

# Solar flux map distribution of a parabolic-spheric dish based on photographic method

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## Abstract

This paper presents a novel method to derive solar flux map of irradiation near to the focal plane of an innovative concentrating point focusing technology facility. The system has a reflector covered by mirrors focusing sun radiation on a Stirling engine. It has been designed and manufactured from the sketch. It consists of a novel dish of 8.6 m in diameter, whose reflector is made of glass mirrors and has a focal distance of about 4.5 m. The profile is the innovative part of this facility where the mirrors have been designed in order to reduce manufacturing costs. The inner part of the concentrator consists in a spherical shape profile and the external part represents a parabolic profile. Flux measurements is obtained integrating photogrammetric and photometric procedures. The approach used here is presented in a real case application which provides pixel values of radiation for the receiver plane. The solar flux map achieved for a sunny day is reported and compared with the one obtained by a ray-tracing analysis.

*Keywords: Solar energy, point focus technologies, dish, flux measurement, spherical reflector.*

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## 1. Introduction

Point focusing technologies are the candidate for achieving high solar flux and operate at high temperatures, never the less, several problems exist for mechanical components and tracking systems. Achieving high temperature brings concentrated solar power to be a highly promising renewable energy source with great potential. High temperature processes are nowadays present in a lot of fields and they are continuing to grow. Interests are strong in many fields, for example, metallurgical processes, CHP (Combined Heat and Power) systems, chemical industries and fuel production. Solar thermal power can help in this way considering temperature level can be as high as conventional fuels. Characterization of solar high flux irradiance technologies is becoming a main item in the growing variety of research fields in Concentrated Solar Power. Few methods to measure solar flux maps currently exist Roger et al. (2014). Although, most of them have not been tested in commercial plants. These methods are mainly classified as direct or indirect measure systems, the first consists in having the sensors placed in the focus plan directly exposed to the concentrated radiation, the second measure the radiant flux through a correction of the flux reflected or emitted by the target surface. The most common method consists in an indirect solution based on photometry using cameras which are able to recognize the brightness reflected by a target from an image. This characteristic is represented by the “grey-level” of each camera pixel and can be calibrated to a flux density value. The calibration can be done with a direct punctual measurement through a direct measure using for example a Gordon radiometer, knowing the total energy reflected on a certain surface or through a solar image knowing the present direct normal irradiation. The point focusing technology presented here consists in a facility realized within a regional research project in order to demonstrate m-CHP. Similar plants have already been presented, Reinalter et al. (2006). The approach used for the design wants to realize a very precise and low-cost Stirling-dish application. The Stirling engine used is the SOLO-V161, fixed on a manual controlled system movement, that easily permits eventual displacement of the equipment in the focal area. The aim of this facility is to realize a precise point focusing concentrator technology, also useful in other applied research for high temperature topics, such as solar fuel production.

This paper presents the methodology used to produce the flux map from an indirect image of the Lambertian target, coupled with a calibration method of the radiation to the grey-scale value following a solar image procedure on the same target.

## 2. System description

The system is mainly composed of a support structure fixed to the ground which include two cinematic joints allowing elevation and azimuth movements where the mirrors are hung. The structure parts realized by laser cutting and the mirror joint regulation permit to have a rigid and precise structure. Six metallic beams are connected to the dish perimeter to support the Stirling engine frame. Two single turn encodes are connected in the two slewing bearing as feedback position measurements with 16 bits resolution each. Both axes are moved from a brushless motor with respect 1.57 kW for the azimuth and 2.89 kW for the elevation. To equilibrate the structure two counterweights are filled with concrete and fixed opposite the dish (Fig. 1).



Fig. 1: Lateral view of the realized system.

