

## SHAPING THE ANGULAR DIVERGENCE AT SUN SIMULATORS FOR CONCENTRATOR MODULES

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**ABSTRACT:** A method for shaping the angular divergence at sun simulators is presented. The method is applied to a sun simulator for concentrator modules which use one light source. Diffuse reflectors with different radial symmetric patterns are used to simulate different levels of circumsolar ratios. The impact of the simulated circumsolar radiation is shown for two different photovoltaic concentrator modules. One module is equipped with reflective secondary optical elements while the other is equally manufactured but without secondary. The module with the secondaries showed a better angular transmission, especially for angles between  $0.5^\circ$  and  $2.0^\circ$ . When the angular divergence at a sun simulator is shaped in order to simulate higher ratios of circumsolar radiation, the efficiency of both modules are found to decrease. However, the relative performance loss of the secondary module is several percent lower than this of the module without secondaries.

**Keywords:** Concentrators, Optical Properties, Characterization

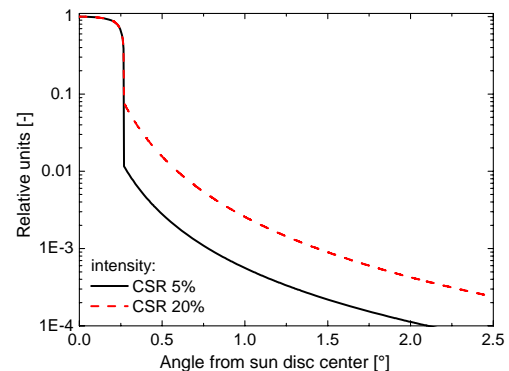
### 1 INTRODUCTION

The solar resource can be divided into a direct and a diffuse part. The direct radiation is typically defined to be the sunlight incoming from the sun within an opening (half) angle of  $2.5$  to  $3.0^\circ$  [1]. The rest of the sunlight constitutes the diffuse irradiation. It is noteworthy that the sun appears as a disc with an opening (half) angle of about  $0.27^\circ$  when seen from Earth. Consequently, the direct irradiation can be further classified into the narrow angle irradiation coming from the sun disc and the rest. The later is called the circumsolar radiation and is typically defined as ratio of the total direct normal radiation (DNI). The circumsolar ratio (CSR) depends on the density of forward scattering particles in the atmosphere and on the air mass. For many locations circumsolar ratios are often smaller than 20% [2-4].

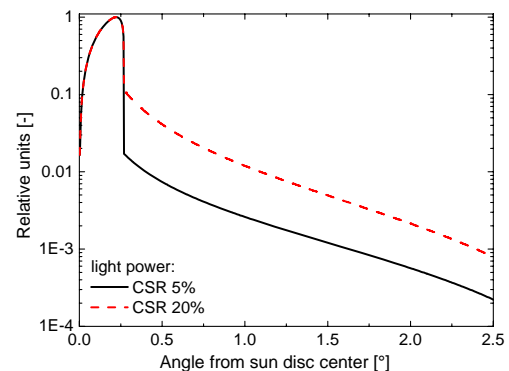
The amount of CSR has no impact on the performance of flat-plate modules. However, this is different for concentrating photovoltaic (CPV) modules which typically have a rather narrow angular transmission. In particular high concentrating CPV systems with concentration ratios around 500X show often an acceptance angle of less than  $\pm 3^\circ$  [5]. These systems cannot utilize the complete DNI over its total angular spectrum. The angular distribution of the DNI is also called sunshape and is typically considered to be radial symmetric. In earlier works by other groups models have been developed which allow for the computation of the sunshape for a certain CSR [2, 3]. Figure 1 shows the relative sunshape for a CSR of 5% and 20%, respectively, calculated with the model presented in reference [2]. Please note the logarithmic scale.

Obviously, most of the intensity is coming from the sun disc. For larger angles the intensity drops drastically. At about  $0.3^\circ$  for a CSR of 5% and  $0.6^\circ$  for a CSR of 20% the intensity is only 1% of its maximum in the sun disc center.

In order to determine the irradiated power one has to integrate the intensity over spherical segments [2]. Figure 2 shows the angular dependence of the irradiated power for a CSR of 5% and 20%, respectively.



**Figure 1:** The relative sunshape is computed for a CSR of 5 and 20% respectively.



**Figure 2:** The relative light power is computed for a CSR of 5 and 20% respectively.

In contrast to the intensity the radial distribution of the light power does not peak in the center of the sun. This is due to the increasing area of the spherical segments with rising radius. Obviously, the relative radial distribution of the total light power is broader than this of the intensity. In particular for a CSR of 20% a significant amount of light is irradiated between  $0.5^\circ$  and  $1^\circ$ . This is of special importance for many CPV modules using Fresnel lenses. Without any modification the angular transmission of Fresnel lens systems

(concentration ratio more than 300X) typically drops for angles greater than  $0.5^\circ$ . Thus, the CSR is expected to influence the performance of these systems in a range of up to 10%.

