SolarPACES 2024, 30th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

Operations, Maintenance, and Component Reliability

https://doi.org/10.52825/solarpaces.v3i.2323

Published: 28 Nov. 2025

Geometric Characterization of Flexible Film Mirrors Parabolic Trough Collectors by 3D Scanning and Receiver Tube Image Analysis

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Abstract. This study presents a methodology for geometrically characterizing the parabolic trough collectors (PTCs) shapes at the Porto Primavera Thermosolar Power Plant (UTPP), located in Brazil, using 3D scanning. The theoretical parabolic profile of the PTCs was compared to the profile obtained from the scanning point cloud, where the deviations identified were presented using a color scale on a 3D map of the solar field. In addition, two point clouds obtained 18 months apart were superimposed to identify changes in the PTCs. The results showed that the northern ends of some PTCs underwent geometric changes, which were attributed to the prevailing winds in the deformed region. In addition, an analysis of the image of the receiving tube on the mirrors was carried, where long-distance photos were taken from in front of the PTCs using a drone to compare the reflection pattern of the receiver tube and identify changes after 18 months of operation that could reduce the ability of the PTCs to direct the sun's rays onto the receiver tubes. The results showed that there were no significant changes in the reflection pattern. Both the 3D scanning and receiver tube image analysis are valuable for geometric characterization and monitoring of large solar fields.

Keywords: Parabolic Trough Concentrator, Flexible Film Mirrors, Geometric Characterization, 3D Scanning, Receiver Tube Image Analysis

1. Introduction

The first concentrated solar power (CSP) plant for electricity generation in Brazil was commissioned on 2022: the Porto Primavera Thermosolar Power Plant (UTPP), located in São Paulo state, Brazil. With a nominal power of 500 kWe, this pilot plant is the only one of its type in the country and its operation represents several new technical challenges, among the most relevant is the solar field efficiency, which uses flexible film mirrors parabolic trough collectors.

The tecnology of flexible film mirrors offer several advantages for commercial parabolic trough concentrators (PTCs) over glass mirrors, their traditional competitors. These advantages include cost-effectiveness, reduced weight, and enhanced durability. Unlike glass mirrors, flexible film mirrors can withstand accidental impacts during manufacturing, transportation, installation, and routine PTC maintenance. Its technology involves a reflective silver layer protected by multiple polymeric film layers, which guard against oxidation and UV degradation. An adhesive on the back of the flexible film allows easy application to smooth, non-porous surfaces, such as thin aluminum or galvanized steel sheets [1,2]. To achieve the desired parabolic profile, essential for the operation of the PTC, it is necessary to install these flexible sheets on rigid guides that effectively transfer their shapes [2].

Despite these advantages, it’s essential to note that PTCs using flexible film technology may face challenges related to the structural stability of the metal sheets applied as the reflective film substrate. These sheets can buckle and dent, even with robust spatial truss support for the mirrors. Therefore, the parabolic profile of a PTC plays a crucial role in its optical performance. Depending on the severity of geometric deformations, the reflected solar beams may not intercept the receiver tube positioned along the focal line, reducing the optical efficiency, in other words, the mirror's ability to accurately direct the sun rays. This is the most relevant parameter since the PTCs are already installed. However, optical efficiency is not determined only by geometric precision and other factors can impact it, among others, reflected light scattering, refraction, and reflection in translucent layers of the mirrors and receiver tubes glass capsules [3–6].

The literature provides several techniques for geometric characterization of PTCs, and can be seen in references [3,7–10]. They share a common feature: the need for customized equipment and complex analysis methods, often relying on specific software and algorithms. However, the 3D laser scanning techniques has gained prominence due to advancements in terrestrial laser scanning (TLS) equipment, making it more precise and accessible. The fundamental idea behind 3D laser scanning is to create an 3D model of the PTC in field. This model can then be compared to the ideal parabolic profile (theoretical model). In compation with similar techniques like photogrammetry, 3D laser scanning offers a significant advantage: it requires less time for data collection. This agility is crucial when it is applied to many PTCs, such as those found in solar fields of power plants [11,12].

