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Camera Based Reflector Degradation Detection

Johannes Wette¹  <https://orcid.org/0000-0003-1389-5176>, Florian Sutter²  <https://orcid.org/0000-0002-2981-5807>, Florian Wiesinger  <https://orcid.org/0000-0002-7062-0497>, Manuel Pérez-García³  <https://orcid.org/0000-0002-6269-7638>, Ivan López-Baena³ and Aránzazu Fernández-García¹  <https://orcid.org/0000-0001-6044-4306>

¹ CIEMAT, Plataforma Solar de Almería, Spain

² DLR, Institute of Solar Research, Spain

³ University of Almería, CIESOL, Spain

*Correspondence: Johannes Wette, johannes.wette@psa.es

Abstract. Reflectors used in the solar fields of concentrated solar thermal technologies must maintain excellent optical properties over the lifetime of the commercial projects. However, the reflector materials are prone to degradation due to environmental stresses. Measurements with portable reflectometers are the state-of-the-art technique to evaluate degradation in the field, determining the most significant optical parameter, the reflectance. Some degradation mechanisms can evolve on reflectors in early stages without compromising reflectance, until they affect a large surface. This is why alternative measurement techniques are necessary. In this work, the development of an easy-to-use field measurement procedure for the degradation of solar reflectors is presented, which was investigated at the OPAC laboratory of the CIEMAT-Plataforma Solar de Almería (PSA). An automated image processing program has been developed, to determine the degraded area of reflectors based on various image sources. The capabilities to measure different scales of defect sizes on different reflector materials, with simple commercial camera equipment and a portable microscope, were analyzed, and future development steps are presented.

Keywords: Solar Reflector Degradation, Automated Analysis, Image Processing

1. Introduction

The degradation of reflectors for concentrated solar thermal (CST) technologies has the potential to drastically reduce the optical yield of these components and thus that of the entire solar fields. Various environmental factors can provoke different degradation mechanisms. Some of the main environmental parameters are temperature, humidity, UV radiation, chemical compounds, and particles in the atmosphere [1]. The degradation mechanisms vary between different reflector materials. For the most common type of reflectors, the standard silvered-glass mirrors, degradation usually affects the front surface (e.g., by mechanical defects or soiling) or the reflective silver layer (mainly by corrosion of the pure metallic silver). Degradation starts to affect the optical yield of the system when the reflectance of the material decreases. This is why the most common measurement applied to solar reflectors is the determination of the reflectance. The significant parameter here is the solar near-specular reflectance, and improvements in measurement techniques have been achieved in recent years [2], [3], along with the ongoing development of guidelines and standards for its determination [4], [5]. Nowadays, the main technique for the measurement of reflectance in the field is the use of portable reflectometers [6]. One of the disadvantages of these reflectometers is the small area covered

by single measurements, which, for the commercial devices, is in the order of 1 cm^2 . To overcome this, a series of measurements is performed to cover larger areas and give representative values for entire facets, collectors or solar fields. The necessary number of measurements depends on factors such as the size, homogeneity of reflectance, the soiling level and the required precision of the results [7]. In recent years, camera-based measurements have been investigated to cover larger areas and determine factors such as reflectance, degradation, soiling and surface slope errors [8], [9]. Usually, for the reflectance, higher uncertainties of the measurements have to be accepted as a trade-off for covering large surface areas.

Certain types of degradation, such as the corrosion of the silver layer, do not develop linearly over time, starting with the creation of microscopic corrosion spots [10], which, depending on the environmental conditions, may continue to grow to cover extended areas [11]. Due to their initial small size and limited covered area and depending on their density, this evolution may take place without considerably altering the total reflectance of the whole facet, not exceeding the instrument resolution of many commercial reflectometers ($<0.1 \%$). Only when an important area fraction is affected, a considerable drop in reflectance is expected. Furthermore, the starting point for corrosion oftentimes lies at the edge of the reflector (insufficient edge sealing) and hence cannot be characterized by reflectometer measurements due to their positioning limitations. Due to these factors, simple measurement by reflectometers is not sufficient to analyse the degradation of the reflectors in these cases. Corroded areas of reflectors often possess a specular reflection close to zero. This is why the simple division between degraded and intact areas can be sufficient in these cases to evaluate the actual state of the reflectors [12]. This can serve as a way to determine the reflectance reduction (corresponding to the degraded area fraction) in the case of larger affected areas, and in the early phases, to be able to make predictions about future behaviour (by growth and creation of corrosion spots). This can be important for commercial projects to gather information on the actual state of the solar field, to adapt O&M strategies, and for yield estimation, as well as for research purposes to investigate and predict the behaviour of new materials.

