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

Measurement Systems, Devices, and Procedures

https://doi.org/10.52825/solarpaces.v3i.2474

Published: 27 Aug. 2025

Advanced Drone-Based Alignment Measurements for Parabolic Trough Collectors

Optical Inspection of Solar Field Installation

Andreas Kämpgen[1,*], David Helten[2], Klaus Pottler[2], and Marc Röger[3]

[1]CSP Services España, S.L., Spain

[2]CSP Services GmbH, Germany

[3]German Aerospace Center (DLR), Institute of Solar Research, Spain

*Correspondence: Andreas Kämpgen, a.kaempgen@cspservices.de

Abstract. A novel drone-based measurement method for the automatic quality check of the field assembly of parabolic trough collectors has been developed. The module as well as receiver alignment of entire parabolic trough loops can be measured using commercially available drones equipped with a visual camera and RTK (real time kinematic) positioning. The measurement principle is based on the geometric relations between aperture edges of the parabolic trough collector and the absorber tube line, which both are measured seamlessly along the collector using robust edge detection algorithms. The measurement method replaces hook-rod based measurements of the receiver alignment and total-station based measurements of the module alignment in a fast and fully automated way while keeping high measurement resolution and accuracy. Due to its speed and versatility to measure receivers with and without protective foil and with the collector in arbitrary orientation, the measurement method can be applied in all project phases ranging from solar field construction over commissioning to operation. The paper presents the progress in the development of the method and the results of the validation measurements performed at the parabolic trough collector loop of the molten salt test platform (EMSP) in Évora, Portugal.

Keywords: Solar Concentrator, Parabolic Trough, UAV, Alignment Measurement, Quality Control, Optical Measurement, Edge Detection

1. Introduction

High-accuracy assembly and installation of parabolic solar fields is important to secure high optical efficiencies during their lifetime [1]. Under the circumstances of a fast solar field installation with mainly unexperienced personnel to minimize costs, this is hard to secure. During this phase of the installation, errors can occur especially in the alignment of the solar collector elements (SCE, "modules") and in the alignment of the heat collector elements (HCE, "receivers") in the solar collector assembly (SCA). In solar field assembly, module and receiver alignment is adjusted during installation, but typically not checked regularly due to the high effort of available methods. During construction, many classical methods are available to ensure sufficient “module alignment”. In the early EuroTrough applications, the alignment of the steel frames (not the concentrator itself) was measured using high-precision bubble levels or precise electronic inclinometers. Newer parabolic trough modules have been designed with accurate alignment devices using pins and fittings. These two methods require good referencing of the torque box/tube to the mirror mounts and cannot be used for quality control. Very early in the development of the Spanish CSP plants, the outermost edges of the mirrors were used for alignment procedures. Comparing the height of the mirror edges along the entire solar collector, which is oriented close to the zenith angle, provides a good measure of the achieved alignment quality. The measurement is carried out using surveying instruments such as theodolites or total stations in robotic or manual mode or, with more effort, but at a much lower instrument cost, utilizing water-hose levelling instruments. If the optical quality of the mirror panels and the entire concentrator is ensured in the production line, the edge method provides good alignment quality. However, third-party quality control is costly, so this type of measurement is usually not performed after installation.

“Lateral receiver misalignment” is particularly common due to assembly or installation errors, welding problems, receiver support deformation, ball-joint/flex-tube forces, and many other effects. The state of the art, fast and accurate measurement of receiver alignment is based on measuring the distance between the absorber tube (or the foils around the glass envelope for protected receivers) and the edges of the concentrator aperture with a hook bar [1]. This approach is not commonly used for general post-installation quality control but rather for root cause analysis when the solar field is not performing well or when receivers or receiver mounts need to be readjusted.

Manual close-range photogrammetry [2], [3] and deflectometry methods [4] are used to measure module and receiver alignment with very high accuracy. Due to the high cost of such manual measurements, they are only used for prototype collector evaluation. Newer methods of airborne solar field characterization like QFly/QScan [5], [6] typically require operational solar fields with circulating heat transfer media. These very advanced methods are often used to optimize operational solar fields but are rarely employed in the assembly phase of a system, although they could assist in a quicker commissioning of solar fields and reducing the startup time of parabolic trough power plants [7].

