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Shade-ring corrections for pyranometer measurements of diffuse solar radiation from cloudless skies

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SUMMARY

When a shade ring is used to shield a pyranometer from direct solar radiation, a correction to the measured diffuse radiation is necessary to account for diffuse radiation intercepted by the ring. A general analysis is developed to relate shade-ring corrections to the radiance distribution of diffuse radiation. The corrections are split into two components: a geometric component based on an isotropic sky and varying with shade-ring dimensions; and an anisotropy component, relatively independent of ring dimensions. Shade-ring corrections are calculated using mean distributions of the radiance of cloudless skies. Tables and figures are given for calculating these corrections as functions of latitude, ring dimensions and time of year. Comparisons with published measurements at a variety of sites reveal generally good agreement with calculations. Some of the discrepancies may be due to differences in aerosol scattering.

1. INTRODUCTION

The accurate assessment of diffuse and direct solar radiation is an important step in using routine radiation records on horizontal surfaces for estimating radiation interception by the diverse surfaces of hills, solar collectors, buildings, vegetation or animals.

Measurements of diffuse solar radiation are usually made by shielding a pyranometer from the direct solar beam. The most precise method is to shade the pyranometer with a small disc, but this method is difficult to maintain in continuous operation and a shade ring is often employed. The ring, which casts a shadow of projected width somewhat larger than the pyranometer sensor, is mounted on a polar axis so as to obscure the entire diurnal path of the sun (Fig. 1). Adjustments are necessary every few days to allow for changing solar declination. Various dimensions of ring are in use and ring designs are described fully by Blackwell (1954), Drummond (1956) and Schmid (1976).

Shade rings obscure not only the sun but also a substantial fraction of the sky, and to derive a true measurement of diffuse solar radiation it is necessary to correct for the diffuse radiation intercepted by the ring. On the assumption of an isotropic distribution of sky radiance, Drummond (1956) derived an expression for the correction factor as a function of ring dimensions, latitude and solar declination. This expression accounts for the geometry of the shade ring but generally underestimates the true correction factor when skies are cloudless or partly cloudy, because it does not fully compensate for the obscured part of the bright region of sky near the sun. To obtain more accurate correction factors requires a detailed comparison of measurements using rings and discs, or other methods, in all kinds of weather. Such an approach was adopted by Painter (1979) who investigated the mean behaviour of the correction factor with solar declination, and with cloud amount as measured by the ratio of diffuse to global radiation on a horizontal surface. An alternative method, particularly suitable when skies are cloudless, is to use the distribution of radiance in the sky to calculate the radiation intercepted by the ring. The same set of distributions can be

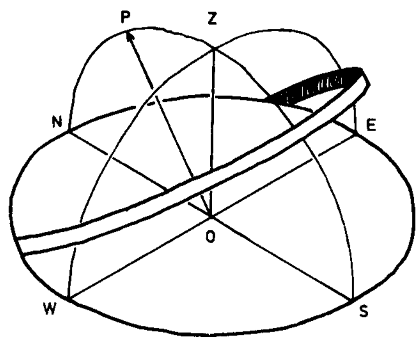

Figure 1. Aerial projected view of a shade ring. The pyranometer is at O. The shade ring is in the plane perpendicular to the polar axis OP and is moved up and down the axis with the seasons. The ring position shown is for 53°N when the solar declination is 16° (6 May or 8 August).

used to estimate corrections for different ring dimensions, and also for different latitudes and seasons if the scattering properties of the atmosphere can be assumed constant. Schöne and Sonntag (1976) and Schmid (1976) demonstrated this approach but used hypothetical distributions of radiance. In this paper we calculate shade ring corrections based on mean distributions of radiance measured with cloudless skies (Steven 1977).

