Estimation of Dust Accumulation in Parabolic Trough Concentrators Using Aerial Laser Reflection

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Abstract

Solar thermal energy has significant potential to supply large part of global energy demands. However, improving the efficiency, performance, and operation and maintenance (O&M) of these systems is critical, as they are highly susceptible to performance lost due to dust deposition, particularly in parabolic trough solar plants. This study investigates dust accumulation on the transparent covers of absorber tubes in parabolic trough collectors over a 60-day experimental campaign. An optical methodology is developed to assess dust deposition by measuring the transmittance of the receiver under three different dirt conditions using a point laser. The resulting transmittance values were >93%, 86% ± 7%, and <79%, respectively. In addition, a linear laser reflectance measurement was captured using a camera mounted on an aerial vehicle to correlate the luminous intensity with the amount of dust deposited. This approach enables the establishment of a transmittance loss criterion for dust accumulation, providing insights for improving O&M practices in solar thermal systems.

Keywords: Dust deposition, Parabolic trough, concentrating solar energy, drones.

1. Introduction

Dust collection in concentrated solar power (CSP) plants presents significant challenges, primarily due to its impact on system efficiency and lifetime. Dust buildup on the mirrors and solar receivers, crucial components for concentrating sunlight, can significantly reduce the amount of solar energy captured, leading to a decrease in the plant's originally estimated total energy output. This reduction in efficiency necessitates frequent, resource-intensive cleaning, especially in arid regions where water scarcity further complicates maintenance efforts. Furthermore, abrasive dust particles can cause surface degradation over time, increasing maintenance costs and potentially shortening the lifespan of optical components. Therefore, the need for effective dust mitigation strategies is crucial to maintaining the efficiency and cost-effectiveness of solar technology (Maghami et al., 2016).

Studies have increasingly focused on quantifying the impact of dust accumulation on optical efficiency, revealing that dirt accumulation can significantly degrade the performance of solar collectors (Hachicha et al., 2019). Niknia et al. (2012) highlighted that dust accumulation on parabolic trough concentrators adversely affects both reflectance and transmittance, which are critical for the efficiency of solar receivers. Zhao et al., (2020) examines the impact of dust accumulation on a linear Fresnel reflector, finding that dust density increases while relative reflectivity decreases over time, with a 9.4% drop in reflectivity for every 1 g/m² increase in dust.

Several factors contribute to the loss of efficiency in solar collectors due to dust accumulation, including the geographical location of the solar plant, the orientation and position of the collectors, nearby facilities like highways or factories that might contribute to dust levels, the frequency of rainfall in the area, and the prevailing wind conditions (Zereg et al., 2022). Each of these factors plays a role in determining how quickly dust builds up on the collectors and how severely it impacts performance (Usamentiaga et al., 2020).

To overcome these challenges, various cleaning methods and equipment have been developed to maintain the

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cleanliness of CSP systems (Bouaddi, et al. 2018). For example, Fernández et al., (2014) optimizes cleaning methods for solar reflectors in CSP plants under semi-desert conditions, finding that demineralized water with a brush is most effective, achieving up to 98.8% efficiency (defined as the difference between reflectance measurements taken before and after cleaning the samples), while steam cleaning is less effective, and adding detergent offers no significant benefit. These findings underscore the importance of regular monitoring and cleaning to preserve the optimal performance of CSP plants.

In response to these challenges, this work uses laser technology mounted on a Remote Piloted Aircraft (RPA) system to detect dust deposition levels on parabolic trough (PT) solar receivers. First, by study how increasing levels of dust deposited on a PT receiver affect light transmittance over time. Second, by impinging a laser beam onto the solar concentrator in an experimental campaign that provides valuable information on the relationship between laser reflected light intensity and energy loss caused by dust deposition. These innovative approaches offer the potential to develop more accurate and effective dust mitigation strategies, ultimately improving the performance and longevity of CSP plants.

2. Materials and Methods

This project introduces an optical system which consists of a laser mounted on a Remotely Piloted Aircraft (RPA) to evaluate dust deposition and surface conditions of parabolic trough receivers in solar power plants. The innovative approach focuses on characterizing the collectors based on varying levels of dirt accumulation, with the goal of establishing a link between dust buildup and consequent energy losses. By quantifying the transmittance losses on the receiver tube at different levels of dirt accumulation, the project provides a detailed understanding of how dust impacts the efficiency of solar energy collection.

