. 807)). If visibility should be reported based on the assessment of light sources, it is recommended that a visual range should be defined by specifying precisely the appropriate light intensity and its application, like runway visual range. Nevertheless, at its eleventh session CIMO agreed that further investigations were necessary in order to resolve the practical difficulties of the application of this definition.

The *illuminance threshold* (symbol E_t) is the smallest illuminance, required by the eye, for the detection of point sources of light against a background of specified luminance. The value of E_t, therefore, varies according to lighting conditions.

The *transmission factor* (symbol *T*) is defined, for a collimated beam from an incandescent source at a colour temperature of 2 700 K, as the fraction of luminous flux which remains in the beam after traversing an optical path of a given length in the atmosphere. The transmission factor is also called the transmission coefficient. The terms transmittance or transmissive power of the atmosphere are also used when the path is defined, that is, of a specific length (for example, in the case of a transmissometer). In this case, *T* is often multiplied by 100 and expressed in per cent.

9.1.2 **Units and scales**

The meteorological visibility or MOR is expressed in metres or kilometres. The measurement range varies according to the application. While for synoptic meteorological requirements, the scale of MOR readings extends from below 100 m to more than 70 km, the measurement range may be more restricted for other applications. This is the case for civil aviation, where the upper limit may be 10 km. This range may be further reduced when applied to the measurement of runway visual range representing landing and take-off conditions in reduced visibility. Runway visual range is required only between 50 and 1 500 m (see Part II, Chapter 2). For other applications, such as road or sea traffic, different limits may be applied according to both the requirements and the locations where the measurements are taken.

The errors of visibility measurements increase in proportion to the visibility, and measurement scales take this into account. This fact is reflected in the code used for synoptic reports by the use of three linear segments with decreasing resolution, namely, 100 to 5 000 m in steps of 100 m, 6 to 30 km in steps of 1 km, and 35 to 70 km in steps of 5 km. This scale allows visibility to be reported with a better resolution than the accuracy of the measurement, except when visibility is less than about 1 000 m.

9.1.3 **Meteorological requirements**

The concept of visibility is used extensively in meteorology in two distinct ways. First, it is one of the elements identifying air-mass characteristics, especially for the needs of synoptic meteorology and climatology. Here, visibility must be representative of the optical state of the atmosphere. Secondly, it is an operational variable which corresponds to specific criteria or special applications. For this purpose, it is expressed directly in terms of the distance at which specific markers or lights can be seen.

One of the most important special applications is found in meteorological services to aviation (see Part II, Chapter 2).

The measure of visibility used in meteorology should be free from the influence of extra-meteorological conditions; it must be simply related to intuitive concepts of visibility and to the distance at which common objects can be seen under normal conditions. MOR has been defined to meet these requirements, as it is convenient for the use of instrumental methods by day and night, and as the relations between MOR and other measures of visibility are well understood. MOR has been formally adopted by WMO as the measure of visibility for both general and aeronautical uses (WMO, 1990*a*). It is also recognized by the International Electrotechnical Commission (IEC, 1987) for application in atmospheric optics and visual signalling.

MOR is related to the intuitive concept of visibility through the contrast threshold. In 1924, Koschmieder, followed by Helmholtz, proposed a value of 0.02 for ε . Other values have been proposed by other authors. They vary from 0.007 7 to 0.06, or even 0.2. The smaller value yields a larger estimate of the visibility for given atmospheric conditions. For aeronautical requirements, it is accepted that ε is higher than 0.02, and it is taken as 0.05 since, for a pilot, the contrast of an object (runway markings) with respect to the surrounding terrain is much lower than that of an object against the horizon. It is assumed that, when an observer can just see and recognize a black object against the horizon, the apparent contrast of the object is 0.05, and, as explained below, this leads to the choice of 0.05 as the transmission factor adopted in the definition of MOR.

Accuracy requirements are discussed in Part I, Chapter 1.

9.1.4 **Measurement methods**

Visibility is a complex psycho-physical phenomenon, governed mainly by the atmospheric extinction coefficient associated with solid and liquid particles held in suspension in the atmosphere; the extinction is caused primarily by scattering rather than by absorption of the light. Its estimation is subject to variations in individual perception and interpretative ability, as well as the light source characteristics and the transmission factor. Thus, any visual estimate of visibility is subjective.