Several research groups have worked on the development of procedures to perform this kind of analysis in the laboratory on small scale samples (usually in the order of $10 \times 10 \text{ cm}^2$). Progress has been made in the standardization of these measurements, and good precision and comparability have been reached [13], also on interlaboratory level which increases the feasible application of the image based corrosion analysis method. In this work, the development of a procedure is presented to determine the degraded area of solar reflectors directly in the solar field. It is based on the automatic analysis of images of reflector areas from square centimetres to several square metres (entire facets). Defect sizes range from microscopic (below $200 \mu\text{m}$) to large parts of the entire facets. Images are taken with a commercial digital camera and a portable microscope and then evaluated by a custom-developed automatic image-processing software.

2. Methodology

The OPAC laboratory, a joint collaboration group between the research centres CIEMAT and DLR at CIEMAT's Plataforma Solar de Almería (PSA), is dedicated to the characterization, optical measurements, aging and durability of materials and components used in CST systems. Even though other components, such as solar receivers or coatings for storage tanks, are investigated, its main focus is on solar reflector materials. The PSA is one of the biggest research facilities worldwide dedicated to the research in the area of CST. Large demonstration facilities of the main technology categories within CST are installed at the PSA, together with their solar collectors, such as parabolic trough collectors (PTC) and central receiver system (CRS) heliostats. One of the recurring tasks at OPAC is the in-situ evaluation of solar reflector surfaces directly in the PSA solar fields. These reflector surfaces range from small

mirror samples, around 10x10 cm², specifically exposed for research purposes, to larger samples, entire facets and collectors covering several square meters. Usually, an evaluation of whole collector fields, as in commercial CST plants, is not part of the tasks.

In the past, no standardized method was available to analyse the degraded area of these types of reflectors. Therefore, in this paper, a procedure is presented to determine the degraded area in a simple but reliable way, with the focus on the development of an automatic image processing routine.

The procedure is intended to be applied to all types of reflectors and size ranges of defects. Depending on the specific conditions of every case, the image acquisition will be adapted. In Figure 1, the schematic representation of the procedure is displayed. The process starts with a simple visual inspection to determine the desired captured area and the type of defects. When larger areas of interest are to be covered, a commercial digital camera is used to take images of the whole facets or samples. Depending on the required resolution, images of selected sub-areas may be taken. In the case of smaller defects, a portable microscope is used. Images from the camera and the microscope can then be evaluated with the automatic processing step.

