The anisotropy of diffuse solar radiation determined from shade-ring measurements

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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 occluded by the ring. The shade-ring correction depends on the dimensions and positioning of the ring and on the anisotropy of sky radiance. In this analysis these factors are separated using a simple model of sky radiance as the sum of a uniform background and a circumsolar component. The predictions of the model are tested against standard distributions of radiance and measured shade-ring corrections for clear skies. The model is also used to describe average distributions of radiance for cloudy skies and is in good agreement with the limited measurements available. This analysis enables measurements of solar radiation to be partitioned more exactly into direct and diffuse components and may also be applicable to the estimation of diffuse irradiance on other shaded surfaces.

1. INTRODUCTION

The interception of solar radiation by divers surfaces is one of the major determinants of their microclimate and is strongly dependent on the surface geometry. Indeed, the very word 'climate' derives from the Greek κλίμα meaning 'slope'. But solar irradiance is usually measured only on a horizontal surface and a variety of empirical techniques have been devised to estimate the corresponding irradiance on inclined surfaces. The general application of horizontal measurements of solar radiation to different surfaces is greatly simplified by separation of the radiation into direct and diffuse components. The direct irradiance of any surface may then be calculated by simple trigonometry and the diffuse irradiance may be similarly estimated if suitable assumptions are made about the angular distribution of radiance in the sky. For simplicity the diffuse radiation is often taken to be isotropic but this assumption can introduce significant errors, particularly on steep surfaces (Steven and Unsworth 1979, 1980a).

Routine measurements of diffuse solar radiation are usually made with a pyranometer shielded from the solar beam by a shade-ring. Most shade-rings conform to the pattern described by Drummond (1956) but the critical dimensions of the ring may differ. The ring is mounted on a polar axis so as to obscure the entire diurnal path of the sun across the sky and is adjusted every few days to allow for changes in solar declination. However, the shade ring also intercepts part of the sky radiation and a correction factor is required to account for the loss. Correction factors may be determined empirically, as in the studies referred to in Table 1, or calculated from the angular distribution of radiance (Drummond 1956; Schmid 1976; Steven and Unsworth† 1980b). Under cloudless skies

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Source</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodankylä</td>
<td>67.5°N</td>
<td>26.6°E</td>
<td>Rossi (1975)</td>
<td></td>
</tr>
<tr>
<td>Helsinki</td>
<td>60.2°N</td>
<td>24.9°E</td>
<td>Rossi (1975)</td>
<td>▼</td>
</tr>
<tr>
<td>Sutton Bonington</td>
<td>52.8°N</td>
<td>1.2°W</td>
<td>Steven and Unsworth (1980b)</td>
<td>○</td>
</tr>
<tr>
<td>Potsdam</td>
<td>52.4°N</td>
<td>13.1°E</td>
<td>Schöne and Sonntag (1976)</td>
<td>□</td>
</tr>
<tr>
<td>Easthampstead</td>
<td>51.4°N</td>
<td>8.0°W</td>
<td>Painter (1981)</td>
<td>●</td>
</tr>
<tr>
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<td>8.5°E</td>
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</tr>
<tr>
<td>Locarno-Monti</td>
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<td>111.8°W</td>
<td>Lebaron et al. (1981)</td>
<td>○</td>
</tr>
<tr>
<td>Pretoria</td>
<td>25.7°S</td>
<td>28.2°E</td>
<td>Drummond (1956)</td>
<td>▲</td>
</tr>
<tr>
<td>Leopoldsvill</td>
<td>4.3°S</td>
<td>15.3°E</td>
<td>Schuepp (1952)</td>
<td>▼</td>
</tr>
</tbody>
</table>

* Now in the Department of Geography, University Park, Nottingham NG7 2RD.
† There is an error in Fig. 3, page 870, of that paper. The scale value at the top of the Y axis should read 1.1, not 1.2.
the required correction ranges from about 10 to 32% according to latitude and the pattern of shade-ring but there are still considerable uncertainties in the proper value of the correction under various weather conditions. These uncertainties limit the accuracy of diffuse radiation measurements and it has been difficult to compare measurements made at different sites or in different seasons, because the corrections depend on latitude and declination in a way that has not been completely understood. Perhaps for these reasons, the measurement of diffuse solar radiation has not generally attracted the attention appropriate to its importance as a climatological variable.