The system operates by directing a linear laser beam onto the receiver tube during night-time conditions, capitalizing on the hypothesis that dust particles scatter light. This scattering effect is expected to influence the reflectance measured by the system, allowing for precise assessments of dust-related degradation in optical performance. The night-time testing is particularly significant as it minimizes the interference of ambient light, thereby enhancing the accuracy of the laser-based measurements. The project’s findings could lead to more efficient maintenance schedules and improved cleaning strategies, ultimately contributing to the optimized performance of solar power plants by reducing energy losses caused by dust accumulation.

2.1 Transmittance validation phase

The methodology begins with an experimental validation phase, utilizing a Z-Laser ZM model laser with an operating voltage of 5–30 V, operating current of 300–400 mA, and a wavelength of 532 nm. The laser was directed at the glass cover of a parabolic trough (PT) collector's solar receiver. Transmittance of the laser light through the glass cover, under varying levels of soiling, was measured using a calibrated radiometer. As a reference, the radiative flux incident from the laser was also measured outside the glass cover to establish a baseline value for comparison.

Figure 1 depicts the technical arrangement for the experimental setup of the validation phase measuring the transmittance of the glass cover of the PT receiver over time. Additionally, the optical system is able to move along the receiver tube, allowing the identification and analysis of average dirt levels. This approach provides a detailed assessment of how surface contamination affects solar energy collection efficiency.

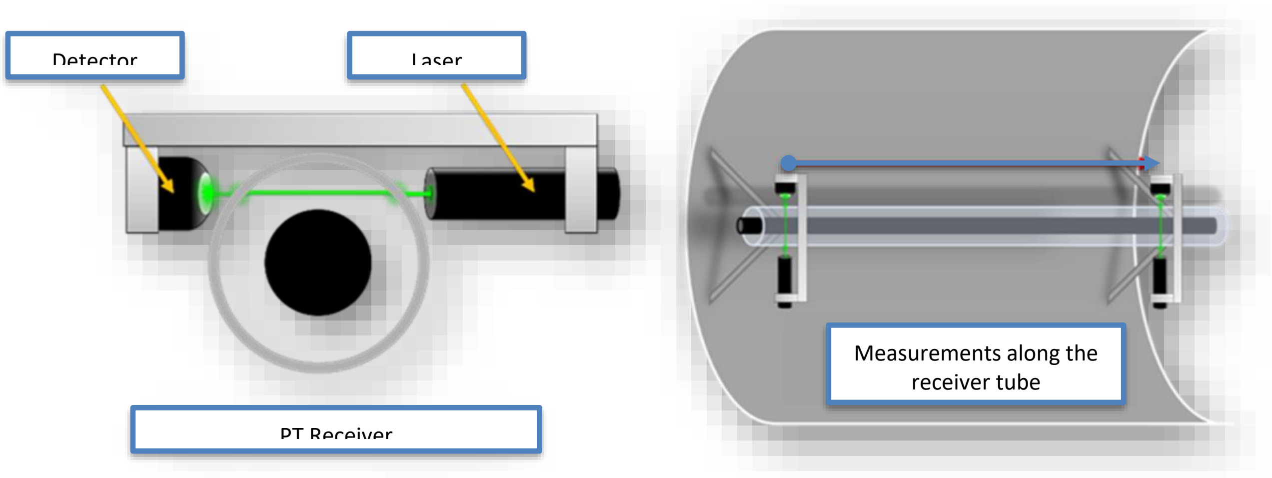


Figure 1: Scheme of the transmittance test of the parabolic trough receiver.

An experimental campaign was conducted in Aguascalientes, Mexico (latitude: 21.88234, longitude: -102.28259) over a 60-day period during April and May 2023, in which dust was allowed to settle on the solar receiver in order to accurately assess the different levels of dirt that were accumulating over time. According to Bouaddi, et al. (2018), the transmittance decreases considerably after the first month of exposure to the outdoors. Therefore, it was decided to divide the accumulation of dirt into three levels. Level L0 represents a recently cleaned receiver. Level L1 represents a receiver that has been outdoors for 15 days. Finally, after two months, an extreme dirt level of L2 is considered (See Table 1).

Table 1: Levels of dust depositions according to the days without cleaning.

Dust deposition level	**L0**	**L1**	**L2**
Days without cleaning	0	15	60

Figure 2 provides a visual representation of dust accumulation on the solar receiver over the course of the 60-day experimental campaign. The image clearly illustrates the progressive buildup of dust over time, highlighting the increasing opacity of the solar receiver surface as the days pass. Each segment of the receiver displays varying degrees of dust deposition, making differences in cleanliness readily apparent. These variations in dust levels are critical as they directly impact the receiver's ability to effectively concentrate and convert solar energy.

