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Flux Density Measurement for Industrial-Scale Solar Power Towers Using the Reflection off the Absorber

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Abstract. Flux density measurement is precious for operation as well as for performance testing of solar power towers. The radiation reflected off the absorber can be used for this task. The disturbance of the plant operation is close to zero. Besides a digital camera, a computer and optionally a radiometer, almost no further hardware is required. That's why it is suitable for industrial-scale receivers. This paper presents several enhancements for this measuring process. Especially the so-called "scan method" appears promising, because it leads to significantly smoother flux density results compared to formerly presented methods. The article also deals with the determination of the irradiation's directional composition as well as with calibration routines. The proposed innovations were demonstrated at the Juelich Solar Tower with its open volumetric receiver and are likely to be suitable for external tube receivers, too. A plausibility check using CFD simulations was carried out. In summary, the discussed techniques show promise for future application at large-scale solar towers.

INTRODUCTION

Measuring the solar flux density distribution at solar power towers offers two main advantages. Firstly, the energy conversion efficiencies of both the heliostat field and the receiver can be determined separately, e. g. in acceptance tests. Secondly, flux density measurement is valuable for supervision and control during operation of a solar tower.

At small-scale prototype receivers flux density has mostly been measured by using a camera and a moving bar so far. At industrial-scale receivers though, the installation of a moving bar is unfavorable due to constructive efforts and costs. Using the radiation reflected off the absorber for measuring the flux density is a promising approach for large-scale receivers. For this purpose, a digital camera captures images of the irradiated absorber. Combined with information about the absorber's reflection properties, the incident flux density can be calculated. [1]

Ho et al. used such a method, assuming that the absorber is a Lambertian reflector [2]. Göhring et al. presented means for taking into account the absorber's reflective dependencies on material inhomogeneities as well as on the directions of incidence and observation (BRDF = bidirectional reflectance distribution function) [3]. This included usage of a second absorber image taken under cloudy conditions and measurements with a gonioreflectometer, subsequently called the "cloud and goref method". The whole procedure is summed up by Fig. 1.

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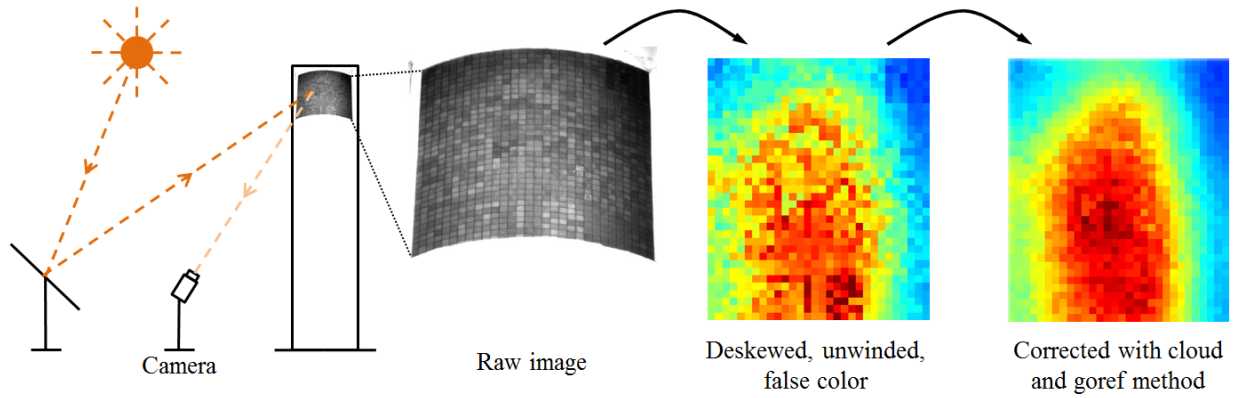

FIGURE 1. Schematic of flux density measurement using the reflection off the absorber

The application of the cloud and goref method is apparently effective, but still has a few disadvantages:

- The gradient of the resulting flux density distribution still shows unrealistic inhomogeneities.
- The reflective dependencies on material inhomogeneities are determined with the aid of an absorber image taken under cloudy conditions. Therefore, it has to be assumed that the absorber surface is irradiated uniformly by the clouded sky and surroundings. This assumption differs from reality.
- An evenly clouded sky is necessary. This is a rare event at good locations for solar towers.
- The light's spectrum of the gonioreflectometer as well as the spectrum under cloudy conditions are different from the sunlight's spectrum during flux density measurement at the operated tower.

