Separation of total irradiance into direct and diffuse components under cumulus cloud conditions

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Abstract. A technique is proposed for separating total irradiance into direct and diffuse components under cumulus cloud conditions. As initial data, values of total irradiance measured with an unshaded pyranometer and reference data for total, direct, and diffuse irradiance for a given area are used.

1. Introduction
It is well-known that the largest part of incoming solar energy is concentrated in the short-wave range of the spectrum. Therefore, actinometric measurements in this range are of particular interest. The main measurable elements of incoming solar irradiance are total $Q$, direct $S$, and diffuse $D$ irradiance, which are related by a relationship

$$Q = S \cdot \sin h + D,$$  \hspace{1cm} (1)

where $h$ is the known height of the Sun, and $S$ and $D$ are unknown values of the components of the total irradiance. To determine them, it is necessary to have one more relationship between $Q$ and $S$ or $D$.

![Figure 1](image1.png)

*Figure 1.* Schematic diagram of a perforated shading band for a pyranometer *a*) and theoretical saw tooth output from the perforated shading band *b*).

The most simple way is to measure the total irradiance, and this requires only one standard unshaded pyranometer. To measure $S$ and $D$, continuous tracking of the Sun is required. Obtaining
continuous series of data with manual observation requires the constant presence of a person, which is very problematic. The use of automatic tracking systems similar to the actinometric complex BSRN [1] is not always possible due to their high cost. Because of this, only the measurement of $Q$ is often used, and $S$, which is the main characteristic of the atmosphere, is estimated only approximately. For this reason, a very preferable way is to develop various simple accessories for the pyranometer, with the help of which it is possible to determine the components of the total irradiance. One such device is the ZEBRA band [2] (Figure 1a). The perforated shading band of the pyranometer allows one to measure total and diffuse irradiance for 60 minutes in turn (Figure 1b), which allows one to obtain a system of two equations

$$\begin{cases}
Q = S \cdot \sin h + D;
\end{cases}$$

by which unknown direct irradiance $S$ can be calculated. The disadvantage in this case is the requirement that the sky remains unchanged for a long time, which is often impossible.

A better but more complex system is the Sunshine pyranometer SPN1 [3], which can determine $Q$, $S$, and $D$ at the same time. The device has a special shading mask and 7 photosensitive elements arranged in the form of a chamomile with one element in the center. With any horizontal orientation of the device, at least one element is always open for $S$ and measures the maximum value of irradiance $Q_{\text{max}} = S \cdot \sin h + D - \Delta D$, and at least one element is always closed from $S$ and measures the minimum value of irradiance $Q_{\text{min}} = D - \Delta D$. The shading mask closes 50% of the whole sky ($\Delta D = \frac{1}{2} D$), and the values of the direct, diffuse, and total irradiance are calculated as

$$\begin{cases}
S = \frac{Q_{\text{max}} - Q_{\text{min}}}{\sin h};
D = 2 \cdot Q_{\text{min}};
Q = Q_{\text{max}} + Q_{\text{min}}.
\end{cases}$$

Accurate results in this case are possible only under a clear sky or under uniform cloudiness evenly distributed throughout the sky. Better results can be obtained if the device is oriented not arbitrarily but to the south [4]. In this case, the shadowing mask can be located only on the side of the possible position of the Sun, which minimizes its area from $\frac{1}{2} D$ to $\frac{1}{n} D$, where $n \geq 2$, depending on the maximum height of the Sun for a given region and a specific measurement period. Thus, for latitude N56° (Tomsk) for June at a maximum height of the Sun $h_{\text{max}} = 57^\circ$, $n = 5$, and for December at $h_{\text{max}} = 11^\circ$, $n = 31$. In this case, (3) is transformed to the form

$$\begin{cases}
S = \frac{Q_{\text{max}} - Q_{\text{min}}}{\sin h};
D = \frac{n}{n-1} \cdot Q_{\text{min}};
Q = Q_{\text{max}} + \frac{1}{n-1} \cdot Q_{\text{min}}.
\end{cases}$$

As seen, what similar devices have in common is that any technical solution allows one to measure two variables from equation (1), by which the third unknown variable is calculated. However, in some cases it is possible to use a standard unshaded pyranometer without any accessories. This paper proposes a technique for separating total irradiance into direct and diffuse components when non-transparent cumulus clouds are used as a natural shaper to determine the value of irradiance.
2. Theory and example of practical implementation
The initial data for the proposed procedure are the diurnal variation of the measured total irradiance \( Q \), the reference long-term average values of the total \( Q_0^* \), the direct \( S_0^* \), and the diffuse \( D_0^* \) irradiance under clear sky for a given region [5]. The separation process consists of 4 steps: checking a series of measured \( Q \) for the presence of clear and \( Cu \) skies, obtaining a model of diurnal variation of the total irradiance \( Q_0 \) under a clear sky, obtaining a model of diurnal variation of the diffuse irradiance \( D_0 \) under a clear sky, and determining the values of the diffuse and direct irradiance under \( Cu \).

