Study of the corrective factor involved when measuring the diffuse solar radiation by use of the ring method

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Abstract

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Reference


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STUDY OF THE CORRECTIVE FACTOR INVOLVED
WHEN MEASURING THE DIFFUSE SOLAR RADIATION BY
USE OF THE RING METHOD

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Abstract—By comparing the diffuse solar radiation on a horizontal plane as continuously measured in Geneva over a full year by using both a fixed ring and a moving disk, we conclude that the ring corrective factor can be evaluated on the basis of simple models, but with a daily uncertainty of the order of 5 per cent. In this study, the isotropy of the diffuse radiation can be used as a reasonable approximation, even if this assumption is not fully verified. More precise measurements would require the use of a disk.

INTRODUCTION

We have performed systematic solar radiation measurements in Geneva, Switzerland since July 1978. These measurements will be continued up to 30 June 1982[1]. Namely, we are measuring global and diffuse radiations on a horizontal plane, global radiation in 5 other different planes, the sky infrared radiation as well as outdoor temperature, humidity, wind velocity and direction. In this paper, we like to report on the corrective factor involved when measuring the diffuse radiation by use of the ring method.

From 1 July 1980 to 30 June 1981, i.e. a full year, we have measured the diffuse radiation on a horizontal plane by simultaneously using two methods: the fixed ring and the moving disk tracking the sun in order to shadow the pyranometer from the direct solar radiation, all other measurements mentioned being performed normally. The second method being very precise we can, by direct comparison, study the corrective factor involved in the first one. Our considerations are limited to the horizontal plane and to our local meteorological conditions.

In the ring method, the axis of the ring is parallel to the earth axis. Translating the ring along its axis allows to follow the sun declination, which means that periodical ring adjustments are necessary. Due to the ring, part of the sky is not viewed by the pyranometer and the diffuse solar radiation is then underestimated. A corrective factor varying along the year must be applied. In our case, it varies between 1.05 and 1.30, the ring being adjusted on a weekly basis. Of course, a corrective factor closer to 1 can be envisaged by using a narrower ring, which would then imply more frequent and more precise ring adjustments.

When using the moving disk method, for the same reasons, a corrective factor must be applied, but it is very close to one (by 1–2 per cent in our case). Even a rough estimate of its value will be satisfactory.

Let us point out that the two methods involved being applied in similar conditions with similar pyranometers (similarly calibrated) allow, by a relative comparison, an absolute determination of the ring corrective factor.

If we assume the diffuse radiation to be isotropic in the sky hemisphere, the corrective factor can be determined from geometrical considerations alone. This assumption is good enough when applied to the case of the moving disk corrective factor but is not fully verified in real conditions, it depends on many continuously changing meteorological parameters. Hence the correction involved in ring measurements is a delicate question.

We are now going to compare our measurements with the isotropic hypothesis as well as with other models.

EXPERIMENTAL CONDITIONS AND MEASUREMENTS

Our local meteorological conditions for the period under study are summarized in Table 1.

The ring is made of a 7 cm wide strip bent with a 17 cm radius. It is painted black on the side viewed by the pyranometer, and painted white on the other side, in order to avoid light reflections on the pyranometer and heating of the ring. The ring position is usually adjusted once a week, and, sometimes twice a week when the sun declination is varying very fast. The moving disk is 8 cm in dia. Its support made of a circular 2 cm wide strip is centered on the pyranometer cell and has a 30 cm radius. The maximum strip length viewed by the pyranometer corresponds to a 67° angle (i.e. the maximum sun height at summer solstice). The support is mounted on a 24 hr electrical motor, the axis of which being parallel to the earth axis and pointing towards the pyranometer. Periodical adjustment are made on a weekly basis concerning the disk position along its support (for the sun declination) and the angular position of the support (for the equation of time).

