

High-Resolution Measurement System for Parabolic Trough Concentrator Modules in Series Production

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Abstract

A new measurement system able to measure the shape accuracy of complete mirrored parabolic trough modules (EuroTrough dimensions: length ≈ 12 m, aperture width ≈ 6 m) in series production was developed. The applied deflectometry measurement technique is based on the reflection of regular patterns in the mirror surface and their distortions due to mirror surface deviations. Key features of the measurement system are its high spatial resolution of about 1 million points per module, its low global measurement uncertainty of less than 0.2 mrad and its total measurement time of less than 9 minutes. This allows a 100% optical quality control of the production of the collector modules for a typical parabolic trough solar thermal power plant. The system is validated by comparison to photogrammetry and laser radar measurements, by measuring a flat reference surface and by a repeatability and sensitivity study. The found uncertainties are within the expected range from theoretical uncertainty analysis and the determined measurement repeatability is high. This makes the new measurement system, called QDec-M, a valuable tool for final geometric quality control of parabolic trough concentrators in series production and for continuous optimization of concentrator optical quality and prototype development.

Keywords: Solar concentrator, shape accuracy, optical quality, quality control, optical measurement, deflectometry

1. Introduction

The solar field consisting of a large number of concentrator modules is the major cost component of a parabolic trough power plant. Deviations of the ideal shape of the reflective surface of the concentrators have a significant impact on the field efficiency and thus on the performance of the power plant. To decrease the manufacturing costs of parabolic trough collectors, while maintaining or even improving their optical quality, economical and accurate measurement systems for inline quality control are needed. At present, the geometric quality of parabolic trough collectors is only checked at the level of the steel support structures. The geometric quality of the curved mirror panels is usually controlled separately at the mirror manufacturer. It is generally supposed that if both components are within specifications then the fully assembled module is also within specification, but there is evidence that this is not always the case and no final quality control in series production is possible so far.

This paper presents a newly developed measurement system capable of measuring mirrored parabolic trough modules at the end of the production line within regular manufacturing cycle time. The software and hardware has been developed by CSP Services and was tested and validated in cooperation with Abengoa in their facilities in Seville, Spain. The measurement technique is based on the principle of deflectometry which has been used in other measurement applications and was initially developed by the German Aerospace Center (DLR) [1,2,3,4].

2. Measurement System

2.1. System Description

The newly developed measurement system is based on the existing QDec system, an optical measurement system for high resolution and high precision quality assurance measurements of the slope deviations of individual CSP reflector panels. The new system is called QDec-M as it is capable of measuring entire modules. It uses a non-contact optical measurement and digital image processing technique based on the deflectometry measurement principle. This method uses the images of reflected regular stripe patterns taken by a digital camera to calculate the local normal vectors of the reflecting surface using vector geometry (Figure 1). The standard system consists of the following basic components: a target screen where the stripe patterns are projected, a camera that takes images of the reflected stripe patterns seen in the mirror object, and a control unit with an industrial computer. Specially developed evaluation software controls the measurement and uses digital image processing to calculate the local normal vectors of the reflecting surface and their deviations to design. For this the positions of the camera, the mirror object and the target screen relative to each other need to be known. More detailed descriptions of the measurement technique can be found in [1,2].

Figure 2 shows the realized set-up for the measurement of a typical parabolic trough module (EuroTrough dimensions: length ≈ 12 m, aperture width ≈ 6 m). The mirrored collector module is positioned horizontally on a support that represents the mechanical boundary conditions in the field (one pylon on each side, module hanging freely) and that provides a reproducible measurement position. A horizontal target with a white surface is placed about 5.5 m above the parabola vertex of the module and has a size of approximately 11.5 m x 5.5 m. Two projectors that project regular line patterns on the target are installed aside the module on the ground. Each of them covers slightly more than half of the target surface. Three cameras that take images of the concentrator module with the reflected line patterns are placed along the center line of the target (red circles). Each one covers a measurement area of slightly more than one third of the module. A fourth camera for taking the calibration photos of the stripe patterns on the target is positioned between the projectors. The position of the parabolic trough module in the measurement system is measured automatically by a total station (about 3m above ground on the right side in Figure 2 right). For this purpose prism adapters can be fixed at reference points at the panel edges. The designed total space required by the measurement set-up including the collector module, supports and target structures is a cube of about 9.0 m x 15.0 m x 8.0 m. The measurements have to be performed in a darkened surrounding to get enough contrast with the digital projectors. This is achieved by moveable curtains that cover the measurement area. A gantry crane from the production line is used to position the modules on the supports.