Assumptions are the symmetrical daily variation of solar irradiance about noon and the constant transparency of the atmosphere in the daytime (at a height of the Sun \( h \geq 30^\circ \)). A necessary condition is the presence of clear-sky areas with a duration of at least 21 minutes. In the chosen example, 1-minute data on solar radiation from the automatic actinometric complex (AAC) of the weather station "Ogurtsovo" (WMO 29638) are used.

2.1. Checking the diurnal variation of \( Q \) for the presence of clear and \( Cu \) skies
Since the proposed procedure works under cumulus clouds, the first step is to check a diurnal variation of \( Q \) for the presence of time intervals with \( Cu \) that can be used for this. At the same time, clear sky areas are identified, which are necessary to work in the next step of the procedure. To detect such areas, different clear sky detectors [6] can be used. In this case, statistical analysis of the \( Q \) series is used for this. To do this, for each point in the range of \( \pm 10 \) minutes, the ratio of change \( C_\theta = \frac{Q}{Q_0^*} \) and the coefficient of variation \( V_\theta = \frac{\sigma}{Q} \) of total irradiance are analyzed. Here \( \bar{Q} \) is the average of the 21st measurement of the total irradiance, \( Q_0^* \) is the reference value of the total irradiance under a clear sky.

A time interval of \( \pm 10 \) minutes was chosen experimentally and allows reliably determining steady states of the sky. Any type of cloud or its absence forms its own actinometric features [7], which can be described by such coefficients. A distinctive feature of the clear sky is a "smooth" course of a series of maximum values of \( Q \) at some time interval (section \( AB \) in Figure 2). Accordingly, for a clear sky a high coefficient \( C_\theta > 0.8 \) and a low coefficient of variation \( V_\theta < 0.1 \) are characteristic. Conversely, \( Cu \) forms sharp changes in a series of \( Q \), the duration and frequency of the change depends on the amount of clouds and the speed of their movement. The maximum values of \( Q \) are formed when the Sun is open \( Q = S_0 + D \), and the minimum values, when it is closed, \( Q = D \). Therefore, \( Cu \) is characterized by a medium and high coefficient \( C_\theta > 0.3 \) and a high coefficient \( V_\theta > 0.3 \). For the example of diurnal variation \( Q \) shown in Figure 2 for June 10, 2016, an evaluation of the correctness of the definition of clear sky and \( Cu \) sections was carried out using a binary classifier and 2-minute all-sky images. For a sample under a clear skies Precision = 87%, Recall = 100% at 131 points, and under a \( Cu \) skies Precision = 100%, Recall = 45% at 540 points.

2.2. Modeling of diurnal variation of total irradiance under clear skies
At the second step of the procedure, a model of the diurnal variation of the total irradiance \( Q_0 \) under a clear sky is calculated. For this, the interpolation polynomial of the long-term average diurnal variation \( Q_0^* \) is corrected by the clear-sky sections of the measured irradiance \( Q \), so that the standard deviation of the model irradiance \( Q_0 \) on such sections amounted to a minimum value. The more there are such sections, the more accurately the model \( Q_0 \) will describe the real state of the atmosphere.

For the example shown in Figure 2 the reference values described by the polynomial

\[
Q_0^* = 3.84 \cdot 10^{14} \cdot x^6 - 1.67 \cdot 10^{10} \cdot x^5 + 2.96 \cdot 10^7 \cdot x^4 - 2.74 \cdot 10^4 \cdot x^3 + 0.13 \cdot x^2 - 30.27 \cdot x + 2456,
\]

(5)

are corrected using the clear-sky section \( AB \) to the polynomial

\[
Q_0 = 3.32 \cdot 10^{14} \cdot x^6 - 1.45 \cdot 10^{10} \cdot x^5 + 2.59 \cdot 10^7 \cdot x^4 - 2.4 \cdot 10^4 \cdot x^3 + 0.12 \cdot x^2 - 26.84 \cdot x + 2195,
\]

(6)
which is used as a clear-sky model for total irradiance \((x)\) is the serial number of the minute in a day).

The standard deviation of the model values on section \(AB\) (the number of measurement points \(n = 120\)) before the correction amounted to \(\sigma_{AB}^* = 50\ W/m^2\), and after correction, \(\sigma_{AB} = 12\ W/m^2\). The fact that in this example the real \(Q_0\) on section \(AB\) is below the average long-term \(Q_0^*\) indicates that on this day the transparency of the atmosphere was below the norm.

![Figure 2](image.png)

**Figure 2.** Calculation of the model for the diurnal variation of the total \(Q_0\) and diffuse \(D_0\) irradiance under a clear sky.