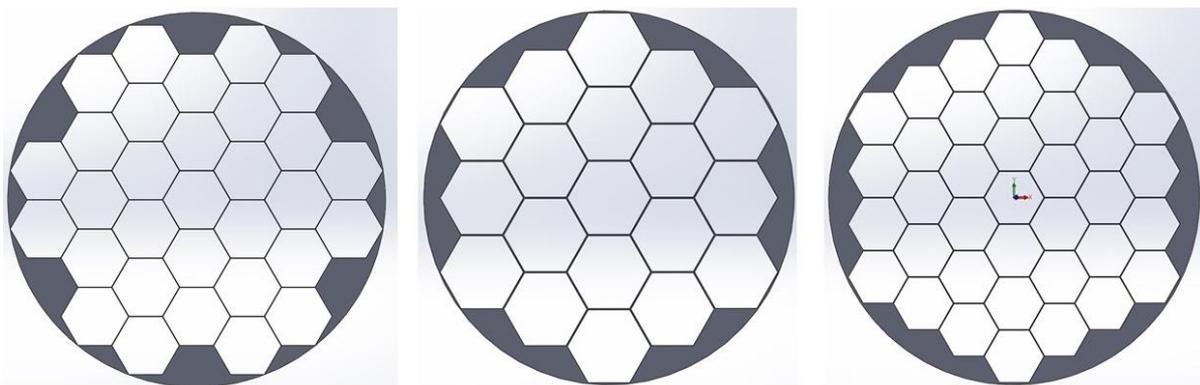
The design of the geometrical shape of the reflector was created with the aim of cost reduction, especially in the realization of the mirrors, whose major costs are due to the glass molds fabrication. For this reason, a spherical shape was chosen; a viable solution for having mirrors not constrained with respect to a radial direction orientation. This permits to fill empty spaces on the dish surface better, by having only two kinds of mirrors instead of three. The overall dish has a diameter of 8.6 m and is covered by two differently shaped mirrors, in the central part and in the peripheral ring (Fig. 2). The spherical part, located in the central zone of the dish, is filled with 30 hexagonal mirrors, the best candidate for filling the circular area. The spherical curvature is 9.293 m and represents the dish profile from 0 to 2.850 m in radius. The external parabolic reflector is built with 32 mirrors shaped as an annulus sector and covers the rest of the dish from 2.850 m to 4.305 m in radius. They are built following a parabolic profile in the radial dish direction and circular shape on the tangential one. The mirrors have a thickness of 0.004 m and are made by glass tempered on the surface. The production method starts from a plane glass formed as the envelope of the final one, heated up to 800°C then shaped by a pressing of two molds and finally quickly cold down by a high air flux on the glass surfaces. They are rigid enough to be self-supporting in all the dish zenith positions. Both the hexagonal and the annulus sector shaped mirrors are supported with six plastic swabs located in the corners for the hexagonal ones and along the radial sides of the others. Each swab locks the mirror and the adjacent one and can move slightly for an eventual needed of position correction. A spherical profile has the advantage that the mirrors are not constrained in having a fix orientation with the radial direction of the dish being the same curvature for all of the mirror tangential vectors.



**Fig. 2: Front view of the system: the reflector presents spherically shaped hexagonal mirrors in the center and parabolic ones in the external ring.**

This permits each spherical mirror to rotate respect its main symmetry axis without changing the dish's profile surface. Thanks to this it is easy to fill the dish better, arranging all the mirrors minimizing the empty space.

This aspect brings the necessity to optimize the filling ratio. The dependent parameters are the mirror shape, mirrors arrangement and the main dimension of the mirror. This combination can fill the dish in different configurations (Fig. 3). Using SolidWorks has optimized the filling of the central part of the dish. The implemented feature "Fill Patterns" fills the defined region with a pattern of features or a predefined cut shape. Three case studies have been considered and the first has been selected (Fig. 3) having a filling ratio of 81.8 %. This choice also allows free space for sensors, in fact the locations of the unused space are concentrated in six defined sectors. In one of them a digital industrial sun sensor has been installed for solar tracking - model ISST5 from the company SOLAR-MEMS.