Shade-ring corrections depend in general on the anisotropy of the sky, and on the dimensions and positioning of the ring. For the special case of an isotropic sky, Drummond showed that the correction could be expressed simply in terms of latitude, solar declination and the ratio of ring width to ring radius. For the case of cloudless skies, Steven and Unsworth (1980b) used 'standard distributions of clear sky radiance' (Steven 1977a) to calculate shade-ring corrections for a range of latitudes and time of year. In this paper the earlier analysis is extended by developing a simple model with two parameters to represent the anisotropy both of cloudless and of cloudy skies. The model enables the complete separation of anisotropy from the other factors in the shade-ring correction. For any particular set of weather conditions it then becomes possible to generalize shade-ring corrections measured at one site at any time of year to sites at other latitudes and other times of year. It is also possible to use empirical measurements of shade-ring corrections to generate the parameters in the model as a means of describing the anisotropy of the sky. The results of the model are compared with published measurements from several sites.

2. Theory

The irradiance \( S_d' \) on a horizontal surface as measured by a pyranometer with a shade-ring is given by

\[
S'_d = S_d - S'_r \tag{1}
\]

where \( S_d \) is the true diffuse irradiance from the whole sky, \( S_r \) the component of the diffuse irradiance that is occluded by the ring and \( S'_r \) the component of irradiance reflected to the sensor from the inner surface of the ring. When this inner surface is blackened, \( S'_r \) is insignificant except at low solar elevations (Lebaron et al. 1980) and the effect of \( S'_r \) is not considered in this analysis.

Drummond showed that \( S_r \) could be approximated by the line integral along the solar path, so that

\[
S_r = b r^{-1} \cos^3 \delta \int_{-t_0}^{t_0} N(\sin \lambda \sin \delta + \cos \lambda \cos \delta \cos t) \, dt \tag{2}
\]

where \( b \) = ring width, \( r \) = ring radius, \( \delta \) = solar declination, \( \lambda \) = latitude and \( N \) is the radiance function of the sky which depends in general on zenith and azimuth angles. The term in parentheses is an expression for the cosine of zenith angle as a function of the dummy variable \( t \), and the limits of integration \( \pm t_0 \) are the hour angles (in radians from solar noon) of sunrise and sunset.

If the diffuse radiation is assumed to be isotropic, so that \( N = N_0 \), then Eq. (2) may be integrated analytically to calculate the ostensible flux \( S_{ro} \) occluded by the ring:

\[
S_{ro} = 2 b r^{-1} \cos^3 \delta N_0 f' \tag{3}
\]

where \( f' = t_0 \sin \lambda \sin \delta + \sin t_0 \cos \lambda \cos \delta \). Substituting the isotropic relation \( S_d = \pi N_0 \) then gives

\[
S_{ro}/S_d = 2 b r^{-1} \pi^{-1} \cos^3 \delta f'. \tag{4}
\]
This ratio is the fraction of the diffuse irradiance occluded by the ring under an isotropic sky and depends only on the geometrical parameters describing the size and position of the ring. Thus, if the sky is isotropic, the measured diffuse irradiance \( S_d \) may be corrected by multiplying by a geometric ring correction \( g \) defined by

\[
g = (1 - S_{rs}/S_d)^{-1}.
\]  

(5)

In Britain, this geometric correction is the only correction applied to routine observations of diffuse irradiance made with a shade-ring (Painter 1981).

In general, the sky radiance is not isotropic and towards the sun there is usually a brighter region of sky which is partly covered by the shade-ring. Drummond (1956) and Painter (1981) used "additional" or 'empirical' corrections to account for the effects of anisotropy but these corrections also depend on the size and position of the ring and are directly applicable only for the latitude and season in which they were determined. Steven and Unsworth (1980b) showed that the shade-ring correction \( S_d/S_d \) could be expressed more conveniently in the form

\[
S_d/S_d = (1 - S_d/S_d)^{-1} = (1 - qS_{rs}/S_d)^{-1}.
\]  

(6)

This equation separates the effect of the purely geometric term \( S_{rs}/S_d \) given by Eq. (5) from an anisotropic factor, \( q \), which is the ratio of the true value of \( S_d \) to its theoretical value \( S_{rs} \) calculated on the assumption that the sky is isotropic. The ratio \( S_d/S_{rs} \) is almost independent of shade-ring dimensions and values computed from the angular distribution of clear sky radiance were used to derive shade-ring corrections for all types of ring at any latitude and time of year (Steven and Unsworth 1980b).