2. Choice of Measurement Principle

In order to overcome the limitation of excessive work effort and to enhance the overall performance of solar fields, a total of eleven assessment methods (including QFly/QScan using either photogrammetry or deflectometry, LIDAR, LED reflection, edge-height, edge-alignment, and hook rod) were evaluated in a preliminary study conducted in collaboration with the German Aerospace Center (DLR).

The edge-alignment method was identified as the optimal approach for further development. The reflection-based and deflectometry-based methods require relatively clean mirrors, which is challenging to achieve in a dusty construction environment. The conventional photogrammetry-based techniques, which do not employ artificial intelligence, are highly accurate; however, they entail a considerable investment of time for evaluation and typically require the expertise of trained professionals. While LIDAR systems are occasionally employed in the assessment of solar concentrators, the uncertainty associated with airborne LIDAR systems remains considerable, ranging from 5 to 10 cm. The state-of-the-art hook rod method lacks the means for cost-effective automation. The team concluded that the optimal compromise regarding automation, speed, complexity, susceptibility to dust, and the ability to measure module alignment also without receivers and receiver alignment also without protective film on the glass tubes are the edge-alignment method.

Subsequently, CSP Services developed a novel module alignment test and a receiver alignment measurement method based on edge scanning algorithms. Both methods are RTK-drone based and facilitate the automated measurement of an entire parabolic trough loop of 600 m collector length within a few minutes with a flight path as illustrated in Figure 1.

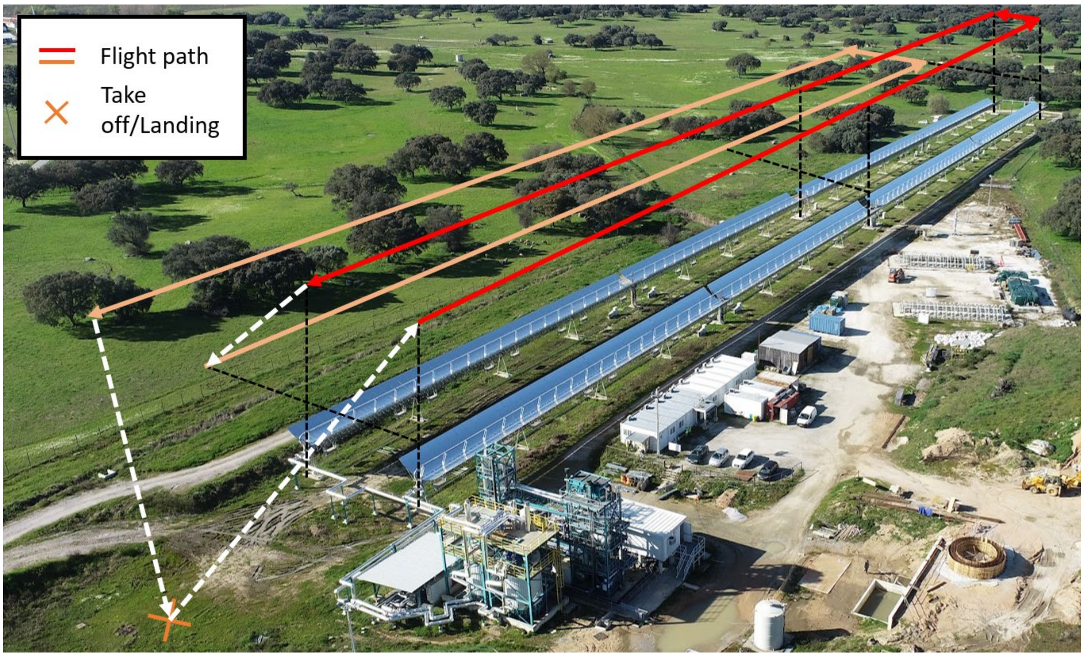

Figure 1. *Typical flight path for module and receiver alignment measurement of parabolic trough loop. The image shows the TSK Flagsol HelioTrough collector loop of the Evora Molten Salt Platform (EMSP) in Portugal with collector in zenith orientation (90°)*

3. Module Alignment Method

A parabolic trough collector is installed in a solar field with individual modules mounted on pylons along the collector. The installation team uses heavy machinery to place collector modules between two pylons and connect them to the other modules. Another team then aligns the modules throughout the collector. For large collectors and those using molten salts, it is crucial to detect any errors in collector alignment before the solar field is commissioned. The presented method is able to measure module alignment with dusty mirror panels and before receiver installation in a fast and robust manner.