**Fig. 3: Optimization results for the filling ratio. CASE 1: 81,8 % (left), CASE 2: 79,5 % (center), CASE 3: 79,0 % (right).**

The curvature of the reflector has been designed taking into consideration the technical specification of the Stirling Engine SOLO V161. The reflector profile needs to take into account the amount of thermal power used to introduce in the cavity of the Stirling, flux distribution and hot spots. The ideal situation, as reported by Reinalter et al. (2006) would be to introduce 40 kWt through the hole as homogeneous as possible around the receiver. The more non-homogeneous is the flux the more possibilities there is to burn the tubes on the receiver. For Eurodish system, reference values are: for solar flux on the receiver is around 1500 kW/m<sup>2</sup>, power delivered by the dish around 44kWt, 38kWt in the cavity and 32kWt inside the receiver (gas side). According to SOLO's manual the maximum thermal power input for their receiver is 33kWt.

A single parabolic profile was not suitable, theoretically having a gaussian as flux map distribution. For this reason, a different geometric shape needs to be selected to maintain a homogenous flux distribution. The work began analyzing the dish profile as a combination of two and three concatenate arcs of parabolic profiles until the final parabolic-spheric solution was selected. In order to maintain a good efficiency in the concentration it is important

to define acceptable tolerances for the geometrical profile and the solar tracking. An analytical function (Li et al. (2013)) to predict the performances of a paraboloidal dish solar concentrator with a cavity, has been applied for the errors estimation. The graphic below shows the results of the intercept factor calculated with our characteristic dimensions of the dish (Fig. 4).

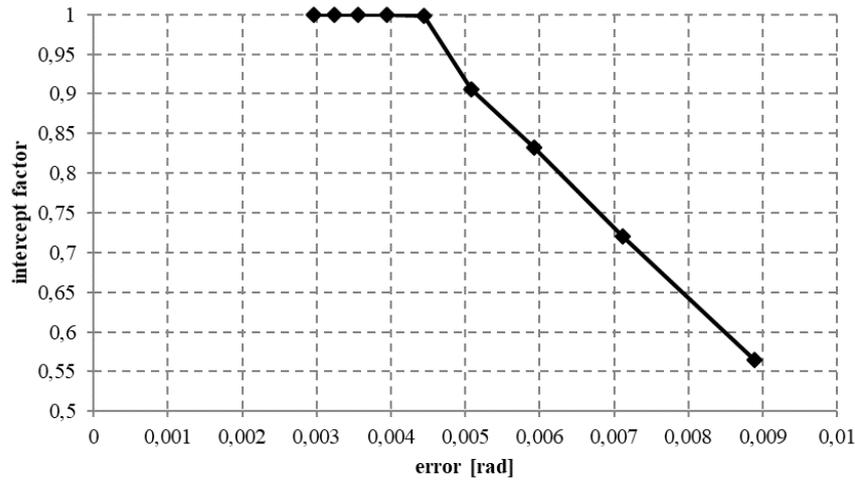


Fig. 4: Intercept factor as a function of total errors.

These results have been validated for our personal application using a ray-tracing software. Errors were simulated whilst modifying the dish profile and introducing an offset for the sun position. Theoretic radiation flux map has been modeled in order to keep peak solar flux on the receiver plane around 1500 kW/m<sup>2</sup>. The design was analytical and then evaluated using ray-tracing methods (Fig.5).