3. THE ANISOTROPY OF CLOUDLESS SKIES

To make further progress, the radiance distribution of diffuse solar radiation from cloudless skies is treated as the sum of a background radiance \( N_b \) and a circumsolar component \( N_\star \), so that

\[
N = N_b + N_\star \Delta(\xi).
\]  

(7)

In this model, the \( \xi \) is the angular distance from the sun and the function \( \Delta(\xi) \) is defined by \( \Delta(\xi) = 1 \) for \( \xi < \xi_\star \) and \( \Delta(\xi) = 0 \) for \( \xi > \xi_\star \), where \( \xi_\star \) is the effective angular radius of the circumsolar zone, i.e. \( N_\star \) is the excess radiance in a circumsolar zone of angular radius \( \xi_\star \), superimposed on a constant background radiance \( N_b \). It is assumed that the shade-ring is not so wide as to occlude the entire circumsolar zone, i.e. \( b/r < 2 \tan \xi_\star \). If \( \xi_\star \) is not too large, all the excess radiation from the circumsolar zone can be treated approximately as if it emanated from the solar position. Then Eq. (2) may be integrated to give

\[
S_r = 2br^{-1} \cos^3 \delta \left( N_b f' + N_\star \xi_\star \cos z_\star \right)
\]  

(8)

where \( z_\star \) is the zenith angle of the sun. Dividing by Eq. (3) then gives

\[
S_d/S_{rs} = N_b/N_0 + C_\star/f'
\]  

(9)

where \( C_\star = (N_\star \xi_\star \cos z_\star)/N_0 \). The term \( N_b/N_0 \) can be eliminated by applying the constraint that both the isotropic and the anisotropic models must give the same diffuse irradiance \( S_d \) on a horizontal surface. Thus, with the same approximations as before,

\[
S_d = \pi N_0 = \pi N_b + N_\star \cos z_\star \Omega_\star
\]  

(10)

where the solid angle subtended by the circumsolar region is given by

\[
\Omega_\star = \int_0^{\xi_\star} 2\pi \sin \theta d\theta = 2\pi(1 - \cos \xi_\star).
\]  

(11)

Then
\[ \frac{N_b}{N_0} = 1 - C_\ast \xi'_\ast, \]  

(12)

where \( \xi'_\ast = 2(1 - \cos \xi_\ast) / \xi_\ast \). The parameter \( \xi'_\ast \) reduces to \( \xi_\ast \) for small angles. Equation (9) may then be written in the form

\[ \frac{S_r}{S_{ro}} = 1 - C_\ast \xi'_\ast + C_\ast / f'. \]  

(13)

The circumsolar model thus predicts that \( S_r/S_{ro} \) is a simple function of three dimensionless parameters: a purely geometric term \( f' \), which describes the disposition of the shade-ring relative to the sensor; \( C_\ast \), which expresses the relative strength of the circumsolar component of radiation; and \( \xi'_\ast \), which is essentially the angular width of the circumsolar region. This angular term appears because the shade-ring takes a finite slice out of the circumsolar region. If \( \xi_\ast \) is small then that slice is a relatively larger fraction of the total solid angle of the circumsolar region.

As a test of the ability of the circumsolar model to represent the effects of actual radiances, values of \( S_r/S_{ro} \) were calculated for cloudless skies from standard distributions of radiances (Steven 1977a). The values were calculated for each month of the year at several latitudes by numerical integration of measured radiances distributions over the solid angle of the shade-ring. This method is more exact than Eq. (2) and is described in detail by Steven and Unsworth (1980b). The radiances distribution for cloudless skies was assumed to depend only on \( z_\ast \); the only effect of latitude and declination in this analysis is to shift the position of the shade-ring in the angular coordinate system. The resulting values of \( S_r/S_{ro} \) calculated with the radiances distribution for \( z_\ast = 65^\circ \) are shown in Fig. 1 as a function of \( 1/f' \). The curves join points plotted at monthly intervals for each of four latitudes. Larger values of \( 1/f' \) occur at high latitudes in winter, but the curve for

