### FLUX DISTRUBUTION FROM A BEAM DOWN SECONDARY REFLECTOR: COMPARSION OF RAY TRACING, ANALYTICAL, AND EXPERIEMTNAL RESULTS

Keech A., Hoffman J.E. Department of Mechanical and Mechatronic Engineering, University of Stellenbosch, Stellenbosch, 7600, South Africa 20733860@sun.ac.za

#### Centre for Renewable and Sustainable Energy Studies

#### Abstract

The aim of this paper is to validate Tonatiuh ray tracing software for central receiver systems. A specific test case was investigated, consisting of one heliostat, a ground level receiver, and a secondary beam down reflector. Validation is performed by comparing the flux distribution predicted by the ray tracer model with an analytical model, and with an experimentally measured flux distribution determined with the use of a flux sensor. It was found that the shape and radial spread of the flux distribution in the secondary focal spot is well predicted by Tonatiuh. However, the ray tracer and analytical model results are similar, with less than 1% difference. The peak flux values from the ray tracer are underpredicted by up to 63% when compared to the flux sensor operating at the lowest end of its range. Therefore, determining the flux level accuracy of Tonatiuh will require repeating experiments with a flux measurement device with a more appropriate measurement range.

Keywords: Concentrating Solar Power, Ray tracing, Beam Down Reflector, Optics

#### 1. Introduction

The ability to predict and model the flux distribution across the receiver forms a critical part of the design of heliostat field layouts, receiver and heliostat optical designs, and optimisation. This makes it possible to evaluate and optimise the performance of the optical system before committing to a design and expensive experimentation and fabrication. Numerical prediction methods such as ray tracing can predict results with high levels of accuracy. The availability of free ray tracing software makes it possible for any researchers conducting studies in CSP applications to perform simulations. However, before such ray tracing software can be used with confidence, the validation of the software must be performed. The objectives of this paper is to validate the Tonatiuh ray tracing software, specifically for the test case of a CSP system with a secondary beam down reflector. A beam down reflector was designed, fabricated, and installed at the Stellenbosch University Helio40 facility. The beam down reflector has the purpose of reflecting incoming irradiation from a heliostat field down to a ground level receiver. Validation is performed by experimentally testing a small-scale beam down CSP system, developing an analytical flux distribution model, and generating a numerical model of the system in Tonatiuh ray tracing software. The results from the experimentation and analytical model are compared the ray tracer results to evaluate the predictive capability of Tonatiuh.

### 2. Flux prediction methods

The performance of the collector subsystem is determined through flux distribution modelling over the receiver aperture, as well as the amount of radiation intercepted by the receiver aperture. The flux distribution results from the irradiation distribution from the sun, the geometry of the collector, as well as the aberrations affecting the path of light from the source to the receiver. The power of the intercepted irradiance is determined with

$$P_R = \iint_{A_P} I(x, y) \, dx \, dy \tag{1}$$

Where  $P_R$  is the power of the intercepted irradiance, and I(x, y) is the flux distribution over the receiver aperture with area,  $A_R$ . Several approaches are available to calculate the flux distribution and, depending on the type of application, the most accurate model with the most affordable computational speed is chosen. All flux distribution models are formulated by implementing or combining the four fundamental approaches to calculating flux distributions. These approaches are shape projection, convolution, cone optics, and ray tracing. (Landman, 2017) describes each of the four approaches. Shape projection is the projection of the four corners of the heliostat onto the receiver plane and enlarges the image due to aberrations. Convolution traces a single ray and uses a convolution of the various aberrations to describes the flux distribution. Cone optics is similar to the convolution approach but reflects several rays with a simple flux distribution function. Finally, ray tracing numerically approximates the flux distribution by tracing multiple rays. In the first three approaches the flux distribution can be defined by an analytical model because the flux distribution knowledge accompanies the reflected rays.

