AIRBORNE SHAPE MEASUREMENT OF PARABOLIC TROUGH COLLECTOR FIELDS

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Abstract

As the optical efficiency of the solar field has a high impact on the overall plant performance, qualification methods determining the geometrical accuracy of solar concentrator systems have gained high importance. However, it has not been possible yet to measure the geometrical accuracy of an entire solar field, resolving the relevant single characteristics like local mirror slope deviations, panel alignment and gravitational deformation. This paper describes the development and assessment of a measurement technique for the qualification of parabolic troughs based on the distant observer method called TARMES (Trough Absorber Reflection Measurement System). Instead of a stationary camera at ground level taking pictures of a turning collector, the new approach called QFly makes use of an airborne camera vehicle which allows a completely automated and fast measurement of all collectors under relevant operating conditions. The new approach was validated against a stationary TARMES and photogrammetric measurement to compare the deviations between the different methods and with the expectations of an uncertainty analysis. The absolute measurement uncertainty of QFly on a module level is around ± 0.1 milliradians.

Keywords: Parabolic trough, optical performance, distant observer, deflectometry, mirror slope deviation

1. Introduction

Solar fields consisting of parabolic trough collectors (PTCs) represent the majority of today's CSP plants. As the optical efficiency of the solar field has a high impact on the overall plant performance, qualification methods determining the geometrical accuracy of solar concentrator systems have gained high importance. Most of the existing techniques are non-contact optical approaches and their application to mirror panels, single or few parabolic trough modules as well as other concentrators have already contributed considerably to collector optimization. However, it has not been possible yet to measure the geometrical accuracy of an entire solar field, resolving the relevant single characteristics like mirror slope deviations, panel alignment, gravitational deformation, module alignment and collector torsion. To overcome the restrictions of ground based measurements, an existing method to determine mirror slope deviations in curvature direction (*SDx*) from a series of images of the concentrator (TARMES [1,2]) was modified in way to enable automated measurement of large fractions of a parabolic trough collector field. This is achieved by airborne data acquisition, i.e. the former stationary camera is replaced by an airborne camera. The method, comprised of measuring the position and orientation of the airborne camera relative to each collector module and of processing the absorber tube reflection images, is called QFly.

The present work focuses on the validation of the measurement system using a single collector module (12 m length) at the Plataforma Solar de Almería. The results produced by QFly are validated against the results obtained from TARMES measurements (ground-based stationary camera) and from photogrammetric measurements.

The article starts with an overview of established measurements systems to estimate the optical performance of parabolic trough collectors (PTCs), focusing on a method called TARMES, which provides the measurement principle for QFly. The characteristics of the QFly system and the measurement methodology will be presented in Section 3 and 4. Section 5 is dedicated to the uncertainty analysis and the validation of

QFly. Based on the results of the validation, an outlook on further activities and up-scaling of number of collectors measured will be given.

2. State of the art of parabolic trough qualification

Among the available methods for collector shape measurements, VSHOT is a laser ray-trace system to characterize both point and line-focusing concentrators [3]. Another method called TOP involves overlaying theoretical images of the absorber tube in the mirrors onto surveyed photographic pictures [4]. TARMES was developed to achieve high accuracy and high spatial resolution and produces slope error maps in curvature direction from a set of photos [1,2]. Normal vectors of the mirror surface are derived from the spatial coordinates of the absorber tube edges, the position of the absorber tube edge reflex on the mirror surface and the nodal point of the camera. The measurement principle of TARMES is presented in Figure 1. VSHOT, TOP and TARMES have in common that the collectors are easily measured facing horizon, while the measurement of a collector module in its prevailing operating position (around zenith) involves considerably increased effort.

Another method called close range photogrammetry (PG) has been extensively applied to various CSP collectors [5]. This technique derives the coordinates of points of interest from a set of images taken from different positions. The points of interest have to be highlighted by special markers. The application of these markers to the collector surface or structure means a high preparation effort. This method can be applied to any collector orientation and with sufficient spatial resolution to detect characteristic shape deviations of glass mirrors and other points of interest like absorber tubes or axes of rotation. It is especially suitable for deformation analyses of prototypes and in cases where no reflective mirror surfaces are mounted. As the spatial resolution depends on the density of markers, it generally delivers a lower resolution than TARMES or QFly.

Another method called deflectometry or fringe reflection uses known regular stripe patterns on a screen or target whose reflection in a specular surface is observed by a digital camera [6]. From the deformations of the stripe pattern in the reflection, the local slopes of the mirror can be calculated. This method is applied to measure heliostats [7], dishes [8], Fresnel mirror panels [9] or single mirror panels of parabolic troughs [10]. However, the application of this method to entire parabolic troughs in the solar field is limited because of the considerable effort in placement and alignment of the screen relative to the concentrator surface. As parabolic trough collectors are line-focusing, in each measurement position only a small stripe of the collector can be measured.