\[ \begin{align*} 
\text{Figure 1.} & \quad \text{The relationship between the shade-ring anisotropy factor} \ S_r/S_{ro} \text{ and the geometric parameter} \ 1/f' \text{.} \\
& \quad \text{calculated from Steven’s clear sky radiances distribution for} \ z_\ast = 65^\circ \text{ for latitudes} \ 0^\circ \text{ (solid);} \ 20^\circ \text{ (long dashes);} \ 40^\circ \text{ (short dashes); and} \ 60^\circ \text{ (dots).} 
\end{align*} \]
60° latitude is truncated because $z_\phi$ does not attain 65° for several months in winter. Similar computations were made using the radiance distributions corresponding to different values of $z_\phi$. The results for four solar zenith angles at a latitude of 50° are shown in Fig. 2. The relationships are nearly linear at each of the latitudes and zenith angles. There are small differences in slope and intercept and a slight curvature in some of the relationships, but the effect of these differences is small. With most shade-rings differences in $S_\phi/S_{ro}$ of $\pm 0.1$ correspond to about 1% error in $S_d$.

Figures 1 and 2 confirm the predicted form of the relationship for the average conditions of anisotropy described as 'standard distributions of clear sky radiance' by Steven (1977a). In that paper it was noted that turbidity had only a second-order effect on the angular distribution of radiance, and it was suggested that a single set of radiance distributions for a range of solar angles would be adequate to describe cloudless skies in most parts of the world. Measurements of the shade-ring correction at a variety of sites allow this hypothesis to be tested. Figure 3 shows values of $S_\phi/S_{ro}$ derived from published measurements of shade-ring corrections, plotted against $1/f'$ according to latitude and season. The locations and sources of the data are listed in Table 1. Open symbols indicate measurements on a single occasion whereas closed symbols indicate averages of several measurements. Where these averages were made over a period of weeks or months, an appropriate median value of $\delta$ was chosen for the calculation of $f'$. The measurements by Lebaron et al. (1980) were made with a shade-ring that was painted grey, and an upward adjustment of 3.5% was made to $S_\phi/S_{ro}$ on the basis of a comparison in their paper between grey and black shade-rings. The values of $S_\phi/S_{ro}$ correspond to these corrected values. The measurements by Painter (1981) are means of all data where the measured
ratio of diffuse to global radiation ($S_D/S_t$) was less than 0.3, and may include some occasions with cloud, but other measurements by Painter, referred to later, suggest that the effect of small amounts of cloud is minimal. Painter also published maximum and minimum values of the shade-ring correction for various seasons, and the error bars in Fig. 3 indicate the corresponding extremes of $S_p/S_{ro}$.

The line in Fig. 3 represents Steven's distributions of radiance. It is a composite drawn from Fig. 2 using the lowest values of $z_*$ in any season to give greater emphasis to the middle of the day. The line is strictly valid for latitudes of 50$^\circ$ but may be used as a first approximation to represent all parts of the world (cf. Fig. 1). The predicted values of $C_*$ and $\xi_*$ are 1.10 and 0.60 radians, respectively, derived from the slope of the line and the value of $1/f'$ when $S_r = S_{ro}$ (Eq. (13)). If the error bars derived from Painter's data represent the natural variation of cloudless sky anisotropy, then, with one or two exceptions, the individual determinations of $S_p/S_{ro}$ lie within the expected range of departures from the line. However, since the line represents average distributions of radiance it is more reasonable to test its predictions with shade-ring corrections that are averages of several measurements. The values at Sodankylä and Helsinki are in good agreement with the prediction, especially when an adjustment is made for the variation of $S_p/S_{ro}$ with latitude (Fig. 1). However, the value at Leopoldville is slightly higher than predicted when a similar adjustment is made. Only the data at Easthampstead and Pretoria have the full
seasonal range required for calculation of $C_*$ and $\xi_*$. The agreement with prediction at Easthampstead is excellent, even when the line is extended beyond its computed range. At Pretoria, however, the relationship appears to indicate a lower value of $C_*$ of about 0.71 and a slightly higher $\xi_*$ of 0.73 radians. Such departures from the prediction could arise from imperfect blackening of the shade-ring, but it is possible that they represent a real difference in the anisotropy of the sky, possibly as a result of the high elevation of Pretoria (ca. 1400 m), or of a difference in the size distribution of the scattering aerosol.

4. The Anisotropy of Cloudy Skies

Radiance distributions of cloudy skies are highly variable, especially for skies with only partial cloud cover. It is not practicable to attempt the prediction of instantaneous shade-ring corrections because there is no standard form of the radiance distribution for a given degree of cloudiness. However, average radiance distributions may be modelled on the assumption that, over a sufficiently long period, cloud will be evenly distributed over all parts of the sky. The complex instantaneous patterns of brightness caused by individual clouds are smoothed by their passage across the sky and the appearance of new cloud formations in other quarters.