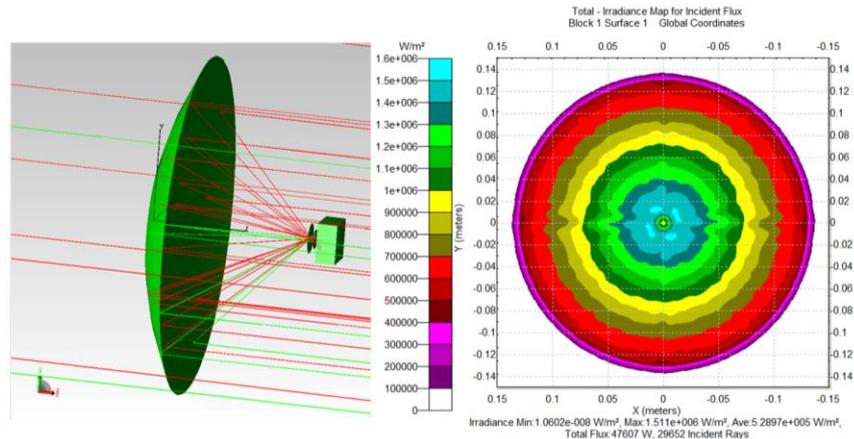


Fig. 5: Ray tracing analysis (left), example of simulation in with a certain offset from the focal plane (right).

The dish has been fully designed and constructed with off the shelves components, excluding the mirrors. The system allows an easy dismount and alignment due to the Stirling engine being fixed on a 3-axis regulation system. This flexibility allows you to easily replace the equipment in focus for different research purposes. The control logic developed on a PLC from Beckhoff, is uncoupled between the dish and the Stirling engine to permit convenient use of the facility when equipment in the focus changes. Tracking control has been implemented both pointing the astronomic sun position and by using ISS75 sensor as feedback. For the coordinate tracking manner in order to improve the precision an accelerometer has been mounted on the structure and a routine is able to calculate the vertical error of the azimuth cinematic joint.

### 3. Experimental setup and methodology

During the design of the solar facility it has been considered the need to measure the radiant flux map and the fact that a small surface in the center of the dish wouldn't be participating in the concentration, because it would have been shadowed by the equipment on the focus point. For such reasons a free space in the center of the dish was left for the camera, with the advantage to have it parallel to the receiver surface normal, thus minimizing geometrical

distortion (Fig. 6).

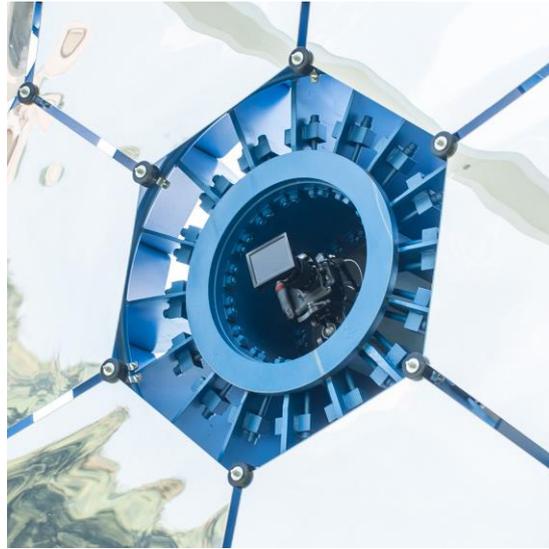


Fig. 6: The camera fixed in the center of the dish.

The support for the camera was realized in order to have the symmetry axis of the parabola collimated with the lens. The target specifically used for this test (a square with 0.45 m side) is placed near to the focal plane a bit forward respect the theoretical focal point because of a mechanical constrain. It has been manufactured with an aluminum plate 0.008 m thick, cooled on the back side by water (Fig. 7). The water flows in two channels machined in the plate with a depth of 0.003 m. The cooling system is implemented with a centrifugal pump connected to a hand primer bulb pump at the inlet to fill the suction pipe and the centrifugal pump. The open water circuit utilizes a 30 liter tank which is hung to the focus structure and is instrumented with two thermocouples placed at the inlet and outlet of the target to protect the system in case it over heats as well as estimating the total energy absorbed in the future. The mass flow in the target with the circuit connected is approximately 15 l/min.



Fig. 7: Back support of the target with the water channel distribution (left), surface target coated with the painting (center), assembled phase (right).