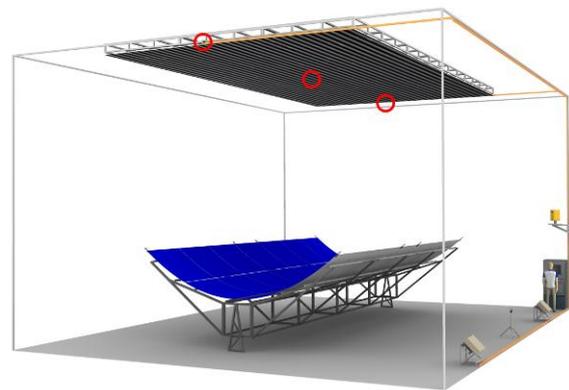
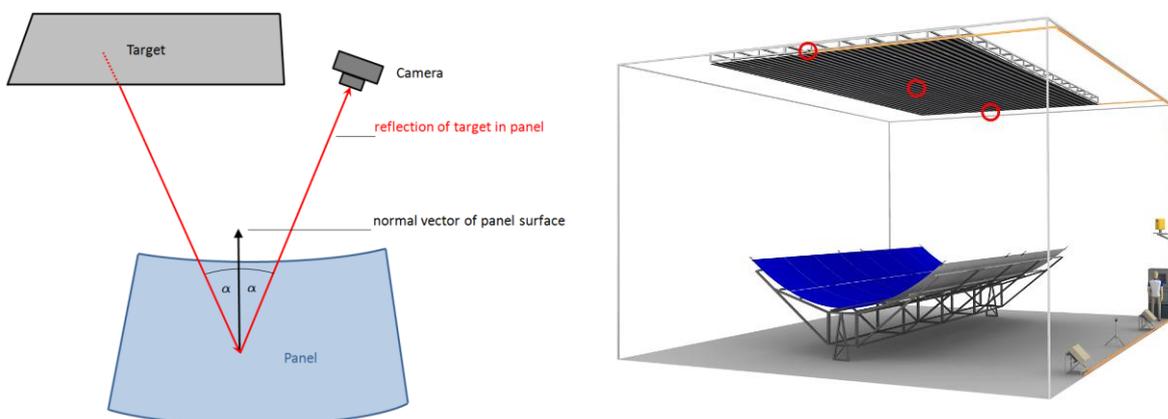


Figure 1: Measurement principle of deflectometry **Figure 2: Set-up of realized measurement system**

Figure 3 and Figure 4 show example measurement images of the stripes on the target and their reflection image in the module. The distortions in the reflected stripe pattern indicate local deviations of the mirror panels. A computer algorithm developed in Matlab® evaluates the images, calculates the surface normal vectors and visualizes the results. It takes into account and corrects all known systematic error influences

such as distorted projection of stripe patterns due to oblique projection angle and projector lens distortions, non-linearity of projector and camera, background lighting, inhomogeneous reflection properties of mirror and target, perspective rectification, lens aberrations, etc. A total measurement time of less than 9 minutes (4 minutes measurement and 5 minutes evaluation) is achieved, which allows a 100% control of the production of the collector modules for a typical parabolic trough solar thermal power plant.

