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Research

SHORT COMMUNICATION

Concerning the Relationship Between Clear-Sky, Global and Direct-Beam, Solar Spectra

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Clear-sky direct-beam and normal global solar spectra were measured with a spectroradiometer with and without a collimating tube. The ratio of the two spectra was found to be well approximated by a simple two-parameter formula suggested by Rayleigh scattering. Copyright © 2002 John Wiley & Sons, Ltd.

INTRODUCTION

Because of the different spectral sensitivities of PV materials, the need to establish standard reference spectra has long been appreciated.[1] Much effort was accordingly invested in modeling[2] and measuring[3] solar spectra under various atmospheric conditions, leading eventually to the international adoption of the so-called AM1·5 G standard global spectrum[4] for PV purposes. Recently, with renewed interest in the potential economic benefits of concentrator PV cells (CPV), there would appear to be a pressing need for an internationally accepted standard spectrum for the direct beam component of solar radiation, i.e., an AM1·5 D standard.

The purpose of this paper is, therefore, to present the first stage of an experimental study of the relationship between natural global and direct-beam solar spectra measured on clear days at various times of the year, at Sede Boqer in the Negev Desert (Lat. 30·8°N, Lon. 34·8°E, Alt. 475 m). The study was prompted by the fact that this particular site is known[5] to have natural clear-sky spectra in close conformity with the established, albeit computer-generated, AM1·5 G standard spectrum.[4] Our motivation was to investigate the possible existence of a simple empirical relationship between global and direct spectra. For, if one were discovered to exist, it would not be necessary to define two independent spectra for PV and CPV measurements: the existing AM1·5 G standard[4] would suffice, *mutatis mutandis*, for both purposes. To the best of our knowledge, none of the previously published work, whether measurement-based or model-based, has discussed the *ratio* of the direct-beam and global spectra.

EXPERIMENTAL METHOD

For our spectral measurements we employed a Li-Cor 1800 spectroradiometer, having a wavelength range 300–1100 nm and a passband of 6 nm. The instrument had been recently re-calibrated by the manufacturer. Global

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Figure 1. Spectroradiometer strapped to movable stand with collimator tube held in place, the latter is used to find normal incidence, and to remove the sky-diffuse and ground-reflected radiation components

spectra were measured by the Teflon dome receptor that is permanently attached to the body of the instrument. Direct-beam spectra were measured by adding a collimator tube[3] constructed from a piece of iron pipe, cut so that its length was ten times its internal diameter. After cutting, the interior of the pipe was turned on a lathe in order to produce fine rings which were subsequently blackened with carbon soot.

The spectroradiometer was strapped to a movable plane so that its sensor could be aligned normal to the incoming solar beam direction. For this purpose, the collimator tube was usefully employed, since, at normal incidence, its shadow becomes invisible. Figure 1 shows the spectroradiometer and collimator tube ready for measurement. Starting approximately 20 min before solar noon, a series of alternating global and beam scans were taken. The first series was in the wavelength range 400–1100 nm, at 2-nm intervals. The second series was taken in the extended range 300–1100 nm, at 1-nm intervals.

For control purposes, two Eppley PSP pyranometers were mounted at normal incidence (one having a removable shading disk subtending a half-angle equal to 1/20 rad). In addition, an Eppley NIP pyrheliometer was mounted on a sun tracker. One of the PSP instruments was a secondary standard whose calibration can be traced to the recent IPC-IX. These three instruments were connected to a Campbell 21X micrologger, set to sample every 1 s and to average every 60 s. This set-up enabled us to establish the correct overall normalization[6] for the global and direct-beam irradiance during the period over which the spectral measurements were taken.