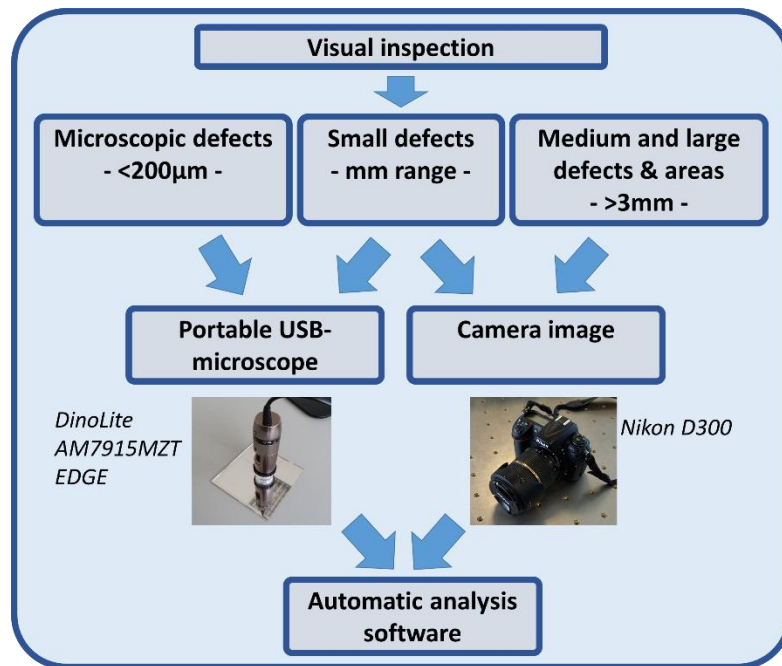


Figure 1. Schematic representation of the methodology for the degradation analysis.

The developed automatic image processing program is entirely developed in Python. The finished code is intended to be open-source and can be provided for interested users upon request. The current version of the software is considered a work-in-progress. It is a stable version successfully providing the minimum capabilities needed for the intended tasks. It is the intention of the working group to further develop the program, improving usability and functionality, as well as adding further capabilities. An overview of the capabilities and basic working principles of the program is given in the following paragraph:

- A graphical user interface (GUI) is provided for ease-of-use (see Figure 2).
- Images of various common formats (e.g. jpeg, png, tiff, etc.) can be loaded into the program for analysis.

- The area of interest is selected manually by a user-chosen number of points defining the outer edges of the zone to be analysed. Optionally, the absolute size of the selected area can be entered to determine the total degraded area.
- A filter is applied to differentiate between intact and degraded area based on a Hue-Saturation-Value (HSV) threshold. Pre-defined parameters for the threshold can be used, as they showed good detection of the areas based on standard images. Alternatively, a semi-automatic determination of the threshold parameters can be used within the program, based on the manual selection of selected sample areas.
- The analysis then provides several visualizations of the degraded and intact areas, a quantification of the respective areas (area ratios or absolute sizes), and generates a standardized summary report.

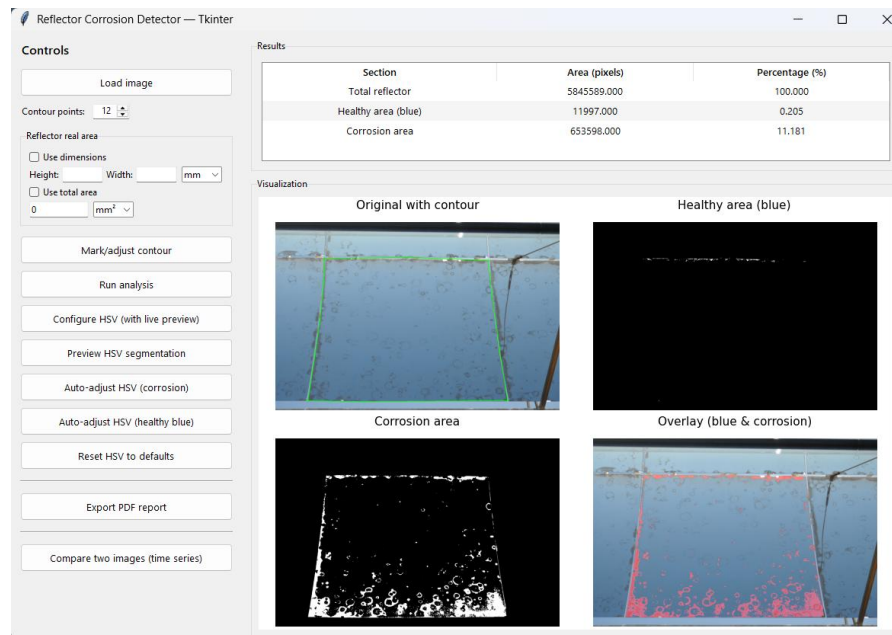


Figure 2. GUI of the developed program with exemplary analysis and visualization.

For image acquisition, a Nikon D300 digital camera with a resolution of 12.3 megapixels is used (Figure 3, left). The program is intended to be used with any kind of camera, which should be selected depending on user needs. Preliminary tests with basic modern smartphone cameras showed promising results concerning the comparability with the standard D300 setup.