3.1 Development

Collector alignment is defined by the deviation of the angles between the individual modules of a collector, relative to each other, and absolute. Module alignment is used equivalently. The measurement principle is based on visual images of the mirror edges of the collector taken by the drone camera at an oblique viewing angle. The mirror edges are detected with sub-pixel accuracy and processed to derive the relative orientation of the parabola aperture with respect to the drone camera. Figure 2 shows the utilized drone system DJI M300RTK with camera payload DJI Zenmuse H20.

Figure 2. *DJI M300RTK, RTK-enabled industrial drone*

To obtain the required imagery, an automated route planning tool is used to ensure that the drone is positioned with high accuracy relative to the collector structures in any operating orientation, and that the camera angle and zoom are adjusted accordingly. Thanks to the RTK system, the images can be georeferenced accurately on centimeter level. An example flight path for a collector in zenith orientation is illustrated in Figure 1 (orange line). The actual measurement is performed along the entire collector with typically two to four measurement points per meter, allowing the relative orientation of each module to be analyzed at a very high spatial resolution. Figure 3 shows the schematics and an example measurement photo.

Figure 3. *Module alignment measurement with edge detection. Images are taken by drone from positions that allow evaluation of alignment deviations along the collector row*

To convert sub-pixel edge positions to sub-millimeter values in the local coordinate system, the local coordinate system must first be well aligned with the drone's global positioning coordinate system. Second, RTK accuracy is used to correct each image for its individual position within the local coordinate system, which varies in horizontal and vertical distances relative to the collector due to practical flight path stabilization limitations.

The data acquisition, evaluation and post-processing steps can be summarized as follows:

1. Design of a universal Digital Twin for all types and geometries of parabolic trough collectors employing nominal geometric concentrator data and solar field dimensions.
2. RTK station setup and calibration of its underlying WGS84 global coordinate system aligned with the local coordinate system of the solar field (for example, ETRS89 UTM).
3. Creation of flight routes, gimbal and camera configurations for the digitalized and georeferenced collectors in the solar field, in dependence on the collector orientation during measurement. To ensure the optimal field of view for the high-resolution zoom camera, sophisticated flight route planning is essential. This entails ensuring the accurate three-dimensional positioning of the drone as well as the corresponding gimbal angle relative to the collector structures.
4. Performing the flight by enabling the drone to automatically trace the necessary path, controlling the data capture and pre-sorting the data. The drone pilot is just monitoring that the mirror edges stay within the field of view along the collector.
5. Image processing: The module edges are fully automatically detected and measured with subpixel precision. The collector orientation is determined for all images and referenced to the orientation at the drive. The orientations are corrected for the relative drone positional changes using the RTK positioning data after translation into the local coordinate system.

The accuracy of the described module alignment algorithm depends on a special image processing software developed in-house. This software is capable of robust and accurate detection of mirror edges within these expansive image sets, as well as the alignment of the collector and drone coordinate systems. In order to safeguard CSP Services' intellectual property, no further information can be provided regarding the design of the edge-detection algorithm.

3.2 Validation

To ascertain the ground truth data for the angular alignment of the collector modules in relation to the drive, the conventional method of determining the height difference between the opposite outer mirror edges was conducted (two opposite mirror edge height measurements yield one angular measurement). This was done for the fourth collector assembly of the EMSP loop using the total station Trimble S8. The angular uncertainty of the device is 1” (1σ), which corresponds to a height uncertainty of 0.5 mm over a distance of 100 m. An additional uncertainty is considered for the hook rod utilized to support the measurement prism. The total angular uncertainty for the ground truth measurement is approximately 0.7 mrad per measurement. The resulting uncertainty is approximately 0.4 mrad when three measurements are averaged per module. The measured collector assembly comprises eight modules, four north of the drive and four south of the drive pylon. Three measurements were taken for each module. The angular alignment results are affected by the torsional behavior of the collector, which is determined by its torsional stiffness and imbalance with regard to friction in bearings and ball or flex joints, as well as possible play in the module interconnections. In the measured zenith collector orientation, a collector imbalance would not generate a significant torque and thus is not expected to be a significant factor.