In order to overcome the disadvantages listed above, vital improvements of this measuring process were developed at the German Aerospace Center (DLR). They are demonstrated at the Juelich Solar Tower with its open volumetric receiver. All techniques described below are supposed to be suitable for external tubular receivers, too.

MEASURING PROCESS

Outline

The following equations are meant to clarify the essential subtasks in measuring the flux density using the reflection off the absorber. For the purposes of shortness and clarity, the equations are given in a simplified form.

Let the absorber surface be divided into segments indexed by i. This division can be done according to the image's pixels. Alternatively, any desired larger absorber segments are possible, too. For each segment i, the subsequent quantities are averaged. For each absorber segment, the reflectivity depends on the direction of the incident radiation. The heliostat field layout defines the possible directions of incidence. Let the heliostat field be divided into areas with the index j. The irradiation from heliostat area j on absorber segment i with the flux density $E_{i,j}$ is reflected off the absorber segment i towards the camera with the reflectivity $\rho_{i,j}$. The reflected radiation is recorded by the camera and transformed into a gray value g_i. This transformation can be represented by a camera factor k, approximately resulting in

$$\sum_j E_{i,j} \cdot \rho_{i,j} \cdot k = g_i \tag{1}$$

The ratio between the flux density $E_{i,j}$ from heliostat field area j on absorber segment i and the total flux density E_i on absorber segment i is named $x_{i,j}$.

$$E_{i,j} = E_i \cdot \mathrm{x_{i,j}} \tag{2}$$

Equation (2) and the introduction of a constant reference reflectivity value $\bar{\rho}$ allow the conversion of Equation (1) to

$$E_i = g_i \cdot \underbrace{\frac{1}{\sum_j x_{i,j} \cdot \frac{\rho_{i,j}}{\bar{\rho}}}}_{\text{"correction"}} \cdot \underbrace{\frac{1}{\bar{\rho} \cdot k}}_{\text{"calibration"}} \tag{3}$$

Equation (3) illustrates the image processing. Firstly, the gray values of the recorded raw image have to be corrected due to the reflective dependencies on material inhomogeneities (absorber segments i) as well as on the directions of incidence (heliostat field areas j). A dependency on temperature is subsequently considered to be negligible. Secondly, a calibration is necessary in order to convert the corrected gray values into flux density values.
In summary, we need to find

- The relative absorber's reflective properties $\frac{\rho_{i,j}}{\bar{\rho}}$ (section „Scan Method“)
- The flux ratios for different heliostat field areas $x_{i,j}$ (section "Directional Composition of Irradiation")
- A calibration procedure (section "Calibration")

Scan Method

A novel approach, called the "scan method", was created in order to determine the absorber's reflection properties. The method is subject of a German patent [4]. International patents are pending. With this technique, a light beam is moved over the absorber on a tight meander-shaped path (Fig. 2 (a)). This beam can be provided by a single heliostat during the day or by artificial light, e. g. a spotlight, at night. At the same time, a series of absorber images is recorded by the camera with a high frame rate. Afterwards, the whole image series is merged into one single image. For each pixel, the pixel's maximum gray value out of all images is taken. By subtracting an image of the absorber without light beam, the influence of diffuse light from the environment is eliminated. Both direct normal irradiance (DNI) fluctuations during the scan as well as cosine effects due to the curvature of the absorber surface are calculatively compensated. The generated image (Fig. 2 (b)) is equivalent to the image which would have been recorded by the camera if the maximum flux density of the light beam had reached every part of the absorber at the same time. This can be considered as a homogenous irradiation which allows determining the reflective variations throughout the absorber surface easily.

In order to assess the influence of the direction of incidence, the scan method is conducted with light from different positions in the heliostat field. For each heliostat field area j, one scan has to be performed from a representative position within this area. Figure 2 (c) shows the division of the Juelich Solar Tower's heliostat field into 16 areas. The corresponding heliostats used for the scans are marked with crosses.