For the analysis of small and microscopic defects (ca. 3 mm and below), a portable digital microscope DinoLite AM7915MZT-EDGE is used (Figure 3, right). It has been shown in the past that the device is capable of detecting the main defect types on solar reflectors with the desired precision [14], [15]. The magnification range allows to cover areas of ca. 1 cm² to 1 mm² with a single image, and detecting artefacts as small as 10-20 µm at the highest magnification. An angular LED lighting allows adaptation to different illumination settings, and a polarization filter can be used to reduce glare from artefacts. The microscope can be connected to portable devices, such as laptops or smartphones, for easy image acquisition with the manufacturer-provided software.

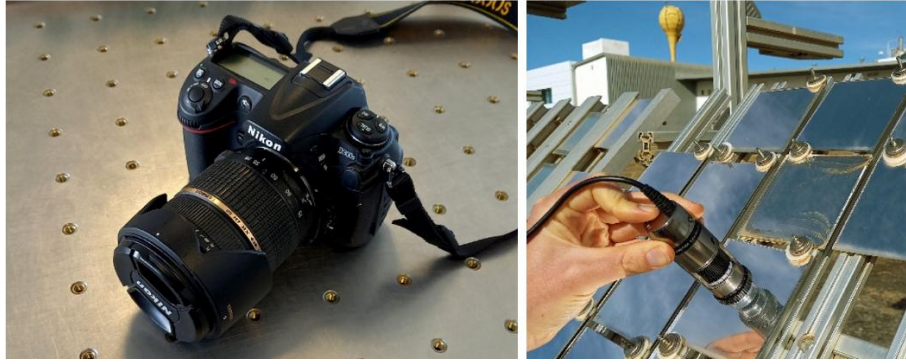


Figure 3. Nikon D300 digital camera (left) and AM7915MZT microscope (right).

Three types of reflector materials are used to test the analysis with the here presented procedure. All materials are commercial or experimental 4 mm silvered-glass mirrors. The first set of pictures is taken on facets of a PTC (Figure 4, left). Some of the facets show widespread corrosion of the silver layer of varying degrees. Some facets show only beginning corrosion at the edges, and others show extreme corrosion covering important parts of the whole facet. The second set of images is taken on two heliostat facets (Figure 4, middle). These facets show a largely intact mirror surface with very localized degradation of various sizes, from millimetres to areas of tens of centimetres in diameter. Both these facet types have been exposed at the PSA for more than a decade and experienced the respective operational conditions, including realistic regular tracking of the collectors.

The third kind of material used are small reflector samples from different manufacturers, exposed on a specifically designed rack in a fixed position facing south with an inclination of 45° to the horizontal (Figure 4, right). These samples show localized corrosion spots with a maximum size of various millimetres, and some edge corrosion.



Figure 4. Reflectors used for the measurement campaign: left) PTC, middle) heliostat, right) sample exposure rack.

To evaluate the capability of the program to successfully identify the degraded areas, first a subjective visual comparison is done. It is verified whether all areas that appear to be corroded are identified correctly. To assess the quality of the results, the images of the entire facets and samples are analyzed and compared to images with a much higher magnification. For the facets, these images are just collected with the same camera, but only covering a detailed area around selected defects. For the small samples, microscopic images of the individual corrosion spots are used for the comparison. It is assumed that the detailed images give an acceptable approximation of the real size of these defect areas.

During the preliminary testing, it was detected that best results were achieved with homogeneous backgrounds. Artefacts reflected by the intact reflector areas on the other hand,

sometimes negatively influenced the detection process. This is why, for this campaign, all images are taken at clear-sky conditions, resulting in a relatively homogeneous blue background, or directly using a grey or white background screen for the small samples.

3. Results and Discussion

In this section, some exemplary results of the analyses of the different reflector types are presented. A qualitative evaluation is performed to verify whether the automatic analysis procedure is capable of identifying degraded areas. In addition, for two cases, larger and smaller defects, a quantitative analysis is presented, comparing results to images of higher magnification.