When visibility is estimated by a human observer it depends not only on the photometric and dimensional characteristics of the object which is, or should be, perceived, but also on the observer's contrast threshold. At night, it depends on the intensity of the light sources, the background illuminance and, if estimated by an observer, the adaptation of the observer's eyes to darkness and the observer's illuminance threshold. The estimation of visibility at night is particularly problematic. The first definition of visibility at night in section 9.1.1 is given in terms of equivalent daytime visibility in order to ensure that no artificial changes occur in estimating the visibility at dawn and twilight. The second definition has practical applications especially for aeronautical requirements, but it is not the same as the first and usually gives different results. Both are evidently imprecise.

Instrumental methods measure the extinction coefficient from which the MOR may be calculated. The visibility may then be calculated from knowledge of the contrast and illuminance thresholds, or by assigning agreed values to them. It has been pointed out by Sheppard (1983) that:

> "strict adherence to the definition (of MOR) would require mounting a transmitter and receiver of appropriate spectral characteristics on two platforms which could be separated, for example along a railroad, until the transmittance was 5 per cent. Any other approach gives only an estimate of MOR."

However, fixed instruments are used on the assumption that the extinction coefficient is independent of distance. Some instruments measure attenuation directly and others measure the scattering of light to derive the extinction coefficient. These are described in section 9.3. The brief analysis of the physics of visibility in this chapter may be useful for understanding the relations between the various measures of the extinction coefficient, and for considering the instruments used to measure it.

Visual perception — photopic and scotopic vision

The conditions of visual perception are based on the measurement of the photopic efficiency of the human eye with respect to monochromatic radiation in the visible light spectrum. The terms *photopic vision* and *scotopic vision* refer to daytime and night-time conditions, respectively.

The adjective *photopic* refers to the state of accommodation of the eye for daytime conditions of ambient luminance. More precisely, the photopic state is defined as the visual response of an observer with normal sight to the stimulus of light incident on the retinal fovea (the most sensitive central part of the retina). The fovea permits fine details and colours to be distinguished under such conditions of adaptation.

In the case of photopic vision (vision by means of the fovea), the relative luminous efficiency of the eye varies with the wavelength of the incident light. The luminous efficiency of the eye in photopic vision is at a maximum for a wavelength of 555 nm. The response curve for the relative efficiency of the eye at the various wavelengths of the visible spectrum may be established by taking the efficiency at a wavelength of 555 nm as a reference value. The curve in Figure 9.1, adopted by the International Commission on Illumination for an average normal observer, is therefore obtained.

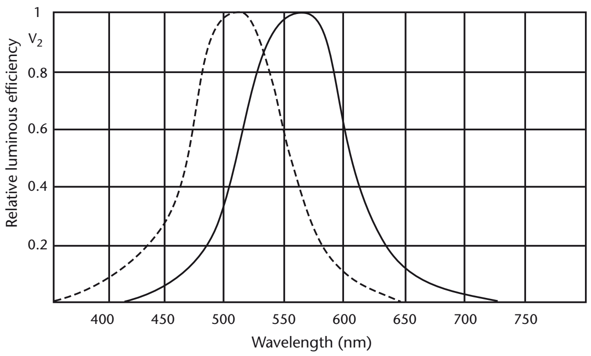

Figure 9.1. Relative luminous efficiency of the human eye for monochromatic radiation. The continuous line indicates daytime vision, while the broken line indicates night-time vision.

Night-time vision is said to be scotopic (vision involving the rods of the retina instead of the fovea). The rods, the peripheral part of the retina, have no sensitivity to colour or fine details, but are particularly sensitive to low light intensities. In scotopic vision, maximum luminous efficiency corresponds to a wavelength of 507 nm.

Scotopic vision requires a long period of accommodation, up to 30 min, whereas photopic vision requires only 2 min.

Basic equations

The basic equation for visibility measurements is the Bouguer-Lambert law:

$$F = F_0 \, e^{-\sigma x} \tag{9.1}$$

where F is the luminous flux received after a length of path x in the atmosphere and F_0 is the flux for $x = 0$. Differentiating, we obtain:

$$\sigma = \frac{-dF}{F} \cdot \frac{1}{dx} \tag{9.2}$$

Note that this law is valid only for monochromatic light, but may be applied to a spectral flux to a good approximation. The transmission factor is:

$$T = F/F_0 \tag{9.3}$$

Mathematical relationships between MOR and the different variables representing the optical state of the atmosphere may be deduced from the Bouguer-Lambert law.