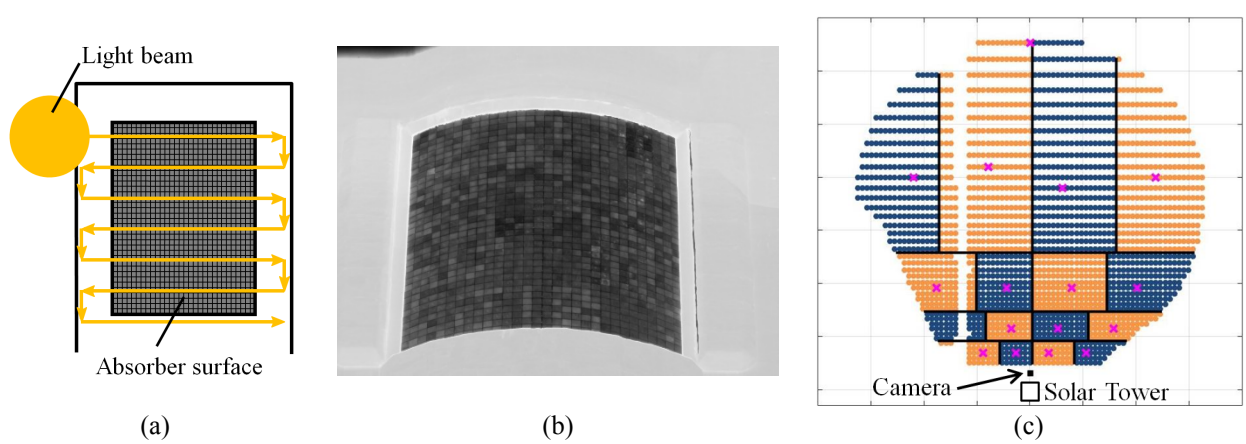

FIGURE 2. (a) Schematic of light path during scan of absorber. (b) Example of merged image after scan. (c) Heliostat field of Juelich Solar Tower divided into 16 areas and heliostats for scans (crosses).

An absorber segment's reflectivity generally depends on the radiation's incidence angle and thus on the position of the heliostat(s) which is / are in use. So to speak, the absorber segment's reflectivity shows a course over the

heliostat field. When choosing a representative heliostat for each heliostat field area, a first approach can be taking the heliostat in the spatial center of each heliostat field area. It is assumed in the subsequent procedure that the absorber segments reflect light from every heliostat within the heliostat field area exactly like they reflect the light from the position of the representative heliostat. Consequently, choosing the central heliostat as representative for an area would only be best if the course of reflectivity was linear over the heliostat field area. If there is some information known about the **actual** course of reflectivity, either from gonioreflectometer measurements or from several scans with different positions of the light source within the field, this can be taken into account for improving the choice of the representative heliostats. Choosing a representative heliostat in a **suboptimal** position contributes to the overall measurement uncertainty which remains to be investigated quantitatively.

The maximum flux density within the light beams from different positions varies due to different distances to the receiver as well as due to unequal mirror geometries if heliostats are used. This effect may disguise the desired information about the directional dependency of reflectivity. As countermeasure, the differences in maximum flux density are determined and compensated. This can be done by conducting an additional scan of a diffusely reflecting reference surface from each scan position. To begin with, a part of the radiation shield near the absorber was used as reference surface at the Juelich Solar Tower.

As long as the absorber's reflective properties remain unchanged, the one-time execution of the scan method is sufficient. Normally, the absorber's reflectivity is likely to change over time due to degradation etc. In this case, the scan method should be repeated from time to time. The question about the frequency of conducting the scan method leads to an optimization between effort and improved measuring accuracy.

Directional Composition of Irradiation

In former studies it was assumed that the complete radiation is emitted from one single point in the heliostat field [3]. As the reflectivity's dependence on the direction of incidence is nonlinear throughout the heliostat field, this can lead to momentous errors. For correct application of the collected reflectivity data it has to be known which ratios of flux density $x_{i,j}$ are provided from the different areas of the heliostat field (Equations (2) and (3)). There are two possibilities to determine the values $x_{i,j}$.