The direct measurement of sunshapes is sophisticated as it requires very accurate equipment and a complex analysis [2-4]. However, in order to analyse the impact of the CSR on the module performance, ideally the sunshape and the IV curve of the module should be measured in parallel. Anyhow, today many CPV modules use triple-junction solar cell, which are known to be very sensitive to changes in the solar spectrum [6]. Since the solar spectrum and the circumsolar radiation are influenced by the atmosphere and the air mass, variations in the solar spectrum are correlated to changes in the circumsolar radiation. Furthermore, the spectrum of the circumsolar radiation is not necessarily the same as the one of the beam coming directly from the sun disc. Consequently, outdoor investigations of the circumsolar impact on CPV modules are not trivial. This is probably the reason why the impact of the CSR on the performance of CPV modules is almost not investigated at all.

This paper describes a method to simulate different artificial circumsolar ratios in a sun simulator. In contrast to outdoor measurements, the ambient conditions can be controlled and varied much better at a sun simulator. This allows studying the impact of changes in the angular spectrum on the performance of CPV modules.

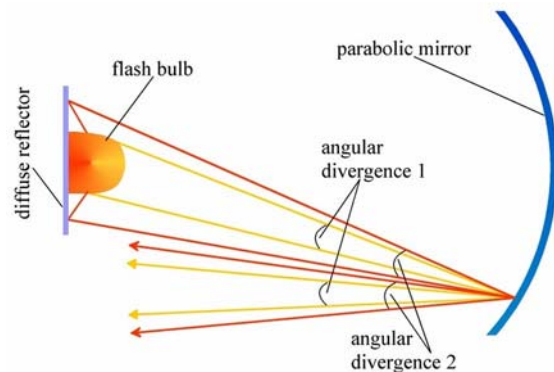
## 2 METHODS AND EXPERIMENTAL

### 2.1 Circumsolar radiation at sun simulator

Sun simulators for CPV modules should meet the same requirements as standard sun simulators for flat-plate modules. However, in addition to intensity, spectral and homogeneity specifications a CPV module sun simulator must meet strict requirements in terms of light divergence and collimation. The light must impinge perpendicular to the module plane within the angular divergence of natural direct sunlight. At some of recently developed sun simulators, this is realized by placing a flash bulb in the focus of a parabolic mirror [7-9]. The light of the flash bulb is reflected by the mirror parallel the optical axis of the parabola. Furthermore, the angular divergence is defined by the angular size of the flash bulb from the perspective of the mirror. Consequently, the focal distance and the geometrical diameter of the flash bulb determine the angular divergence of the sun simulator.

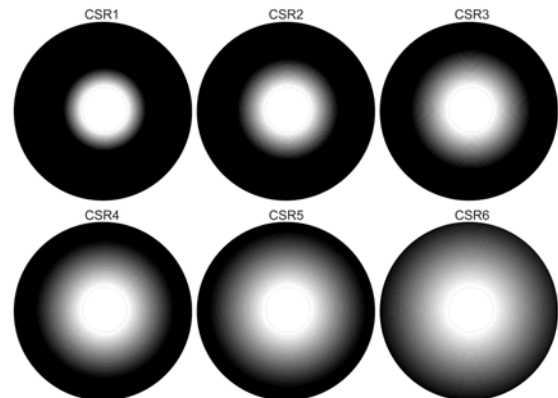
In this paper the sun simulator set up described in reference [9] is used. The flash bulb has a diameter of about 6 cm and it is positioned in the focus of a 2 m parabolic mirror with a focal length of 6 m. The flash bulb is mounted on a black painted plate with a rough surface. This suppresses light from being reflected toward the mirror, which would increase the angular size of the flash bulb. Thus, from the perspective of the parabolic mirror the flash bulb appears within an angle of about  $\pm 0.3^\circ$  [9]. Aside from this conventional operation mode a reflector can be positioned around the flash bulb in order to increase the angular size of the simulated light. Consequently, the angular divergence of the simulated light is shaped as well. Figure 3 sketches the angular divergence in the conventional operation case.

Furthermore, the angular divergence for the light reflected at the reflector is shown.



**Figure 3:** A sketch of the used optical setup is shown. A flash bulb is located in the focus of a parabolic mirror. In addition, a diffuse reflector is mounted around the bulb. The (direct) light of the flash bulb contributes to the angular divergence 1, which is about  $\pm 0.3^\circ$  at the used setup. The light of the reflector contributes to the increased angular divergence 2.