The ray tracing approach is an accurate method of performing flux predictions and is considered to be a numerical model. The purpose of the ray tracer is to replicate the optical interactions of light with other objects to predict the flux distribution at the receiver aperture. Monte Carlo ray tracing techniques generate random numbers according to the probability density function (PDF) which describes the likelihood of a random variable to take a certain value. The PDF can be used to determine the energetic and directional properties of the photons being reflected. A realistic model can thus be generated by tracking the simulated photons until the point of absorption (Landman, 2017).

(Landman, 2017) concluded that the accuracy of flux distribution methods is related to computational effort. Analytical models are used for applications that require computational efficiency, but the flux distributions are approximated and in certain applications are not able to achieve suitable accuracies (Landman, 2017). Numerical methods are the most accurate but are computationally intensive since calculations must be performed at each ray-surface interaction and many rays must be traced to develop meaningful flux distributions. The ray tracer codes are flexible and have versatility to building complex shapes and geometries (Yellowhair, et al., 2014).

(Bode, 2017) found that Monte Carlo ray tracing methods are the preferred numerical simulation technique because of their ability to accept complex geometries and flexibility.

# 3. Tonatiuh

The ray tracing software used in this study is Tonatiuh which was developed by the National Renewable Energy Centre of Spain (CENER), with support from the National Renewable Energy Laboratory (NREL), who developed another modern ray tracing code, SolTrace (Blanco, et al., 2009). Tonatiuh is a freely available, open source, Monte-Carlo ray tracer used for the design, simulation, and analysis of complex solar concentrating systems.

Tonatiuh is unique since it is an open source code which can enable software users to modify the code towards their needs and preferences and make it more versatile. Tonatiuh has several advantages. The software has a beginner friendly, easy to use Graphical User Interface which helps reduce the learning curve of the software. It is one of the favoured CSP simulation tools and is known for providing high accuracy results. Plug-ins allow the user to extend new features, complex systems with more realistic materials can be simulated, CAD files can be imported, and a built in tool is available for flux distribution calculations (Jafrancesco, et al., 2018).

Tonatiuh has scripting functionalities which results in faster and more efficient simulations. This software can also automatically generate heliostat field layouts without specifying each individual heliostat which simplifies the modelling process. Any CSP system can be modelled, and the optical layouts and irradiance profiles can be plotted within the code. The ability to visually follow the rays in the GUI efficiently helps to debug optical designs and to help the user's understanding of the system (Jafrancesco, et al., 2018).

Tonatiuh has been validated in previous studies. (Blanco, et al., 2009) compared Tonatiuh to another freely available Monte-Carlo ray tracing software SolTrace (Wendelin, et al., 2013) and found that Tonatiuh simulates the optical behaviour of single and multi-reflecting systems well. It was found that for various simulations, the differences between the two ray tracing software was not more than 2.4% which was sufficient for the investigation.

A screenshot from a simulation modelled in Tonatiuh is presented in Figure 1 below. The Stellenbosch University Helio40 facility (33.9321° S, 18.8602° E) with a beam down reflector installed at the top of the receiver tower is modelled. The individual rays are represented as yellow lines that are traced down from the sun, which is represented as a sun plane, and reflected off the heliostat mirror up to the beam down mirror where it is reflected down onto the target.



Figure 1. Example of a photon map modelled in Tonatiuh

# 3.1. Development of Tonatiuh model

The following section will discuss the steps involved to model the experimental setup in Tonatiuh. The execution of the Tonatiuh model includes defining input parameters such as the sun shape, the system stages, and the optical properties of the reflecting surfaces.

# 3.1.1. System objects

Three main objects were developed in the ray tracer, namely the heliostat field, the receiver, and the beam down reflector. The heliostat field in this model consists of one heliostat. The

heliostat is modelled as a rectangle with a focal distance equivalent to the distance between the heliostat and the beam down reflector. The heliostat was assigned solar tracking behaviour with an aim point which is the coordinates of the centre of the beam down mirror. The beam down reflector was modelled as a flat rectangle, angled to point downwards towards the target. The receiver is modelled as a square flat plate located on ground level.