### 2.3. Modeling of diurnal variation of diffuse irradiance under clear skies

At the second step of the procedure, a model of diurnal variation of the diffuse irradiance \(D_0\) under clear sky is calculated. The ratio of direct and diffuse irradiance under a clear sky for any values of \(S\) practically linearly depends on the atmosphere transparency, and it can be regarded as a constant value \([8]\). Thus, for the normal (reference) transparency of the atmosphere

\[
\frac{S_0^*}{D_0^*} = \text{const} = r_h. \tag{7}
\]

Proceeding from this and taking into account the opposite of the change in the values of the direct and diffuse irradiance, we can write

\[
\frac{\Delta S_0}{\Delta D_0} = -r_h \cdot \sin h, \quad \tag{8}
\]

from which a correction for the series \(D_0^*\) is obtained as

\[
\Delta D_0 = -\frac{\Delta Q_0}{r_h \cdot \sin h + 1}. \tag{9}
\]

Thus, for this example the reference diurnal variation polynomial

\[
D_0^* = -3.12 \cdot 10^8 \cdot x^3 - 5.04 \cdot 10^4 \cdot x^2 + 0.78 \cdot x - 148 \tag{10}
\]

is corrected to the polynomial (Figure 2)

\[
D_0 = -4.2 \cdot 10^8 \cdot x^3 - 5.59 \cdot 10^4 \cdot x^2 + 0.88 \cdot x - 167. \tag{11}
\]

It should be noted that with reduced transparency of the atmosphere, \(D\) is always above the norm.
2.4. Calculation of diffuse and direct irradiance

After calculating the models of diurnal variation of \( Q_0 \) and \( D_0 \), one can obtain the system of equations (2) and determine the unknown \( S \). To obtain the first equation it is necessary to use the condition \( Q > 1.1 \cdot Q_0 \) when the Sun was open (coefficient 1.1 is the guard interval), for the second one, the condition \( Q < D_0 + 120 \cdot \sin h \) when the Sun was closed by a non-transparent cumulus (where 120 W/m\(^2\) is the sunshine level). This approach is inconvenient because the Sun cannot be both open and closed at the same time. Therefore, \( S \) and \( D \) will be determined sequentially and at different times. In this case, the delay time in the measurements will depend on the \( Cu \) amount and the speed of its movement. Using diffuse irradiance allows one to determine \( S \) and \( D \) at the same time, because it is present at any state of the Sun.

\[
\begin{align*}
Q &> 1.1 \cdot Q_0, \\
Q &< D_0 + 120 \cdot \sin h
\end{align*}
\]

Figure 3. Dependence of coefficient \( b \) on the ratio
\[
m = \frac{Q - Q_0}{D_0}.
\]

In the general case, the diffuse irradiance under \( Cu \) can be represented as
\[
D = D_{op} + D_{cl},
\]
where \( D_{op} \) is the diffuse irradiance when the Sun is open, and \( D_{cl} \) when the Sun is closed. The diffuse irradiance can be reconstructed as
\[
D_Q = \begin{cases} 
D_{op} = D_0 \cdot (1 - b) + (Q - Q_0), & Q > 1.1 \cdot Q_0; \\
D_{cl} = Q, & Q < (D_0 + 120 \cdot \sin h),
\end{cases}
\]
where \( b \) is an empirical coefficient that takes into account the amount of \( Cu \) clouds (in unit fractions) and depends on the ratio \( m = \frac{Q - Q_0}{D_0} \) (Figure 3) [9].

As a rule, there are always intermediate states when the Sun shines through the thin edges of \( Cu \) or these clouds are not sufficiently dense. Such short time missing values in a series of restored \( D_0 \) can be filled using a linear or some other interpolation method. This is possible because diffuse irradiance cannot change abruptly. Figure 4 shows the calculated \( D_Q \) and the factual \( D \) (measured with AAC) diffuse irradiance.
Figure 4. Calculated $D_{op}$ (red dots) and $D_{cl}$ (dark blue dots) and factual $D$ diffuse irradiance.

The errors of the reconstructed diffuse irradiance under open Sun (the number of points $n = 73$) and under closed Sun ($n = 44$) for this example are $\sigma_{op} = 43 \text{ W/m}^2$ and $\sigma_{cl} = 7 \text{ W/m}^2$, respectively.

At the end of the procedure, using the known $Q$ and $h$ and calculated $D_Q$, direct irradiance is determined as

$$S_Q = \frac{Q - D_Q}{\sin h}. \quad (14)$$

3. Conclusions

The proposed technique allows separating total irradiance $Q$ into its components direct $S$ and diffuse $D$ irradiance under non-transparent cumuliform clouds, in particular, at $Cu$ hum. and $Cu$ fr. In this case, the clouds themselves are used as a shading screen to determine diffuse irradiance. For Southwestern Siberia, the frequency of $Cu$ during summer time is more than 30% [5]. Therefore, the number of possible situations for using this technique is quite large. The accuracy of separating the $Q$ components primarily depends on the accuracy of the models for diurnal variation of the total $Q_0$ and diffuse $D_0$ irradiance components under clear sky, which should describe, as closely as possible, the actual state of the atmosphere.

Acknowledgments

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