For simulating various angular distributions six different reflectors are used, which are shown in Figure 4. These reflectors consist of white paper with different printed concentric patterns. In particular the greyscale is increased with augmenting radius to the centre. The gradient of the greyscale is varied for the different reflectors.



**Figure 4:** The six reflectors with different concentric greyscale patterns are shown (CSR i). The white circle in the middle of the reflectors corresponds to the size of the flash bulb. The total diameter of the reflectors is about 35 cm.

The paper surface of the reflectors is rather rough so that the light is scattered diffusely. This is important since a direct reflection may impact the lateral homogeneity of the simulated light.

The white circle in the centre of each picture shown in Figure 4 corresponds to the diameter of the flash bulb. Many concentric circles with increasing greyscale are printed. This should decrease the reflection with increasing angle. Thus, the simulated light intensity should decrease with increasing radial angle - as observed for natural sun shapes (see Figure 1). Please note that the particular patterns of the reflectors are designed intuitively for the first experiments. Thus, the

“sun shape” at the simulator is not expected to be equal to natural sun shapes. However, the angular spectrum is roughly similar which should be sufficient for relative measurements with different modules.

For the experiments at first an IV measurement of a CPV module without any reflector around the flash bulb is conducted. The irradiation during this measurement is determined by measuring the photocurrent of a calibrated  $\text{Ga}_{0.50}\text{In}_{0.50}\text{P}/\text{Ga}_{0.99}\text{In}_{0.01}\text{As}/\text{Ge}$  triple-junction solar cell ( $I_{ref}^0$ ). This reference cell is located behind a collimator tube providing an opening (half) angle of about  $2.5^\circ$ . In further measurements the different CSR reflectors ( $i$ ) (see Figure 4) are mounted and the IV curve of the CPV module is measured again. In addition, the signal of the reference cell is measured in parallel ( $I_{ref}^i$ ). The photocurrent of the reference cell is expected to increase with a higher amount of reflected light. The relative increase of the reference cell’s photocurrent defines the CSR simulated indoors (*indoor-CSR*).

$$indoor - CSR = \frac{I_{ref}^i - I_{ref}^0}{I_{ref}^0} \cdot 100\%$$

Please note, that the determination of the indoor-CSR includes the assumption that the flashes can be repeated ideally. At the sun simulator used the intensity of repeated flashes varies in the range of  $\pm 1\%$ .

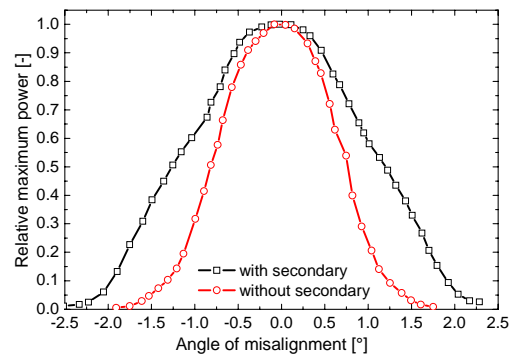
## 2.2 Angular transmission of the investigated modules

In this paper two CPV modules of the FLATCON® type are investigated [10]. Both modules are equipped with  $\text{Ga}_{0.50}\text{In}_{0.50}\text{P}/\text{Ga}_{0.99}\text{In}_{0.01}\text{As}/\text{Ge}$  triple-junction solar cells and use  $40 \times 40 \text{ cm}^2$  Fresnel lenses. Furthermore, both modules have an optical aperture area of  $2400 \text{ cm}^2$  and a geometrical concentration ratio of 385X. Eventually, the only difference between the modules is that one is equipped with reflective secondary optical elements [11, 12]. The secondaries redirect spilled light rays onto the solar cells. Consequently, the angular transmission is expected to be improved when these secondary optical elements are applied.

The modules are mounted on a support structure which can be rotated around one rotation axis. More than 30 IV measurements at constant simulator settings and different angles of misalignment are performed for each module. The angle of misalignment is measured with a laser mounted on the support structure. The angle is derived by measuring the lateral displacement of the laser spot in a distance of 6 m.

## 3 RESULTS

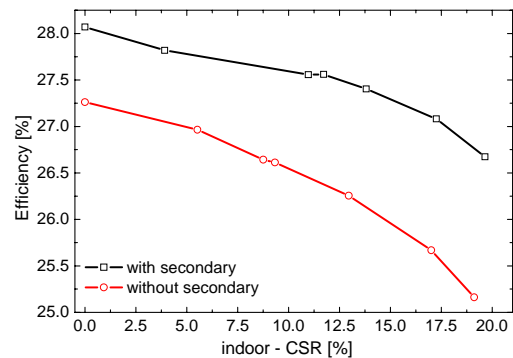
The IV curves of the two investigated modules are measured at the sun simulator. From the IV curves the maximum power points are derived. Figure 5 shows the angular dependence of the maximum power points. Please note that relative values are shown, which refer to the maximum power at well aligned conditions ( $0^\circ$  misalignment).