In Figure 5, an example of a strongly corroded PTC facet is displayed. The original image, and results of the analysis procedure, an overlay with the corroded area in red, and black (intact) and white (degraded) image are displayed. The shown extent of corrosion is rare in commercial facets, and it can be appreciated that areas of different corrosion intensity (resulting in different gray tones in the image) exist simultaneously on this facet, while the more common case is a total degradation in very limited parts on the facet, often located on the edges. The case presented here makes a perfect evaluation with the software impossible, as it is limited to a simple degraded-intact decision. This results in certain zones that appear corroded to the naked eye in the original image, but are not recognized as degraded by the software.

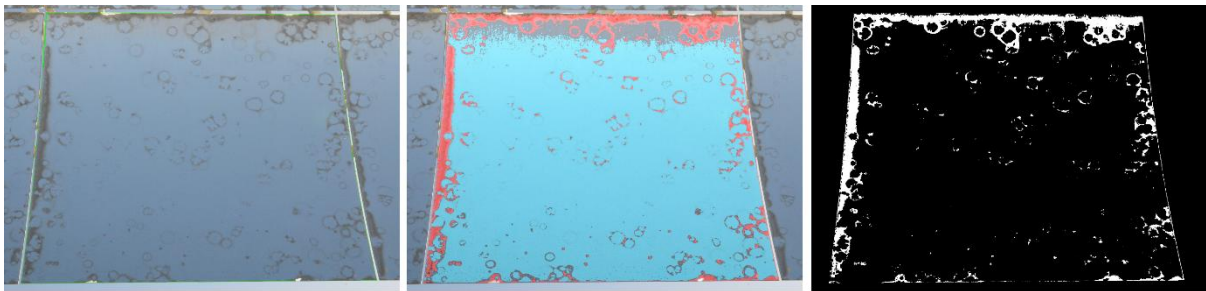


Figure 5. Images of one PTC facet with extreme corrosion of various intensity levels: left) original image, middle) corroded area marked in red, right) black (intact) and white (degraded) image.

An example of the more common case of corrosion on silvered-glass reflector facets is displayed in Figure 6. Here, a facet is shown that presents a largely intact reflective area, with a relatively well-separated, corroded area in the upper part, close to the edge. On the left of the figure, the original image is shown and on the right, the output of the automatic analysis, with the corroded part in red. Qualitatively, the analysis is able to detect the degraded area.



Figure 6. Images of one heliostat facet with well-defined corrosion: left) original image, right) after analysis, corroded area marked in red.

Figure 7 shows a more detailed analysis of the same facet. On the left, an image is shown, taken at a short distance to cover only the degraded area, with a ruler placed on the facet as a reference. The automatic analysis is performed on this image, and the results are compared to the analysis of the whole facet from Figure 6. The resulting marked areas are displayed in Figure 7, middle (whole-facet analysis), and on the right (detailed view analysis). It can be seen that the agreement between the two levels of detail is good, and only small artefacts detected on the right are not detected automatically on the whole-facet analysis. The degraded area for the two cases, calculated by the process, is 995.7 mm^2 and 1130.9 mm^2 respectively, which corresponds to a relative difference of 12 %. The difference mainly stems from the undetected degraded areas for the whole-facet analysis. In addition, an influence of the geometric conversion between the scales of the different image magnification cannot be discarded.