2. Theory and definitions

The radiation S_d' measured by a pyranometer with a shade ring is given by

$$S_d' = S_d - S_r + S_r' \qquad (1)$$

where S_d is the true diffuse radiation from the whole sky, S_r is the diffuse radiation intercepted by the ring, i.e. radiation that would otherwise have fallen on the sensor, and S_r' is radiation reflected to the sensor from the inner surface of the ring. Since this surface is usually painted black and is never irradiated by the direct solar beam, S_r' is usually negligible and is omitted in the following analysis. To correct for S_r, the measured diffuse radiation must be multiplied by a factor k given by

$$k = S_d/S_d' \simeq S_d/(S_d - S_r) = 1/(1 - S_r/S_d) \qquad (2)$$

It is convenient to separate k into two terms by writing

$$k = 1/(1 - qf) \qquad (3)$$

where $f = S_{r0}/S_d$ and $q = S_r/S_{r0}$.

Here S_{r0} is the diffuse irradiance that would be intercepted by the ring if the radiance distribution were isotropic. This formulation separates the geometric contribution to the correction from the effect of anisotropy in the sky. The factor f is the horizontal view factor of the shade ring, i.e. the area of the ring projected on a horizontal plane relative to the equivalent projected area for a hemisphere of the same radius. The factor q is related to the relative brightness of the obscured region of sky and will be shown to be almost independent of shade-ring dimensions for all practical sizes of shade ring.

To demonstrate the difference between a geometric shade-ring correction based on an isotropic sky and the full correction k, it is useful to define the geometric correction g by analogy with Eq. (3) as

$$g = 1/(1-f) \quad . \quad . \quad . \quad . \quad (4)$$

When the sky radiance N is known as a function of zenith angle θ and azimuth ϕ, then S_r may be calculated by integrating the radiance projected onto the horizontal plane over the area of the ring, i.e.

$$S_r = \iint_{\text{ring}} N(\theta,\phi) \cos\theta \sin\theta \, d\phi \, d\theta \quad . \quad . \quad (5)$$

The finite area of the pyranometer sensor is neglected in this analysis, but this introduces significant errors only if the size of the sensor is comparable with the ring radius.

Drummond (1956) showed that the area integral (Eq. (5)) could be approximated by a line integral along the solar path giving

$$S_r \simeq (b/r) \int_{-t_0}^{t_0} N\{\theta(t),\phi(t)\} (\sin\lambda \sin\delta + \cos\lambda \cos\delta \cos t) \, dt \quad . \quad (6)$$

in which b = ring width, r = ring radius, t_0 = hour angle (in radians) of sunset from solar noon, δ = solar declination and λ = latitude. The parameter t is used here as a dummy variable, the sun's position being fixed. Schmid (1976) pointed out that the line integral approximation is valid only for narrow shade rings, and suggested that $b/r = 0{\cdot}2$ may be an upper limit for this approach.

For the special case of the isotropic sky, with N constant, Drummond integrated Eq. (6) analytically, yielding

$$S_{r0} = 2b\,N\,r^{-1} \cos^3\delta\,(t_0 \sin\delta \sin\lambda + \sin t_0 \cos\delta \cos\lambda) \quad . \quad (7)$$

Consequently, since $S_d = \pi N$ for an isotropic sky, the geometric part of the correction factor is given by

$$f = 2b\,\pi^{-1}\,r^{-1} \cos^3\delta\,(t_0 \sin\delta \sin\lambda + \sin t_0 \cos\delta \cos\lambda) \quad . \quad (8)$$

To evaluate q it is necessary to know the distribution of sky radiance. The present analysis uses the 'Standard distributions of clear sky radiance' presented by Steven (1977). In that study, measurements of radiance at selected points in the sky were made on cloudless days with a wide range of atmospheric turbidities. It was observed that while S_d varied considerably with changing turbidity, the ratios of radiance values to S_d varied very little. Normalizing the radiance values N with respect to S_d enabled averages to be taken and the standard distributions represent means of normalized sky radiance for four solar elevations. These distributions were approximated to a high degree of accuracy by a series of functions as described by Steven and Unsworth (1979). By substituting the functions into Eq. (5), area integrals were evaluated numerically to obtain S_r/S_d.