RESULTS

Figure 2 shows a graphical plot of the global and direct-beam irradiance readings taken with the PSP and NIP instruments during an approximately 45-min period surrounding solar noon on 21 December 2001. Although there was some very slight cloudiness in the vicinity of part of the horizon (mainly to the north), it was decided

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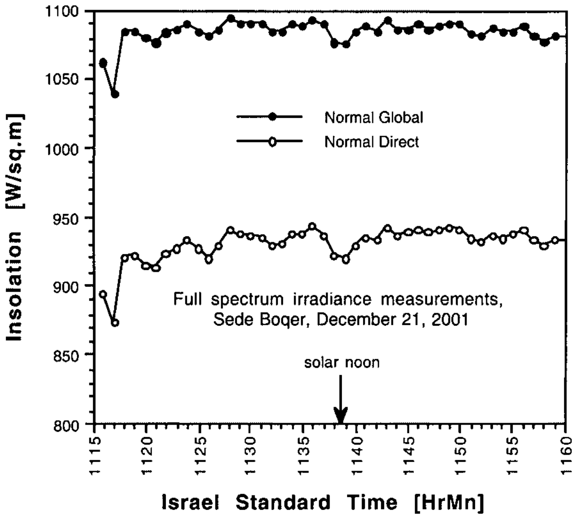

Figure 2. Calibrated normal, global and direct-beam, full-spectrum insolation monitored during the spectural runs

to make this first experimental run on the day of the winter solstice in order to avail ourselves of the maximum value of air mass (1·62, pressure-corrected) that is attained at this latitude.

The observed ± 1% 'ripple' in Figure 2 is somewhat *large* compared to typical clear-day noontime measurements of this type we have made in the past.[5] This was probably due to some residual water vapor, as evidenced by the slight cloudiness, mentioned previously, that was visible along the northern edge of the horizon, particularly at the start of the experiment. However, it will be noticed in Figure 2 that a relatively smooth 'plateau' existed during the time period 11:44–11:50, during which the irradiance was constant to within ± 2 parts per thousand. Therefore, the spectra that were measured during this time period were earmarked for special attention. During this time period the corresponding value of the (pressure-corrected) air mass was 1·62.

Figure 3 plots the global and direct-beam spectra that were measured during the 11:44–11:50 time period mentioned above. The global spectrum was taken at 11:46 and the direct beam spectrum at 11:47. There is an unimportant uncertainty of approximately ± 30 s in these time assignments due to the finite time it takes

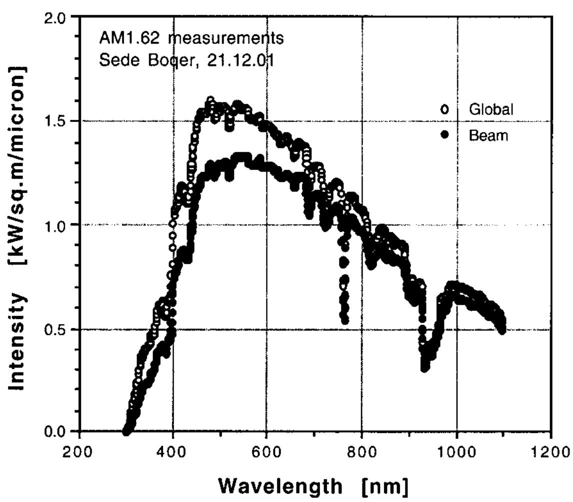

Figure 3. Normal global and direct beam spectra measured at Sede Boqer during the noontime period, 21 December 2001. Both spectra have been slightly renormalized so that the integral of the global spectrum from 300–1100 nm is 797·0 W m^{-2}, a value derived from the AM1·5 G standard.[4] (The corresponding direct-beam integral is 682·2 W m^{-2})

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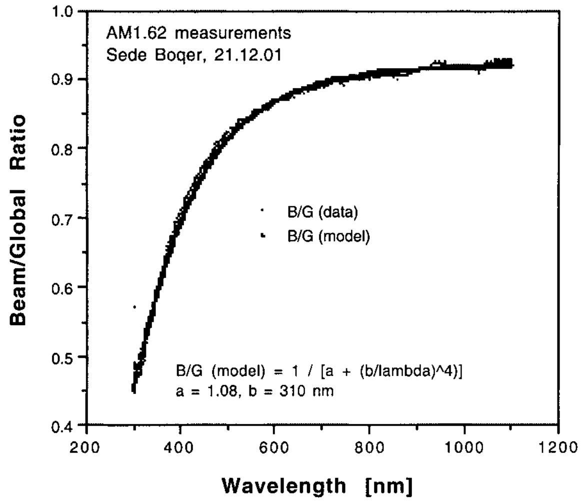

Figure 4. The ratio of the direct-beam to global spectra shown in Figure 3

the spectroradiometer to scan the 300–1100 nm wavelength range. Furthermore, in Figure 3, all readings have been re-scaled by a factor of 0·92 so that the integral of the global spectrum corresponds to the integral over the standard AM1·5 G spectrum[4] over the range of wavelengths measured, i.e., 797 W m^{-2}.