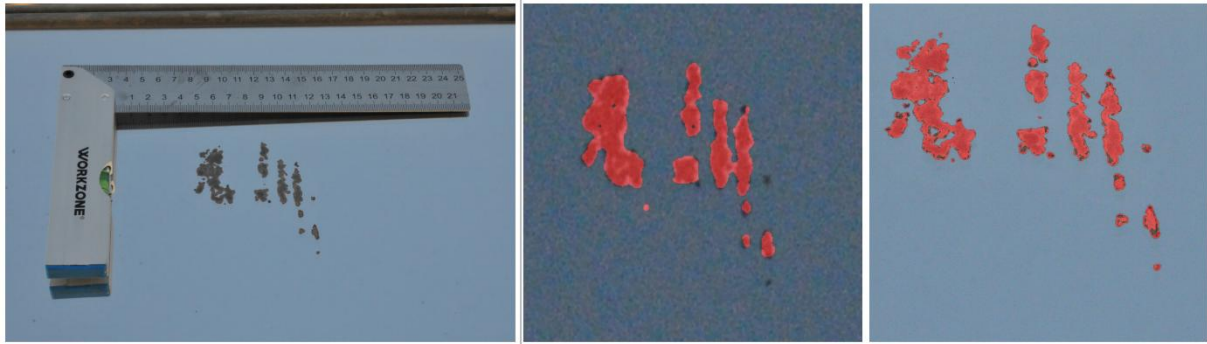


Figure 7. Detailed view of corroded area on facet H2: left) original image with ruler as scale, middle) corroded area analyzed on whole-facet image, right) corroded area analyzed on detail image.

As preliminary studies with the portable microscope were conducted in the past, for this study, only the detection limit of the setup was of interest. In Figure 8, images of low (left) and high (right) magnification are displayed. A corrosion spot of around 3.2 mm diameter can be seen in the low-magnification image. Defects of up to 5 mm fit into a single image. When larger defects have to be analyzed, several images can be stitched together. In the high magnification image, a defect with an approximate diameter of $200 \mu\text{m}$ can be distinguished, with separate artefacts of ca. $10 \mu\text{m}$ diameter, which is the limit of resolution of the device.

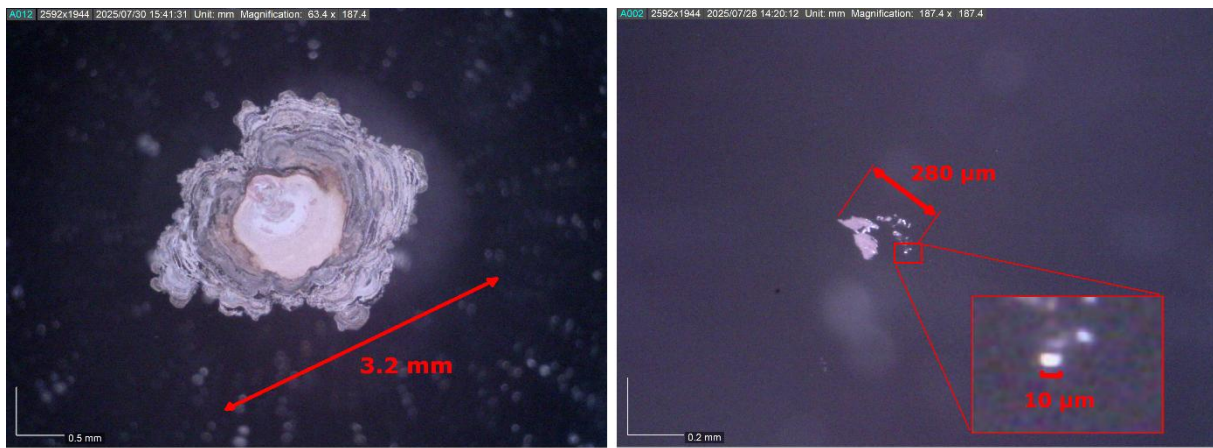


Figure 8. Microscopic images of medium and small size defects in the silver layer. Left) corrosion spot of around 3.2 mm diameter. Right) degradation spots with total diameter of around $200 \mu\text{m}$ with artefacts as small as $10 \mu\text{m}$.

A similar comparison, as shown before for the entire facets, is presented in the following paragraph as an example for the small samples with corrosion spots and edge corrosion. In Figure 9, the $10 \times 10 \text{ cm}^2$ sample is displayed with the visualization of the analysis. On the left, the original image is presented, in the middle the corroded area in red and on the right, for

better visibility, a black and white image, with the corrosion in white. As can be seen, the corroded spots and edges are identified by the software. For a further analysis, the spots marked in red in the middle image are compared with the microscopic evaluation.