From equations 9.1 and 9.3 we may write:

$$T = F/F_0 = e^{-\sigma x} \tag{9.4}$$

If this law is applied to the MOR definition $T = 0.05$, then $x = P$ and the following may be written:

$$T = 0.05 = e^{-\sigma P} \tag{9.5}$$

Hence, the mathematical relation of MOR to the extinction coefficient is:

$$P = (1/\sigma) \cdot \ln (1/0.05) \approx 3/\sigma \tag{9.6}$$

where ln is the log to base e or the natural logarithm. When combining equation 9.4, after being deduced from the Bouguer-Lambert law, and equation 9.6, the following equation is obtained:

$$P = x \cdot \ln (0.05)/\ln (T) \tag{9.7}$$

This equation is used as a basis for measuring MOR with transmissometers where x is, in this case, equal to the transmissometer baseline a in equation 9.14.

Meteorological visibility in daylight

The contrast of luminance is:

$$C = \frac{L_b - L_h}{L_h} \tag{9.8}$$

where L_h is the luminance of the horizon, and L_b is the luminance of the object.

The luminance of the horizon arises from the airlight scattered from the atmosphere along the observer's line of sight.

It should be noted that, if the object is darker than the horizon, C is negative, and that, if the object is black ($L_b = 0$), $C = -1$.

In 1924, Koschmieder established a relationship, which later became known as Koschmieder's law, between the apparent contrast (C_x) of an object, seen against the horizon sky by a distant observer, and its inherent contrast (C_0), namely, the contrast that the object would have against the horizon when seen from very short range. Koschmieder's relationship can be written as:

$$C_x = C_0 \, e^{-\sigma x} \tag{9.9}$$

This relationship is valid provided that the scatter coefficient is independent of the azimuth angle and that there is uniform illumination along the whole path between the observer, the object and the horizon.

If a black object is viewed against the horizon ($C_0 = -1$) and the apparent contrast is –0.05, equation 9.9 reduces to:

$$0.05 = e^{-\sigma x} \tag{9.10}$$

Comparing this result with equation 9.5 shows that when the magnitude of the apparent contrast of a black object, seen against the horizon, is 0.05, that object is at MOR (P).

Meteorological visibility at night

The distance at which a light (a night visibility marker) can be seen at night is not simply related to MOR. It depends not only on MOR and the intensity of the light, but also on the illuminance at the observer's eye from all other light sources.

In 1876, Allard proposed the law of attenuation of light from a point source of known intensity (I) as a function of distance (x) and extinction coefficient (σ). The illuminance (E) of a point light source is given by:

$$E = I \cdot x^{-2} \cdot e^{-\sigma x} \tag{9.11}$$

When the light is just visible, $E = E_t$ and the following may be written:

$$\sigma = (1/x) \cdot \ln \{I/(E_t \cdot x^2)\} \tag{9.12}$$

Noting that $P = (1/\sigma) \cdot \ln(1/0.05)$ in equation 9.6, we may write:

$$P = x \cdot \ln(1/0.05)/\ln(I/(E_t \cdot x^2) \qquad (9.13)$$

The relationship between MOR and the distance at which lights can be seen is described in section 9.2.3, while the application of this equation to visual observations is described in section 9.2.

9.2 VISUAL ESTIMATION OF METEOROLOGICAL OPTICAL RANGE

9.2.1 General

A meteorological observer can make a visual estimation of MOR using natural or man-made objects (groups of trees, rocks, towers, steeples, churches, lights, and so forth).

Each station should prepare a plan of the objects used for observation, showing their distances and bearings from the observer. The plan should include objects suitable for daytime observations and objects suitable for night-time observations. The observer must also give special attention to significant directional variations of MOR.

Observations should be made by observers who have "normal" vision and have received suitable training. The observations should normally be made without any additional optical devices (binoculars, telescope, theodolite, and the like) and, preferably, not through a window, especially when objects or lights are observed at night. The eye of the observer should be at a normal height above the ground (about 1.5 m); observations should, thus, not be made from the upper storeys of control towers or other high buildings. This is particularly important when visibility is poor.