# 3.1.2. Sun shape and position

The solar position is defined by specifying the azimuth and elevation angles of a specific day and time based on the method from (Geyer & Stine, 2001):

$$\delta = \operatorname{asin} \left( 0.39795 \cdot \cos(0.98563 \cdot (N - 173)) \right)$$
(2)

The declination angle is represented by  $\delta$  and N is the number of days since 1 January.

The altitude angle  $\alpha$  is defined as the angle between a central ray from the sun and the horizontal plane that contains the observer and is calculated with

$$\alpha = \operatorname{asin} \left( \sin \delta \cdot \sin \phi + \cos \delta \cdot \cos \omega \cdot \cos \phi \right)$$
 (3)

Where  $\omega$  is the hour angle and  $\phi$  is the latitude angle. The azimuth angle is measured from due north in a clockwise direction and is calculated with

$$AA = a\cos\left[\frac{\sin\delta \cdot \cos\phi - \cos\delta \cdot \cos\omega \cdot \sin\phi}{\cos\alpha}\right]$$
(4)

The azimuth angle can be in any one of four trigonometric quadrants, and a test must be performed to ascertain which is the correct quadrant. *AA* is the untested result, which is tested to become *A*. If  $sin\omega > 0$ , then  $A = 360^{\circ} - AA$ , otherwise A = AA.

The sun shape profiles available in Tonatiuh are the pillbox and Buie sun shapes. Both sun shapes were applied in separate simulations to identify changes in the flux distributions (See Section 5.1). When defining the sun shapes the default values were used, thus for the pillbox sun shape the maximum half angle was 4.65 mrad, and for the Buie sun shape, the CSR was set to 0.02. When comparing the sun shapes, all input parameters were the same for each simulation except for the sun shape profile.

#### 3.1.3. Optical properties

The optical properties for the reflecting surfaces in Tonatiuh are defined by the reflectivity and slope error. The reflectivity and slope error were assumed for the heliostat and beam down mirror. The reflectivity is set to 0.9, which is a conservative figure, and the slope error was set to 1 mrad. These values were chosen based on design requirements for a heliostat facet design from (Landman, 2017) where the minimum requirements were 90% reflectivity and <1.2 mrad surface slope error. A sensitivity analysis for these two optical properties is performed in Chapter 6.3.

#### 4. Circular Gaussian approximation method

A simple flux density model is useful when required to perform a quick and approximate analysis. The flux maps and flux values simulated in Tonatiuh are compared to those generated in the analytical model and measured from experimental results to validate the open source software.

The approximate analytical flux distribution model that was used is the Heliostat Field Layout CALculations (HFLCAL) method as described by (Schwarzbözl, et al., 2009) that uses convolution methods. The HFLCAL method assumes that the reflected flux image of each heliostat is defined by a single circular Gaussian distribution (CGD). A main advantage of HFLCAL is the fully analytical nature that allows for the mathematical expressions for the maximum flux and intercept to be closed mathematical expressions. At each x, y coordinate on the receiver surface the flux can be calculated with the expression.

$$FD(x,y) = \frac{P_h}{2\pi\sigma_{HF}^2} e^{\frac{-(x^2+y^2)}{2\sigma_{HF}^2}}$$
(5)

