Measurement of Small Angle Ray Deviations for Concentrating Solar Applications: Circumsolar Radiation and Mirror Beam Spread

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Abstract: Inaccuracies of Solar concentrators cause energy spillage. Other small angular ray deviations like circumsolar radiation and mirror beam spread will affect the performance as well. General setups to measure both and exemplary results are presented.
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1. Introduction

In concentrating solar applications, solar radiation is redirected to a receiver by concentrator optics. Inaccuracies or angular deviations lead to spillage of energy due to rays not hitting the receiver aperture. These deviations are dominated by the angular accuracy of the collector (mirror or refractor shape; manufacturing, tracking and installation accuracies). However, in addition small angular deviations may have a significant effect as well.

In this paper we describe two sources of small angular deviations and means to measure them: circumsolar radiation and beam spread by mirror surfaces. Circumsolar radiation originates from small angle scattering of solar beam radiation in the atmosphere. It is described by the sunshape distribution providing the angular distribution of direct beam irradiance, and the circumsolar ratio (CSR) giving the portion of total direct irradiance originating from a given angular region around the solar disc. Mirror beam spread originates from small angle scattering by a potential roughness of mirror materials and coatings. Such roughness may be increased during mirror lifetime by e.g. cleaning and abrasion. Both angular ray deviations are measured using CCD based setups.

2. Measurement setup for circumsolar radiation

In contrary to other instruments we use a direct CCD imaging, camera based approach to assess circumsolar radiation. The challenging huge difference in magnitude between the radiance of the sun and the circumsolar region is addressed by hardware adaptions and high dynamic range (HDR) imaging. In the design of the imaging optics the highly linear CCD is protected from excess irradiance, overexposure and heat loads, and secondary images caused by reflections from optical components are suppressed. The schematic setup and a photograph of the camera system mounted on a tracking unit are shown in Fig.1 below.

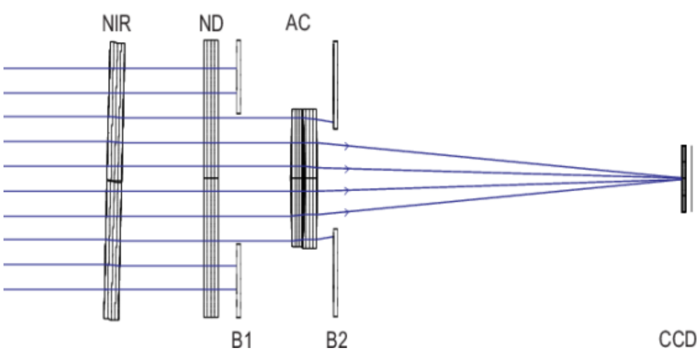

Fig. 1. Setup for imaging of solar disc and circumsolar radiation. Left: optical components: NIR = infrared filter; ND = neutral filter; B1,B2 = apertures; AC = achromatic lens; CCD = imaging sensor; Right: Camera system (white casing) mounted on a tracker.

3. Exemplary results for circumsolar radiation and sunshape distributions

In HDR imaging, several images of different exposure times are combined to one single image, which requires a highly linear CCD with anti-blooming. Exposure times are chosen accordingly to allow for a sufficient overlap between images. The sunshape distribution and CSR are derived from processing of the resulting image. Fig. 2 shows as exemplary results an image of a situation with very vague cirrus clouds corresponding to a CSR of

(11.5 ± 0.1)% and measurements of DNI and CSR for a sunny day. All measurements so far have been performed at Freiburg, Germany. Time resolution of measurements can be much higher than shown in Fig.2 right, allowing for quasi-continuous monitoring of CSR.