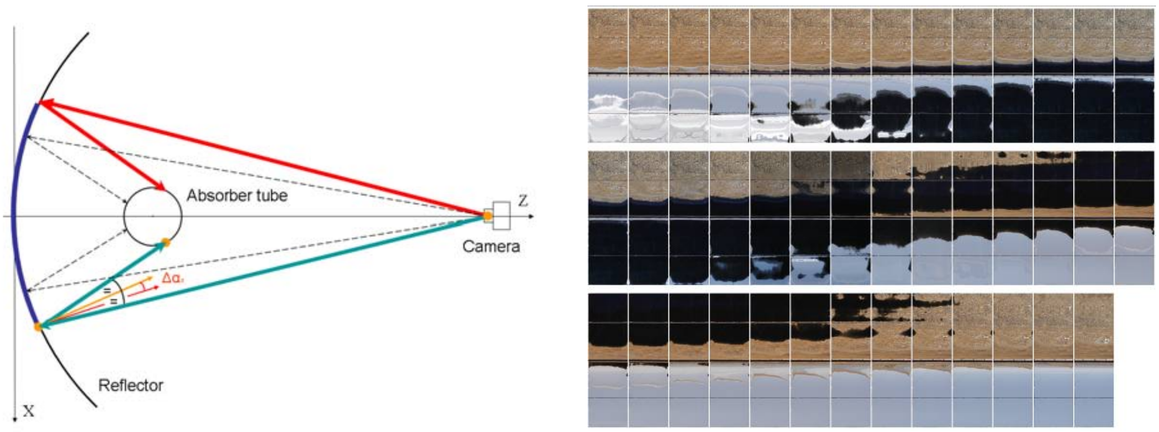


Figure 1: Left: Cross section of parabolic trough with the coordinates required for the calculation of the local slope. Right: Series of orthoimages of one mirror row while the collector is turning. The absorber tube reflex moves from the bottom up.

Referring to the state of the art, TARMES is the method with the lowest effort of instrumentation. A high resolution digital camera is required for the image acquisition. The position of the camera relative to the collector must be known with high accuracy. The position is calculated using a laser distance meter to measure the distance between camera and the parabola vertex and inclinometers to obtain the collector elevation. Due to the low instrumentation effort, TARMES is adequate to be used in combination with airborne image acquisitions. Apart from the challenges of this modification, which will be described in the next section, there are several advantages:

• Characterization of the collector in relevant operating position:

Depending on the structure of the PTC, there are significant differences between the optical performance in horizon and zenith position. Hence, the results obtained with the methods presented above are not appropriate to judge the performance under operating conditions. With an airborne data acquisition, any relevant operating position can be measured.

• Automatic measurement of large solar fields with reasonable effort:

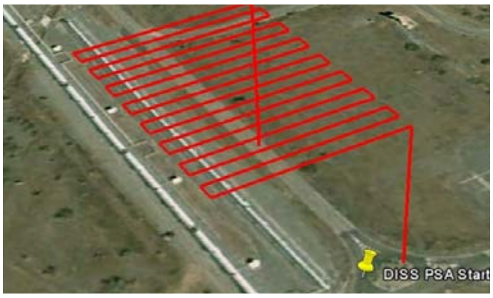
The presented methods are characterized by rather high effort and required man power in relation to the characterized surface and the dimensions of a solar field. As this effort is proportional to the number of modules to investigate, the data acquisition and evaluation for entire solar fields is hardly possible. An automated airborne image acquisition and evaluation would enable the qualification of entire solar fields.

• Unobstructed view and straightforward image processing:

Especially for TARMES, a large distance between camera and collector as well as undisturbed absorber tube reflection images without the reflection of other structures in the mirror are favourable conditions. With an airborne image acquisition and the collector facing upwards, these conditions are likely to be met.

3. QFly measurement concept

The TARMES measurement principle shown in Figure 1 is based on a stationary camera. Here, the variety of view angles on the PTC is achieved by rotating the collector between consecutive images. With airborne image acquisition, the collector must remain at a certain elevation angle. The variety of view angles is achieved by moving the camera perpendicular to the collector axis. Figure 2 shows a possible flight path over a collector loop at the Plataforma Solar de Almería (PSA) as well as an orthoimage of an entire EuroTrough collector module.



