**ROTATING SHADOWBAND FOR MEASURING SUNSHAPES**

**Ragini Kalapatapu1, Peter Armstrong2, Matteo Cheisa2**

1.Graduate student, Research Assistant, Masdar Institute of Science and Technology, Abu Dhabi, UAE, PO- 54224, Phone: +971567339450, email: rkalapatapu@masdar.ac.ae

2.Prof.Dr., Masdar Institute of Science and Technology, Abu Dhabi, UAE, Ph: +97128109150

Abstract

Thermodynamic and economic performances of Concentrated Solar Power (CSP) plants are sensitive to optical design parameters, such as concentration and acceptance angle. Beam attenuation due to aerosols and the effect of varying sunshape profiles are important in creating accurate optical models that can take into account the specific solar resource conditions of a region. Failing to consider the aforementioned effects can result in economic loss due to overestimation of annual yields, which are normally based on ordinary solar resource assessment instruments (Pyrheliometer). On the other hand, high-resolution long-term solar radiation measurements are expensive and labor intensive. This paper describes the potential of a small and low-cost field instrument called the sunshape rotating shadowband radiometer (SR)2 to measure the circumsolar radiation profile hundreds of times in a day automatically and unattended. Numerical experiments have been performed on the flux map of the (SR)2 and the results of the inverse calculations give us the key parameters (slope and intercept) to produce the sunshape curve of the site. A summary of the numerical results is presented. Modification of an existing rotating shadowband instrument is underway for use in siting CSP plants and investigations of aerosols and their effect on atmospheric radiation balance.

Keywords: Circumsolar Ratio, Sunshape, Inverse Model, Aerosols, Atmospheric Scattering.

1. **Introduction**

This paper proposes a new instrument for measurement of sunshape profiles; first we discuss the importance of measuring the sunshape profiles and their effect on the performance of CSP plants. Our proposed sunshape rotating shadowband (SR)2 instrument is described in section 4 and numerical methods for the retrieval of sunshape are discussed. Results of the simulations have been discussed in Section 5 which describes the potential of our instrument in measuring the sunshape profiles.

The circumsolar region is an area of enhanced sky brightness surrounding the solar disk due to the forward scattering of radiation caused by atmospheric aerosols and other constituents. The angular distribution of energy in this region, or *sunshape*, is important because of the following [1], [2]:

* Depending on the acceptance angle of a solar concentrating system, overestimation of power output may occur because the acceptance angle of CSP plants is typically lower than the acceptance angle of common DNI measurement instruments (see Table2)
* The sunshape profile can play a significant role in determining the overall flux distribution in the focal plane of concentrating systems and hence the intercept factor of the receiver (see Figure 1 and Table 1)
* Aerosols play an important role in determining the sunshape profile.

 The measurements of sky radiation excluding the circumsolar region can be used to determine the large angle scattering from aerosols. However, without measuring the solar aureole, no information is available on the small angle scattering. One must acquire solar aureole data to determine the full aerosol scattering phase function. An installation with high-resolution cameras and detectors costs over US $80000 and requires frequent visits to check alignments and clean components. Motivated by these considerations, a low-cost instrument based on an existing rotating shadowband radiometer1, is proposed for continuous measurement of the radiance profile coming from the circumsolar region.

1The rotating shadowband radiometer (RSR) is also known as a rotating shadowband pyranometer (RSP) when the detector in question is a conventional pyranometer such as the LiCor PY200.