The global radiation on a horizontal plane (G), the “ring” and “disk” diffuse radiations on the same plane are measured by 3 Kipp and Zonen (CM5 type) pyranometers. Instantaneous measurements are recorded every 6 min with a data acquisition system. The pyranometers are calibrated by relative comparison with another one of the same type which is periodically calibrated at the World Radiation Center at Davos in Switzerland.

Let us call “brute diffuse” (Db) what corresponds directly to the pyranometer output, the “true diffuse”
Table 1. Meteorological characteristics for the period analyzed. Geneva, Switzerland: 46°12' lat. N 6°02' long E. Global and diffuse radiation on the horizontal plane: month total expressed in kWh/m². Monthly mean temperature given in °C

<table>
<thead>
<tr>
<th>MONTH</th>
<th>GLOBAL</th>
<th>DIFFUSE</th>
<th>DIF/GL</th>
<th>AV. TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td>JULY</td>
<td>163.1</td>
<td>58.5</td>
<td>36 %</td>
<td>18.4</td>
</tr>
<tr>
<td>AUGUST</td>
<td>164.4</td>
<td>53.2</td>
<td>32 %</td>
<td>21.0</td>
</tr>
<tr>
<td>SEPTEMBER</td>
<td>150.0</td>
<td>44.6</td>
<td>34 %</td>
<td>17.8</td>
</tr>
<tr>
<td>OCTOBER</td>
<td>68.5</td>
<td>33.0</td>
<td>49 %</td>
<td>10.6</td>
</tr>
<tr>
<td>NOVEMBER</td>
<td>31.8</td>
<td>18.8</td>
<td>59 %</td>
<td>5.6</td>
</tr>
<tr>
<td>DECEMBER</td>
<td>28.6</td>
<td>20.0</td>
<td>69 %</td>
<td>1.6</td>
</tr>
<tr>
<td>JANUARY</td>
<td>31.3</td>
<td>22.1</td>
<td>71 %</td>
<td>0.9</td>
</tr>
<tr>
<td>FEBRUARY</td>
<td>48.0</td>
<td>30.4</td>
<td>63 %</td>
<td>1.7</td>
</tr>
<tr>
<td>MARCH</td>
<td>80.9</td>
<td>44.5</td>
<td>55 %</td>
<td>9.9</td>
</tr>
<tr>
<td>APRIL</td>
<td>143.1</td>
<td>69.8</td>
<td>49 %</td>
<td>12.8</td>
</tr>
<tr>
<td>MAY</td>
<td>144.2</td>
<td>79.5</td>
<td>55 %</td>
<td>14.4</td>
</tr>
<tr>
<td>JUNE</td>
<td>187.4</td>
<td>78.7</td>
<td>42 %</td>
<td>18.8</td>
</tr>
</tbody>
</table>

(D) being the sum of the “brute diffuse” and the diffuse radiation hidden by the ring or the disk (Dh):

\[ D_R = D_{br} + D_{dh} \]

\[ D_D = D_{Dh} + D_{De} = D_{Dh}(1 - D_{Dh}/D_D) \]

The index R or D refers to the ring or the disk.

The ratio \( D_{Dh}/D_D \) is very small. It can be analytically computed assuming the diffuse radiation to be isotropic, thus allowing a precise determination of the true diffuse radiation \( D_D \) (see Appendix 1).

We also have:

\[ D_R = D_D = D = D_{Dh}(1 + D_{Dh}/D_{Dh}) = D_{Dh} \cdot f \]

where \( f \) is the corrective factor relative to the ring method.

Experimentally we get: \( f = D_D/D_{Dh} \). We can also compute, using models, the corresponding quantity:

\[ f_{th} = 1/(1 - D_{Dh}/D_R) \]

On the Figs. 1A and 2A, the dots represent the daily average value of the \( f \) quantity, along the year (for the two periods January 1981–June 1981 and July 1980–December 1980) vs the year day number.

Different day types (clear, slightly cloudy or cloudy) are selected by considering the ratio \( D/G \) of the diffuse radiation to the global radiation, this ratio being always within the limits 10–100 per cent.