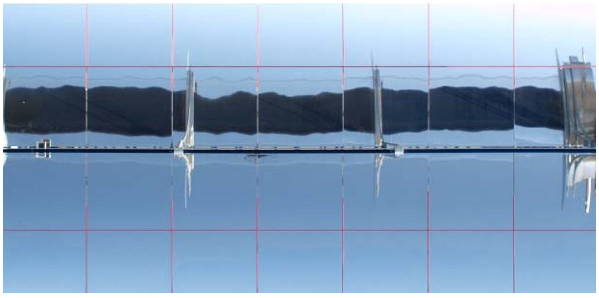


Figure 2: Left: Simulated QFly flight path over the DISS loop at the PSA. Right: Orthoimage from airborne image acquisition. Gaps between mirror panels were highlighted with red tape to ease detection of panel cross points (see section 5.1.2)

Independent from the way of image acquisition, both TARMES and QFly require the same information to enable the determination of the slope deviations from the data. This is in particular the camera position relative to the collector (three spatial coordinates and three angles describing the orientation of the optical axis) as well as the distortion parameters of the lens. The following aspects of airborne image acquisition were identified as major challenges for a successful implementation of QFly:

- Determination of camera and collector position: With commercial available GPS systems, localisation accuracy below 2 meters is hardly possible. However, the camera position relative to the collector module must be known with an uncertainty less than 50 mm for a typical distance camera to module of 40 meters. Different options to increase the localisation accuracy were investigated like differential GPS, tracking total station or close range photogrammetry. The chosen approach to meet the high demands on accuracy and level of automation will be described in Section 4.2.

- Non-ideal image quality: Measurement images of a PTC close to zenith position are favourable since only the reflection of the sky and the absorber tube are observed in the mirror. However, perfect CSP conditions like a clear sky and intense solar radiation may cause difficulties in the image processing, since direct reflections of the sun and/or weak contrast to the ground may occur.
- Evaluation of large data sets: Former TARMES evaluations are characterized by low automation level. Interactive input from the user is required to locate module corners, to adapt the threshold for the detection of the absorber tube reflex and to detect artefacts. For large datasets, a higher degree of automation is desired.
- Hardware restrictions: The provided quadrocopter can operate up to wind speeds of 6 m/s. However, even at lower wind speeds, gusts may cause motion of the camera and consequently decrease image quality. Payload is restricted to 0.7 kg without major reduction of the flight time per battery cycle. This has consequences for the selection of lightweight camera and lens.

In the following section, details of the measurement procedure are described. Possible solutions for the above mentioned challenges are presented.

4. Measurement procedure

The measurement procedure can be split into preparation and image acquisition on the one hand, and the image processing and evaluation of the collector performance on the other hand. Even though QFly is up to now only used for the characterization of a single collector module, all steps of the measurement procedure were structured in way to enable the evaluation of an arbitrary number of modules without further modifications.

4.1 Hardware and image acquisition

A radio controlled quadrocopter, a so called AUMAV (**A**utonomous **U**nmanned **M**icro **A**erial **V**ehicle) has been used to carry out the measurements. It is delivered with a servo-motor-operated camera arm that enables pitch movement and compensates limited roll motions during flight. The quadrocopter control system connects directly to an Olympus PEN camera with a resolution of 12 megapixels combined with a 17 mm lens. With that camera as payload, flight times of up to 45 minutes can be realized. For autonomous flight procedures the AUMAV can read in so called waypoint files containing all information to characterize the flight route, the camera orientation and timing of the image acquisition. To design and automatically create these waypoint files, a software tool has been programmed. It incorporates specific solar field properties like plant location and orientation, field layout and type of collector investigated. Starting from a single PTC measurement, the software tool can relocate and adapt the flight path to entire collectors or loops. Pre-checking the flight route and simulating the image acquisition from the scheduled camera positions enable the optimization of measurement flights before lift-off of the quadrocopter. That way, an individual flight path can be planned efficiently, ensuring that the image series contains all the information necessary for the image processing and appropriate measurement accuracy. After these preparations, the quadrocopter launches for the image acquisition flight. It approaches the collector laterally and the camera starts to take images, as soon as it enters the acceptance angle of the collector, e.g. the reflex of the absorber tube is then visible in the images. About 30 to 50 images are taken along that range. Additional images from a variety of perspectives are taken to enable the determination of the camera position as described in the next section.