Figure1. Intercept factor Vs. Circumsolar Ratio for Euro Troughs [3], [4], [5].

|  |  |  |
| --- | --- | --- |
| *CSR* | *Collector Efficiency accounting for optical, surface and sunshape errors*  | *Collector Efficiency accounting for Gaussian source with optical and surface errors* |
| 0.0082 | 0.8426 | 0.8454 |
| 0.01 | 0.8394 | 0.8425 |
| 0.0270 | 0.8302 | 0.8398 |
| 0.0345 | 0.8266 | 0.8357 |
| 0.0571 | 0.8165 | 0.8241 |
| 0.0888 | 0.8149 | 0.8188 |
| 0.1061 | 0.8060 | 0.8102 |
| 0.1461 | 0.8040 | 0.8062 |
| 0.2042 | 0.7968 | 0.7963 |
| 0.2938 | 0.7778 | 0.7737 |
| 0.3990 | 0.7434 | 0.7329 |
| 0.4708 | 0.7324 | 0.7210 |
| 0.5260 | 0.6994 | 0.6847 |
| 0.5870 | 0.6748 | 0.6602 |
| 0.6920 | 0.6468 | 0.6387 |

Table1. Collector efficiency for Euro Troughs for different CSR’s of the LBL sites [3], [4], [5].

Direct radiation is measured by pyrheliometer or absolute cavity radiometers with apertures given in Table 2.

|  |  |  |
| --- | --- | --- |
| *No* | *Type or Make of Radiometer* | *Acceptance Angle* |
| 1. | Eppley-Angstrom Pyrheliometer[6] | 5o |
| 2. | Eppley Normal Incidence Pyrheliometer [6] | 5.7o |
| 3. | Spectropyrheliometer [8] | 6o |
| 4. | Kipp and Zonen/ Linke-Feussner Pyrheliometer (Actinometer) [6] | 9.6o |
| 5. | Absolute Cavity Radiometer [7] | 5o |

Table2. Different types of radiometers and their acceptance angles

**2. Rotating Shadowband Radiometers (RSR)**

The RSR is being used widely, as shown in Table 3, to measure total radiation and, with its pyranometer shaded from direct sun, to measure the diffuse component which, when subtracted from the global horizontal radiation, gives the direct radiation and, using cosine of the zenith angle, the DNI.

|  |  |
| --- | --- |
| *No* | *Places using Rotating Shadowband Radiometer*  |
| 1. | National Wind Technology Center M2 Tower, Colorado [9] |
| 2. | Solar Radiation Research Laboratory-Schott, Irradiance Inc., Ascension Technology, Inc. [9] |
| 3. | Solar Technology Acceleration Center (SolarTAC), MRI, Aurora, Colorado [9] |
| 4. | SMUD, Anatolia, California [9] |
| 5. | SOLRMAP: Tucson, AZ; South West Solar Technologies, AZ; Escalante, NM; Milford, UT; Los Angeles, CA; Kalaeloa Oahu, HI, La Ola Lanai, HI; Swink, CO; San Luis Valley, CO [9] |
| 6. | Nevada Power Clark Station (NPCS), Nevada and University of Nevada, Las Vegas (UNLV) [9]  |
| 7. | Lowry Range Solar Station (LRSS) and Xcel Energy Comanche Station (XECS), Colorado [9] |
| 8. | Sacramento Municipal Utility District (Anatolia), California [9] |
| 9. | Elizabeth City State University (ECSU), North Carolina [9] |
| 10. | Bluefield State College (BSC), West Virginia [9] |
| 11. | Humboldt State University (SoRMS) and San Clemente Island Data (SCID), California [9] |
| 12. | South Park Mountain Data (SPMD) and Lamar Low-Level Jet Project (LLLJP), Colorado [9] |
| 13. | ARM Radiometer Characterization System (RCS), Oklahoma [9] |
| 14. | Oak Ridge National Laboratory (ORNL), Tennessee [9] |
| 15. | Multifilter Rotating Shadowband Radiometer at Southern Great Plains (SGP), North Slope Alaska (NSA), Tropical Western Pacific (TWP), SHEBA (Surface Heat Budget of the Arctic) (SHB) [10]  |
| 16. | ARM Mobile Facility- FKB (Black Forest, Germany), GRW (Graciosa Island, Azores), HFE (Shouxian China), NIM (Niamey, Niger), PYE (Point Reyes, CA), SBS ( Steamboat , CO)[10] |
| 17. | Solar MilleniumMeteostations, Spain [11] |
| 18. | Ultra Violet Multifilter rotating shadowband radiometers at Colorado State university, University of California at Davis’ Climate Station by SUNY- Albany, and ASRC (YES) [12] |
| 19. | Reines Hall, University of California, Irvine Campus by Yankee Environmental Systems (YES) [13] |
| 20. | UT Austin, Clear Lake (NASA), Edinburg (UT Pan American), UT El Paso, Canyon (WTAMU) [14] |
| 21. | Fifteen stations at Texas from Texas Solar Radiation Database [14] |
| 22. | National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories (SNL), New Mexico [15] |
| 23. | PSA, and several locations in southern Spain and Morocco by DLR [16] |
| 24. |  CSIRO YES MFR7 Earth Observation Center (1); Atmospheric Research (2,3) [17] |
| 25. | Global Monitoring Division, NOAA, US [18] |
| 26. | Pacific Northwest National Laboratory (PNNL), University of Hawaii- Manoa, and Aerosol Monitoring Network at Arizona, California, Washington and Australia [19] |