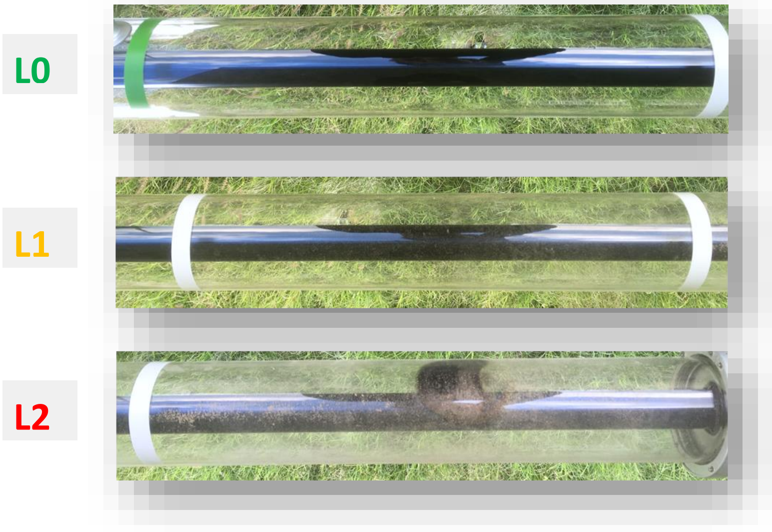


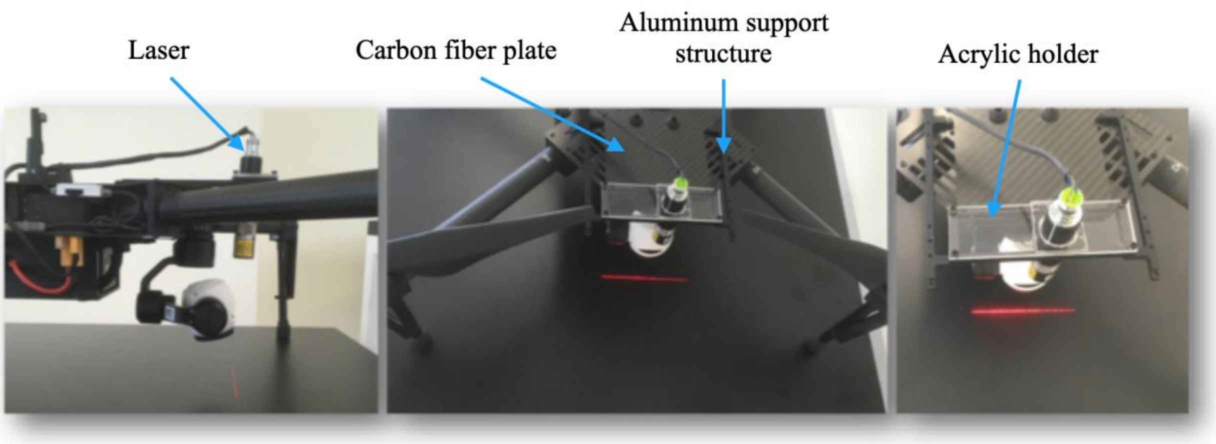
Figure 2: Levels of dust accumulation along the experimental campaign.

Figure 3 illustrates the transmittance measurement methodology using a laser system. The images showcase three different scenarios corresponding to increasing levels of dust deposition on the glass cover, labeled as L0 (clean), L1 (moderate dust), and L2 (heavily soiled). As observed, the laser reflectance becomes increasingly pronounced with higher dust accumulation, highlighting a reduction in the laser's transmittance through the glass. This effect directly correlates to a decrease in the irradiance reaching the radiometer, underscoring the significant impact of soiling on optical efficiency. It is important to note that these tests were conducted at night to eliminate unwanted reflections from the sun, ensuring that the laser served as the sole light source detected by the radiometer.

Figure 3. Experimental setup for measuring transmittance of the parabolic trough receiver over the experimental campaign.