When visibility varies in different directions, the value recorded or reported may depend on the use to be made of the report. In synoptic messages, the lower value should be reported, but in reports for aviation the guidance in WMO (1990*a*) should be followed.

9.2.2 Estimation of meteorological optical range by day

For daytime observations, the visual estimation of visibility gives a good approximation of the true value of MOR.

Provided that they meet the following requirements, objects at as many different distances as possible should be selected for observation during the day. Only black, or nearly black, objects which stand out on the horizon against the sky should be chosen. Light-coloured objects or objects located close to a terrestrial background should be avoided as far as possible. This is particularly important when the sun is shining on the object. Provided that the albedo of the object does not exceed about 25 per cent, no error larger than 3 per cent will be caused if the sky is overcast, but it may be much larger if the sun is shining. Thus, a white house would be unsuitable, but a group of dark trees would be satisfactory, except when brightly illuminated by sunlight. If an object against a terrestrial background has to be used, it should stand well in front of the background, namely, at a distance at least half that of the object from the point of observation. A tree at the edge of a wood, for example, would not be suitable for visibility observations.

For observations to be representative, they should be made using objects subtending an angle of no less than 0.5° at the observer's eye. An object subtending an angle less than this becomes invisible at a shorter distance than would large objects in the same circumstances. It may be useful to note that a hole of 7.5 mm in diameter, punched in a card and held at arm's length, subtends this angle approximately; a visibility object viewed through such an aperture should, therefore, completely fill it. At the same time, however, such an object should not subtend an angle of more than 5°.

9.2.3 Estimation of meteorological optical range at night

Methods which may be used to estimate MOR at night from visual observations of the distance of perception of light sources are described below.

Any source of light may be used as a visibility object, provided that the intensity in the direction of observation is well defined and known. However, it is generally desirable to use lights which can be regarded as point sources, and whose intensity is not greater in any one more favoured direction than in another and not confined to a solid angle which is too small. Care must be taken to ensure the mechanical and optical stability of the light source.

A distinction should be made between sources known as point sources, in the vicinity of which there is no other source or area of light, and clusters of lights, even though separated from each other. In the latter case, such an arrangement may affect the visibility of each source considered separately. For measurements of visibility at night, only the use of suitably distributed point sources is recommended.

It should be noted that observations at night, using illuminated objects, may be affected appreciably by the illumination of the surroundings, by the physiological effects of dazzling, and by other lights, even when these are outside the field of vision and, more especially, if the observation is made through a window. Thus, an accurate and reliable observation can be made only from a dark and suitably chosen location.

Furthermore, the importance of physiological factors cannot be overlooked, since these are an important source of measurement dispersion. It is essential that only qualified observers with normal vision take such measurements. In addition, it is necessary to allow a period of adaptation (usually from 5 to 15 min) during which the eyes become accustomed to the darkness.

For practical purposes, the relationship between the distance of perception of a light source at night and the value of MOR can be expressed in two different ways, as follows:

(a) For each value of MOR, by giving the value of luminous intensity of the light, so that there is a direct correspondence between the distance where it is barely visible and the value of MOR;

(b) For a light of a given luminous intensity, by giving the correspondence between the distance of perception of the light and the value of MOR.

The second relationship is easier and also more practical to use since it would not be an easy matter to install light sources of differing intensities at different distances. The method involves using light sources which either exist or are installed around the station and replacing I, x and E_t in equation 9.13 by the corresponding values of the available light sources. In this way, the Meteorological Services can draw up tables giving values of MOR as a function of background luminance and the light sources of known intensity. The values to be assigned to the illuminance threshold E_t vary considerably in accordance with the ambient luminance. The following values, considered as average observer values, should be used:

(a) $10^{-6.0}$ lux at twilight and at dawn, or when there is appreciable light from artificial sources;

(b) $10^{-6.7}$ lux in moonlight, or when it is not yet quite dark;

(c) $10^{-7.5}$ lux in complete darkness, or with no light other than starlight.

Tables 9.1 and 9.2 give the relations between MOR and the distance of perception of light sources for each of the above methods for different observation conditions. They have been compiled to guide Meteorological Services in the selection or installation of lights for night visibility observations and in the preparation of instructions for their observers for the computation of MOR values.