MODELS AIMING AT THE RING CORRECTION EVALUATION

They allow the evaluation of the \( D_{Dh}/D_R \) ratio and the determination of the \( f_{th} \) corrective factor.

Blackwell[2], Schuepp[3] and Drummond[4] propose models assuming the isotropy of the diffuse solar radiation. These 3 models as compared in Ref.[4] give very similar results. We will consider only Drummond’s approach employing entirely analytical computations which is a great simplification.

Let us call \( i(a, h) \) the diffuse radiation density per unit of solid angle, the two angles \( a \) (azimuth) and \( h \) (height) defining a given direction of the sky hemisphere.

If we have \( i(a, h) = i_0 = \text{constant} \)

then

\[ D_R = i_0 \int \int \text{sinh} \, d\sigma \quad \text{with} \quad d\sigma = da \, dh \, \text{cosh} \]

and

\[ D_R = i_0 \pi. \]

The factor sinh is due to the fact that the pyranometer cell is sensitive in the horizontal plane.

For the ring we have:

\[ D_{Dh} = i_0 \int \int \text{sinh} \, d\sigma. \]

This integral can be computed in the ring case by using Drummond’s formulas[4].

The corresponding \( f_{th} \) factor is represented in our case by the curve of Fig. 1. \( f_{th} \) is constant over a day.

Robertson[5] investigated the diffuse radiation in angular regions very close to the sun by means of disks of different diameters covering the sun. He proposed a model with a diffuse radiation density decreasing with increasing angular distance to the sun. It is difficult to apply such a correction because it implies non-analytical methods and therefore long numerical computations; in addition the corrective factor depends on the sun height.

Such a model studied by Schmid[6] and adapted to our case gives much too large values for \( f_{th} \), as compared to
our direct measurements. So this model is neither convenient nor satisfactory and we disregard it.

A diffuse radiation density depending on the height \( h \) is proposed by Sonntag [7]:

\[
i(a, h) = i_0 \sinh \quad \text{where } i_0 \text{ is constant.}
\]

The previous integrals for \( D_a \) and \( D_{an} \) become very simple in this case.

The corresponding \( f \)th factor is represented for our case in Fig. 2. Again \( f \)th is constant along a day.

**COMPARISON BETWEEN MODELS AND OUR MEASUREMENTS**

We have retained Drummond's [4] and Sonntag's [7] models. Fig. 1A, B, C, D show how they compare with our measurements.

The normalized difference between the dots (measurements) and the curve (model) is represented in the histograms 1abcd and 2abcd. By normalized difference we mean the quantity \((f_{th} - f)/f_{th}\). We also give in each case the mean value and the standard deviation.

We see that for both models (Figs. 1a, 2a) the standard deviation is similar.

Considering now the different cases defined by the \( D/G \) ratio, we see that the isotropy assumption is well adapted to cloudy days (Fig. 1B), the corresponding histogram (Fig. 1b) being close to a Gaussian distribution and being pretty well centered. This model is not as good for slightly cloudy days or clear days (Fig. 1C, D). In the former case (Fig. 1C) the corrective factor is underestimated which can be due to a large
Fig. 2. Ring corrective factor for diffuse radiation measurement. Comparison between direct measurements and Sonntag's model (1/sinh) on a daily mean radiation basis.

Table 2. Drummond's model as compared to instantaneous measurements (see text)