The model used in this analysis is of the same form as that for cloudless skies. Partly cloudy skies still tend to have a region of high radiance near the sun, both from atmospheric scattering and from intense forward scattering at the edges of neighbouring clouds (the silver lining of metaphor). With increasing cloud cover the average distribution of radiance tends to become more even. To match these observations, it is proposed that the average diffuse solar irradiance $S_d$ may be partitioned according to the degree of cloudiness into an isotropic component $S_{d0}$ corresponding to overcast skies and an anisotropic component $S_{d*}$. The two components are assumed to operate for different portions of the time, and this time is partitioned between $S_{d0}$ and $S_{d*}$ in proportion to the number of hours of bright sunshine, $n$, as a fraction of the maximum possible, $n_0$. This variable is measured by the Campbell–Stokes sunshine recorder. The anisotropy of $S_{d*}$ is modelled in the same way as for cloudless skies (Eq. (7)) with identical coefficients $C_*$ and $\xi_*$. In addition, the average background radiance $N_b$ is assumed to be the same for both isotropic and anisotropic components. This latter assumption is introduced for the sake of simplicity and as a first approximation, but it is plausible because the average diffuse irradiance under an overcast sky is not very different from the diffuse irradiance under a cloudless sky. Thus

$$S_d = S_{d0} + S_{d*}$$

(14)

where

$$S_{d0} = (1 - n/n_0)\pi N_b$$

(15)

and from Eqs. (10) and (12)

$$S_{d*} = (n/n_0)\pi N_b (1 - C_* \xi_*)^{-1}.$$  

(16)

This time-averaged radiance distribution model for cloudy skies has the familiar form of a circumsolar component superimposed on a constant background, and a new circumsolar parameter $C$ can be defined as the cloud sky equivalent of $C_*$. Thus, by the same process as Eq. (16),

$$S_d = \pi N_b (1 - C \xi_*)^{-1}.$$  

(17)

Substitution of Eqs. (15), (16) and (17) into Eq. (14) then gives

$$C = (n/n_0)C_* \xi_*(1 - n/n_0)^{-1}.$$  

(18)

The model for cloudy skies thus predicts that $C$ is progressively reduced from $C_*$ when
\( n = n_0 \) (cloudless sky) to 0 when \( n = 0 \) (overcast). The angular width of the circumsolar region, \( \xi_a \), is assumed constant in this model.

The predictions of this model may be tested using measurements of shade-ring corrections for cloudy skies. Painter (1981) tabulated means and extremes of such measurements for five ranges of solar declination. The condition of the sky was represented by the ratio of diffuse \( S_d \) to global radiation \( S_i \) in nine ranges from \( S_d/S_i = 0.1 \) (clear sky) to \( S_d/S_i = 1.0 \) (overcast). To make the comparison with Eq. (18), a regression equation between \( S_d/S_i \) and \( n/n_0 \) was used (Steven 1977b)

\[
S_d/S_i = 0.99 - 0.86n/n_0.
\]  

(19)

A similar equation with different fitted coefficients was given by Cowley (1979) but Eq. (19) was preferred because it satisfies the requirement that \( S_d/S_i \) should approach unity when there is no bright sunshine. The curve in Fig. 4 was derived by combining Eqs. (18) and (19) and using the values \( C_a = 1.01 \) and \( \xi_a = 0.60 \) derived earlier to predict the circumsolar parameter \( C \) as a function of \( S_d/S_i \). The plotted points were derived from Painter's tabulated mean values of shade-ring corrections as follows. Values of \( S_d/S_i \) and \( f' \) were extracted from these data as previously described. For each range of \( S_d/S_i \), \( S_i/S_i \) was plotted as a function of \( 1/f' \) and a line fitted by linear regression. The points in the regression line were weighted with the reciprocal squares of the ranges of \( S_d/S_i \) determined from Painter's tabulated extremes. This procedure was the nearest equivalent to weighting with the reciprocal of variance. Values of \( C \) and \( \xi_a \) were obtained from the slope and the intercept with \( S_d/S_i = 1 \), as before, and these values are plotted in Fig. 4.