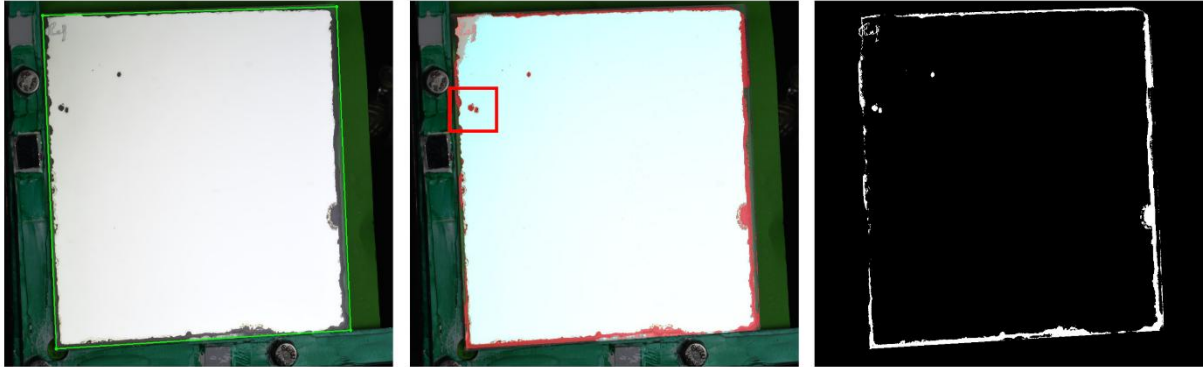


Figure 9. Images of 10x10 cm² sample with corrosion spots and edges: left) original image, middle) corroded area marked in red, right) black (intact) and white (degraded) image.

In Figure 10 left, a microscopic image of these corrosion spots is presented with a magnification of 59.9x covering a total area of around 5x5 mm². The analysis of this image (Figure 10 right) is compared to the zoom of the area of the total sample analyzed (Figure 10 middle). It can be seen that the degraded area on the microscopic image is detected successfully. The analysis of the full sample images detects the main spots, but does not identify the surrounding detached areas as corroded. This leads to an underestimation of the degraded area, similar to the case of the whole facet. The degraded areas are 4.55 mm² and 3.96 mm² for the microscope and camera image respectively, resulting in a difference of 13 %.



Figure 10. Left) microscopic image of selected corrosion spots of 10x10 cm² sample. Middle) zoom of analyzed degraded area on sample image. Right) analyzed area on microscopic image, corrosion marked in red.

4. Conclusions and outlook

A procedure is proposed to analyze the degraded areas on solar reflectors of different sizes and with different levels of detail. The procedure covers defects ranging from the sub-millimeter scale up to considerable parts of entire facets. It relies on measurements with a commercial digital camera and portable microscope, and the subsequent analysis with a custom automated image processing step. The procedure gives reliable results for the most common type of corrosion, which is relatively well separated from intact areas. It has limitations in analyzing large-scale corrosion of varying intensity, as it relies on a simple degraded-intact separation. The lower limit of detection for microscopic defects is in the range of 10 µm. The corroded part of the silver layer usually shows a specular reflectance close to zero. For the well separated

corrosion case, the loss of intact area then correlates well with the decrease in reflectance of the reflectors. This will be further investigated for the cases with corrosion of varying intensity.

It is intended to further develop the automatic image processing to make it more versatile, easy-to-use, and capable of producing more reliable results for varying degradation conditions. Some of the next tasks to be addressed for the optimization of the procedure include:

- Update the identification of degradation (use of local, gradient-based filters; identification of different degradation intensities, better background separation)
- Better automation (improve edge detection of facets and geometric conversion, avoid the need to define thresholds)
- Investigation of the adaptation to include reflectance measurements
- Possible future adaptation for large scale use (entire collectors and solar fields)

Author contributions

Johannes Wette: Conceptualization, Methodology, Validation, Writing – original draft. **Florian Sutter:** Supervision, Validation, Writing – review & editing. **Florian Wiesinger:** Methodology, Validation, Software, Writing – review & editing. **Manuel Pérez-García:** Supervision, Resources, Writing – review & editing. **Ivan López-Baena:** Investigation, Methodology, Software, Visualization, Writing – review & editing. **Aránzazu Fernández-García:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing

Competing interests

The authors declare that they have no competing interests.