The ideal target for the experiment would be Lambertian in order to be entirely diffusely reflecting. In practice the target available deviates from Lambertian reflectance. Materials and finish exposed are the most important parameters influencing this property. Moreover, in concentrate solar power with high intensity flux we also have critical condition in terms of surface heating and thermal stress. The surface is covered with an alumina based paint mixed with calibrated particles. This choice permits to have a controlled surface finish and a material that from the literature is one of the best candidate for reflectance characteristics (Harner and Menzies, 1989). After a mechanical cleaning of the surface to eliminate aluminum oxide the mixed slurry (powder and liquid in a 3 to 1 ratio by weight) has been applied to the surface with a roller and a brush trying to have a uniform coating. During this process it was difficult to keep the slurry homogeneous because the powder tended to deposit despite the liquid part. After the coating, the surface was not perfectly homogeneous because of different thicknesses and roughness. To improve sandpaper has been used adjusting thickness and roughness. After this the aluminum plate was heated at 93°C for 2 hours following the product specification. The target at this point was assembled with some screws to the back side with the water channel using a high temperature silicone sealant for a reliable seal in flanges.

To map the irradiance distribution over the focal plane, a new method inspired by Ho and Khalsa (2012) was used.

The method consists in estimating a radiometric scale factor for the brightness values (BV) of the image pixels to the irradiance values of the target. A reference image of the sun is taken with neutral density filters to estimate the scale factor, then photographs of the target are taken with same exposure parameters but different neutral density filters. The map of the irradiance distribution is thus obtained using the scale factor from BV to irradiance taking also into consideration the filter factors for the new photograph.

The main innovation here presented is given by the design of the reflector: (i) its moderate size allows a removable target (Fig. 7) to be used and (ii) the camera can be placed with the optical axis orthogonally aligned to the target. This represents a big simplification in the method as the target can be removed from the focal plane of the solar concentrator allowing an image of the target to be acquired while exposing it at one sun and another image while placed over the focal plane of the solar concentrator. The scale factor from brightness values (BV) of the image to irradiance values of the target were here done measuring the DNI with a pyrheliometer Kipp & Zonen, CHP1. With the aim to validate the method, and to characterize the target reflectivity, also an image of the sun was taken.

Being the images of the target acquired with the same camera (using different exposure times) and by measuring the actual DNI reaching the target, values of the irradiance flux can be estimated regardless of the values of target reflectivity. The exposure factors between the image of the target acquired when exposed at one sun with respect to when exposed over the focal plane of the reflector were considered. Moreover, with respect to the method presented in Ho and Khalsa (2012), accurate geometrical parameters of the camera were estimated through a bundle adjustment with self-calibration (Brown, 1971; Remondino and Fraser, 2006). Using the parameters given by the camera calibration, and measuring the distance between the target and the camera, an accurate value for the ground sample distance – GSD (the pixel size expressed in object space units) was determined. The GSD is then used for calculating the area imaged by each pixel in the object space.

Also, in this paper the working f-number was used instead of the f-number by considering the actual magnification given by focusing the camera not at infinity but at 6m, distance of the target from the camera.

A Nikon D3X 24 Mpx DSLR camera mounting a 0.105 m lens was used for the tests. Neutral density filters were used to reduce the exposure values within the acceptable ones for the camera thus avoiding signal saturation. Different gradations were used according to the weather conditions (hazy or clear sky) with optical density typically in the range 2.0-4.0. The images, acquired in RAW format by the camera, were linearized using the software DCRAW, then MATLAB environment was used for successive computation and analyses.

Preliminary tests were performed acquiring the images from the ground, then an ad hoc mount has been built to accommodate the camera in the center of the parabola. This setup allows the image to be acquired almost perpendicularly to the target. A wireless remote controller (Fig. 8) for setting the camera parameters and downloading the images online has also been developed using a microcomputer Raspberry Pi and gphoto2 open source software.