The total power  $P_h$  from a single heliostat on a receiver plane is calculated with

$$P_h = I_D \cdot A_m \cdot \cos \theta_i \cdot f_{at} \cdot \rho \tag{6}$$

Where  $I_D$  is the direct solar irradiation,  $A_m$  is the surface area of the heliostat, and  $\theta_i$  is the angle between the incidence rays of the sun and the heliostat normal vector at the time of testing. The attenuation factor is represented as  $f_{at}$  and  $\rho$  is the mirror reflectivity. The effective deviation  $\sigma_{HF}$  is the convolution of four Gaussian error functions, namely the sun shape error  $\sigma_{sun}$ , the beam quality  $\sigma_{bq}$ , the astigmatic error  $\sigma_{ast}$ , and the tracking error,  $\sigma_t$ . The error function is calculated with

$$\sigma_{HF} = \frac{\sqrt{D^2(\sigma_{sun}^2 + \sigma_{bq}^2 + \sigma_{ast}^2 + \sigma_t^2)}}{\sqrt{\cos(rec)}}$$
(7)

The slant range is represented as *D*, and  $\cos(rec)$  is the cosine of the angle between the normal vector of the receiver and the reflected ray. The beam quality error is a function of  $\sigma_{SSE}$  and accounts for deviations in mirror curvature from the ideal shape and imperfections of the reflecting surface.

The beam quality equation below is from (Landman, 2017) which is a modification that was shown to improve the correlation of the CGD model to that of the ray tracer by considering the effect of the incidence angle on the flux distribution.

$$\sigma_{bq}^2 = 2\sigma_{SSE}^2 (1 + \cos\theta_i^2) \tag{8}$$

The surface slope error for the HFLCAL model is determined using an iterative process described by (Collado, 2010). The  $\sigma_{SSE}$  of the modelled flux distribution is adjusted until the peak flux of the HFLCAL model matches the peak of the ray traced results. The HFLCAL method only makes use of a Gaussian distribution. A representative standard deviation of the astigmatic dispersion as a circular Gaussian beam is given by (Landman, 2017) to transition from a pillbox type distribution to an equivalent Gaussian distribution so that the astigmatic error can be applied in the HFLCAL method.

$$\sigma_{ast}^2 = \frac{h_{tan}^2 + w_{sag}^2}{32d^2}$$
(9)

Tangential and sagittal dimensions of the image produced on the receiver are represented with  $h_{tan}$  and  $w_{sag}$  respectively and is calculated with equations from (Landman, 2017):

$$h_{tan} = 4\sigma_{SSE} \cdot d \tag{10}$$

$$w_{sag} = 4\sigma_{SSE} \cdot d\cos\theta_i \tag{11}$$

The total flux density on the receiver surface is determined by the summation of the fluxes contributed by each of the heliostats.

#### 5. Experimentation

Experiments were conducted at the Helio40 solar research facility situated on the Mechanical and Mechatronic Engineering building roof at Stellenbosch University. The purpose of the experiment is to record flux readings from the flux sensor and to characterise the heliostat flux distribution profile on the target through image processing. Figure 2 below illustrates the experimental setup for one heliostat. A 1.83 m x 1.22 m heliostat was used to generate a flux image on the beam down mirror situated at the top of an 18 m heigh tower. A 1.25 m x 2.5 m beam down mirror reflects the flux onto a target at ground level. Table 1 lists the instrumentation used in the experiment. The DNI readings are obtained from the Southern African Universities Radiometric Network (SAURAN) (Brooks, et al., 2015).

#### Table 1. Experimental setup instrumentation

Equipment	Details	
Flux sensor	Hukseflux SBG01 water cooled sensor	
Data Acquisition unit	Keysight LXI Data Acquisition Unit/Switch Unit 34972A	
SLR Camera	Nikon D5100	

The heliostat is calibrated to shine in the centre of the beam down mirror and the second reflected image is reflected onto the target. The target is painted a matte white to approximate a Lambertian target. The flux sensor is placed approximately in the middle of the focal spot to take readings of the peak flux. While the flux readings are being recorded on the data acquisition unit, the characerisation of the heliostat profile is conducted with the method described by (Grobler, 2015). A photo of the reflected image is taken with a camera. The MATLAB image processing toolbox is used to process the photos, and the brightness of each pixel will represent the intensity of the flux values. The intensity values are scaled linearly with the flux readings from the flux sensor to determine the flux distribution. The flux distribution from the experiments can be compared to the flux images from the analytical HFLCAL model and from Tonatiuh.