Table 9.1. Relation between MOR and intensity of a just-visible point source for three values of E_t

MOR	*Luminous intensity (candela) of lamps only just visible at distances given in column P*		
P (m)	*Twilight ($E_t = 10^{-6.0}$)*	*Moonlight ($E_t = 10^{-6.7}$)*	*Complete darkness ($E_t = 10^{-7.5}$)*
100	0.2	0.04	0.006
200	0.8	0.16	0.025
500	5	1	0.16
1 000	20	4	0.63
2 000	80	16	2.5
5 000	500	100	16
10 000	2 000	400	63
20 000	8 000	1 600	253
50 000	50 000	10 000	1 580

Table 9.2. Relation between MOR and the distance at which a 100 cd point source is just visible for three values of E_t

MOR	*Distance of perception (metres) of a lamp of 100 cd as a function of MOR value*		
P (m)	*Twilight ($E_t = 10^{-6.0}$)*	*Moonlight ($E_t = 10^{-6.7}$)*	*Complete darkness ($E_t = 10^{-7.5}$)*
100	250	290	345
200	420	500	605
500	830	1 030	1 270
1 000	1 340	1 720	2 170
2 000	2 090	2 780	3 650
5 000	3 500	5 000	6 970
10 000	4 850	7 400	10 900
20 000	6 260	10 300	16 400
50 000	7 900	14 500	25 900

An ordinary 100 W incandescent bulb provides a light source of approximately 100 cd.

In view of the substantial differences caused by relatively small variations in the values of the visual illuminance threshold and by different conditions of general illumination, it is clear that Table 9.2 is not intended to provide an absolute criterion of visibility, but indicates the need for calibrating the lights used for night-time estimation of MOR so as to ensure as far as possible that night observations made in different locations and by different Services are comparable.

9.2.4 Estimation of meteorological optical range in the absence of distant objects

At certain locations (open plains, ships, and so forth), or when the horizon is restricted (valley or cirque), or in the absence of suitable visibility objects, it is impossible to make direct estimations, except for relatively low visibilities. In such cases, unless instrumental methods are available, values of MOR higher than those for which visibility points are available have to be estimated from the general transparency of the atmosphere. This can be done by noting the degree of clarity with which the most distant visibility objects stand out. Distinct outlines and features, with little or no fuzziness of colours, are an indication that MOR is greater than the distance between the visibility object and the observer. On the other hand, indistinct visibility objects are an indication of the presence of haze or of other phenomena reducing MOR.

9.2.5 Accuracy of visual observations

General

Observations of objects should be made by observers who have been suitably trained and have what is usually referred to as normal vision. This human factor has considerable significance in the estimation of visibility under given atmospheric conditions, since the perception and visual interpretation capacity vary from one individual to another.

Accuracy of daytime visual estimates of meteorological optical range

Observations show that estimates of MOR based on instrumental measurements are in reasonable agreement with daytime estimates of visibility. Visibility and MOR should be equal if the observer's contrast threshold is 0.05 (using the criterion of recognition) and the extinction coefficient is the same in the vicinity of both the instrument and the observer.

Middleton (1952) found, from 1000 measurements, that the mean contrast ratio threshold for a group of 10 young airmen trained as meteorological observers was 0.033 with a range, for individual observations, from less than 0.01 to more than 0.2. Sheppard (1983) has pointed out that when the Middleton data are plotted on a logarithmic scale they show good agreement with a Gaussian distribution. If the Middleton data represent normal observing conditions, we must expect daylight estimates of visibility to average about 14 per cent higher than MOR with a standard deviation of 20 per cent of MOR. These calculations are in excellent agreement with the results from the First WMO Intercomparison of Visibility Measurements (WMO, 1990*b*), where it was found that, during daylight, the observers' estimates of visibility were about 15 per cent higher than instrumental measurements of MOR. The interquartile range of differences between the observer and the instruments was about 30 per cent of the measured MOR. This corresponds to a standard deviation of about 22 per cent, if the distribution is Gaussian.

Accuracy of night-time visual estimates of meteorological optical range

From table 9.2 in section 9.2.3, it is easy to see how misleading the values of MOR can be if based simply on the distance at which an ordinary light is visible, without making due allowance for the intensity of the light and the viewing conditions. This emphasizes the importance of giving precise, explicit instructions to observers and of providing training for visibility observations.