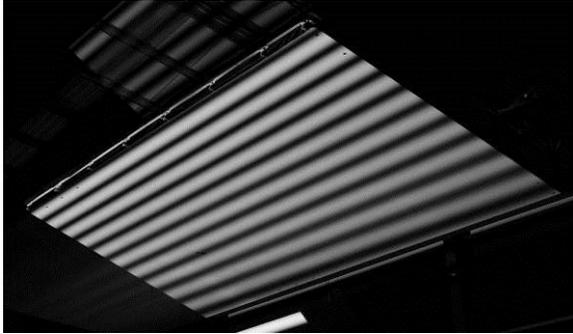


Figure 3: Example images of projected stripe patterns on target screen

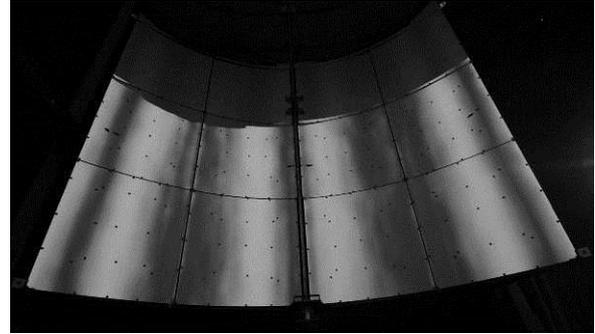


Figure 4: Example images of reflected stripe patterns used for evaluation

2.2. Measurement Results

The primary measurement results of the system are maps of surface slope deviations in x (curved) direction and y (non-curved) direction. Typical resolution is about 1 million measurement points which corresponds to a spatial resolution of 10 mm x 10 mm per measurement spot for a EuroTrough type concentrator. The partial measurements of the three cameras used to cover the entire module surface are stitched together to get one final result. Figure 5 shows an example of measured slope deviations in x direction of a test collector module. The test module was assembled as an individual module for R&D purposes. Presented results and quality parameters are therefore not representative for series production quality. The sign convention is such that angular deviations are positive for deviations that cause reflections of ideal incoming rays above the focal line and negative for deviations that cause reflections below the focal line.

A typical, repetitive waviness of the individual mirror panels can be recognized. Some of the panels exhibit systematic positive or negative deviations of the entire panel, which indicates a tilt. The RMS (root mean square) value of the slope deviation of the module (SD_x) is 1.9 mrad. The RMS value of the focus deviation (FD_x) for this module is 8.1 mm.

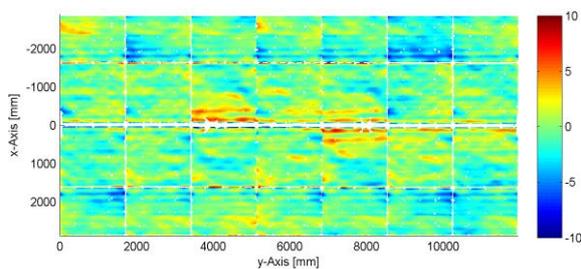


Figure 5: Slope deviation from ideal surface in curved direction (x direction), in mrad

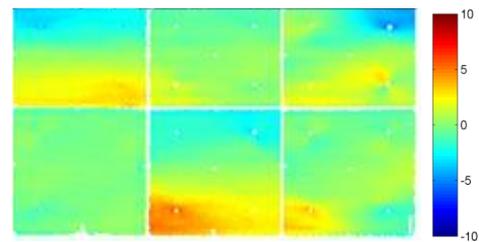


Figure 6: Difference in local slope deviations between module with loose and tightened panel screws, in mrad

As the measurement system has a high spatial resolution and high repeatability, even small influences on the mirror shape, such as the mirror mounting procedure and the influence of the junction between mirror pad and mounting point can be investigated. Figure 6 shows the differences in local slope deviations between module with loose and tightened panel screws. The white dots represent regions where photogrammetry target stickers have been applied. Since they cover the reflective surface, these areas could not be measured. At some mounting points the angle of the mirror bracket surface was slightly deviated in order to study its effect on the mirror shape. It can be clearly seen that tightening the panel mounting screws at the deviated

mirror brackets introduces moments and stresses that can deform the mirror panels considerably. This type of measurements can be used to specify reasonable tolerances for the assembly of the steel structures and to identify systematic errors in the collector design or assembly process during prototype development.

3. Validation

The measurement results were validated by measuring a full-size collector module with close-range photogrammetry and with a laser radar for comparison and by measuring a large water surface as a flat reference object. Additionally, a repeatability and sensitivity study to investigate the influence of the module positioning was performed. Finally, the results are compared to the expected uncertainties based on a theoretical uncertainty study.

3.1. Comparison to Photogrammetry and Laser Radar Measurement

3.1.1 Photogrammetry

Photogrammetry (PG) is a measurement technique that employs information from digital images to determine the geometric properties of objects [5]. As it is a developed industrial standard tool it can serve as a valid cross-check for the deflectometry method. In CSP applications, photogrammetry is commonly used to determine the shape and possible deformations of large-scale solar concentrator structures [6, 7]. However, with a higher density of measured points, PG can also be exploited to measure the shape of the concentrator surface.

In the present case 29 points on each panel (812 points on the entire module) were used for the measurement. The measured coordinates have been interpolated and slope deviations have been calculated (Figure 7). The difference between the measured slopes with photogrammetry and deflectometry (PG-DF) are shown in Figure 8. The remaining local differences between both measurement methods are mostly a result of the low resolution of the photogrammetric measurement. The comparison shows that large scale deformations of the individual panels are measured correctly with both measurement methods. There are slight systematic differences in the inner panels. On the left side the upper panels are slightly negative and the lower panels are slightly positive. On the right side this effect occurs vice versa.