Another technique that does not require complex methods or special customized equipment is called Distant Observer Method - DOM. This technique verifies the alignment of mirrors based on the observation of the reflection of the receiver tube, seen by an observer aligned with the parabola optical axis. As the observer distances themselves from the parabola, the image of the receiver tube enlarges until it entirely fills the concentrator's opening and the observer can determine if any mirrors fail to reflect the receiver tube's image, in other words, without the dark reflection of the tube, which signals a misalignment. If a digital camera is employed in place of the observer, the captured image can be analyzed to quantitatively assess the interception factor of solar irradiation on the receiver tube [3]. Diver and Moss [10] applied the DOM technique in a complementary way to verify the alignment of the mirrors in a parabolic trough after being aligned using the TOP (Theoretical Overlay Photographic) technique.

This paper presents the methodology used for the geometric characterization of PTCs that use flexible polymeric film mirrors by 3D laser scanning technique, where the parabolic profile obtained was compared to the theoretical profile of the PTC. In addition, two point clouds of the solar field obtained at different times were superimposed to identify changes in the PTCs after 18 months of operation. The results obtained in these two periods were also compared using the receiving tubes image analyses as a complementary technique, where the original DOM method must be adapted by capturing images from a great distance with a drone equipped with a camera.

2. Methodology

2.1 Solar field 3D laser scanning

The solar field of UTPP was scanned at two different time points. The initial survey was performad in August 2022, utilizing a Leica RTC360 TLS model. Subsequently, in February 2024, a second scan was carried out using a Faro Focus Premium TLS model. Both models achieve a resolution of 2 million points per second and maintain a reading error of less than 3 mm (estimated for the scanning distance used). Notably, the latter model incorporates a more advanced LIDAR sensor. This upgraded sensor enhances scan quality and allows for customized configuration of reflectance parameters, effectively reducing noise caused by reflective mirro surfaces during scanning. The following steps were applied to both 3D scans:

1. Solar field heating to the average operating temperature (around 300°C) to dilate the receiver tubes.
2. PTCs positioning 30° above the horizon line, allowing scanning the entire front curvature of the mirrors.
3. Scanning the entire solar field with TLS, data recording, and point cloud processing.

The *Figure 1* shows the point cloud mapped by TLS Faro Focus Premium model and obtained in the Faro Scene software. It is possible to observe that solar field features wind fences on the East and West sides, while the South side benefits from a steeper slope acting as a natural barrier. However, the North side relies solely on protection from adjacent buildings within the solar thermal plant, making it the most exposed side to prevailing winds.

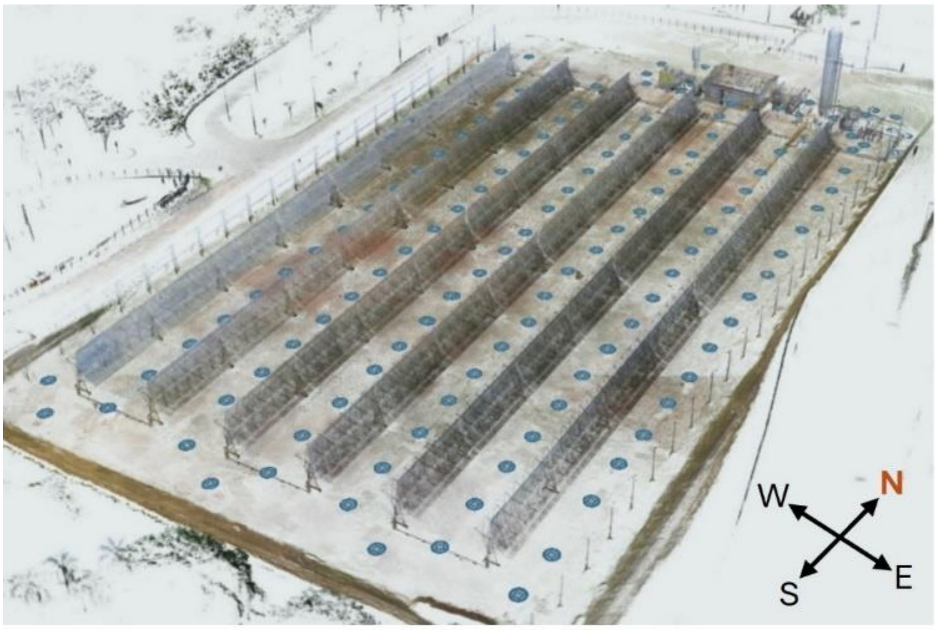

Figure 1. *Point cloud of the UTPP solar field obtained by TLS*

2.2 Geometric comparation of PTCs to the theoretical parabolic profile

The parabolic profile of the PTC has a focal length of 1995 mm and an aperture of 7000 mm, and can be seen in *Figure 2-a*. These data were used to create a 3D reference model of the theoretical parabolic profile. The analysis of the geometric deviations in the PTCs concerning the theoretical parabolic profile was performed by superimposing the theoretical profile of the parabola with the PTCs point cloud in the CloudCompare software, using the C2M (Cloud to Mesh) method presented in [13]. It is applied to detect differences between a point cloud and a mesh, in this case, the 3D theoretical model shown in *Figure 2-b*.