The alignment of the collector was measured three consecutive times using the new drone method after the collector was rotated to zenith from the eastern direction (performed on November 23, 2023 at 14:31, 14:33 and 14:35). Figure 4 depicts the mean of the three drone measurements, represented in dark blue. The local measurement precision for each measurement along the collector has been estimated from the standard deviation of the three drone measurement results and is plotted with light blue error bars.

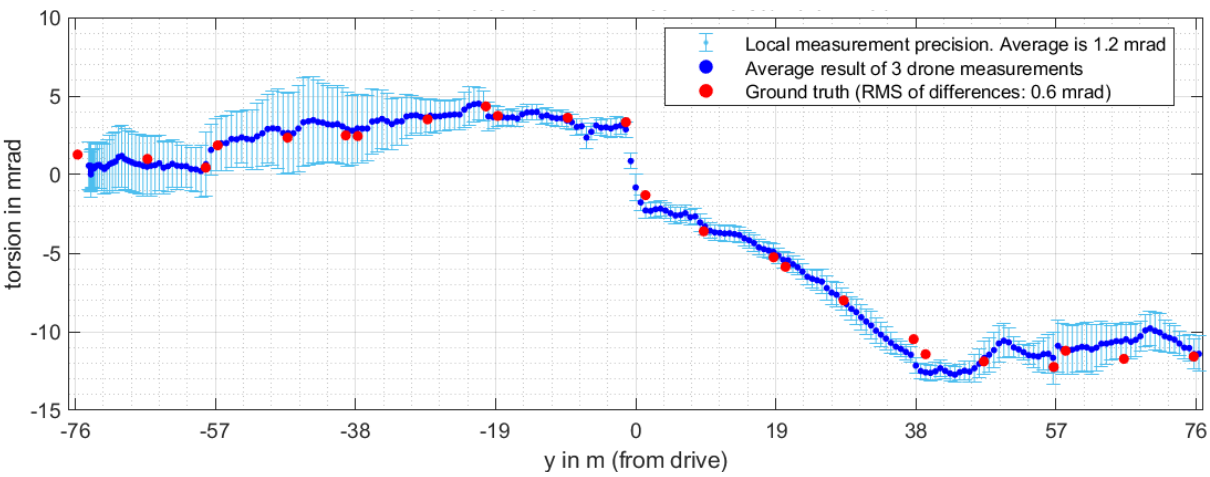

Figure 4. *Verification of uncertainty for drone-powered measurements of the collector alignment at the fourth collector (SCA 4) of the EMSP molten salt test loop in zenith orientation. Previously, the collector was rotated to zenith from the eastern direction*

The mean local measurement precision of all values along the collector is 1.2 mrad, which is consistent with the perspective uncertainty of the camera in relation to the collector aperture. The RTK precision of 2-3 cm at a distance of approximately 25 m from the parabola corresponds to an angular viewing uncertainty of 0.8-1.2 mrad. The high sampling density enables precise alignment analysis at the mirror level and enhances error detection, particularly for significant inter-module discontinuities and torsional effects. At the module level, a statistical measurement uncertainty of 0.4 mrad is estimated. The systematic measurement uncertainty is contingent upon the alignment of the drone positioning system (WGS84 with centimeter-level precision provided by RTK correction) and the collector coordinate system, as well as the presence of systematic errors in the image processing and systematic collector assembly errors in the outer mirror rows. The systematic error for the validation drone measurements has been estimated to be 0.3 mrad. The total measurement uncertainty can be estimated by the equation $\sigma_{total} = (\sigma_{statistical}^2 + \sigma_{systematic}^2)^{0.5}$, which yields a value of 0.5 mrad.

The discrepancies between the drone and the conventional ground measurements have been assessed, yielding a root mean square (RMS) value of 0.6 mrad. This is adequate for identifying any significant misalignment. Table 1 presents a summary of the measurement uncertainties and the differences of the comparison to the ground truth measurement.