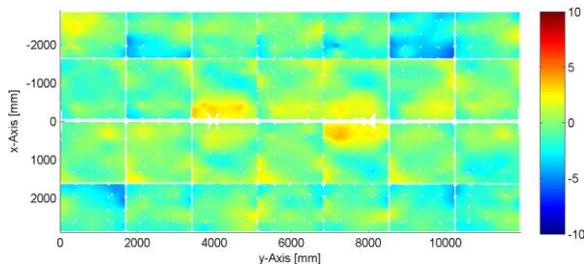


Figure 7: Slope deviation from ideal surface in curved direction, measured with PG, in mrad

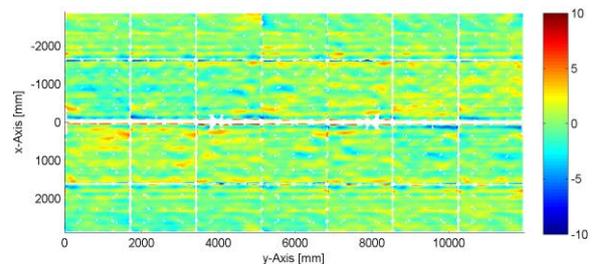


Figure 8: Difference in slopes in curved direction between PG and deflectometry, in mrad

3.1.2 Laser Radar Measurement

A laser radar is a non-contact coordinate measurement device capable of measuring large point clouds at stationary surfaces.

The product used for the presented measurements is the Nikon MV330 (Figure 9). It uses a focused coherent IR laser with modulated frequencies to get the range information of the target point. In combination with encoders to track the azimuth and elevation the coordinates can be determined in a spherical coordinate system [8]. The software used with the laser radar is SpatialAnalyzer (SA) created by New River Kinematics. In order to be able to scan the whole reflector without restationing the laser radar it was mounted on a tripod as shown in Figure 10.



Figure 9: Laser radar (photo taken from <http://www.nikonmetrology.com>)



Figure 10: Laser radar measurement setup

The Nikon laser radar routines allow scanning a surface target-less with two different methods. ‘Vision Scanning’ measures points on the surface at the current beam location. With ‘Metrology Scanning’ a small surface patch will be scanned around the beam location and the intersection point will be returned with a proprietary averaging method.

For this study the less accurate, but faster ‘Vision Scanning’ method with a stacking of eight has been used. The stacking parameter improves the signal to noise ratio through an averaging process. Nikon recommends stacking values of no less than two. A perimeter of four points has been measured for each mirror at its corners to define the scanning region. The laser radar then measures a grid of points with a configurable point distance in between the perimeter points. The point distance has been chosen to get a comparable resolution to the QDec-M system. The measurement process of the 28 mirror panels took around 5 hours. A similar scanning process with the more accurate ‘Metrology Scanning’ method would have taken 5 to 6 days. Principally the laser radar is able to measure points on specular surfaces, but since it does not refocus under the ‘Vision Scanning’ mode it was necessary to coat the reflector with a black opaque painting to reduce noise in the measurements.

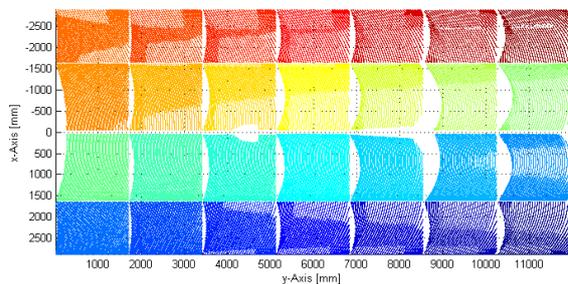


Figure 11: Measured point clouds

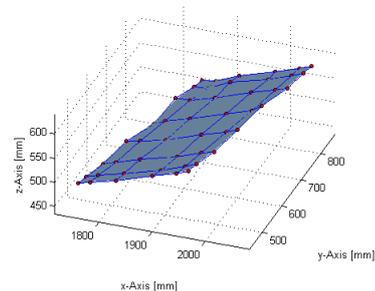


Figure 12: Non-uniform rational B-splines (NURBS) for a segment of a mirror panel

To compare the laser radar measurement to the QDec-M measurement and to calculate the slope a non-uniform rational B-splines (NURBS) surface has been approximated panel wise through the scattered point clouds. The optimization of the weights, the control point grids and the degrees of the NURBS surfaces was done with genetic algorithms. The least squares of the coordinate deviations to the measured point cloud were used as cost-function to determine the fitness of each individual. The initial populations were generated

using the topological information of a parabolic cylinder [9, 10, 11].