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References

- [1] A. García-Segura *et al.*, "Degradation types of reflector materials used in concentrating solar thermal systems," *Renew. Sustain. Energy Rev.*, vol. 143, p. 110879, Jun. 2021, doi: 10.1016/j.rser.2021.110879.
- [2] M. Montecchi, "Proposal of a new parameter for the comprehensive qualification of solar mirrors for CSP applications," *AIP Conf. Proc.*, vol. 1734, no. 1, p. 130014, May 2016, doi: 10.1063/1.4949224.
- [3] F. Sutter, S. Meyen, A. Fernández-García, and P. Heller, "Spectral characterization of specular reflectance of solar mirrors," *Sol. Energy Mater. Sol. Cells*, vol. 145, pp. 248–254, Feb. 2016, doi: 10.1016/j.solmat.2015.10.030.
- [4] A. Fernandez-Garcia *et al.*, "Parameters and Method to Evaluate the Reflectance Properties of Reflector Materials for Concentrating Solar Power Technology Technology - Official Reflectance Guideline Version 3.1," *SolarPACES*, Apr. 2020.
- [5] F. Wolfertstetter *et al.*, *Recommendations for reflectance measurements on soiled solar mirrors*, 2022.

- [6] J. Wette, F. Sutter, R. Sánchez-Moreno, and A. Fernández-García, "Comparison of Commercial Reflectometers for Solar Mirrors," *SolarPACES Conf. Proc.*, vol. 1, 2022, doi: 10.52825/solarpaces.v1i.666.
- [7] G. Zhu, D. Kearney, and M. Mehos, "On characterization and measurement of average solar field mirror reflectance in utility-scale concentrating solar power plants," *Sol. Energy*, vol. 99, pp. 185–202, Jan. 2014, doi: 10.1016/j.solener.2013.11.009.
- [8] J. Coventry, C.-A. Asselineau, E. Salahat, M. A. Raman, and R. Mahony, "A robotic vision system for inspection of soiling at CSP plants," presented at the SOLARPACES 2019: International Conference on Concentrating Solar Power and Chemical Energy Systems, Daegu, South Korea, 2020, p. 100001. doi: 10.1063/5.0029493.
- [9] M. Tian *et al.*, "Toward Autonomous Field Inspection of CSP Collectors With a Polarimetric Imaging Drone," *SolarPACES Conf. Proc.*, vol. 1, Dec. 2023, doi: 10.52825/solarpaces.v1i.623.
- [10] F. Sutter *et al.*, "Durability Testing of Silvered-Glass Mirrors," *Energy Procedia*, vol. 69, pp. 1568–1577, May 2015, doi: <http://dx.doi.org/10.1016/j.egypro.2015.03.110>.
- [11] R. Lahlou *et al.*, "Study and comparison of naturally-aged and As-received silvered-glass reflectors," presented at the SolarPACES 2017: International Conference on Concentrating Solar Power and Chemical Energy Systems, Santiago, Chile, 2018, p. 230007. doi: 10.1063/1.5067235.
- [12] F. Buendía-Martínez, A. Fernández-García, F. Sutter, L. Valenzuela, and A. García-Segura, "Advanced Analysis of Corroded Solar Reflectors," *Coatings*, vol. 9, no. 11, Art. no. 11, 2019, doi: 10.3390/coatings9110749.
- [13] F. Wiesinger *et al.*, "Detection of corrosion on silvered glass reflectors via image processing," *Results Eng.*, vol. 25, p. 103781, Mar. 2025, doi: 10.1016/j.rineng.2024.103781.
- [14] J. Wette, "In-field Analysis of Microscopic Degradation of Solar Reflectors," presented at the SolarPACES 2021, Online, 2021. [Online]. Available: <https://dgm.inventum.de/app/media-library/show/eventItem/57addb8e-d3c0-4f9f-9e43-5b02a775a57e>
- [15] J. Wette, F. Sutter, F. Wiesinger, R. Sánchez-Moreno, and A. Fernández García, "In-situ analysis of microscopic corrosion evolution of solar reflectors," presented at the FEMS EUROMAT 2023, 2023.