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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% 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, 7.2 and 7.2.1.3).

8.1.1 Definition

According to WMO (2010),[2] sunshine duration during a given period is defined as the sum of the time 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.

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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).

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 can (depending on the amount of dust) be erroneous because of an imperfectly adjusted threshold or spectral dependencies.

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% 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:

$$G/G_0 = a + b \cdot (SD/SD_0) \tag{8.1}$$

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% in summer, and rose up to 30% 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 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, or alternatively to deliver 1 min means of global (G) solar irradiance.

(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 multi-sensor 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 $V_{th} = 120\ \mathrm{W\ m^{-2}} \cdot R\ \mu V\ \mathrm{W^{-1}\ m^{2}}$, which is calculable 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, 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.

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

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:

$$I \cdot \cos\zeta = G - D \tag{8.2}$$

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:

$$(G - D)/\cos\zeta > 120\ \mathrm{W\ m^{-2}} \tag{8.3}$$

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).

Different algorithms, based on different assumptions, can be used to estimate sunshine duration from the measurement of only one pyranometer.

The Slob and Monna method (Slob and Monna, 1991) 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 extra-terrestrial irradiation (G_0) by taking into account extinction in the atmosphere. The attenuation 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 continuous sunshine 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 attenuation 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 Annex 8.A. The uncertainty is about 0.6 h for daily sums, though recent work (Hinssen and Knap, 2007; WMO, 2012) showed that the expanded uncertainty ($k = 2$) on daily totals can exceed 1 h.

The Carpentras method assumes the possibility of parameterizing and calculating over 1 min intervals an irradiance threshold (G_{thr}) of G as a function of the most frequent in situ conditions of atmospheric turbidity and solar elevation (h). The corresponding algorithm of this method is given in Annex 8.B. The achievable expanded uncertainty ($k = 2$) for daily totals is about 0.7 h (WMO, 2012).

The application of the Carpentras method can be optimized by using 1 min average global and direct irradiances (used as reference) for a few consecutive years (at least four), which makes it possible to determine the coefficients for the parameterization of the 1 min G_{thr} for the specific location. This minimizes the total relative error of daily SD calculated by the Carpentras method over a long period of time (years) by using the SD cumulative differences, and also provides an evaluation of the achievable uncertainty of the Carpentras method (Morel et al., 2012).

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.

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).

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.

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:	Thickness: 0.4 ± 0.05 mm
Refractive index: 1.52 ± 0.02	(a) Central noon line engraved transversely across inner surface	Moisture effect: Within 2%
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
	(c) Double base with provision for levelling and azimuth setting	Graduations: Hour-lines printed in black

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 heated device, is about 1% of the monthly mean in summer and about 5% to 10% 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 et al., 1986).

The morning values are frequently affected 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 (≤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 or gloss 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.

The siting classification for surface observing stations on land (see Part I, Chapter 1, Annex 1.B of this Guide) provides additional guidance on the selection of a site and the location of a sunshine detector within a site in order to optimize representativeness.

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 datasets covering long periods.

If the method is applied to the total dataset 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 datasets 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 datasets 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 dataset 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%, 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 $n = 0, 1, 2, \dots 180$). 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%. 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 dataset 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 8.A. 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 $= I_0 \sin(h)$, $I_0 = 1\,367$ W m^{-2} (for extra-terrestrial irradiance)
I $= I_0 \exp(-T_L/(0.9 + 9.4 \sin(h)))$, $I_0 = 1\,367$ 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
$D = 0.4$

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

ANNEX 8.B. ALGORITHM TO ESTIMATE SUNSHINE DURATION FROM 1 MIN GLOBAL IRRADIANCE MEASUREMENTS

(Carpentras method; see WMO, 1998, 2012)

This method, developed at the WMO Regional Radiation Centre of Carpentras (France) and described by Oliviéri (WMO, 1998), consists of an algorithm that calculates the SD every minute through the measurement of 1 min means of global irradiance (G) compared with a threshold value (G_{thr}) that is parameterized by two coefficients (A, B) and the solar elevation h (specifically sin (h)).

The following variables are applicable:

h	Elevation angle of the sun in degrees (see Part I, Chapter 7, Annex 7.D)
G	Global irradiance on a horizontal surface in W m^{-2} (1 s sampled, 1 min averaged)

Equations used:

$G_{thr} = F_c$ x Mod
Mod = 1 080 (sin (h))$^{1.25}$
$F_c = A + B \cos (2\pi d/365)$

where Mod represents the global irradiance obtained from a cloudless day model (clear sky and mean value of turbidity); F_c represents a factor, the empirical value of which is close to 0.7; and d is the day number of the annual sequence.

The F_c factor, generally varying between 0.5 and 0.8, depends on the climatic conditions of the location, and the A, B coefficients can be empirically calculated by long-term comparison between SD and pyrheliometer measurements (Morel et al., 2012). Alternatively, the presence of near or, even better, co-located instruments for atmospheric turbidity permits an improved determination of the F_c factor. A variability of the A and B coefficients has been observed in relation to latitude (B tends towards negative values for the southern hemisphere, while A decreases with latitude).

The algorithm is run every minute and can be expressed as follows:

Sun elevation	$h < 3°$	$h \geq 3°$	
Criteria	No decision	Is $G \geq G_{thr}$?	
		If “yes”	If “no”
Result	SD = 0 min	SD = 1 min	SD = 0 min

The solar elevation must be calculated every minute contemporarily to the sun hour angle, right ascension and geocentric declination according to the astronomical formulae reported in Part I, Chapter 7, Annex 7.D.

The data filtering ($h \geq 3°$) is applied before the execution of the main test and permits the filtering of errors due to the imperfection of the model, the height of the sun (low heights) and the atmospheric refraction. A tolerance of 3° above the horizon is accepted for the requirement that the SD detectors have an uninterrupted view of the sun at all times of the year. The errors introduced by the data filtering on h produce a small underestimation that, due to their systematic nature, can be corrected after a long period of measurements. A comparison of this method with other methods and with reference SD data is reported in WMO (2012).

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