Note that, in practice, the use of the methods and tables described above for preparing plans of luminous objects is not always easy. The light sources used as objects are not necessarily well located or of stable, known intensity, and are not always point sources. With respect to this last point, the lights may be wide- or narrow-beam, grouped, or even of different colours to which the eye has different sensitivity. Great caution must be exercised in the use of such lights.

The estimation of the visual range of lights can produce reliable estimates of visibility at night only when lights and their background are carefully chosen; when the viewing conditions of the observer are carefully controlled; and when considerable time can be devoted to the observation to ensure that the observer's eyes are fully accommodated to the viewing conditions. Results from the First WMO Intercomparison of Visibility Measurements (WMO, 1990*b*) show that, during the hours of darkness, the observer's estimates of visibility were about 30 per cent higher than instrumental measurements of MOR. The interquartile range of differences between the observer and the instruments was only slightly greater than that found during daylight (about 35 to 40 per cent of the measured MOR).

9.3 INSTRUMENTAL MEASUREMENT OF THE METEOROLOGICAL OPTICAL RANGE

9.3.1 General

The adoption of certain assumptions allows the conversion of instrumental measurements into MOR. It is not always advantageous to use an instrument for daytime measurements if a number of suitable visibility objects can be used for direct observations. However, a visibility-measuring instrument is often useful for night observations or when no visibility objects are available, or for automatic observing systems. Instruments for the measurement of MOR may be classified into one of the following two categories:

(a) Those measuring the extinction coefficient or transmission factor of a horizontal cylinder of air: Attenuation of the light is due to both scattering and absorption by particles in the air along the path of the light beam;
(b) Those measuring the scatter coefficient of light from a small volume of air: In natural fog, absorption is often negligible and the scatter coefficient may be considered as being the same as the extinction coefficient.

Both of the above categories include instruments used for visual measurements by an observer and instruments using a light source and an electronic device comprising a photoelectric cell or a photodiode to detect the emitted light beam. The main disadvantage of visual measurements is that substantial errors may occur if observers do not allow sufficient time for their eyes to become accustomed to the conditions (particularly at night).

The main characteristics of these two categories of MOR-measuring instruments are described below.

9.3.2 INSTRUMENTS MEASURING THE EXTINCTION COEFFICIENT

Telephotometric instruments

A number of telephotometers have been designed for daytime measurement of the extinction coefficient by comparing the apparent luminance of a distant object with that of the sky background (for example, the Lohle telephotometer), but they are not normally used for routine measurements since, as stated above, it is preferable to use direct visual observations. These instruments may, however, be useful for extrapolating MOR beyond the most distant object.

Visual extinction meters

A very simple instrument for use with a distant light at night takes the form of a graduated neutral filter, which reduces the light in a known proportion and can be adjusted until the light is only just visible. The meter reading gives a measure of the transparency of the air between the light and the observer, and, from this, the extinction coefficient can be calculated. The overall accuracy depends mainly on variations in the sensitivity of the eye and on fluctuations in the radiant intensity of the light source. The error increases in proportion to MOR.

The advantage of this instrument is that it enables MOR values over a range from 100 m to 5 km to be measured with reasonable accuracy, using only three well-spaced lights, whereas without it a more elaborate series of lights would be essential if the same degree of accuracy were to be achieved. However, the method of using such an instrument (determining the point at which a light appears or disappears) considerably affects the accuracy and homogeneity of the measurements.

Transmissometers

The use of a transmissometer is the method most commonly used for measuring the mean extinction coefficient in a horizontal cylinder of air between a transmitter, which provides a modulated flux light source of constant mean power, and a receiver incorporating a photodetector (generally a photodiode at the focal point of a parabolic mirror or a lens). The most frequently used light source is a halogen lamp or xenon pulse discharge tube. Modulation of the light source prevents disturbance from sunlight. The transmission factor is determined from the photodetector output and this allows the extinction coefficient and the MOR to be calculated.

Since transmissometer estimates of MOR are based on the loss of light from a collimated beam, which depends on scatter and absorption, they are closely related to the definition of MOR. A good, well-maintained transmissometer