2.2 RPA laser reflectance system

The remotely piloted aircraft (RPA) system comprises a DJI Matrice 100 drone equipped with a Zenmuse Z3 camera, both of which are operated via a remote controller for precise control and functionality. Several support designs were created to adapt the laser to the RPA, addressing the critical issue of weight restrictions. To minimize any impact on battery performance, a design was developed that weighs just 48 grams, ensuring that the RPA´s efficiency remains unaffected. Figure 4 depicts the support structure designed to securely mount



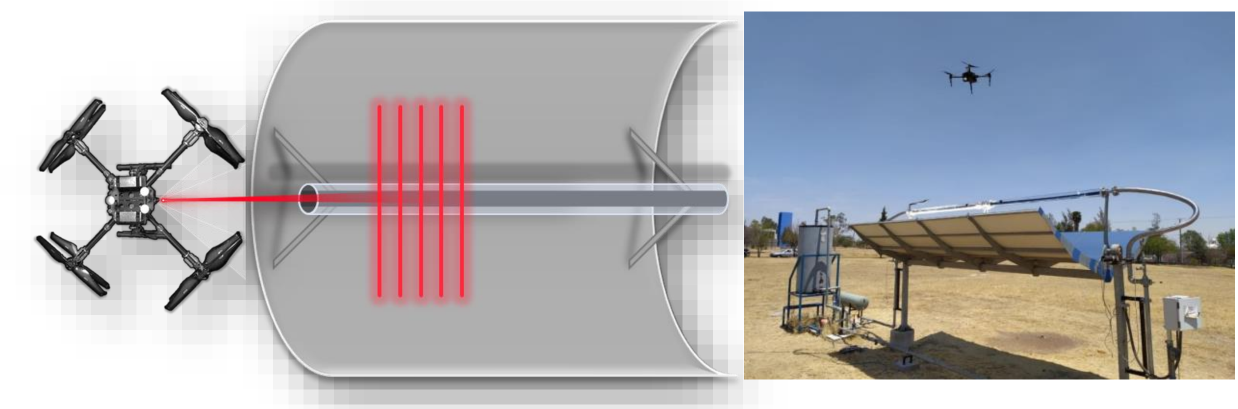
the laser onto the drone, ensuring it does not interfere with the camera movement or drone’s stability.

Figure 4. Support structure designed to adapt the laser to the RPA system.

The drone's Zenmuse Z3 camera captures images of the solar tube receivers at night, synchronized with the time frames in which transmittance measurements are conducted throughout the experimental campaign. This synchronization ensures that the luminance data captured by the drone's camera can be directly correlated with the transmittance losses measured by the radiometer, allowing for a precise assessment of the optical performance degradation caused by dust accumulation.

A proprietary software application was developed using Python to process the images captured by the drone. This software analyzes luminance levels in the images to identify variations caused by dust accumulation on the solar tube receivers. By employing advanced image processing algorithms, the system evaluates the luminance distribution and correlates it with the degree of soiling and transmittance losses. Based on this analysis, the software generates a qualitative report detailing the dirt status of the receivers, enabling quick assessment of their cleanliness.

Figure 5 illustrates the methodology for sweeping the receiver tube of the parabolic trough (PT) concentrator using the laser. The setup involves the drone systematically directing the laser beam along the length of the receiver tube while maintaining a steady position to ensure consistent measurements. This process allows for a detailed evaluation of the reflectance and transmittance characteristics of the receiver tube, providing



valuable insights into the impact of varying levels of soiling on the optical efficiency of the system.

Figure 5. Graphical representation of the RPA system and the laser system flying over the PT concentrator for the experimental campaign (left). Actual RPA system and PT concentrator.

In addition, two types of flights were conducted to assess the system's performance. The first, a moderate flight, involved a test flight with various maneuvers within the designated flight test area of approximately 3,500 m^2, without any predetermined sequence. The second type was a static flight, in which the drone remained stationary at a height of 10 meters. This static flight allowed for a focused evaluation of the system’s stability and precision in capturing data without the influence of movement, providing a controlled environment to validate the accuracy of the optical measurements. These two flight scenarios were essential for determining how well the system could perform under both dynamic and static conditions, offering insights into the operational flexibility and reliability of the technology in real-world applications. Understanding the flight times of an RPA is essential when structural modifications are made, as these can affect performance and battery life. This knowledge ensures safe operation and sufficient time to cover large areas, like CSP plants, while maintaining reliability. It also supports mission planning, optimizing energy use, and ensuring effective integration into maintenance tasks (See Table 2).

Table 2: RPA flight estimated times from 90% to 30% battery level.