4.2 Determination of camera position

Precise determination of the camera position has highest relevance for the measurement accuracy. Since the quadrocopter built-in GPS with an achievable accuracy of 2 m under ideal conditions is not sufficient, other options were investigated. Differential GPS could be an option but was not available. Attaching a remote prism to the quadrocopter to track its position with a total station was an option, but because of increased load, increased cost and problems with synchronization between image acquisition and tracking, this approach was rejected. Furthermore, all these localization measurements would only return the camera position in an arbitrary coordinate system without information about the orientation of the optical axis. As a consequence, a photogrammetric evaluation of the measurement images has been considered a feasible approach. As points of interest in the images, the module corners and additional coded markers placed around the PTC were used. With this information, the camera position and orientation relative to any module of the solar field can be determined. Additional results from this step are the distortion parameters of the camera lens. Being side-products in normal close-range photogrammetry, these parameters are of high importance in the present case, because they enable completely automated post processing of the image data.

The photogrammetric evaluation is the first step in the evaluation procedure. At first, the images are evaluated by a commercial evaluation software (Aicon 3D studio), which is used to determine the coordinates of only the coded markers distributed evenly around the PTC. From the camera positions and the roughly known position of the PTC corners relative to the initially defined coordinate system, the PTC corners can be detected in the images and used as additional observations. At the end of that process, the 3D coordinates of all PTC corners as well as all camera positions are known with high accuracy in the same coordinate system (uncertainty of PTC corners about ± 5 mm, camera positions about ± 6 mm for relevant heights above the PTC of 30 m). At that stage, all information for orthoimage creation, distortion correction and calculation of the slope errors is available. Figure 3 shows and areal image (left) and a measurement flight reconstructed by photogrammetry (right). Only the camera positions on the straight line directly above the module (marked with asterisk) contribute to the evaluation of the slope deviations, while the other perspectives are used to enhance the accuracy of the photogrammetric camera localization.

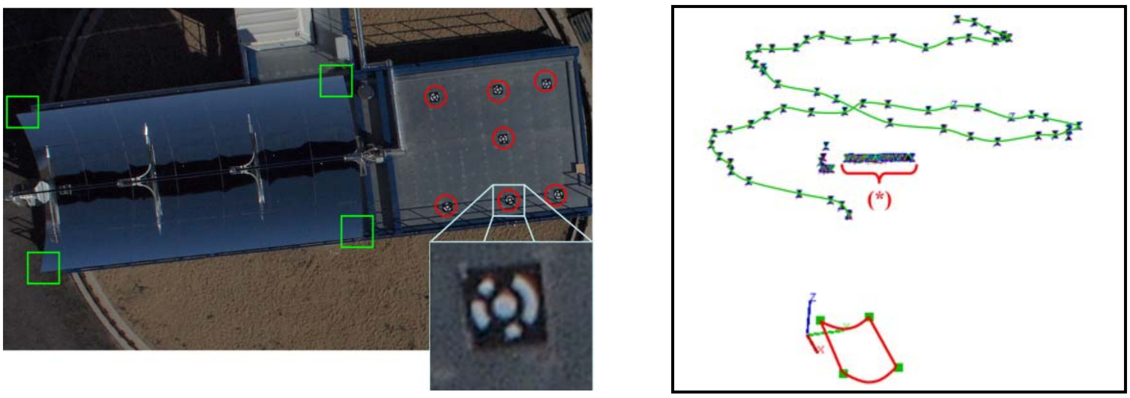


Figure 3: Left: Aerial image with additional coded markers (inside red circles) and region of interest (green rectangles) for the detection on the module corners. Right: 3D setup of a measurement flight reconstructed by photogrammetry. Square markers represent the module corners. The camera positions are marked with crosses. Asterisk: Camera positions used for slop deviation evaluation.

The uncertainty analysis presented in section 5 reveals that the uncertainty in measuring the camera position is a sensitive parameter and may contribute significantly to the measurement uncertainty of the collector performance, if not minimized. The estimation of the uncertainty of the photogrammetric localization procedure is described in detail in section 5.1.1.

4.3. Image processing and evaluation

The spatial information of the measurement setup (camera position relative to collector module) is used to create a set of orthoimages. The reflex of the absorber tube in each orthoimage is detected via thresholding. Depending on lighting conditions, different combinations of the color channels and filters are used to minimize the occurrence of artifacts. At the end of the image processing, there is a matrix containing the edges of the absorber tube reflexes assigned to the different camera positions. Based on the principle shown in Figure 1, this information is used to calculate the slope deviation at the position of the absorber reflex.

5. Uncertainty analysis, results and validation

The TARMES measurement principle has been validated for a measurement set up characterized by a stationary camera and rather large distances between collector and camera of approximately 200 m [1,2]. The QFly measurement set up is different, so that modifications in the uncertainty of the input parameters have to be considered. This is in particular the uncertainty of the camera position and the accuracy of the detection of the absorber tube reflex. This section addresses several aspects of the uncertainty analysis, e.g. the overview of all input parameters, estimation of the order of the uncertainty of these parameters and their influence on the local measurement uncertainty. At the end of this section, there is a comparison of shape deviations of the same collector in zenith position obtained with different measurements: QFly (airborne camera), TARMES (stationary camera) and a high spatial resolution close range photogrammetry, which serves as absolute reference. The results of that comparison have to be judged with respect to the expected measurement error resulting from the uncertainty analysis.