Figure 2. Example of experimental setup for one heliostat

## 6. Results

In this chapter, the measured results from experimentation and the results from analytical modelling will be compared to the ray traced results to validate the flux distribution predictive accuracy of Tonatiuh software for a beam down CSP system.

## 6.1. Peak flux

Figure 3 below provides a comparison of the peak flux values obtained from experimental testing, ray tracing, and from the HFLCAL analytical model.



Figure 3. Comparison of measured and predicted peak flux values

Values were determined using each method at the date and time at which an experiment was conducted. In addition, the geometric concentration ratio was used as an easy and robust method to quickly approximate results. The concentration ratio is defined as the surface area of the concentrator divided by the surface area of the receiver. The peak flux values obtained from each method are compared to the results predicted by the ray tracer. The data labels in each bar in Figure 3 provides the percentage differences between the values obtained from Tonatiuh and the other respective methods. The analytical model (Chapter 2) agreed well with ray tracing predictions with a difference of less than 1%. Peak flux values calculated with the geometric concentration ratio also agreed well with the ray tracer results with a maximum difference of up to 13% which is acceptable given the simplicity of the method. When the peak flux values from the ray tracer and from experimental testing are compared a difference of up to 63% is found.

#### 6.2. Flux distribution

Figure 4 below shows the flux distribution profiles for the secondary focal spot on the receiver. The sub-figures on the left, middle, and right of Figure 4 are the flux profiles from the analytical model, the ray tracer, and from experimentation, respectively.



Figure 4. Flux distribution profiles from the analytical model (left), ray tracer (centre), and experimental (right)

A total of  $1 \times 10^7$  rays were used in the ray tracer simulation. The experimental flux image was developed from a photo that was taken of the secondary focal spot on the receiver surface during experimental testing using image processing described in Chapter 4.1. During testing, the position of the sun caused the safety railing on the sunroof to produce a shadow on the receiver, which can be seen in the far right sub-figure in Figure 4. This is not predicted in the analytical model or the ray tracer. The shape of the precited focal spots appear to be relatively well predicted when compared to the experimental flux image, despite there being a difference in peak flux values. The pillbox sun shape was used in Tonatiuh which explains why the focal spot appears to flatten towards the centre.



Figure 5 presents the radial distribution of the secondary focal spot on the receiver.

Figure 5. Comparison of measured and predicted flux distributions

Results are shown for three different times of the day, namely in the morning, noon, and late afternoon, at wall clock times of 10:29 am, 12:57 pm, and 15:06 pm, respectively. These are times when photos were taken of the focal spot during testing.

It is observed that the focal spot distributions remains relatively well predicted throughout the day when compared to the experimentally measured flux distributions and resembles a Gaussian distribution. The ray tracing predictions agree with the HFLCAL model predictions from the centre at 0 m to a distance of 0.2 m. A consistently large difference in peak flux values is observed when comparing experimental results to predicted results with an error of between 45% and 63% throughout the day.

The large discrepancy between measured and predicted peak flux values will be investigated in the following sub-chapters.

## 6.3. Ray tracing parameter variation

A possible reason for the discrepancy could be attributed to ray tracing underprediction. This will be investigated in the following sub-chapters.

## 6.3.1. DNI input values

It is observed from Figure 3 and Figure 5 that the experimentally measured values always exceed the predicted values from ray tracing. The use of incorrectly measured DNI values can be eliminated as a possible source of error because an optimistic DNI value of 1000  $W/m^2$  in Tonatiuh, while keeping all other inputs the same, still resulted in underpredicted flux values. This is shown in Figure 6 by comparing peak flux values.