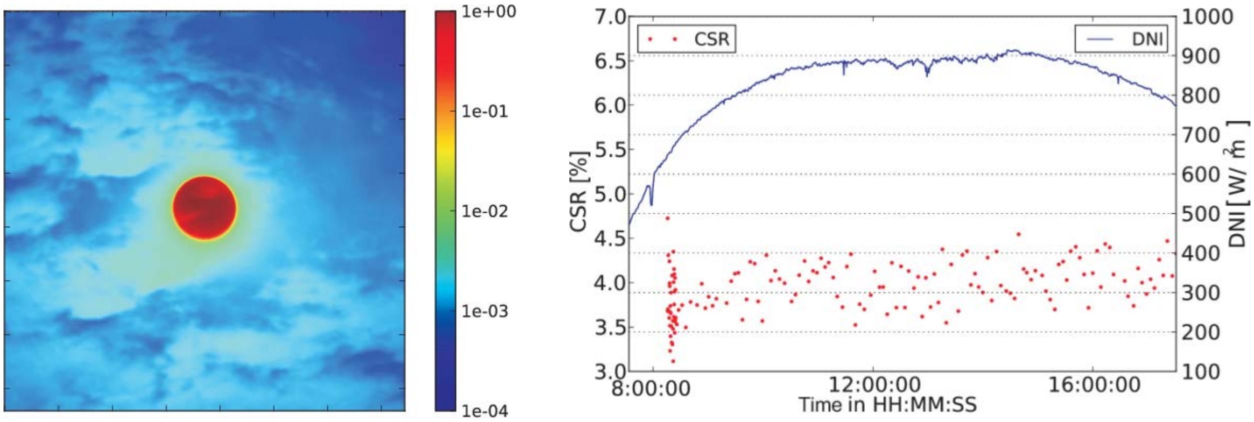

Fig. 2. Left: HDR image of a sky situation with vague cirrus clouds resulting in a CSR of 11.5%. Color scale is normalized to max=1. Right: CSR and DNI measurements taken on a clear sunny day (August 21, 2013) with CSR values in the range of approx.. 3-5%.

Sunshape distributions gained for certain CSR values have been averaged and compared to distributions published previously by Neumann et al [1]. The results are shown in Fig.3. Image processing in principle enables us to derive continuous distributions, which in turn allows to derive CSR values for different variable angular acceptance or angular aperture specific to a certain concentrator design. Distributions derived here are similar to those derived by [1], but clearly there are differences. Further investigation and collection of more data also at sites more relevant and representative for concentrating solar applications (CSP, CPV) are subject to future work.

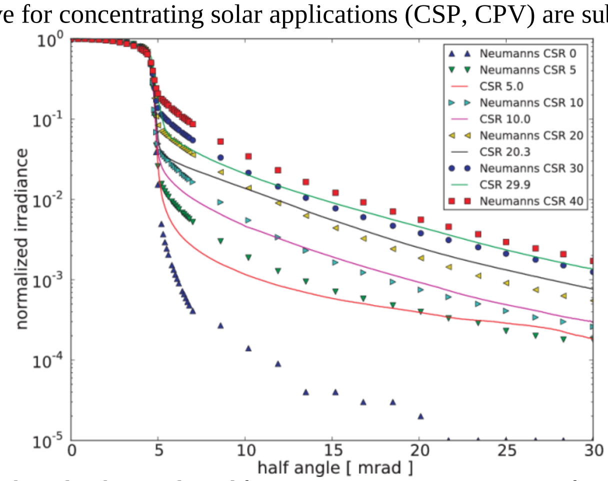

Fig. 3. Average sunshape distributions derived from averaging seven measurements of equal CSR (solid lines) are compared to distributions published previously by Neumann et al [1] (dots).

4. Measurement setup for beam spread of mirror surfaces

For a detailed performance evaluation and comparison of different mirror materials suitable for concentrating solar applications as well as the assessment of performance degradations due to e.g. abrasion, the exact determination of specular reflectance is required. In addition, measurement of the amount and distribution of small angle scattered radiation is desirable, preferably for continuously variable angular acceptance specific to a given concentrator design. For this purpose, Fraunhofer ISE developed the measurement setup for very low angle beam spread VLABS. It is in principle based on the setup published previously in [2], but with some important changes. It is sketched in Fig.4 below. Light from narrow band LED sources of different wavelength is collimated and after interaction with the sample focused onto a detector. In contrary to [2] where slits of variable sizes defined the detector aperture, we use a CCD as a detector. The image of the light source pinhole defining the angular divergence of the incident light is taken and processed (a) without sample to derive the instrument signature and (b) after reflection from a mirror sample to derive the mirror beam spread.

For the detailed evaluation the deconvolution approach proposed in [3] is enhanced. The reflected radiation as detected by the CCD is the convolution of the signature of light source and instrument and the reflecting properties of the sample. Therefore a convolution of the measured apparatus signature and a model function M(ϕ) describing the scattering of the sample as a function of scattering angle ϕ is fitted to the measured data of a reflector sample by adaption of the parameters of M(ϕ). The specular reflectance within a defined acceptance angle is then calculated by integration of M(ϕ) up to the chosen acceptance angle. This way the specular reflectance at the wavelength of the respective light source can be directly determined and no measurement of reference sample is required. This has been verified by measuring a standard reference mirror provided by the Dutch TNO.