5.1 Measured quantities and their uncertainties

The calculation of the local slope deviations of the mirror according to the TARMES/QFly method involves three spatial coordinates:

- The position of the nodal point of the camera and the orientation of the optical axis
- The position of the reflex of the absorber tube on the mirror surface
- The position of the edge of the absorber tube, from which originates the corresponding reflex on the mirror surface

Other parameters, which have an influence on the result, are properties of the concentrator like slope deviations in longitudinal direction. Hence, the uncertainties of these parameters, whether measured directly or calculated, must be known to estimate the measurement uncertainty of the slope deviation. For the calculation of the uncertainty of the local slope deviation, the GUM Workbench [11] was used. Using the equation to calculate the local slope deviation from the input data, the GUM Workbench calculates numerically the first order derivates. For a PTC module with EuroTrough dimensions (1.71 m focal length and 5.77 m aperture width), the expected measurement uncertainty has been calculated based on estimates for the uncertainties of the input parameters. In this paper, all uncertainties are expressed in terms of one standard deviation.

5.1.1 Camera position relative to collector module

Close range photogrammetry is typically used to estimate spatial coordinates of any object. However, during the bundle adjustment optimization process, the position and orientation of the camera is additionally calculated and has similar accuracy as the object points. To check the measurement uncertainty of the camera position using photogrammetry, a tracked prism was mounted above the nodal point of the camera and the prism position was measured with a tracking total station. The total station measurement uncertainty in this mode is below 5 mm [12].

The camera was mounted to a lifting platform to enable image acquisition in the same height as encountered in the flight routes of QFly. From the platform, the camera took images of an arrangement of coded targets similar to the QFly setup. For each image, the position of the prism, and in this way, the camera, was also measured with the total station. Various measurements were necessary to identify and eliminate additional sources of uncertainties like camera movement due to wind and the synchronization between total station measurement and triggering the camera.

Figure 4 gives an overview of the measurement setup and the results. From Figure 4, we observe a deviation between the two methods in horizontal direction of about 8 mm for a height above ground of 30 meters. Considering the uncertainty of the total station conservatively with an amount of 3 mm, the uncertainty in position of the camera nodal point relative to the prism (±3 mm) and additional influences caused by unintentional movement of the platform (±3 mm), the uncertainty of the absolute horizontal camera position is calculated to be about ±6 mm. As for QFly, the relative camera position to the collector module corners (estimated uncertainty about ±5 mm) is relevant, the total uncertainty in horizontal direction ($\delta x^2+\delta y^2$) was calculated to ±8 mm. Photogrammetric uncertainty analysis suggests a double uncertainty for z-direction (vertical) than for *x*- or *y*- directions (horizontal). Hence, the total uncertainty in vertical direction is assumed to ±11 mm.

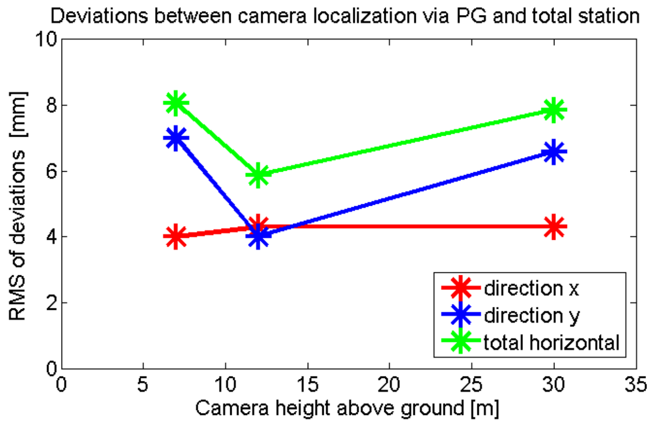


Figure 4: Left: Camera and remote prism set up observed trough the ocular of the total station, as applied to determine the absolute accuracy of the camera localization by photogrammetry. Right: Obtained horizontal deviations vs. height of the camera above ground level. No increase of the uncertainty with height could be observed, since other factors like the total station accuracy and unintentional movement due to wind of the platform are the dominating effects, especially for the measurement at 7 m height.