Figure 6. Influence of DNI on ray tracing predictions

# 6.3.2. Optical properties

Another possible reason for the discrepancy could be due to the optical properties assigned to the reflecting objects. A sensitivity analysis is performed for the reflectivity and slope error properties to investigate the effect that the properties have on the results. A DNI input of 1000 W/m<sup>2</sup> and a pillbox sun shape is used for the analysis. The values are adjusted by  $\pm$  10% and are tabulated below in Table 2.

Sensitivity Parameters	Peak Flux W/m <sup>2</sup>	% Difference	Average Flux W/m <sup>2</sup>	% Difference
$\rho = 90\%$ ; $\sigma_{slope} = 1 \text{ mrad}$	1270.9	-	1001.4	-
$\rho = 99\%; \sigma_{slope} = 1 \text{ mrad}$	1349.3	6.2	1040.5	3.9
$\rho = 81\%; \sigma_{slope} = 1 \text{ mrad}$	1216.4	4.3	960.9	4.0
$\rho = 90\%$ ; $\sigma_{slope} = 1.1$ mrad	1274.6	0.29	995.8	0.56
$\rho = 90\%$ ; $\sigma_{slope} = 0.9$ mrad	1297.29	2.08	1005.4	0.4

Table 2. Sensitivity analysis of mirror optical properties

It is observed that the reflectivity affects the flux results more than the slope error. When the reflectivity was adjusted, the peak flux values on the receiver changed by up to 6.2% and the average flux values changed by up to 4%. When the surface slope error values were adjusted, the peak flux values were less affected, with a difference of up to 2.08% for the peak flux and up to 0.56% for the average flux. Thus, increasing or decreasing the values of the optical properties does influence the results, but not by a significant amount.

Thus, the parameters for the optical properties could not be the main reason for the 63% discrepancy between the peak flux results as the flux values were not significantly affected by the slope error or the reflectivity.

## 6.3.3. Sun shape input parameter

The third possible reason could be due to the sun shape used in the ray tracer. Two sun shapes are available in Tonatiuh, namely the pillbox and Buie sun shapes, and both were used in a simulation to observe the effect it has on the peak flux values. Figure 7 below presents the predicted flux distributions at 12:57 pm for the ray tracer when the sun shape is varied, the experimentally measured flux distribution, and the analytically predicted distribution. It is observed that differences induced by modifying the sun shape is not significant, with a 3.5% difference in peak flux values when  $1 \times 10^8$  rays are used in the simulations.



Figure 7. Influence of sun shape on ray tracer predictions

## 6.4. Experimental error analysis

The discrepancy in peak flux values could alternatively be explained by experimental overreading. The experimental apparatus used during testing was a flux sensor, data logger, camera, and the instruments from the SAURAN solar resource station.

When irradiation is measured with the flux sensor at a fraction of the full measurement range, the sensor output ideally varies linearly with the heat flux. The deviation from this ideal behaviour is known as non-linearity which is expressed as a percentage of the measurement range. The non-linearity specification is  $\pm 2\%$  of the measurement range for the flux sensor (Hukseflux Thermal Sensors, 2016). Thus, the non-linearity contributes  $4 \times 10^3$  W/m<sup>2</sup> to the uncertainty budget which is a significant amount relative to the scale of irradiance levels incident on the target during testing. The factory calibrations were used with a calibration uncertainty of  $\pm 6.5\%$ . This is not significant compared to the large uncertainty due to non-linearity.

According to the datalogger user manual (Agilent Technologies Inc., 2012), the datalogger used to record values from the flux sensor has a measurement error of  $\pm (0.003\% \text{ of reading} + 0.0007\% \text{ of range})$ . This results in a measurement uncertainty of  $\pm 0.28\%$ .

The DNI measurements were taken using a Kipp & Zonen CHP1 pyrheliometer that was last calibrated in 2016 according to (Fitzgerald, 2019). The user manual for the pyrheliometer reports a daily measurement uncertainty of  $\pm 1\%$ .