The first option is the usage of a raytracing software. Secondly, the heliostats can be consecutively and area-wise (de)focused with flux density measurements conducted after every shift. The difference between two flux density measurements equals the flux density out of a single heliostat area. Compared to the application of a raytracing software, this method is more precise, but also more extensive. Moreover, it can only be conducted during run-up or shut-down of the plant if no energetic losses are acceptable during operation.

Calibration

The final step in measuring the flux density distribution is the conversion of processed gray values into flux density values. Therefore a calibration is needed (Equation (3)). Measuring the flux density at one single point using a radiometer is sufficient. This was employed by Röger et al. [1] and Göhring et al. [3] in the past.

If a radiometer is not available, the calibration can be performed by focusing the beams of several heliostats onto the absorber and calculating the incident power with a raytracing software. It is necessary to avoid any spillage and to measure the DNI as well as the heliostats' reflectivity. This procedure was conducted at Juelich Solar Tower for the first time. Figure 3 shows an exemplary calibration curve for 10 heliostats which have been focused subsequently. The line's gradient represents the desired calibration factor.

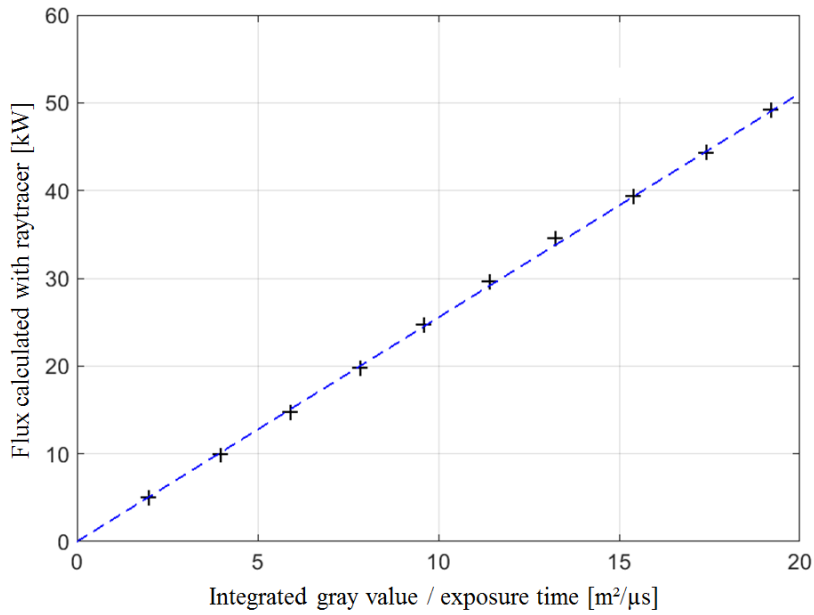

FIGURE 3. Exemplary calibration curve using 10 heliostats and raytracing

The light's spectrum depends on the air mass and the sun's elevation angle respectively. As the camera system shows a certain spectral sensitivity, the calibration procedure has to be conducted for different times during the day [5].

Equation (3) shows that the calibration procedure should be repeated if there has been a significant change either in the absorber's reflectivity or in the characteristics of the camera system since the last calibration.

RESULTS

Flux Density Distribution

Irradiation from a Single Heliostat

For a start, the flux density distribution within the beam of a single heliostat was measured at the Juelich Solar Tower. The evaluation was conducted with both the cloud and goref method as well as with the new scan method. The heliostat examined for flux density measurement and the heliostat used for the scan are identic. This is the best possible setup regarding the application of the scan method as the irradiation while measuring the flux density is monodirectional and the reflective properties are determined for exactly the same direction. Figure 4 illustrates the results for such a case.