Measurements of the direct solar beam at normal incidence inevitably include a component of diffuse radiation from the solar aureole observed near the sun. While there may be sound pedagogical reasons for wanting to exclude the effect of the aureole from measurements of the direct beam, it is in practice impossible to eliminate it altogether.

Moreover, radiation from the aureole has essentially the same directional properties as true direct solar radiation, and for the practical concerns of climatology it is reasonable to combine the aureole with the direct beam. Almost all the energy of the aureole comes from a zone of angular diameter 10 degrees (Ångström and Rodhe 1966), which is close to the average effective aperture of many standard pyrheliometers surveyed by Ångström and Rodhe. To assign radiation from the aureole to the direct solar beam, the integral in Eq. (5) was evaluated over a 10° diameter circumsolar zone and the resulting estimate of aureole irradiance was subtracted from the computed values of S_r. The ring correction factors given in the next section are thus based on a definition of S_d that excludes radiation from the region within 5° of the sun.

3. Computed shade-ring corrections

Computed shade-ring corrections are shown in Fig. 2 for Sutton Bonington (52·8°N 1·3°W) where the shade ring is the standard UK Meteorological office design with $b = 50$ mm and $r = 254$ mm. The lower curve shows the geometric ring correction g (Eq. (4)). The upper curves show computed values of k (Eqs. (2) and (3)) for clear skies at four solar elevations. The differences between the upper four curves are an indication of the diurnal variation in k, which is small but consistent; correction factors at high solar elevation are about 0·01 higher than at low solar elevation. The seasonal variation is larger and may amount to 0·07 over the year. The largest correction factors are required at the equinoxes when the shade ring is closest to the sensor. The seasonal variation in k is less than the corresponding

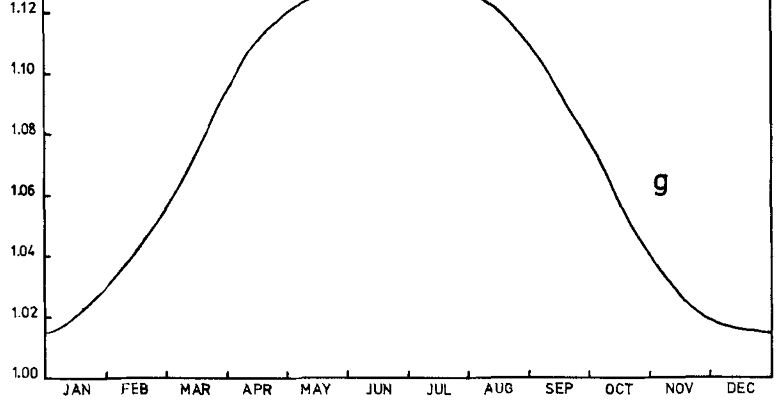

Figure 2. Seasonal variation of computed shade-ring corrections at Sutton Bonington, 52·8°N, b/r = 0·2. The dotted curves k are for cloudless skies at four solar elevations: 25° —— ——, 35° — • —, 45° – – –, 55° . . . . . The solid curve g shows the geometric ring correction.

variation in g because, when f becomes smaller in winter, the bright region near the sun – not entirely accounted for in the aureole as defined earlier – occupies a larger fraction of the ring area. The factor q therefore increases and partly compensates for the decrease in f.

4. Comparisons with direct measurements

Although the clear sky radiance distributions were measured at Sutton Bonington, Steven (1977) argued that they have a more general validity. Computations were made using the same distributions with various ring dimensions and with ring orientations appropriate to other latitudes. Table 1 shows a comparison between the computed results and direct measurements of the ring correction made by ourselves and by other authors. Our measurements were made on several clear days in 1971 and 1979 using the ring and a disc alternately to shade a Kipp pyranometer (model CM2). The disc had a diameter of 155 mm and was held at 0·9 m from the pyranometer, thus subtending an angle of 10° at the sensor. There were variations of $\pm 0{\cdot}02$ between successive evaluations of k and the data presented are averages. The results of other authors were mostly obtained by similar techniques but the disc dimensions varied. The angles subtended by the discs are listed in Table 1. The computed values at Sutton Bonington appear to be slightly large compared with measurements at the same site, but it must be emphasized that the computations are based on average radiance distributions and variations from day to day are inevitable. In general, agreement between measurement and calculation is good at most sites. Some discrepancies are discussed in section 6.