Table 1. *Statistical differences of module alignment for drone method and conventional measurements. SCA4 was rotated to zenith from the eastern direction*

Method	Measurement Time	Measurement uncertainty
Drone measurement	November 23, 2023 14:31, 14:33, 14:35	Statistical (local, mirror): 1.2 mrad Statistical (module): 0.4 mrad Systematic: 0.3 mrad Total (module): 0.5 mrad
Ground measurement (total station)	November 21, 2023 14-15 h	Statistical (local, mirror): 0.7 mrad Statistical (module): 0.4 mrad Systematic: 0.2 mrad Total (module): 0.4 mrad
Differences (local)		0.6 mrad (RMS)

The achieved RMS value of 0.6 mrad in the comparison to the ground truth is superior to what was anticipated based on the local measurement uncertainties of the two measurement methods. The comparison is facilitated by the fact that the underlying measuring principle is the same for both measurements. For instance, individual mirror height errors will affect local measurements in a uniform manner. The favorable outcome serves to confirm the accuracy of the developed drone measurement and validate the determined measurement uncertainties.

4. Receiver Alignment Method

In the installation of a solar field, the receivers are installed subsequent to the installation and alignment of the collector. Depending on the specific collector design, it may be necessary to adjust the positions and alignment of the receiver to ensure that it is positioned along the focal line of the concentrator. The metal absorber tubes of the receivers are welded together to form a continuous pipe along the entire length of the collector. If this process is not executed with precision, it may result in misaligned receivers, which could diminish the optical efficiency of the collectors. Defective welding may cause a deformation of the receivers which may lead to premature tube failure. The objective of the proposed new method is to enable quality assurance personnel to promptly assess the alignment of the receivers in the collectors. This approach will facilitate the identification of receiver misalignment or welding issues immediately following receiver installation, thereby enhancing the receiver installation procedures and accelerating the commissioning process.

4.1 Development

The term "receiver alignment" is defined as the horizontal receiver deviations (dx) from the ideal focal line, relative to a given parabola oriented towards zenith. A common method for measuring the performance-relevant lateral receiver alignment is based on the distance measurement between the absorber tube and the outer mirror edges along the collector with the use of a hook rod [1]. In the new airborne method, this measurement principle is adopted but performed seamlessly along the collector using visual high-resolution images in lieu of the cumbersome sampling with the hook rod. The contours of the mirror and receiver are identified with sub-pixel precision and processed to determine the relative offset of the receiver from the focal line of the parabola aperture. The measurement is conducted along the entire collector, with typically two to four measurement points per meter, enabling the analysis of the relative orientation of each module at a high spatial resolution. Figure 5 illustrates the schematics and an exemplary measurement photo.

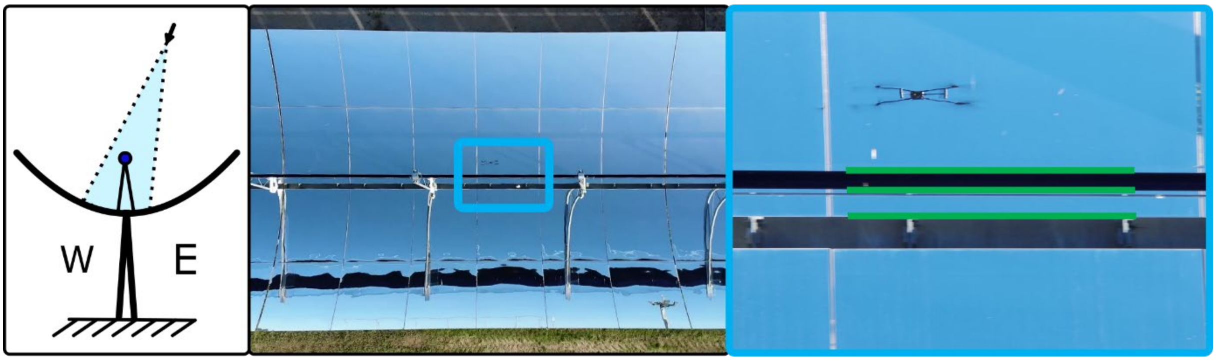

Figure 5. *Receiver alignment measurement principle with edge detection. Areal pictures are captured from positions permitting alignment evaluation along the collector*

The steps of the data acquisition, evaluation and post-processing are analogous to those of the measurement of the module alignment method, albeit with an adapted flight route. Post-processing is more complex for two reasons:

1. The measurement of receiver alignment must consider the temperature of the steel tubes, as this affects the heights of the receivers, particularly at either end of the collector wing. Here, the receiver supports exhibit a significant inclination, resulting in significantly reduced receiver heights when the absorber tube temperatures deviate considerably from their normal operating temperatures.
2. In contrast with the conventional hook-rod approach, the drone method is susceptible to misalignment between modules across the collector and torsions of the collector or module structure, which frequently manifest as identical twists in the concentrator and receiver line orientations. Therefore, the innovative method necessitates the incorporation of collector alignment data (such as the novel drone-based measurements detailed in Chapter 3) in the evaluation of lateral receiver alignment.

4.2 Validation

The validation of the novel drone-powered lateral receiver alignment method is based on the aforementioned hook rod method. For this purpose, a custom-made tool is used which consists of a hook with a sufficiently long, non-deformable yet light rod with a linear scale at the distance of the mirror edge. The receiver alignment is verified near the receiver supports. Along the very straight glass envelope in between two receiver support points, very low deviations from a linear behavior can be assumed. The ground truth receiver alignment measurement accuracy is limited by the accuracy of the measurement tool, the reading precision and the deviations of the edges of the outer mirror rows. The measurement uncertainty (excluding systematic mirror position deviations) is estimated to be 3 mm for the Evora test loop, considering its wide aperture and test loop manufacturing accuracies.

The ground truth data was collected for SCA 4 of the EMSP in the zenith orientation (90°) using an elevator platform. Two measurements were taken at each receiver support, with one on either side of the support, resulting in a total of 80 measurement points. The loop was not filled with heat transfer fluid and the collector impedance heating was deactivated. Electric heating was only activated at the REPAs, which exhibited temperatures in the region of 300°C. Due to the missing heat transfer medium and the good insulating properties of the vacuum receivers, the absorber tube temperatures were estimated to reach 150°C when exposed to unconcentrated solar radiation (not in track). The anticipated receiver tube heights and glass envelope-mirror edge distances were corrected according to this mean absorber tube temperature. The corrections for the lateral distances are in the sub-millimeter range, with a maximum value of 0.6 mm for the last receiver supports. Additional uncertainties arising from potentially misaligned receiver support rotation axes are neglected.

The receiver alignment was determined with the drone-powered method in zenith collector orientation on November 23, 2023, at 13:55. The data obtained has been corrected for the ground truth alignment of the collector. It is presented in Figure 6 for comparison with the ground truth receiver alignment results. For the purposes of this comparison, the mean deviation in the drone receiver alignment has been set equal to the mean ground truth receiver alignment deviation, given that the ground truth method measures in absolute units.

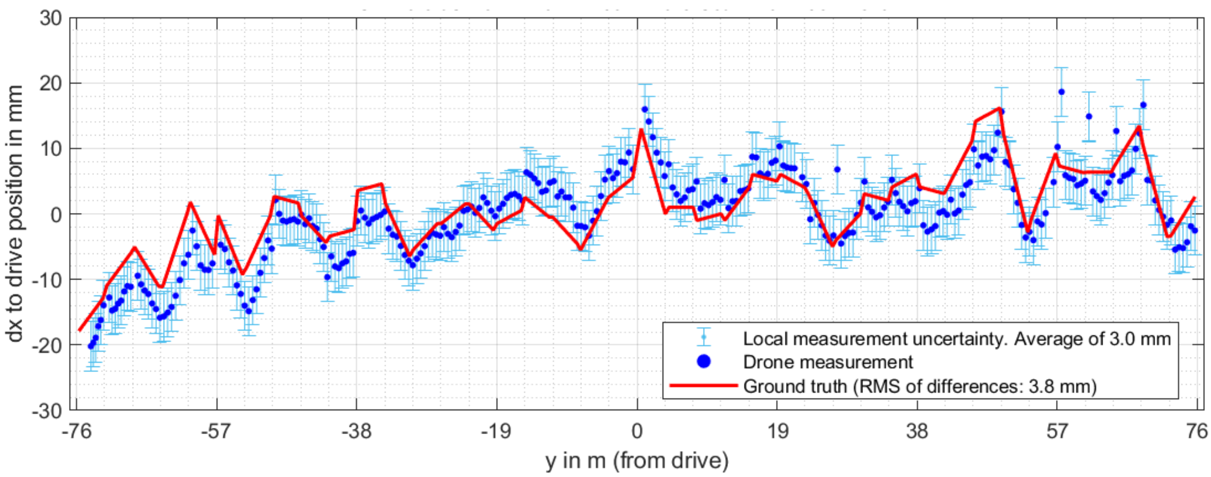

Figure 6. *Verification of uncertainty for drone-powered measurements of the lateral receiver alignment at collector “SCA 4” of the Évora loop in zenith orientation*