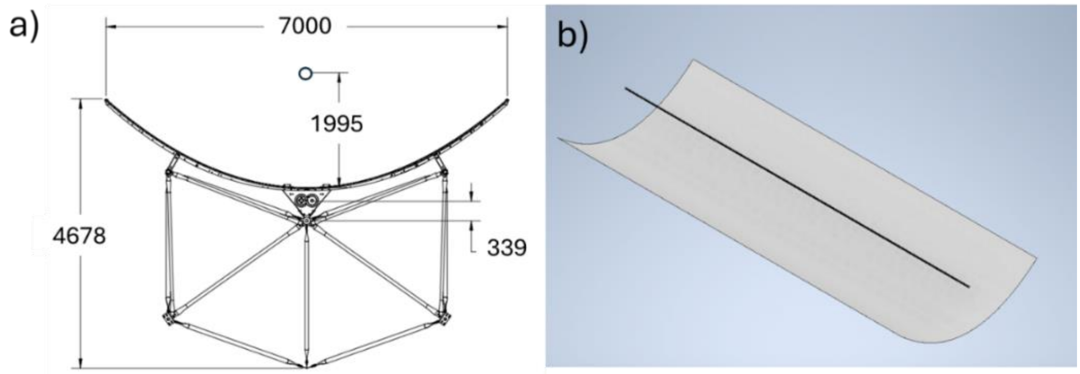

Figure 2. *a) Theoretical geometry of PTC; b) 3D model of the theoretical parabolic profile*

2.3 Geometric changes analyses in PTCs after a period

To analyze geometric changes in the PTCs after 18 months of operation, two 3D scans carried out in August 2022 and February 2024 were compared by superimposing the point clouds. During both scans, the solar field was heated, and the PTCs were positioned according to the steps described in section 2.1, ensuring similar conditions in both point clouds. The deviation analysis utilized the Iterative Closest Point (ICP) method, initially proposed by Besl and McKay [14]. This method involves registering 3D models by identifying corresponding points in different point clouds. Over time, the ICP method has been adapted for point cloud registration with mesh surfaces. In this study the ICP algorithm implemented in CloudCompare software was used.

2.4 Receiver tube image analysis

The receiver tubes image analysis was performed by DOM technique as a complement to 3D scanning. Nonetheless, due to the interference in surroundings it was not possible taking images with a camera with optical zoom and a tripod, so the original technique was adapted using a drone equipped with an UHD camera, which took images from the PTCs around 500m away.

The distant images were taken during both 3D scanning prospects by the steps presented below:

1. The PTCs were heated to obtain the operating temperature and expansion of the receiver tubes and positioned at the same angle used in the 3D scanning.
2. The drone was moved away from the PTCs until the images from the receiving tubes on the mirrors occupied their entire area. This occurred at about 500m.
3. The drone was slowly moved in a west-east direction and several photographs were taken when it was in front of the parabola of each PTC. This is noticed when the mirrors acquire the dark color of the receiver tubes.
4. The distant images of the PTCs were taken at two different times, 18 months apart. These images were compared with the aim of identifying relevant changes in the reflection pattern of the receiver tubes in the mirrors.

3. Results and discussions

3.1 Geometric deviations in PTCs compared to the theoretical parabolic profile

The CloudCompare software and the C2M analysis method were applied to identifying geometric deviations in the PTCs in comparison to the theoretical parabolic profile, based on the last points cloud obtained in February 2024. This analysis resulted in a 3D map of the UTPP solar field. The imperfections intensity is visually represented using a color scale as shown in *Figure 3*. Additionally, a distribution curve of the deviations appears just above the scale. The positive deviations indicate movement toward the East, while negative deviations indicate movement toward the West. In general, the deviations observed are distributed across the solar field.