The instruments excluding the flux sensor therefore contribute  $\sqrt{6.5^2 + 0.28^2 + 1^2} = 6.58\%$  to the uncertainty budget which is not significant and can only account for at most 10% of the 63% discrepancy between the ray tracing and experimental results.

Factors such as vibrations due to wind loads and mirror deformations also affect the shape and distribution of the real focal spot which would result in the real and simulated focal spots having differences. An additional source of error is introduced because the camera could not be positioned perfectly normal to the target. This means that the image was captured from a non-zero angle of incidence, but this error was reduced during image processing. The target was also modelled to be a Lambertian surface which means that the incidence flux is diffusely reflected in all directions and thus the camera does not have to be perfectly normal to the target.

#### 7. Conclusions and recommendations

A small-scale beam down CSP system was used as a test case to validate the Tonatiuh ray tracing software. The shape of the flux distributions and the radial distribution of the focal spot appeared to be well predicted. The peak flux values however were underpredicted by up to 63%. After investigating potential reasons for this discrepancy, it was clear that the flux readings from the flux sensor were too high and were the main source of discrepancy. The flux sensor measurement uncertainty due to non-linearity was very high, contributing  $4 \times 10^3$  W/m<sup>2</sup> to the uncertainty budget. This is due to the flux sensor operating at the lowest end of its range during experimental testing.

Conclusions regarding the predictive accuracy of the Tonatiuh ray tracing software for a beam down CSP system therefore requires further investigation, using an irradiation sensor with a more appropriate measurement range, and confirming that the flux readings are inaccurate at low measurement ranges through additional testing.

### 8. References

Agilent Technologies Inc., 2012. *Agilent 34970A/34972A Data Acquisition/Switch Unit User's Guide,* Colorado: Agilent Technologies Inc..

Blanco, M., Mutuberria, A. & Garcia, A., 2009. Preliminary validation of Tonatiuh. s.l., s.n.

Bode, S., 2017. *Development of a ray-tracer for concentrating solar power systems,* Stellenbosch: Stellenbosch University.

Brooks, M. et al., 2015. SAURAN: A new resource for solar radiometric data in Southern Africa, s.l.: Journal of Energy in Southern Africa.

Collado, F. J., 2010. One-point fitting of the flux density produced by a heliostat. *Solar Energy*, 84(4), pp. 673-684.

Fitzgerald, D., 2019. SAURAN solar radiometic data for the public. [Online] Available at: <u>https://sauran.ac.za/station-documents/SUN/SUN%20Station%20Details.pdf</u> [Accessed 27 September 2022].

Geyer, M. & Stine, W. B., 2001. Power from the sun. s.l.:s.n.

Grobler, A., 2015. *Aiming strategies for small central receiver systems,* Stellenbosch: Stellenbosch University.

Hukseflux Thermal Sensors, 2016. User manual SBG01: Water cooled flux sensor, Delft, Netherlands: Hukseflux Thermal Sensors B.V..

Jafrancesco, D. et al., 2018. Optical simulation of a central receiver system: Comparison of different software tools. *Renewable and Sustainable Energy Reviews*, 94(June), pp. 792-803.

Landman, W. A., 2017. *Optical performance of the reflective surface profile of a heliostat,* Stellenbosch: Stellenbosch University.

Schwarzbözl, P., Schmitz, M. & Pitz-paal, R., 2009. *Visual Hflcal – a Software Tool for Layout and Optimisation of Heliostat Fields.* s.l., SolarPaces 2009 International Conference. Wendelin, T., Dobos, A. & Lewandowski, A., 2013. *SolTrace: A Ray-Tracing Code for Complex Solar Optical Systems,* United States of America: National Renewable Energy Laboratory.

Yellowhair, J., Ortega, J. D., Christian, J. M. & Ho, C. K., 2014. *Solar optical codes evaluation for modeling and analyzing complex solar receiver geometries.* San Diego, California, Nonimaging Optics: Efficient Design for Illumination and Solar Concentration XI, 91910M.