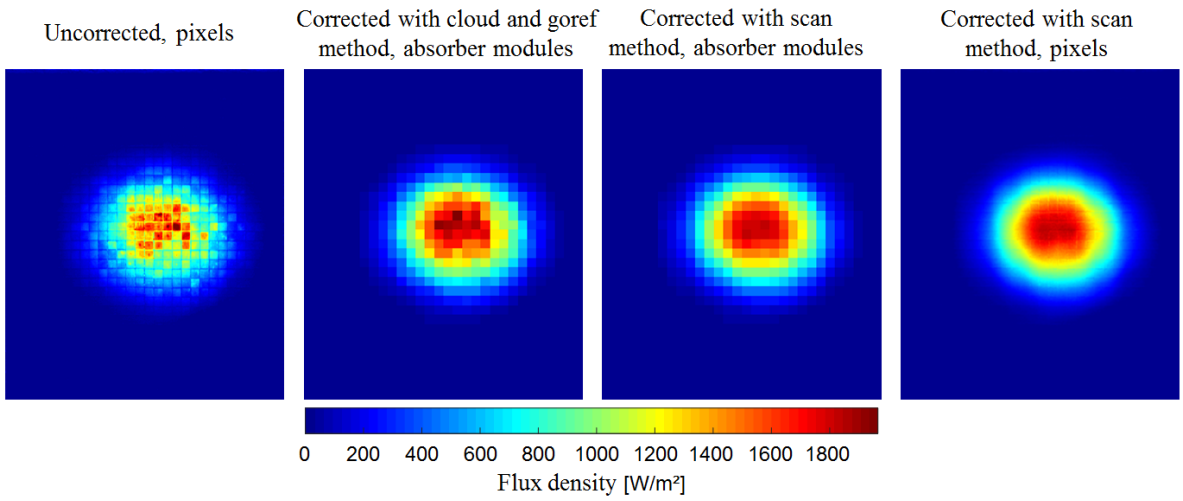

FIGURE 4. Flux density measurement with a single heliostat in use. Reflectivity correction method and size of absorber segments are stated.

The Juelich Solar Tower's absorber is 5.22 m high, 4.35 m wide and consists of 1080 absorber modules. These modules can be used as absorber segments i for simple image processing. This arrangement is used for the second and third images in Fig. 4. It is obvious that the scan method significantly improves the smoothness of the flux density results when compared to the cloud and goref method. The fourth image in Fig. 4 shows one flux density value for each image pixel. Its comparison to the uncorrected image illustrates that the acquisition and utilization of the absorber's reflective properties via scan method works excellently.

Irradiation from Many Heliostats Spread over the Whole Field

During regular operation of a solar tower, many heliostats are used and the receiver is irradiated from different areas of the heliostat field. The scans at the Juelich Solar Tower were conducted with 16 different heliostats (Fig. 2 (c)) while recording 17 frames per second. Afterwards, the scan data was applied to flux density measurements during several receiver tests. Figure 5 shows the results for 16 March 2017, 14:58:56 (UTC+1). The directional composition of irradiation was determined by consecutively defocusing the heliostats in the different areas after the flux density measurement.

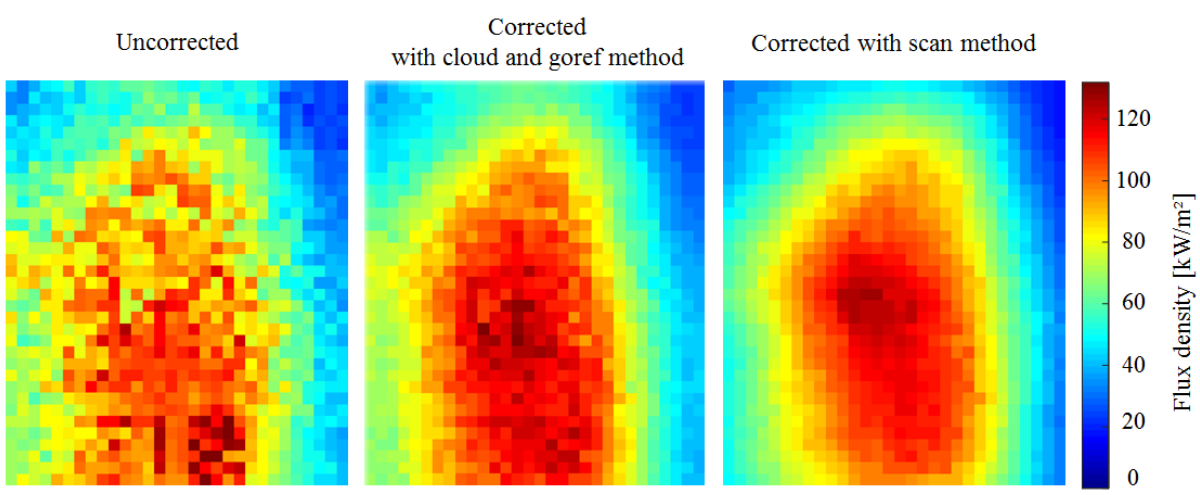

FIGURE 5. Flux density measurement at Juelich Solar Tower on 16 March 2017, 14:58:56 (UTC+1)