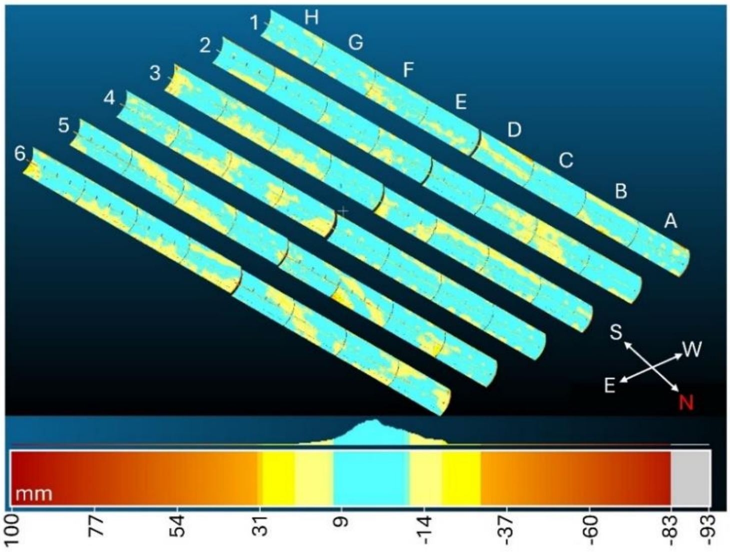

Figure 3. *Geometric deviations identified in the PTCs relative to the theoretical parabolic profile*

Through a visual analysis in the PTCs, it was possible to identify, due to irregular reflection, regions with systematic bulging of the mirrors in their lower and upper portions, as highlighted in *Figure 4*. This pattern is similar to the identified in *Figure 3* in PTCs 1-BH, 2-H, 3-BCFG, 4-BCG, 5-F, 6-EFG. The probable cause is the metal sheets buckling (loss of stability) that support the flexible films, resulting in their bending.

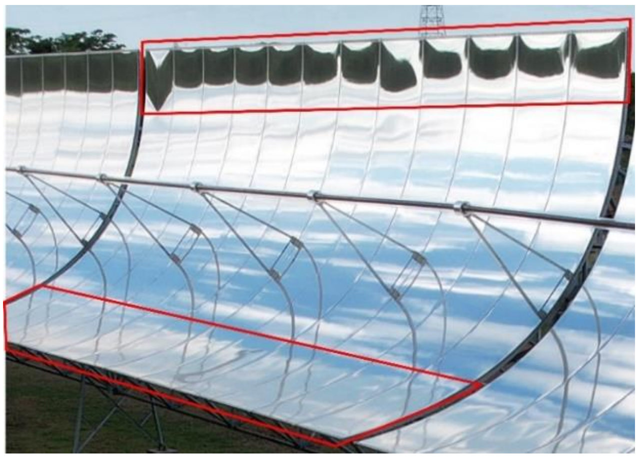

Figure 4. *Bulging regions of the flexible film mirrors in PTC 1-B*

3.2 Geometric changes in PTCs after a period of operation

A 3D map with a color scale was obtained by the cloud points superimposed to indicate the deviations after 18 months of PTCs operation. It was created using the ICP method in the CloudCompare software and the results are shown in *Figure 5*. For the applied method, the intensity of imperfections is considered in absolute value. Above the color scale, a distribution curve of the deviations can also be seen.

The analysis of *Figure 5* suggests that certain PTCs experienced deformations during the evaluation period, particularly in the North end modules. The probable cause is the frequent exposure of the parabolic surfaces to winds from the Northeast direction when they are not operational, with their focal axis positioned 30° below the horizon line. Notably, the Northern side of the solar field lacks significant wind barriers, except for the plant building in front of PTCs 3 to 5. Consequently, the North end of PTC 6 is particularly vulnerable to Northeast winds.