Table3. Different places using the RSR from different sources

J.J.Michalsky et al [20] describes a rotating shadowband radiometer comprised of a silicon cell pyranometer and a stepping motor with 0.9-degree steps that drives a shadowband about a polar axis. The vertical component that contains the latitude adjustment track is oriented due north- south, with the base and the latitude adjustment is made to orient the motor axis parallel to the rotation axis of the earth. The shadowband thus moves in hour angle. Data acquisition and control is accomplished using a microprocessor. The motor is driven in one direction and only one digital line is required to send pulses to the stepping motor. Also, a correction is made to account for the excess radiation blocked by the shadowband during the diffuse horizontal solar radiation measurement. The unfiltered silicon channel responds to wavelengths between 300 and 1100 nm and does not have a uniform spectral response. J.J.Michalsky et al [21] describe a multi-filter rotating shadowband radiometer whose detectors are temperature stabilized near 40oC, and therefore, a temperature correction is not required.

**3. Sunshape Model**

An empirical circumsolar brightness model was proposed by the Buie et al, which is invariant to a change in location and being only dependent on one variable, the circumsolar ratio, (χ). Over the two regions of the solar disk and the circumsolar aureole, the radial distribution of intensity (Φ) in the circumsolar region is defined using the following equations [1]:

Φ (θ) = cos (0.326\*θ)/cos (0.308\*θ), {0< θ<4.65 mrad}

Φ (θ) = eκθϒ, {θ>4.65 mrad}

Where κ= 0.9ln (13.5χ) χ (-0.3), γ= 2.2ln (0.52χ) χ (0.43)-0.1

κ is a scaling factor determined by the intercept of the curve in log- log space, γ is the slope of the curve.

The linear relationship between the intensity of the circumsolar region to that of the radial distribution in log- log space can be seen in figure 2 for different circumsolar ratios from 0.1 to 0.5.

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 Figure2. Sunshape curves obtained from Buie’s equations for CSR’s from 0.1 to 0.5.

**4. Sunshape Rotating Shadowband Radiometer (SR)2**

The Sunshape Rotating Shadowband Radiometer, (SR)2 which is a modification of the RSR, may be used for solar resource assessment, climate research, and to collect real-time data useful to derive global or regional weather forecasting models at very low cost and can be made to measure the sunshape hundreds of times in a day. The instrument and analysis algorithm together can retrieve the radial profile of solar flux across the sun’s disc and through the circumsolar region. Flux profiles, or sunshapes, can be used to infer absorption and scattering of solar radiation in the atmosphere, to estimate total aerosol column mass and size distribution (especially when used in conjunction with multi-filter detectors), and to evaluate atmospheric radiation balance.

The modifications on typical RSRs entail using a modified optical receiver (slit), a 12,800-step per revolution shadowband drive, and a 106-dynamic-range signal conditioner. Effective resolution of 64,000 steps/revolution is achieved by scanning the circumsolar region five times. Five sub steps are created by the fact that the sun’s position changes 360/64000 degrees every 13.5 seconds. The (SR)2 cost is about the same as that of a conventional RSR. A conventional 800-step/revolution RSR costs about $3000 and measures direct and diffuse solar radiation but does not measure the circumsolar profile.