It is important to point out that the unscaled numerical integrals of these two spectra, from 300 to 1100 nm, are respectively 866·1 W m^{-2} for the global spectrum, and 741·3 W m^{-2} for the direct beam. Their ratio (0·856) compares quite well, to within known NIP-PSP calibration transfer errors,[6] with the corresponding ratio of the parallel NIP-PSP measurements ($0{\cdot}864 \pm 0{\cdot}001$) averaged over the above-mentioned time 'plateau' in Figure 2. This indicates that there is no serious overall calibration error, if any, in the spectroradiometer. In any event, because we are mainly interested in the *ratio* of direct-beam to global spectra, as measured with a single instrument, any calibration errors in the spectroradiometer would have minimal, if any, effect on our conclusions.

In this respect, of greater interest than the absolute shape of these spectra is the shape of their ratio. Figure 4 shows the ratio of two spectra shown in Figure 3. In this figure, the data are shown as small dots. (Superimposed on these dots is an algebraic curve, which will be discussed below.) It is worthy of note that the smoothness of the curve shown in Figure 4 was somewhat singular for this experimental run. We compared each measured beam spectrum with the global spectra that immediately preceded and followed it. In *all* cases, the overall shape of the ratio was quite similar to that shown in Figure 4 (for the experimental runs made at both 1- and 2-nm wavelength intervals), except for some slight waviness in the 900–1000 nm wavelength region. From its wavelength range, this waviness may be attributed to the presence of water vapor, probably in the form of small, invisible, passing clouds, partially obscuring the direct beam insolation. The unusual monotonicity of Figure 4, by contrast, probably indicates a relative absence of such vapor during the 'plateau' period 11:44–11:50 that was discussed in connection with Figure 2.

THEORETICAL ANALYSIS

Consider first a highly simplified situation, in which the sun is at the zenith (which never quite happens at the latitude of Sede Boqer) and the spectroradiometer is horizontal and upward-facing. If G represents the global insolation and B represents its direct-beam component, then the ratio:

$$B/G = 1/(1 + D/B) \tag{1}$$

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where D represents the diffuse component. Now, because of Rayleigh scattering, the beam component would be depleted according to λ^4, compared with the diffuse component, since the latter is scattered from all parts of the sky. Hence, we might expect the beam-to-global ratio to have a wavelength dependence:

$$B/G = 1\Big/\left[1 + (\lambda_0/\lambda)^4\right] \tag{2}$$

where λ is the wavelength and λ_0 is a scale factor that characterizes the particular state of the atmosphere (i.e., the content of aerosols, water vapor, ozone, etc.[7]) when the measurements are made.

Now, in a more realistic situation in which the instrument is tilted, thus allowing some ground-reflected insolation to enter the spectroradiometer, G will contain a third component R in addition to B and D. An additional R/B term would then have to be added to the denominator of Equation (1). In the artificial case of the ground being a perfect mirror, this addition would simply increase the values of each of the two existing terms in the denominator of Equation (2). In a less artificial situation, in which the ground both scatters the light in a non-specular manner and changes its spectral content, it might be reasonable to approximate the R/B component as a power series expansion in $1/\lambda$. The constant term would add to the value of 1 in the denominator of Equation (2), whereas the remaining terms would add to the $(\lambda_0/\lambda)^4$ part, possibly distorting its pure fourth-power form.