TABLE 1. Comparison of computed and empirically determined shade-ring correction in various parts of the world

Location	Latitude	Dates	b/r	η	Source	k	Computed k
Sodankylä	67·5°N	summer	0·21	12°	Rossi (1975)	1·21	1·20
Helsinki	60°N	summer	0·25	12°	Rossi (1975)	1·23	1·24
Sutton Bonington	52·8°N	June	0·20	10°	present work	1·14	1·17
Potsdam	52·4°N	June	0·20	8°	Schöne & Sonntag (1976)	1·11	1·17
Easthampstead	51·4°N	May–August	0·20	9°	Painter (1979)	1·18	1·17
,,	,,	equinox	,,	,,	,,	1·18	1·19
,,	,,	Nov–Feb	,,	,,	,,	1·13	—
Kloten	47·5°N	25 August	0·13	6°	Schmid (1976)	1·095	1·11
Locarno-Monti	46·2°N	3 October	0·09	6°	Schmid (1976)	1·094	1·06
Pretoria	25·7°S	January	0·33	5°	Drummond (1956)	1·29	1·32
,,	,,	March	,,	,,	,,	1·32	1·38
,,	,,	June	,,	,,	,,	1·20	1·27

η is the angle subtended by the disc used to shade the comparison pyranometer.

5. The influence of shade-ring dimensions on correction factors

By evaluating Eq. (5) with an isotropic radiance distribution and various ring dimensions and comparing with Drummond's approximation, Eq. (8), it was found that Drummond's approximation overestimates g by only 0·01 when $b/r = 0{\cdot}35$ and by proportionally smaller amounts for narrower rings.

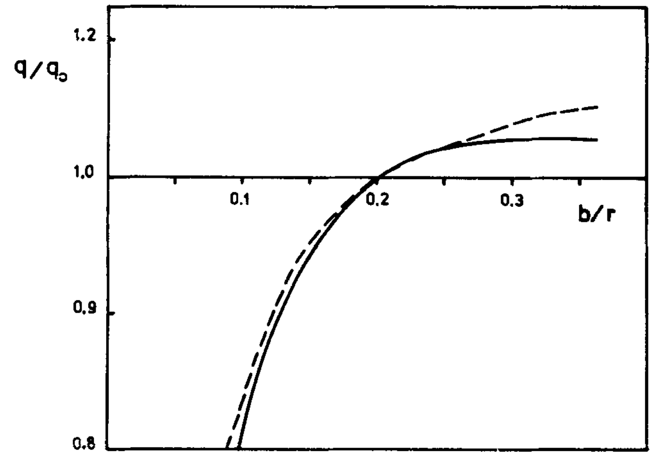

Figure 3. The effect of ring width on the anisotropy correction q. Here q is expressed relative to its value q_0 when $b/r = 0{\cdot}2$. The curves, calculated for 53°N, correspond to solar declinations of −2° (——— March) and 23° (- - - - June).