Once again, it is clearly visible that the scan method enhances the smoothness of the measured flux density distribution. This can be explained with the influence of the incidence angle on reflectivity. For the cloud and goref method, this influence is examined for a single absorber module with a gonioreflectometer. It has to be assumed, that all modules show the same behavior. But in fact, this influence varies for different absorber modules. By conducting the scan method from different positions within the heliostat field, the directional dependency is determined for all absorber modules individually, which leads to the improvement visible in Fig. 5.

Total Flux

The choice of correction method does not only affect the smoothness of the flux density distribution. There are also differences regarding the measured total flux, which can be calculated by integrating the flux density over the absorber surface. For the measurement shown in Fig. 5, the total flux with scan method is about 4 % lower than the flux with the cloud and goref method.

Regarding the flux values with the scan method, a plausibility check using a CFD model of the receiver was carried out [6]. For five different operating conditions with hot air temperatures in the range from 380 to 600 °C, the measured values of flux, mass flow and receiver inlet temperature were used as input for the CFD simulations. The measured and the simulated receiver outlet temperatures were compared and already showed fine agreement. This indicates a reasonable accuracy of the measured flux values. If the flux value was stuck with a big error, the simulated temperature would be noticeably different from the measured temperature.

CONCLUSION

Compared to the formerly used cloud and goref method, the scan method has several advantages for measuring the flux density distribution on external receivers of solar towers. It enables detecting the reflectivity's directional dependencies for each segment of the absorber individually, which leads to smoother flux density distribution results. While examining the reflection properties, the irradiation is more even and the direction of incidence as well as the light's spectrum are more similar to the real conditions during operation of the solar tower. Cloudy conditions are not necessary.

Moreover, enhancements in determining the directional composition of irradiation as well as for calibration were demonstrated.

In conclusion, the presented innovations appear promising for future application at industrial-scale solar power towers.

OUTLOOK

A detailed analysis of measurement uncertainty is in progress. Besides common sources of measurement uncertainty, e. g. regarding the image acquisition, there are some new issues which are specific for the proposed enhancements. For example, the homogenous irradiation of the absorber using the scan method can only be achieved approximately. This is mainly due to the shape of the light path and the camera's frame rate.

The measurement techniques will be refined. For instance, the scans at the Juelich Solar Tower will be repeated under more favorable conditions in order to get even better results. This includes scanning a reference surface made of diffusely reflecting polytetrafluoroethylene (PTFE) instead of the radiation shield.

Furthermore, a validation campaign using a radiometer at the Juelich Solar Tower is planned for the near future.

Journal papers will be published in order to present the results in detail.

In the medium term, scans at night using a spotlight will be tested and the methods' transferability to external tube receivers will be investigated.

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REFERENCES

1. M. Röger, P. Herrmann, S. Ulmer, M. Ebert, C. Prahl and F. Göhring, "Techniques to measure solar flux density distribution on large-scale receivers", Journal of Solar Energy Engineering **136(3)** (2014), 031013
2. C. K. Ho and S. S. Khalsa, "A Photographic Flux Mapping Method for Concentrating Solar Collectors and Receivers", Journal of Solar Energy Engineering, **134** (2012), 041004
3. F. Göhring, O. Bender, M. Röger, J. Nettlau and P. Schwarzbözl, "Flux density measurement on open volumetric receivers", Proceedings of SolarPACES (2011), Granada, Spain, Sept. 20–23
4. M. Offergeld, M. Röger and H. Stadler, German Patent No. 10 2016 226 033 (23 November 2016)
5. S. Ulmer, E. Lüpfert, M. Pfänder and R. Buck, "Calibration corrections of solar tower flux density measurements", Energy **29**, 925–933 (2004).
6. H. Stadler, D. Maldonado, M. Offergeld, P. Schwarzbözl and J. Trautner, "CFD model for the performance estimation of open volumetric receivers and comparison with experimental data", *submitted to Solar Energy*