The precision or statistical measurement uncertainty of the drone-based method is contingent upon the imaging resolution, statistical image processing errors and, similarly to the hook-rod measurement, on the positional deviations of the edges of the inner mirror row. The systematic measurement uncertainty depends on the measurement uncertainty of the collector torsion, systematic errors in the image processing and systematic collector assembly errors in the mirror row. For the validation measurements it is estimated to be 2.6 mm. The total uncertainty is estimated by $\sigma_{total} = (\sigma_{statistical}^2 + \sigma_{systematic}^2)^{0.5}$, yielding an estimated range of 4.0 mm. The uncertainty for the validation measurements is estimated to be 3.0 mm. The differences between the drone and the conventional ground measurements have been assessed and the RMS value was found to be 3.8 mm. Table 2 summarizes the measurement uncertainties and the differences of the comparison to the ground truth measurement.

Table 2. *Statistical differences of receiver alignment tests for drone and conventional method*

Method	Measurement Time	Measurement uncertainty
Drone measurement	November 23, 2023 13:55	Statistical: 3.0 mm Systematic: 2.6 mm Total: 4.0 mm
Ground measurement (hook rod)	November 21, 2023 15-16 h	Statistical: 3.0 mm Systematic: 2.0 mm Total: 2.8 mm
Differences (mean set to 0)		3.8 mm (RMS)

The RMS of 3.8 mm is within the expected range for the two measurement methods. This is adequate for using the drone method in commercial projects. The measuring principle is the same for both measurements, but different mirror rows are used (outer for hook-rod, inner for drone). The systematic measurement error is not considered in the comparison because the mean deviations of the drone measurements were set to the ground measurement's mean deviation. The positive validation result confirms the determined measurement uncertainties of the drone measurement.

5. Summary

The novel methods use advanced edge detection algorithms and are highly flexible. They can be applied to check both module and receiver alignment quality prior to solar field operation at any elevation angle and do not require clean mirrors. The collector alignment technique does not require mounted receiver tubes, so it can be directly applied after module placement. The receiver alignment technique also works with protective receiver covers. Both methods can serve as immediate feedback to the alignment team. It is estimated that a typical 50 MW solar field with up to 100 km of collector length can be measured within a few hours. The methods are complementary to the conventional aerial "QFly/QScan" technology [5]. The uncertainty associated with the drone-based “module alignment” check was validated against ground truth measurements, with a resulting value of 0.4 mrad (RMS, over 190 m collector length). The measurement uncertainty for the “receiver alignment” test has been validated against ground truth measurements, with a resulting value of approximately 3 mm (RMS, over 190 m collector length). The ability to assess alignment quality across an entire solar field is crucial for mitigating the risk of failures, accelerating the ramp-up process, and ultimately reducing the levelized cost of electricity (LCOE) of parabolic trough power plants, as previously outlined in [7]. The measurement uncertainties of the drone-based method and its primary characteristics are presented in Table 3.

Table 3. *Main features of the new drone-based alignment check method*

Property	Value
Measurement time	Several minutes (for one loop)
Collector elevation angle	Any between 0° and 180°
Receiver status	With or without white protective film
Heat transfer medium (HTF)	With or without HTF
Module alignment uncertainty (RMS)	0.5 mrad
Receiver alignment uncertainty (RMS)	4.0 mm