Flight type	**Moderate flight**		**Static flight**	
	W/o Laser	W/ laser	W/o Laser	W/ laser
Duration (sec)	593	583	602	555

3. Results and discussion

This section presents the results obtained throughout the 60-day experimental campaign. Initially, the results of the average transmittance measured on the receiver tube are presented and then the analysis of the images obtained from the RPA campaign is performed.

3.1 Transmittance validation results

From the analysis campaign of the transmittance obtained from the incident laser on the glass cover of the receiver, operating intervals can be determined (see Table 3). For example, it is determined that the glass cover of the solar receiver presents levels above 93% when compared to the reference value of transmittance (when this is measured outside the glass cover). From 15 days to two months the transmittance decreases to 86 $\pm$7% on average, and once it approaches two months of outdoor exposure, it decreases to an average of 79%.

Tab. 4: Estimates of mean transmittance by the level of dust deposition on the collector tube.

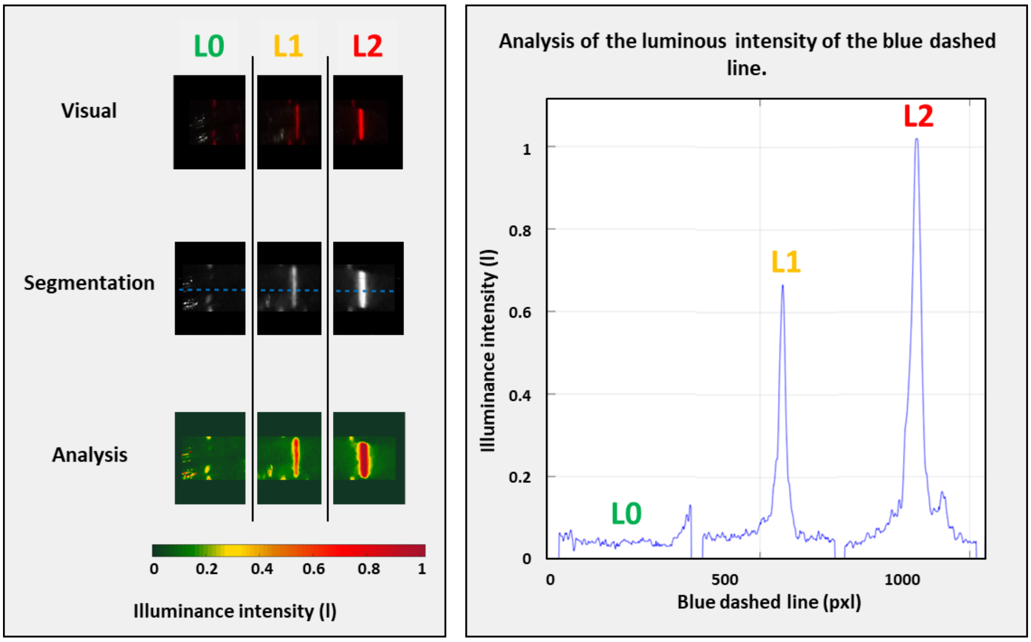
Dust deposition level	L0	L1	L2
Transmittance relative to reference (%)	> 93	86 $\pm$7	< 79

It is worth noting that the experimental campaign was carried out in months with little rainfall. However, the strong wind currents and morning dew cause dust to settle on the receiver. Although these data are a particular case for the location, they serve as evidence that long periods of time produce substantial dust accumulations that affect the performance of solar technology.

3.2 RPA reflectance results

The reflectance profile of the solar receivers was derived from images captured during the drone's nighttime overflight of the parabolic trough collectors. Figure 4 highlights the graphical interface of the custom Python-based software developed for analyzing laser incidence images under varying dust deposition levels on the receiver tube. In Figure 4 (left), a blue dashed line indicates the segmentation line where light intensity is measured in arbitrary units (AU), normalized to 0-1 from U8-bit data (256 levels) for consistency. The analysis results are represented with a color-coded scale, where green, yellow, and red correspond to the dust deposition levels L0 (clean), L1 (moderately soiled), and L2 (heavily soiled), respectively. These visualizations provide a clear qualitative and quantitative representation of soiling levels along the receiver tube. Figure 4 (right) displays a graph plotting luminous intensity along the blue dashed line as a function of pixel position. The peaks in intensity correspond to the laser's interaction with the dust deposition levels on the receiver. The L0 profile exhibits minimal reduction in intensity, indicating a clean surface, whereas L1 and L2 profiles show increasingly diminished intensity due to higher dust accumulation. This integrated visualization enables precise assessment of the correlation between dust levels and the optical performance of solar receivers, facilitating a better understanding of the impact of soiling on energy efficiency and aiding in optimizing maintenance strategies.