**Figure 5:** The angular dependence of the maximum power is shown for the two investigated modules. The module with secondary shows a better angular transmission than the one without secondary optics.

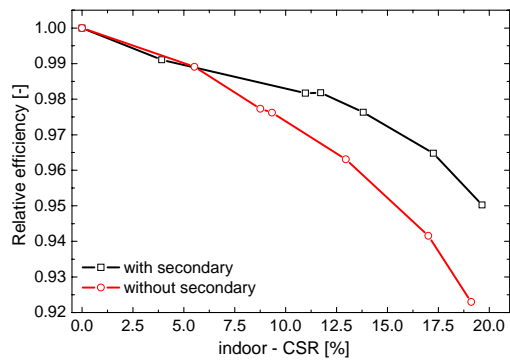
The maximum power of both modules drops significantly for misalignment angles greater than  $0.5^\circ$ . However, the relative power loss is lower for the module with secondary optical elements. Especially for misalignment angles between  $0.5$  and  $2^\circ$  the secondary module outperforms the reference module.

The IV curves of both modules are measured when the different CSR reflectors (Figure 4) are mounted. Again the maximum power point is derived for every IV curve. Then the efficiency of the modules is calculated by correlating their maximum power to the direct normal light power irradiated on their optical aperture. The DNI is measured with the calibrated reference cell. Figure 6 shows the efficiencies of both modules versus the *indoor-CSR* (see section 2.1).



**Figure 6:** The efficiency of the two investigated modules is shown versus the amount of simulated CSR.

Obviously the efficiency of the module with secondary optics is higher than for the reference module. Furthermore, the efficiency of both modules decreases with increasing CSR. However, the relative CSR impact seems to be lower for the secondary module. This becomes obvious when normalizing the efficiency, as shown in Figure 7.



**Figure 7:** The normalized efficiency of the two investigated modules is shown versus the amount of simulated CSR.

At a simulated CSR of about 19% the module without secondaries shows a performance loss of about 8% relative to its maximum power at 0% CSR. In contrast the module with secondaries loses only 5% relative to its maximum power.

#### 4 DISCUSSION

Comparing Figure 2 and Figure 5, it is obvious that the secondary module should perform better at a CSR of 20%. However, at a relatively low CSR of 5% about 99% of the energy is expected to income within an angle of  $\pm 0.3^\circ$ . Consequently for these narrow angles the secondary optics is not necessarily expected to be advantageous.

The indoor experiments show that an increase of simulated CSR has a larger (negative) impact on the module without secondaries. This confirms what can be expected from the angular transmission measurements. However, even when no CSR is simulated the efficiency of the secondary module is about 0.7% higher. Since both modules consist of the equal components, this is remarkable. At an irradiation with a divergence of about  $\pm 0.3^\circ$  the reflective secondary is not expected to boost the efficiency significantly and both modules would be expected to have about the same performance. The difference in efficiency at a simulated CSR of 0% may be due to two reasons:

- In principle the simulator can have some kind of offset circumsolar radiation.
- The secondary optics can outweigh imperfections of the primary Fresnel lenses and/or positioning errors.

The latter explanation seems to be more reasonable. In particular the positioning accuracy of the investigated modules is expected to decrease the modules efficiencies.

Regarding the results shown in Figure 6 and Figure 7 one can see that the determined *indoor-CSR* is not equal for the two modules. Ideally the determined *indoor-CSR* is always the same when CSR reflector is not changed. However, differences of up to 2.5% are found for one CSR reflector. This might be due to variations in the flash light intensity. Furthermore, it is possible that small differences in the placement of the reflectors cause these differences.

#### 5 SUMMARY AND CONCLUSIONS

The presented method on shaping the angular divergence at a sun simulator is simple. It requires a state of the art sun simulator for concentrator modules which use a single light source. The angular divergence of the simulated direct light can be shaped by placing different reflectors around the light source. For the first experiments the angular spectrum was shaped intuitively. However, the simulated circumsolar radiation is expected to be roughly similar to this of natural sunlight. This set up should be sufficient to compare the impact of the circumsolar radiation on different concentrator modules. The results found for FLATCON<sup>®</sup> modules with and without secondary optics appear reasonable. In particular it is found that reflective secondaries decrease the performance loss at elevated circumsolar ratios in the range of several percent.

For an investigation of the absolute circumsolar impact the simulated sunshape must be measured directly. At flash light simulators this requires very fast and linear light detectors (e.g. CCD chips). Once the simulated sunshape of a particular reflector is known new reflectors can be designed which simulate sunshapes very similar to these of natural sunlight.

#### 6 ACKNOWLEDGEMENTS

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