The measurement method can be employed on a periodic basis in operational solar fields to identify actual anomalies and potential equipment defects, thereby enabling corrective actions to be taken before costly failures occur. For test facilities and prototype loops the method provides the ability to quickly and automatically assess collector and receiver alignment, which is essential for testing. This is particularly crucial when employing molten salt as a heat transfer medium or when engaging with collectors that do not meet the quality control benchmarks of commercial projects. The novel method also provides an efficient means for improved solar field quality verification and root cause analysis of issues in existing solar fields. When coupled with drone-based concentrator measurements [5], concentrator slope deviations can be measured across the entire solar field without being affected by the uncertainty of an estimated absorber tube alignment. Further development steps are necessary to transition from the prototype to a commercially viable product. It is of the utmost importance that functional testing ensures the functionality of the technology across a range of scenarios and environments. By soliciting user feedback, valuable insights can be obtained from the market, potential usability issues can be identified, and the necessity of additional features can be determined. Finally, through an iterative improvement process, the system can be refined based on the feedback and testing results.

Data availability statement

The access to measurement data is restricted to the EuroPaTMoS research partners.

Underlying and related material

None

Author contributions

Andreas Kämpgen lead conceptualization, performed formal analysis, developed software code, supervised tasks and wrote the draft of the paper. David Helten worked on drone control, investigation, application of software code and data-verification. Klaus Pottler assisted in project administration and supervision. Marc Röger assisted in funding acquisition, lead the investigation of the possible measurement assessment methods and reviewed the paper.

Competing interests

The authors declare the following competing interests: In accordance with public funding goals of commercial deployment, the authors, in their position as active staff or founders of the CSP Services group companies have a commercial interest in marketing the presented algorithms.

Funding

Work in the EuroPaTMoS-project was funded by the ERA-NET Cofund CSP (grant 838311) with co-funding from Spain (CDTI, grant SERA-20211002), Germany (Federal Ministry for Economic Affairs and Climate Action, grant 03EE5059A), North Rhine-Westphalia (grant PRO/0090) and the European Union's Horizon 2020 Framework Program for R&I.

Acknowledgement

We thank our EuroPaTMoS project partners for their support, especially the staff of TSK-Flagsol GmbH and the operators of the parabolic trough loop at the Évora Molten Salt Platform, including staff from the University of Évora and from the German Aerospace Center. We also thank our former colleagues from DLR and CSP Services who participated in the research.

References

[1] K. Pottler, S. Ulmer, E. Lüpfert, M. Landmann, M. Röger, C. Prahl, “Ensuring Performance by Geometric Quality Control and Specifications for Parabolic Trough Solar Fields,” in SolarPACES Conf. 2013, Energy Procedia, 2014, 2170-2179, doi: 10.1016/j.egypro.2014.03.230.

[2] K. Pottler, E. Lüpfert, G. H. G. Johnston, M. R. Shortis, “Photogrammetry: A Powerful Tool for Geometric Analysis of Solar Concentrators and Their Components,” J. Sol. Energy Eng., vol. 127, pp 94-101, Febr. 2005, doi: 10.1115/1.1824109

[3] J. K. Stynes, B. Ihas, "Absorber Alignment Measurement Tool for Solar Parabolic Trough Collectors," in Proc. ASME 2012 6th Int. Conf. on Energy, Parts A and B., San Diego, California, USA, pp. 437-447, doi: 10.1115/ES2012-91283

[4] N. Janotte, E. Lüpfert, K. Pottler, M. Schmitz, „Full parabolic trough qualification from prototype to demonstration loop,” in SolarPACES Conf. 2016, AIP Conf. Proc. 1850, 2017, pp 020010, doi: 10.1063/1.4984334

[5] C. Prahl, M. Röger, C. Hilgert, "Air-Borne Shape Measurement of Parabolic Trough Collector Fields," in SolarPACES Conf. 2016, AIP Conf. Proc. 1850, 2017, 020013, doi: 10.1063/1.4984338

[6] C. Prahl, M. Röger, B. Stanicki, C. Hilgert, "Absorber tube displacement in parabolic trough collectors - A review and presentation of an airborne measurement approach," J. Sol. Energy, 2017, vol. 157, pp. 692–706, doi: 10.1016/j.solener.2017.05.023

[7] K. Pottler, S. Ulmer, T. Thaufelder, T. Schmidt, K. Regina, "Reducing LCOE through Measurement-Based Quality Assurance and Hybrid Performance Testing in Solar Fields," in SolarPACES Conf. 2019, AIP Conf. Proc. 2303, 2020, 110007, doi: 10.1063/5.0029550