Three different kinds of the shadow bands and receivers (point, slit and circular) are considered to assess the effect of shading and detector geometry on the sensitivity of sunshape retrieval:

* A globe that shades the detector almost completely; a slit parallel to the polar axis allows radiation from a portion of the sky or the solar disk, depending on the solar-slit hour angle, to reach the detector.
* A half globe that blocks at least half the sky as the edge approaches and passes over the solar disc.
* A regular 6o shadow band that allows radiation from most of the sky to reach the detector at all times.



Figure3. Point, Circular and Slit receiver on the detector.



Figure 4.Full Globe, Half Globe and Traditional shadowband Radiometers.

The diffuse radiation on the shaded receiver is the difference of total sky radiation and the direct radiation from the disk and the aureole (with a correction for the part of the diffused sky, covered by the shadowband). Flux on a point receiver after being covered by the shadow band around the disc of the sun is given by:

Irsr= Isky- Idirect

For a receiver having finite area of A with conventional and half globe shadowband as discussed previously, the difference of uniform sky radiation and the direct radiation is multiplied with the area of the slit [1], [22]:

Whereis Zenith angle, GZ is Zenith radiance, Φ is the solar intensity of the disk and the circumsolar region with increasing angular displacement. The above equation divides the sky into two quadrants and assumes a sky clearness index of less than 0.2 (clear sky) and radiation distribution index of 1.68 for each hemisphere as given by Muneer et al [22]. Modeling of flux on the receiver gives the inverse of the sunshape curves as shown in Figure5.

In case of a full globe, during solar noon, the detector inside the sphere receives maximum signal from the solar disk when the slit is right on top of the receiver and then the intensity decreases as the slit rotates to shade the receiver. Figure 6 shows the full globe simulation for different CSRs using Buie’s model [1].

Inverse calculations are performed on the (SR)2 signal (Figs 5 and 6) in order to identify the sunshape profile as defined by Buie's model through the use of slope and intercept values. These values are then compared with the sunshape model used in generating the (SR)2 signal in the first place. To assess the sensitivity of the identification, the same analysis is performed after adding Gaussian noise to the shadowband intensity curve for χ=0.5. As the shadowband moves over 200 steps, the receiver captures the sky radiation plus the disk and the aureole radiation, which in Figures 5-8 is normalized to 1.

 Figures 7-8 correspond to a CSR of 0.5 for which κ and g are 2.1158 and -2.2997 respectively with a finite circular receiver. For a point receiver, same values are obtained with inverse calculations of the slope and intercept from the generated curve of the shadowband for open, half and full globe models. But, in case of a circular receiver, there exists a deviation in the values of κ and g, by 0.0044 and -0.001 for regular shadowband and half globe shading device, 0.0024 and 0.0007 respectively for full globe.



 Fig 5. Simulated conventional shadowband signal Fig6. Simulated Full globe signal



Fig 7 All three shading devices with CSR=0.5 Fig 8. All three shading devices with SNR=30 and CSR=0.5

**5. Results and Discussions**

The following tables show the inverse calculation results to obtain the values of κ and γ for all the three types of bands with point and circular receiver. Different signal to noise ratios are tried to check for the deviation of the results from the original values for all cases.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  **Signal** **to Noise Ratio**  | **Parameters** | **Open Band** | **Half Globe** | **Full Globe** |
|  |  | Deviation from original values  |
| **65** | κ | 1.8121 | 1.1973 | -0.0164 |
|  |  γ | -0.5872 | -0.3835 | 0.0054 |
| **70** | κ | 0.8365 | 0.3999 | 0.0028 |
|  | γ | -0.2627 | -0.1122 | -0.0008 |
| **80** | κ | -0.238 | -0.3 | 0.0021 |
|  | γ | 0.079 | 0.1035 | -0.0007 |
| **90** | κ | -0.3837 | -0.0478 | 0.0004 |
|  | γ | 0.1281 | 0.0162 | -0.0001 |
| **100** | κ | 0.0195 | 0.0039 | -0.0001 |
|  | γ | 0.0037 | 0.0016 | 0 |
| **110** | κ | 0.0008 | 0.0006 | 0.0001 |
|  | γ | -0.0026 | 0.0006 | 0.0001 |