5.1.2 Position of absorber tube reflex in orthoimage

There are two steps in the image processing that have an influence on the position of the absorber tube reflex:

- The creation of the orthoimage of the aperture plane, which is carried out by a spatial transformation of the image coordinates taking into account the camera position relative to the collector module and lens distortion parameters
- Thresholding to distinguish between tube reflex and background

To determine effects originating from the projection and distortion correction, the positions of the gaps between mirror panels in the orthoimage were compared to the true position in the module. Thereby the standard deviation of uncertainties caused by remaining distortion was verified to be below 2.5 mm within the complete collector area. Due to inaccurate thresholds, varying image brightness or reflected structures similar to the absorber tube the uncertainty of the absorber tube edge detection accuracy is estimated to 2 pixels, what for the instant investigation corresponds with an uncertainty of about 8 mm.

5.1.3 Deviations of absorber tube from focal line

Since the absorber tube represents the “pattern” used for the deflectometry, its position relative to the ideal focal line must also be known with high accuracy. It was recognized during the validation measurements, that there is significant movement of the absorber tube caused by elevation angle changes of the PTC module. Different means to measure the deviation of the absorber tube from the focal line were tested to reduce systematic errors caused by wrong assumptions about the actual tube position. However to uncertainty of the obtained absorber tube position still has to be estimated realistically being about 2 mm in horizontal direction and 4 mm in vertical direction. That implies that the main part of the overall uncertainty of the current measurement setup is induced by this effect and further effort should be spent in developing more accurate measurement methods.

A different approach considered for qualification of parabolic trough modules is neglecting potential deviations of the absorber tube from focal line. Hereby a combination of deviations of mirror slope and absorber tube position is obtained, which is relevant for overall collector performance. In this case, however, slope deviations of the mirror surface cannot be resolved separately. Further investigations are intended to survey the adequacy of establishment a new collector parameter describing this optical overall efficiency.

5.2 Local measurement uncertainty

The uncertainties of the input parameters estimated in the previous sections served as input for the calculation of the uncertainty of the local slope deviation. In Table 1, the results obtained with the GUM workbench are displayed. The formulas for the local uncertainty as used in the GUM Workbench were also implemented in Matlab, in order to have a graphical representation of the expected distribution of the measurement uncertainty over the module. This spatial distribution is presented in Figure 6 together with actually observed deviations.

Uncertainty in …	**Assumed Uncertainty**	**Uncertainty in *SDx* for point at parabola vertex (*x*=0 mm, *y*=0)**		**Uncertainty in *SDx* for point at outer (*x*=2885 mm, *y*=0)**	
		absolute [mrad]	**relative [%]**	**absolute [mrad]**	**Relative [%]**
Deviation of absorber tube from focal line	2 mm horiz. 4 mm vert.	0.58	86	0.67	36
Position of reflex on mirror in curvature direction	8.4 mm	0.20	10	0.23	4
Position of camera relative to PTC	8 mm horiz. 11 mm vert.	0.13	4	0.14	2
Slope deviation longitudinal direction *SDy*	4 mrad	0	0	0.78	49
Height deviations from ideal collector geometry	2 mm	0	0	0.34	9
Resulting uncertainty in *SDx*		**0.6**		**1.1**	

Table 1: Final assumptions used for the calculation of the local and global measurement uncertainty of QFly

5.3 Global measurement uncertainty

Describing the overall quality on a module level, the RMS value of all local slope deviations is an appropriate parameter. Since the errors of single measurement points are partly correlated due to widespread influence of input parameters and as the definition of the RMS causes an asymmetric distribution of expected measurement results, an ordinary propagation of uncertainty is not applicable. Hence, a Monte Carlo approach was used to estimate the uncertainty of the RMS value. Each input parameter was overlaid with a Gaussian distributed noise corresponding with an individual spatial pattern to approximate expected correlations between adjacent measuring points. The resulting asymmetric distribution function of the RMS has an expected value (mean of repeated measurements) differing from the best estimate of the real RMS. By calculating the RMS just out of measured slopes leads probably to a slight overestimation of the real value, while the best estimate of the measurand actually depends on the expected uncertainty of the input parameters. By considering this effect the measured RMS value on module level amounts 2.38 mrad, while the best estimate was calculated to 2.23 mrad with an uncertainty of ±0,1 mrad based on a level of confidence of 68.3%.