Be that as it may, a reasonable starting point would be to try an empirical fit of the form:

$$B/G = 1\Big/\left[a + (b/\lambda)^4\right] \tag{3}$$

which is the model that has been used in Figure 4. It is seen that this simple model fits the data remarkably well. For the data presented here, the two parameters take the values $a = 1{\cdot}08$ and $b = 310$ nm. In fact, this same curve fits all of the data we measured on 21 December 2001 quite well, *modulo* the H_2O waviness that was discussed above.

One should probably not attach any universal relevance to these particular values of the parameters a and b, since they may vary from month to month: a possibility that we plan to investigate further. We note, however, that December is the month that presents the largest noontime zenith angle and, correspondingly, the largest admixture of ground-reflected irradiance in G. Therefore, since a relatively pure fourth-power inverse wavelength dependence is found in the denominator of Equation (3) for this month, we should expect this feature to be preserved throughout the year.

In this respect, we may compare the re-scaled measured AM1·62 natural global spectrum that was plotted in Figure 3, with the international standard AM1·5 G reference spectrum.[4] This comparison is shown in Figure 5.

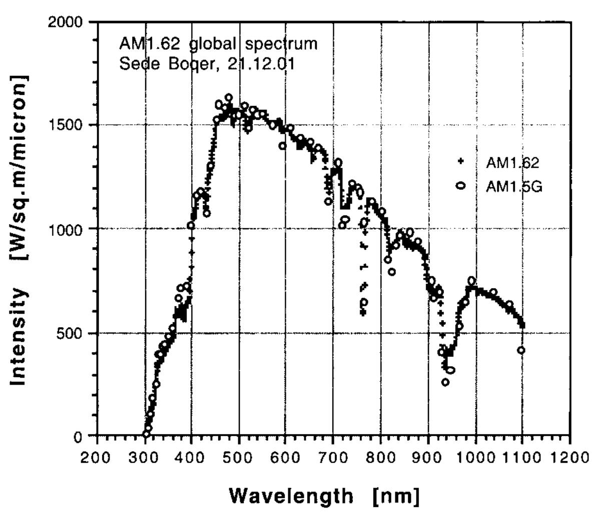

Figure 5. The re-scaled AM1·62 global spectrum (crosses), measured at Sede Boqer during the noontime period on 21 December 2001, compared with the standard[4] AM1·5 G reference spectrum (circles)

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The striking degree of similarity that can be observed between these two global spectra allows us to anticipate that the parameter values $a = 1{\cdot}08$ and $b = 310$ nm, derived from the present set of measurements, when inserted in Equation (3), may already serve as a fairly good indication of a provisional way to generate an appropriate AM1·5 D working spectrum from the existing AM1·5 G standard.[4]

SUMMARY AND CONCLUSIONS

We have measured the ratio of the direct-beam to global solar spectra B/G, on an almost-cloudless day during the noontime period in mid-winter. The results indicate a smooth wavelength dependence, which is well approximated by a simple two-parameter formula, based on a model in which Rayleigh scattering dominates the direct-beam component.

Because these measurements have, so far, been performed at only a single time of the year, it is unclear by how much the model parameters a and b will vary at different seasons, but we expect this simple algebraic form to persist throughout the year.

The practical importance of the smoothness of the observed B/G ratio lies in the fact that, by a suitable (yet-to-be-determined) choice of the parameters a and b, it could allow one to define a reference AM1·5 D spectrum which would be 'naturally' related to the existing standard AM1·5 G reference spectrum,[4] however *ad hoc* the latter might be. Such a pair of matched reference spectra is desirable because they would enable the efficiencies of concentrator and non-concentrator photovoltaic cells and devices to be compared in a uniform manner.

Yet another potential significance[8] of these a and b parameters is that they might constitute a convenient two-parameter means of characterizing different types of experimental conditions: e.g., 'desert clear', 'desert hazy', and of relating them all to the standard global AM1·5 G reference spectrum.[4] (We are indebted to Daryl Myers for drawing our attention to this after reading the first draft version of our paper.)

We plan to repeat these measurements on sample clear days throughout the coming year in order to examine the variability of the parameters a and b. We shall also attempt to unravel the sky diffuse and ground-reflected components of G via the use of artificial horizon masks.[8]

Acknowledgements

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