Fig. 4.



Reflectance analysis of the aerial optical system on the solar receiver of the parabolic trough concentrator (normalized from U8-bit). Details of the methodology are shown in the left. Intensity plot is shown in the right.

Fig. 4 illustrates the luminous intensity (I) along the blue dashed line, correlating with different levels of dust accumulation (L0, L1, L2) on the receiver surface. The intensity profile shows a clear progression from L0 to L2, where L0 represents the cleanest state with the lowest intensity peaks, indicating minimal dust accumulation. As the dust levels increase (L1 and L2), the peaks in the intensity graph become more pronounced, with L2 showing the highest intensity peak, reflecting the greatest amount of dust accumulation. This suggests that as more dust accumulates, the reflectivity of the laser is increased by the scattering of the dust particles. Although the L2 level shows saturation, this case represents an extreme scenario where dust accumulation is already very significant. However, one of the strengths of this system is its adaptability; the operational conditions can be adjusted to meet the specific needs and circumstances of the user. This flexibility is a key advantage, as it allows the system to be fine-tuned for different environmental conditions and levels of dust accumulation. For example, in situations where dust levels are lower or where precision is more critical, the system's sensitivity can be increased to detect even minimal changes in dust deposition. Conversely, in harsher environments where dust accumulation is more pronounced, the system can be adjusted to prevent saturation and ensure accurate measurements. This adaptability also means that the system can be integrated into a variety of solar energy facilities, regardless of their geographical location or the specific environmental challenges. Whether in arid desert regions with frequent dust storms or in more temperate climates with occasional dust accumulation, the system can be calibrated to provide reliable and actionable data. This ensures that solar power plants can maintain optimal efficiency and reduce energy losses due to dust, ultimately leading to better performance and lower operational costs.

4. Conclusions

As shown by the results of the experimental campaign, it was found that there is a direct correlation between the dust accumulated in the parabolic trough receivers and the transmittance/reflectance generated by the incidence of a laser on it. It is possible to determine the operating conditions of the system by measuring the transmittance by shining a laser on the glass cover of the receiver and measuring it by a radiometer; subsequently, it is possible to identify that the greater the accumulation of dust, the greater the reflectance of the incidence of a laser captured by a camera mounted on an aerial vehicle.

Significant advances have been made in the research and development of an RPA that allows for the rapid and effective estimation of dust accumulation in solar thermal plants. It was determined that adding the optical elements necessary to carry out this experiment does not represent a significant cost for the time and quality of flight of an RPA with the characteristics presented here. Finally, the main hypothesis regarding the visualization of dust on transparent materials using a laser has proven to be promising, particularly in low-light conditions, where very evident variations in the intensity of dust accumulation on the receivers were observed. In addition, this developed methodology has the advantage of being fast, economical, programmable and, when operated at night, it does not interfere with the operating conditions of the solar plant.

Among the results obtained are the following:

- A dust accumulation analysis methodology was successfully developed using an RPA.
- The necessary hardware was developed to implement the methodology in the RPA without compromising airworthiness.
- Three types of dirt were characterized, ranging from the most typical cases of dirt to extreme cases.
- The necessary software was developed to perform real-time signal processing, which is configurable according to the needs and specifications of potential users.

Although the software currently provides a qualitative assessment in its initial stage, with the labeling generated by the developed methodology primarily identifying areas of the concentrators that require cleaning, this information meets the immediate operational needs of solar plants. However, we acknowledge the need to advance the methodology to deliver more quantitative insights. Future research will aim to quantify the thermal energy losses directly attributable to varying levels of dust accumulation on solar collectors and establish a robust correlation with the optical losses identified in this study. This next step will enhance the utility of the methodology by providing actionable data on the impact of soiling on overall system performance, thereby enabling more precise maintenance strategies and performance optimization for solar plants. By integrating thermal performance metrics with the optical data, the goal is to create a comprehensive model that predicts how dust affects overall system efficiency in concentrated solar power (CSP) plants. This model will consider not only the immediate impact of reduced reflectance and transmittance but also the long-term effects of dust on thermal energy conversion efficiency. Additionally, future experiments may involve real-time monitoring of both optical and thermal losses under different environmental conditions, allowing for the development of predictive maintenance strategies and optimized cleaning schedules. This work will contribute to enhancing the reliability and cost-effectiveness of CSP technology by minimizing energy losses due to environmental factors.

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