There is a close correspondence between the curve and the values of \( C \) from Painter's data, except for values of \( S_d/S_i \) in the range 0.2 to 0.5 where the prediction falls below the measured values. Part of the explanation for the discrepancy may be that there is no unique relationship between the two parameters \( n/n_0 \) and \( S_d/S_i \) used to describe sky conditions and Eq. (19) is only an approximate relationship for average conditions. By applying this equation to relate the two parameters, the model effectively assumes that the ratio \( S_d/S_i \) in cloudless skies is always 0.13. In fact, \( S_d/S_i \) has a wide range due to variation in turbidity, and values as high as 0.5 are not unusual on days with continuous bright sunshine (Unsworth and Monteith 1972; Steven 1977b). The effect of turbidity on the form of anisotropy is minimal (Steven 1977a) and therefore under cloudless but turbid
skies we expect $C = C_\ast$. The model assumes, however, the presence of cloud whenever $S_d/S_t > 0.13$ and the predicted value of $C$ is reduced.

The values of $\xi_\ast$ also show some evidence of a slight decline with increasing cloudiness. This effect may result from the change in the nature of the scattering aerosol. Cloud water droplets are larger than aerosols and in the edges of discrete clouds, where single scattering is important, the scattered radiation may be concentrated more strongly in the forward direction. However, neither this effect, nor the discrepancies in $C$, are large enough to cause serious errors in the application of the model for shade-ring corrections.

5. Discussion

The results of this study indicate that a simple model of the anisotropy of diffuse solar radiation adequately explains the shade-ring correction and its dependence on site, season, the dimensions of the ring and the cloudiness of the sky. The calculations described in this paper allow measurements of solar radiation to be partitioned more exactly into direct and diffuse components. The theory developed here may also be used to generalize measurements of shade-ring corrections to other seasons and latitudes and to shade-rings of different dimensions. In the present model, the sky conditions are described in terms of the ratio of diffuse to global radiation, a variable which is convenient because no additional measurements are required for its calculation. $S_d/S_t$ may not be the most appropriate parameter to use because it is not simply related to cloudiness. The relative fraction of bright sunshine is more closely related to cloud and this measurement is usually available with solar radiation data, but at present it suffers from the inconvenience of being difficult to automate. Other parameters can also be used to represent sky conditions and one of them may be more closely linked to the way in which anisotropy changes. For the present purpose, however, there is no need for such refinements as the accuracy of diffuse radiation measurements is limited by other factors, such as calibration, cosine error and reflection from the shade-ring.

In principle it is possible to apply this model in other circumstances. I know of no verified models of sky anisotropy to cover the general case of partly cloudy skies and the present model is simple, requiring only the two parameters, $C$ and $\xi_\ast$. However, as this model is derived strictly from horizontal measurements, it may be unwise to apply it to non-horizontal surfaces. Steven and Unsworth (1979, 1980a) showed that in both cloudless and overcast skies it was insufficient to treat the background radiance as isotropic when calculating the irradiance of vertical walls and a further parameter was required to describe the variation of $N_b$ with zenith angle. The present model may, however, be applicable to the estimation of the diffuse irradiance of horizontal surfaces that are partly shaded, as in urban streets or in forest canopies.

Acknowledgments

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References


Painter, H.E. 1981 The shade ring correction for diffuse irradiance measurements.  
        *ibid.*, 26, 361–363.

Rossi, V. 1975 The shadowing-ring correction for sky radiation pyranometers.  
        Finnish Met. Inst. Contrib., No. 82.

Schmid, W. 1976 Aufbereitung und Qualitätskontrolle langjähriger Messunterm-  
        lagen der Globalstrahlung und Himmelsstrahlung.  

Schöne, W. and Sonntag, D. 1976 Die Schattenringkorrektion beim Pyranometer mit galvanisch  
        erzeugte Thermosäule.  

Schuepp, W. 1952 Enregistrement séparé des composantes du rayonnement  
        solaire.  

Steven, M. D. 1977a Standard distributions of clear sky radiance,  

Steven, M. D. and Unsworth, M. H. 1977b The angular distribution and interception of diffuse solar radi- 

Steven, M. D. and Unsworth, M. H. 1979 The diffuse solar irradiance of slopes under cloudless skies.  

Steven, M. D. and Unsworth, M. H. 1980a The angular distribution and interception of diffuse solar radi- 
        ation below overcast skies.  
        *ibid.*, 106, 57–61.

Steven, M. D. and Unsworth, M. H. 1980b Shade-ring corrections for pyranometer measurements of  
        diffuse solar radiation from cloudless skies.  
        *ibid.*, 106, 865–872.

        *ibid.*, 98, 778–797.