<table>
<thead>
<tr>
<th>DIF/GL</th>
<th>MORNING</th>
<th>NOON</th>
<th>AFTERNOON</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MEAN</td>
<td>STANDARD</td>
<td>MEAN</td>
</tr>
<tr>
<td>INTERVAL</td>
<td>VALUE</td>
<td>DEVIATION</td>
<td>VALUE</td>
</tr>
<tr>
<td>10-100%</td>
<td>-0.8 %</td>
<td>6.8 %</td>
<td>-3.4 %</td>
</tr>
<tr>
<td>70-100%</td>
<td>-6.6 %</td>
<td>5.4 %</td>
<td>-0.7 %</td>
</tr>
<tr>
<td>40-70%</td>
<td>-5.0 %</td>
<td>8.0 %</td>
<td>-7.6 %</td>
</tr>
<tr>
<td>10-40%</td>
<td>-1.8 %</td>
<td>8.6 %</td>
<td>-4.0 %</td>
</tr>
</tbody>
</table>
contribution of circumsolar diffuse radiation partly hidden by the ring. In the latter case (Fig. 1Dd) larger relative errors are expected when measuring low diffuse radiation values.

Sonntag’s model seems more adapted for clear and slightly cloudy days (Fig. 2CcDd) than for cloudy days (Fig. 2Bb).

Let us point out that, independently of the model chosen, the dots corresponding to daily average are spread out and consequently the daily $f$th factor is anyhow affected by a 5 per cent uncertainty. In these conditions the two models retained are equally satisfactory.

A similar analysis based on Drummond’s model has been made for instantaneous measurements selected in the morning (at mid-time between sunrise and noon) at noon and in the afternoon (at mid-time between noon and sunset). Results are summarized in Table 2 with mean values and standard deviations defined as in previous histograms and showing much larger fluctuations.

By similar methods we have searched for correlations between the $f$ corrective factor and some meteorological parameters. But we have not found any indication allowing to improve the situation. Too many parameters are involved with random variations and weak correlations.

We then consider that a daily determination of the $f$ corrective factor looks as a reasonable compromise.

CONCLUSIONS

By studying and comparing the diffuse solar radiation on a horizontal plane as measured by means of both the ring method and the disk method, we come to the following conclusions:

The ring corrective factor can be evaluated on the basis of simple models. However, meteorological parameters induce daily mean fluctuations of the order of 5 per cent that affect directly the daily evaluation of the corrective factor. This uncertainly cannot be reduced by simple considerations. Only sophisticated studies and complicated computations could maybe help.

Within the above limits, two models look satisfactory for the corrective factor evaluation. One is based on the isotropy of the diffuse radiation. Obviously, this assumption is not fully verified, as shown in our study, but, taking into account the complexity of the phenomena involved, it can be kept, in this particular study, as a reasonable hypothesis.

The pyranometer accuracy, affected by many different effects (8), makes it difficult at the present time to go further in refined procedures.

If good diffuse solar radiation measurements are needed, it is necessary to use the disk and not the ring. The disk method is obviously a much better method.

These conclusions are valid only for our meteorological and experimental conditions (for instance, the ring size). They can be used for other similar conditions or considered as a guideline for very different conditions.

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REFERENCES


8. Private communication related to the International Energy Agency (Task III).

APPENDIX I

Evaluation of the corrective factor involved when measuring the diffuse radiation on the horizontal plane by use of a moving disk.

\[
D_{Dn}/D_0 = (e^r - r^2)\cos a' \cos \phi (\sin \delta_n - \sin \delta) - \sin \phi (\cos \delta_n - \cosh \delta) \\
+ (r/d) \left[ \sin \phi \sin \delta + \cos \phi \cos \delta \cos a' \right] \\
= \text{moving support width (2 cm in our case)} \\
d = \text{distance from the moving disk to the pyranometer cell (30 cm in our case)} \\
a' = \text{solax time angle (0° at noon, 15° variation per hour)} \\
\phi = \text{latitude} \\
\delta = \text{sun declination} \\
\delta_n = \text{maximum sun declination} \\
h_s = \text{arc (tg(90° - \cos a'/ctg \phi)) corresponds to the lower limit when integrating the disk support effect} \\
r^2 = \text{disk reduced radius. \pi r^2 represents the disk surface not overlapping the support} \\
\]

The first term corresponds to the moving disk support, the second one to the disk itself. The overlapping area is taken into account in the first term.

The diffuse radiation is assumed here to be isotropic.