5.4 Validation

A single representative PTC module (EuroTrough on KONTAS rotatable test bench at PSA) was used for the validation measurements. Three different methods were applied to determine the mirror shape of that module in zenith position:

- A photogrammetric measurement of the module was carried out. Since the photogrammetric result is not affected by the uncertainties listed in Table 1, this result may serve as an absolute reference for both TARMES and QFly. Selected mirror panels were equipped with a target raster of 0.15 x 0.15 m edge length for resolving the long-wave deviations of the mirror panels from the ideal shape. With moderate effort, this was only possible for two of the seven mirror panel rows. Photogrammetry deviations are estimated to be in the range of 0.1 mm, which would result in local uncertainties in slope error deviations of 1 mrad.
- A TARMES measurement with a stationary camera on an elevator platform approximately 25 m above the parabola vertex serves as a second reference for QFly. Using TARMES, the camera position is known with high accuracy due to the use of high resolving inclinometers for the determination of the module orientation. The local measurement uncertainty is estimated to be in the range of 0.6 to 1.1 mrad.
- The QFly system took images from a comparable orientation relative to the collector as the before mentioned TARMES measurement. Local measurement uncertainty in slope error deviations is estimated to be in the range of 0.6 to 1.1 mrad.

These three measurements are expected to deliver the same slope deviation results within the previously presented error budgets. Figure 5 shows the results obtained from a TARMES measurement and a QFly measurement of the same PTC module. The numbers assigned to each mirror panel in the plot are RMS values of the slope deviations *SDx* (compared to an ideal parabolic shape). The characteristics of the local slope deviations *SDx* are almost equal, although there are small differences between some panels in the overall RMS values of the *SDx*.

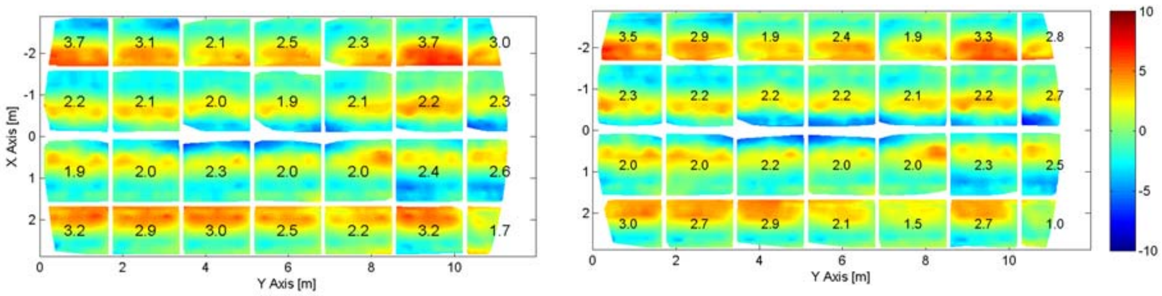


Figure 5: Left: *SDx* values [mrad] measured by TARMES. Right: *SDx* values of the same module as measured by QFly

To assess the observed differences between both methods, Figure 6 shows the difference matrix (left) and the expected measurement uncertainty of QFly (right).

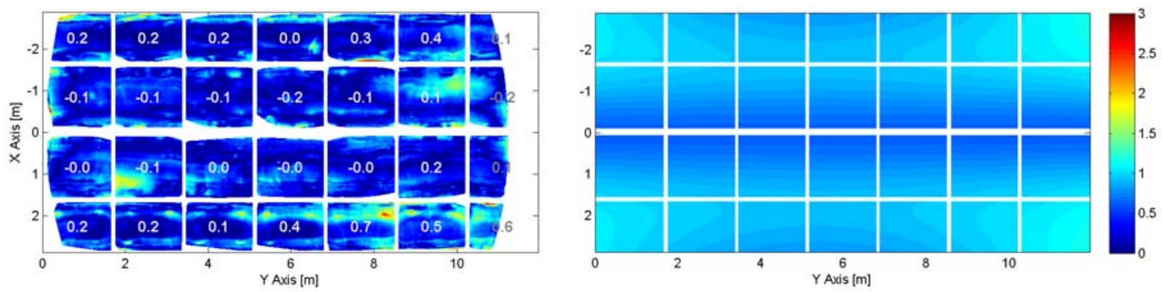


Figure 6: Left: Difference between *SDx* [mrad] from QFly and TARMES. Right: expected QFly measurement uncertainty (one standard deviation) for that particular measurement setup.

It can be stated that the local differences are well within the expectations resulting from the uncertainty analysis. During the time period of two weeks between both measurements, the collector module was in operation. Some of the deviations observed may be real deformations of the collector. This might be especially the case for the panels in the lower row of the module, where local deformations close to the panel attachment points are visible. Additionally, the absorber tube position affects the measurement result. Although absorber tube position is taken into account in both measurements, there is still potential in enhancing the determination of this particular input parameter. In Figure 6 left, the differences in *SDx* rise for the outer facets with higher *y*-values. This can be explained by a not exactly determined *z*-position (vertical) of the absorber tube. On the module level the RMS of *SDx* values was measured to 2.38 mrad by QFly and 2.47 mrad by TARMES, which lies well within the respective measurement uncertainties.