 Table4. The deviation from original κ and ϒ for a point receiver at different Signal to Noise Ratios

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  **Signal** **to Noise Ratio**  | **Parameters** | **Open Band** | **Half Globe** | **Full Globe** |
|  |  | Deviation from original values |
| **110** | κ | 2.0074 | 1.7947 | 1.1047 |
|  | γ | -0.6447 | -0.5762 | 0.3421 |
| **115** | κ | 1.7855 | 1.3662 | 0.7645 |
|  | γ | -0.5737 | -0.4377 | 0.2711 |
| **120** | κ | 1.1717 | 1.0476 | 0.5839 |
|  | γ | -0.3743 | -0.3342 | -0.2645 |
| **130** | κ | 0.8444 | 0.7103 | 0.5538 |
|  | γ | -0.2695 | -0.2265 | -0.1876 |
| **135** | κ | 0.6111 | 0.5296 | 0.4633 |
|  | γ | -0.1945 | -0.1685 | -0.1450 |
| **140** | κ | 0.448 | 0.3383 | 0.1173 |
|  | γ | -0.1424 | -0.1074 | -0.0982 |
| **145** | κ | 0.3323 | 0.3507 | 0.0574 |
|  | γ | -0.1051 | -0.1113 | -0.0058 |
| **200** | κ | 0.0123 | -0.0053 | 0.0004 |
|  | γ | -0.003 | 0.0026 | -0.0002 |

Table5. The deviation from original κ and γ for circular receiver at different Signal to Noise Ratios.

From the above two tables, we see that the full globe design results in radial distribution estimates closer to the true sunshape as described by Buie’s equations [1]. Also, for a SNR of 100, we can observe from Table 6, that the point receiver shows less deviation from original values in comparison with the circular receiver. . Hence, we can obtain the sunshape plot for a specific site with the obtained κ and γ from the shadowband signal, which can be used for analyzing the forward scattering of aerosol particles and optical depth by method of Harrison et al [23]. Satellite based estimates of solar radiation can also be compared with this instrument as discussed by Myers [24].

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  |  | **Point receiver** |  |  |  |
|  | **SNR** | **Parameter** | **Original values** | **open band** | **half globe** | **full globe** |
|  | 100 | Κ | 2.1158 | 2.1298 | 2.1198 | 2.1174 |
|  |  | ϒ | -2.2997 | -2.3042 | -2.3011 | -2.3003 |
|  |  |  | **Circular Receiver** |  |  |  |
|  | SNR |  |  |  |  |  |
|  | 100 | Κ | 2.1158 | -0.0142 | 0.0114 | 0.2227 |
|  |  | ϒ | -2.2997 | -1.6128 | -1.6231 | -1.6939 |

Table6. Comparison between results of point receiver and circular receiver for the same SNR

**6. Conclusion**

Numerical simulations show that the flux mapping on the (SR)2 receiver is the inverse of the sunshape curves which gives us the evidence of the potential of this instrument to be used for measuring the solar radiation angular distribution. Amongst the three different shadowband designs, the full globe shadowing both the sky hemispheres gives the best results that are closer to the values of κ and γ from Buie’s sunshape equations. A point receiver with a full globe band is proved to be the best model; however, it is not practically possible to have a point receiver. So, we aim to have a modified optical receiver with a narrow slit for this purpose. Furthermore, the internal reflections in a full globe shading device, not yet modeled, may require further design changes. Construction of a prototype is in progress at the Laboratory of Energy and Nano Science, Masdar Institute of Science and Technology and the prototype will undergo extensive testing beside a SAM [25], CIMEL [26], and conventional tracking NIP instruments.

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