TABLE 2. VALUES OF THE ANISOTROPY FACTOR q IN EQ. (3)

Lat. (°N)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
0	1·4	1·3	1·3	1·3	1·4	1·5	1·4	1·3	1·3	1·3	1·4	1·5
10	1·6	1·4	1·3	1·3	1·3	1·3	1·3	1·3	1·3	1·4	1·6	1·7
20	1·9	1·6	1·4	1·3	1·3	1·3	1·3	1·3	1·3	1·5	1·8	1·9
30	2·3	1·9	1·6	1·3	1·3	1·2	1·2	1·3	1·4	1·7	2·1	2·4
40	3·0	2·3	1·8	1·5	1·3	1·2	1·3	1·4	1·6	2·0	2·6	3·2
50		3·1	2·1	1·6	1·4	1·3	1·3	1·5	1·8	2·5		
60			2·7	1·8	1·5	1·4	1·4	1·6	2·1			

Figure 3 shows that ring width has little effect on the anisotropy correction q except for narrow shade rings. When $b/r < 0{\cdot}2$, the ring does not exclude all the circumsolar aureole as defined in section 2. The effect of changing declination does not exceed 2%. Table 2 shows values of q computed for the 15th day of each month at various latitudes, with $b/r = 0{\cdot}2$. The tabulated values are for solar elevations in the middle of the day, but variation of q during the day is small. Southern hemisphere values of q may be found by adding 6 months to the date. The shade-ring correction under cloudless skies for any latitude, season and ring dimensions can therefore be estimated from Eq. (3), using Drummond's approximation for f and tabulated values of q. Where b/r is substantially different from 0·2 a correction to q may be derived from Fig. 3, but an error in q of $\pm 0{\cdot}1$ (when $b = 0{\cdot}2$) leads to an error of only $\pm 0{\cdot}01$ in the overall correction k. It is unreasonable to expect better accuracy than about ± 1% in measurements of diffuse solar radiation.

6. DISCUSSION

Drummond separated the correction factor k into the product of the geometric correction g (Eq. (4)) and an empirical correction h. Since $k = gh$, the empirical correction is given in terms of the present analysis by

$$h = (1-f)/(1-qf) \qquad . \quad . \quad . \qquad (9)$$

This factor depends both on q and f and does not separate the effects of geometry and sky anisotropy. Drummond's values of h are therefore valid only for one type of ring and at one latitude. Drummond found a seasonal variation in h which he attributed to seasonal changes in atmospheric turbidity. However, h depends on q and f which both vary seasonally for geometric reasons and while turbidity may have an effect on q, the total correction factor k is relatively insensitive to changes in q and the resulting effect is likely to be small.

Table 1 shows reasonable agreement between measurement and computation for the few measurements that are available. Comparisons with more long term averages are desirable. Some of the discrepancies in Table 1 may be due to uncertainties in the radiance distribution. The closest radiance measurements were made 10° from the sun (Steven 1977) and the distributions were extrapolated in the circumsolar region. Most of the uncertainty introduced by the extrapolation has been removed by the exclusion of the solar aureole, but there may be a residual error. Such an error, however, would have the same sign for all the results and thus cannot explain all the differences observed.

Some of the measurements reported were at relatively high elevations (Pretoria $\simeq$ 1400 m, Kloten and Locarno-Monti $\simeq$ 400 m), where the distribution of radiance in a clear sky may be different from that at sea level. Rayleigh scattering decreases with lower air densities (Elterman 1968) and Mie scattering by dust particles may become relatively more important. Unsworth and Monteith (1972) reported sharply decreasing aerosol turbidity with altitude during an ascent of Ben Nevis (1340 m) but the same trend may not apply on elevated plateaux as opposed to isolated hills. Pyrheliometer measurements at high elevations in the Himalayas (e.g. Silver hut glacier, 5700 m) have revealed remarkably large turbidities, considerably larger than values obtained at Mauna Loa, Hawaii at 3400 m (Bishop *et al.* 1966, Mani *et al.* 1977).

There may also be differences between different geographic locations in the type of scattering from aerosols. The directional distribution of Mie scattering depends on the size distribution of the aerosol particles. The radiance distributions used in these calculations are typical of clear days in summer in the English Midlands and they may not be applicable in regions where the natural or artificial aerosols are of a different type.

Under cloudless skies the methods described here allow diffuse radiation on individual days to be estimated with an accuracy better than 5%. More detailed studies are necessary to investigate shade ring corrections when the sun is low in the sky or when the sky is partly cloudy.

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