As the result of the photogrammetric evaluation is not affected by the absorber tube position, for two facet rows, the *SDx* obtained by QFly was compared to the *SDx* determined via photogrammetry (see Figure 7). The numbers assigned to each panel represent the difference of the RMS values of the *SDx* between QFly and photogrammetry measurement. Here, the deviations of the RMS values of the panels are small, while local deviations are mainly caused by the limited spatial resolution of the photogrammetry.

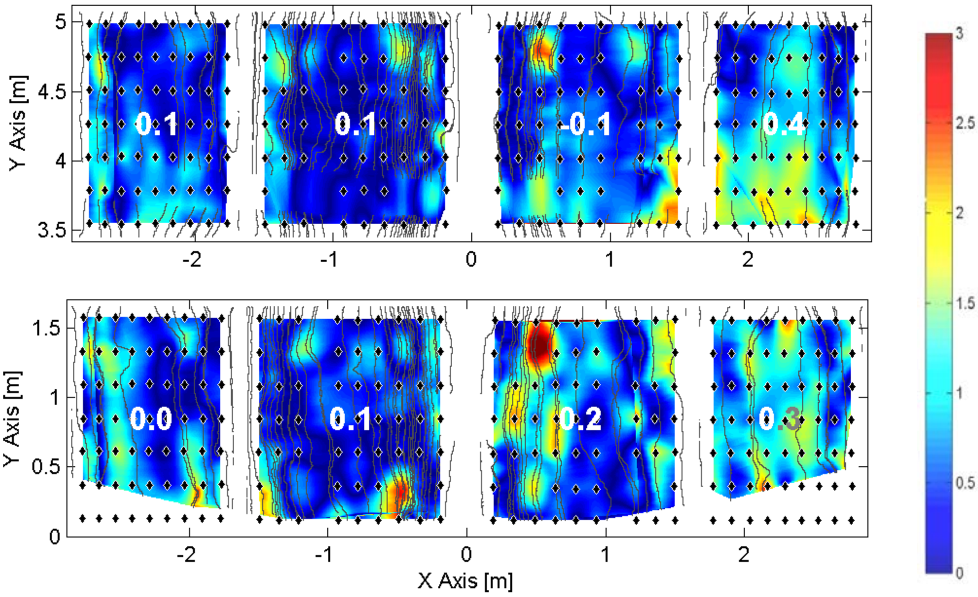


Figure 7: Comparison of *SDx* values [mrad] obtained by QFly and photogrammetry for two facet rows. Black dots are points measured by photogrammetry. Vertical randomly curved lines represent detected absorber tube edges in QFly. Most deviations between both methods can be explained by the limited spatial resolution and missing points of the photogrammetry.

6. Conclusion and outlook

The air-borne shape measurement method for parabolic trough collectors QFly was successfully tested and validated. Measuring a EuroTrough PTC module with QFly, TARMES and photogrammetry yielded in similar results within the expected uncertainties.

QFly consist of a remote controlled and camera-equipped quadrocopter. The collector shape is calculated from photos of the mirror surface showing the absorber tube edge reflex, also known as TARMES measurement principle. Close range photogrammetry is used to deduce camera position, orientation and lens distortion parameters.

An uncertainty analysis revealed that sensitive input parameters are the correct determination of camera and collector position, correct edge detection of the absorber tube reflex in the mirror, and a correct determination of the absorber tube position. Using a photogrammetric approach, it was demonstrated, that the camera position can be determined with an uncertainty of about 8 mm in horizontal direction for flight heights of

30 m. Existing software for the generation of orthoimages and edge recognition was enhanced, and a concept to evaluate large datasets was prepared. The uncertainty analysis predicted a local uncertainty in *SDx* to be between 0.6 and 1.1mrad, depending on the position within the collector module. The global uncertainty of the RMS of *SDx* values of a whole collector module was estimated to be about 0.1 mrad. Comparison of the QFly measurement with TARMES measurement showed a very good agreement within the expected uncertainties. The RMS of *SDx* values over the whole collector module was measured to 2.5 mrad by TARMES and 2.4 mrad by QFly.

Also, the comparison of *SDx* values obtained from a photogrammetric measurement with the QFly results showed a good agreement. Differences of RMS values of *SDx* on a mirror panel level were in the range from 0.0 to 0.4 mrad. These deviations can be explained by limited spatial resolution of the photogrammetry.

Upcoming activities are to upgrade the measurement technology to characterize large parts of solar fields including a post-processing to obtain module and collector alignment and to develop metadata analysis of the large datasets.

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