1. Introduction

The half angle of the solar disk is 0.266°. Radiative transfer models (RTMs) (e.g., LibRadtran, 65) model the irradiances at surface as if the sun were a point source. On the contrary, pyrheliometers measure the radiation coming from the direction of the sun with a half-aperture angle equal to 2.5° according to WMO standards. Aperture angles or acceptance angles can be greater for systems converting solar energy into power. Therefore, the measuring devices or power systems take into account the circumsolar irradiance (CSI), while RTM do not.

On a horizontal plan, beam horizontal (BHI) and diffuse horizontal (DHI) irradiances are given by:

\[ \text{BHI}_{\text{measured}} = \text{BHI}_{\text{sun-center}} + \text{CSI} \]
\[ \text{DHI}_{\text{measured}} = \text{DHI}_{\text{sky-vault}} - \text{CSI} \]

BHI\text{sun-center} and DHI\text{sky-vault} are those estimated by the RTM. The CSI received by a horizontal surface should therefore be added or subtracted to the modeled irradiances.

2. Typical half-aperture angles

WMO primary standard for pyrheliometer: 2.5°
WMO secondary standard for pyrheliometer: 2.5° - 5°
BSRN stations = 2.5° (Eppley Normal Incidence Pyrheliometer, NIP)
Concentrating Solar Power : ~ 0.7° to 2.4°
Concentrating Photovoltaic: 0.7° to 5°
Source: http://techrtransfer.universityofcalifornia.edu/NCD/10320.html

3. Calculation of CSI with libRadtran

CSI is not a direct output of LibRadtran (www.libradtran.org). If polar and azimuth angles are specified, LibRadtran can provide irradiation in addition to irradiance. The CSI is the sum of irradiances around the sun center. The radiation L (W/m²/°sr) is the solar flux per unit area and solid angle.

\[ \text{CSI}(\theta, \varphi) = \int_0^\pi \int_0^{2\pi} L(\theta, + \theta, \varphi + \varphi) \sin \theta \cos \theta d\theta d\varphi \]

The radiance is not homogenously distributed on the sky vault. The figure on left shows the radiance for various polar and azimuth angles around the sun centre. The closer to the sun center, the higher the radiance.

The integration of the radiance over the hemisphere gives the diffuse irradiance.

For a half-aperture angle equals \( \alpha \), the CSI on horizontal surface is:

\[ \text{CSI}(\theta, \varphi, \alpha) = \int_0^\alpha \int_0^\pi L(\theta, + \theta, \varphi + \varphi) \sin \theta \cos \theta d\theta d\varphi \]

Figures below show the CSI from libRadtran with an angle of 2.5° half-aperture angle for cloudless and cloudy skies. The CSI is low; its maximum is close to 12 W/m².

For cloudy-sky calculations, the aerosol optical depth (AOD) is set to 0.4. Other atmospheric parameters are kept default.

Cloudless sky (CSI in W/m²)

4. CSI in clear sky, libRadtran vs SMARTS

In addition to CSI calculations with libRadtran, we also use the SMARTS model to verify our results. The SMARTS model (Gueymard 1995) computes clear-sky spectral irradiances for specified atmospheric conditions. The algorithms used by SMARTS were developed to match the output from the MODTRAN complex band models within 2%.

CSIs computed with SMARTS are less than those computed with LibRadtran. The values remain very low compared to BHI: mean CSI is 6 – 7 W/m² with LibRadtran and 3 – 5 W/m² with SMARTS. Both CSIs are generally less than 1% of the BHI.

<table>
<thead>
<tr>
<th>Station</th>
<th>Mean (W/m²) libRadtran</th>
<th>Mean (W/m²) SMARTS</th>
<th>Bias (%)</th>
<th>RMSE (%)</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carpentras</td>
<td>5.40</td>
<td>2.74</td>
<td>49</td>
<td>54</td>
<td>0.890</td>
</tr>
<tr>
<td>Tamarrasset</td>
<td>5.94</td>
<td>3.75</td>
<td>37</td>
<td>48</td>
<td>0.673</td>
</tr>
<tr>
<td>Sede Boger</td>
<td>7.41</td>
<td>4.58</td>
<td>38</td>
<td>48</td>
<td>0.468</td>
</tr>
</tbody>
</table>

Adding modeled CSI does not improve the quality of BHI, whether we use LibRadtran or SMARTS. Comparisons of BHI with and without CSI against ground measurements made at clear-sky instants in BSRN stations reveal similar performances.


5. CSI in cloudy skies

Under cloudy skies, and especially thin clouds, scattering increases the solar disk, as illustrated on the figure. This may lead to a significant increase of the CSI.

Thomalla et al. (1983) have reported very large values of CSI at normal incidence (normalCSI) under thin cirrus clouds (table below). The circumsolar ratio (CSR) is defined as the ratio of normal CSI to the sum of the direct irradiance received from the sun at a point source (BNI) and normal CSI. The greater the CSR, the greater the influence of the CSI on the irradiance.

<table>
<thead>
<tr>
<th>SZA</th>
<th>COD</th>
<th>AOD</th>
<th>BNI (W/m²)</th>
<th>BNI* normalCSI (W/m²)</th>
<th>CSR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30°</td>
<td>0.3</td>
<td>0.2</td>
<td>641</td>
<td>757</td>
<td>38</td>
</tr>
<tr>
<td>30°</td>
<td>0.5</td>
<td>0.2</td>
<td>530</td>
<td>676</td>
<td>28</td>
</tr>
<tr>
<td>30°</td>
<td>1.0</td>
<td>0.2</td>
<td>326</td>
<td>485</td>
<td>49</td>
</tr>
<tr>
<td>70°</td>
<td>0.3</td>
<td>0.2</td>
<td>248</td>
<td>352</td>
<td>42</td>
</tr>
<tr>
<td>70°</td>
<td>0.5</td>
<td>0.2</td>
<td>151</td>
<td>243</td>
<td>61</td>
</tr>
<tr>
<td>70°</td>
<td>1.0</td>
<td>0.2</td>
<td>42</td>
<td>84</td>
<td>98</td>
</tr>
</tbody>
</table>

These calculations are made for a similar angular aperture than those made with libRadtran. But here, CSI is often greater than 100 W/m², and the CSR is close to 100% for large solar zenith angle (SZA) and cloud top optical depth (COD) equals 1.

The CSI in clear-sky from libRadtran are close to those obtained by Thomalla et al. (1983). The difference observed in cloudy sky can be due to the fact that the 3D effect is taken into account in their model and not in libRadtran.

6. Conclusion

1. The CSI can be computed from the RTM libRadtran. The calculated CSI under clear-sky are close to those reported in scientific literature and are generally less than 1%.
2. Taking CSI into account does not improve significantly the quality of BHI estimated from libRadtran.
3. The CSI under cloudy sky can be very important (greater than 100 W/m², or 50%) according to various sources. These high values are not obtained by using libRadtran, probably because the fact of 3D effect is not taken into account in libRadtran.
4. Further study will be done to quantify the proportion of different effects on CSI under cloudy sky (3D effect, particle size distributions and others), especially in case of thin ice cloud.