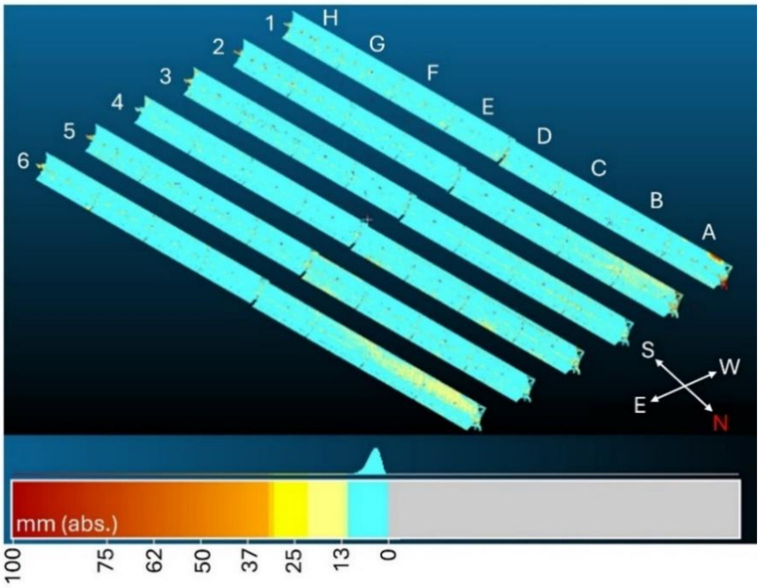

Figure 5. *Geometric deviations identified in the PTCs relative to the first scan performed*

The photos obtained by the adapted DOM technique and taken during both 3D scanning prospects (August 2022 and February 2024) were compared with each other. The images of the two PTCs with the most apparent deviations in the point cloud superimposed analysis are shown in *Figure 6*. By visually comparing the two reflection patterns in PTC 2, it was not possible to identify significant changes, however, the module H in PTC 6 showed a noticeable modification in the reflection pattern, where the image obtained in 2024 shows less mirrors region in dark color when compared with 2022. This difference is not related to changes in the parabolic profile, as shown in *Figure 5*, but it was attributed to a receiver tube bending caused by thermal gradients induced by the presence of nitrogen during operation, which resulted in a permanent deformation in the receiver tubes of this module and its incorrect positioning in relation to the focal line of the parabolic trough. This occurrence was reported by the plant operators a few months after the first drone images were taken.

Figure 6. *Images of PTC 2 and 6 in two different times: August 2022 and February 2024*

For modules A and B whose most changes above 10 mm can be seen in PTC 6 in *Figure 5* (yellow regions), no significant modifications were identified in the reflection patterns in *Figure 6*. This indicates that the geometric changes were insufficient to deflect solar beams from intercepting the receiver tubes. All other PTCs in the solar field did not show significant changes in reflection patterns, consistent with the results shown in *Figure 5*. However, all PTCs have systematic deformations at the upper and lower edges of the parabolic profile, as can also be seen in the *Figure 6,* where the deformation of high intensity (larger than 10 mm) were also identified in comparison with the theoretical profile, for example, module B in PTC 1, as shown in *Figure 3*.

4. Conclusions

The comparison of the last 3D scanning (February 2024) with the theoretical profile of the collector showed scattered deviations, however, with more occurrence in the lower portion of the mirrors, possibly due to the loss of stability of flexible film mirrors (buckling). On the other hand, the comparison between 3D scanning at two different times after 18 months of operation (August 2022 to February 2024) showed geometric changes at the northern ends of some collectors. Strong winds were reported between the prospect period, with gusts above 30 m/s, which may justify the observed deformation pattern.

The distant observer method did not identify relevant changes in the images of the receiver tubes when comparing the two surveys. This result is consistent with the 3D scanning point cloud comparison, which showed small deviations. However, all collectors showed a systemic loss of reflective capacity in the lower portion of the mirrors, where a loss of stability in the reflective film was observed.

Both methods used in this geometric characterization are highly relevant for monitoring parabolic trough plants with large solar fields since they use equipment and software available on the market and have a non-complex analysis method. This paper aims to present the detailed methodology employed, its results, and its analysis.

Author contributions

Nelson Ponce Junior: Writing – original draft, Investigation, Methodology. **Jonas R. Gazoli:** Writing – review & editing, Conceptualization. **Roberto M. G. Velasquez:** Validation, Supervision**. Osvaldo J. de Souza:** Project administration. **Alan R. Nunes:** Formal analysis, Data curation.

Competing interests

The authors declare that they have no competing interests.

Funding

This research was funded by the project entitled “Otimização da operação de usina termosolar submetida às condições do clima brasileiro com estudos sobre armazenamento térmico do tipo thermocline” within the scope of R&D ANEEL program (project PD-00061-0063/2022) and financed by CESP – Cia Energética de São Paulo.

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