Fig. 8: Equipment used for the image acquisition fixed on the support.

#### 4. Results

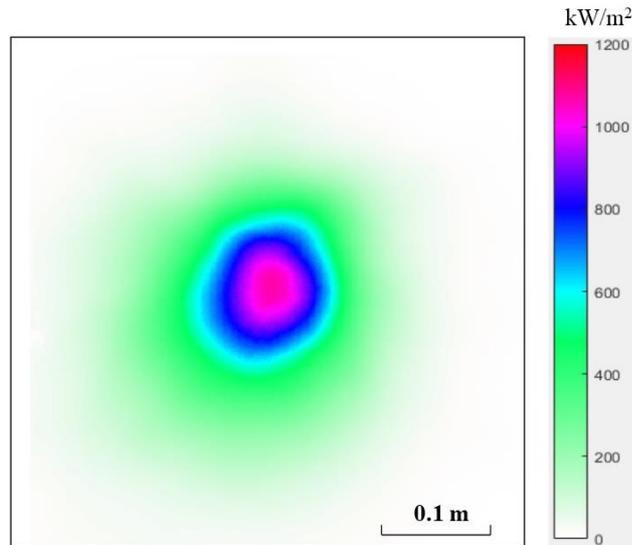
Tab. 1 summarizes the main parameters and settings of an experimental test carried out on 31<sup>st</sup> July 2018. The resolution of the camera in combination with the used lens and the camera-to-target distance allowed for a submillimeter resolution of the radiant flux map. The result of the irradiated target placed near the focal plane,

shows very precise circular shapes. It means that the dish geometry is very accurate and homogenous. Some other specific measurements of the flux map will be done in the future to validate the profile and the ray tracing model used for the design.

**Tab. 1. Main parameters and settings of an experimental test.**

Parameters and settings	Values and characteristics
DNI measured by the pyrheliometer	918 W/m <sup>2</sup>
Camera	Nikon D3x 24 Mpx full frame sensor DSLR
Sensor characteristics	CMOS – 5.95 μm pixel size
Calibrated principal distance	107.29 mm
Camera to target distance	6 m
Ground sample distance – GSD (the pixel size expressed in object space units)	0.34 mm
Irradiance for each GSD <sup>2</sup> on the target illuminated by one sun	108.63 μW
Working f-number	f/16.3
Area of the entrance pupil	34.028 mm <sup>2</sup>
Exposure settings for the camera pointed at sun	1/1000 sec, f/16, ISO 100
Exposure settings for the image of the target over the focal plane of the solar concentrator	1/15 sec, f/16, ISO 100
Exposure settings for the image of the target exposed at 1 sun	4 sec, f/16, ISO 400

Figure 9 shows the irradiance map of the target placed on the focal plane of the solar concentrator.



**Fig. 9: The obtained irradiance distribution map with the proposed photogrammetric method.**

## 5. Conclusion

The presented work proposed a photographic method as an efficient and inexpensive way to estimate the concentration map on focusing technologies. The method has been applied to a real facility installed nearby Trento (Italy) and has demonstrated an easy system for solar flux map characterization. The advantage with respect to other solutions to avoid any additional equipment near to the focal plane for estimating pixel radiation intensity or total amount of energy received has been practically verified. Moreover, a comparison between design data and measurements is done. The design of the facility has been validated both for the spherical and paraboloidal portion of the reflector. The target used treated with alumina-based painting demonstrates to be Lambertian and resistant for the high concentration value obtained. Considering the archived results, the method will be improved analyzing error sources and accuracy. From a comparison between the flux map calculated by ray-tracing and the measured

one, the conclusion is that the tolerances calculated for the dish geometry, tracking errors and mirrors precision have been respected. . Future activity will be focused on the measurement of the reflectivity of the Lambertian target to validate the method proposed for the analysis.

## 6. Acknowledgement

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