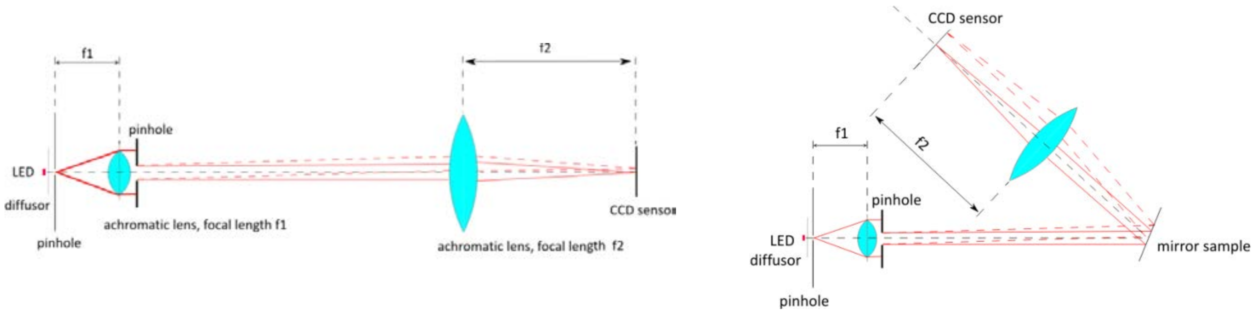

Fig. 4. Sketch of the VLABS setup. Left: measurement of the signature of the light source and instrument; Right: sample measurement.

5. Exemplary results for beam spread of mirror surfaces

As glass mirrors show significant surface scatter only after abrasion, exemplary results measured with VLABS on an aluminum based mirror are shown in Fig.5 below. Specular reflectance is given as function of acceptance angle. For acceptance angles typical for solar applications, it is significantly lower than the hemispherical reflectance. Our results contribute to the discussions in the context of the SolarPACES reflector characterization guideline [4].

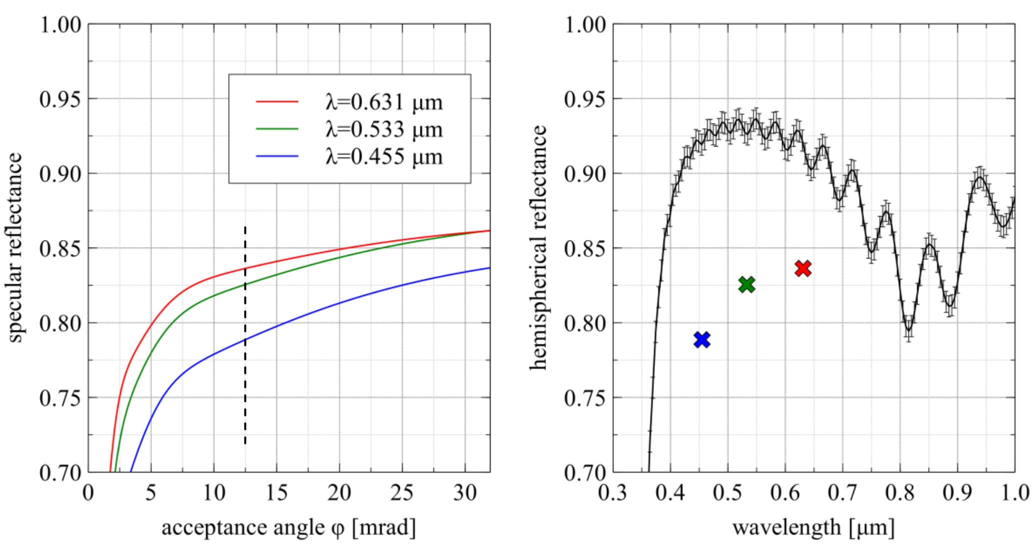

Fig. 5. Specular reflectance of an aluminum based mirror sample at near-normal incidence (8°). Left: vs. acceptance angle for 3 wavelengths; Right: specular reflectance for acceptance of 12.5 mrad (crosses, see dotted line in left graph) are compared to the hemispherical reflectance, plotted over wavelength. The hemispherical reflectance is measured with another instrument, uncertainties are indicated by error bars.

6. Acknowledgements

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7. References

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