Figure 13 shows the result of the laser radar measurement (LR) given as slope deviations. The remaining noise in the coordinate measurement leads to considerable noise in the slope deviations due to the small distances between the measurement points. This is especially the case for the left side of the module, close to the position where the laser radar was positioned and high elevation and azimuth angles of the laser occur. In order to reduce this noise a filter was applied that averages the measurement points in a neighborhood of 21x21 points (Figure 14). This average filter eliminates most of the noise, but also filters some of the existing local deviations. The RMS value of the slope deviations (SDx) for this measurement is 1.7 mrad.

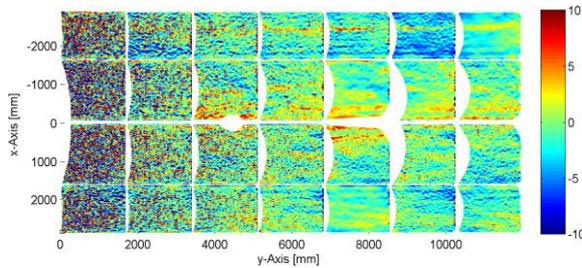


Figure 13: Slope deviation from ideal surface in curved direction, measured with LR (raw data), in mrad

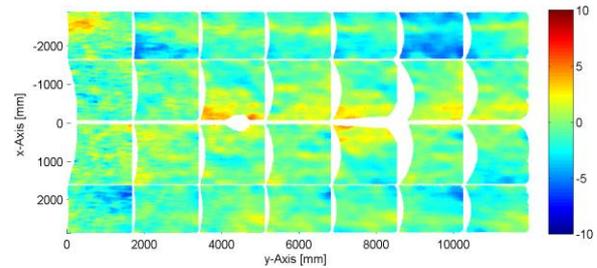


Figure 14: Slope deviation from ideal surface in curved direction, measured with LR (filtered), in mrad

Figure 15 shows the differences between the filtered laser radar measurement and the deflectometry measurement (LR-DF). In general there is a good agreement. Local differences can be seen that are mostly caused by the remaining noise (left side) and the reduced local resolution of the laser radar due to the strong applied filter. As in the photogrammetry comparison there are slight systematic differences in the inner panels. On the left side the upper panels are slightly negative and the lower panels are slightly positive. On the right side this effect occurs vice versa.

Figure 16 shows the differences between the filtered laser radar measurement and the photogrammetry measurement (LR-PG). In general there is a good agreement. Local differences can be seen that are mostly caused by the remaining noise (left side) and the low spatial resolution of the PG measurement that is not able to detect small local deviations. The systematic deviations of their inner panels are no longer present, which indicates a systematic deviation of the deflectometry measurement.

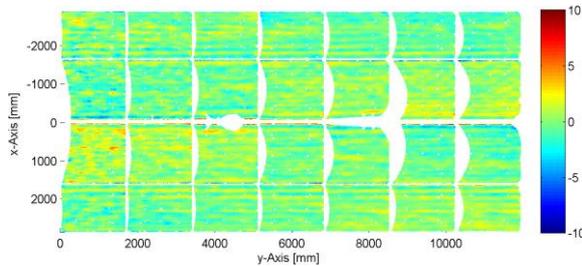


Figure 15: Difference in slopes in curved direction between LR (filtered) and DF, in mrad

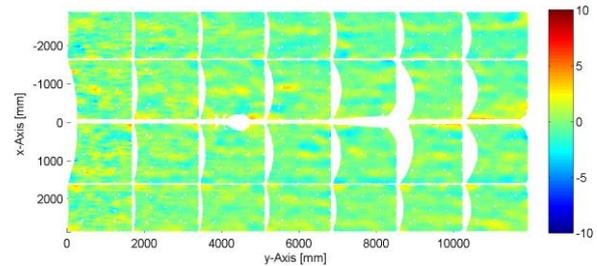


Figure 16: Difference in slopes in curved direction between LR (filtered) and PG, in mrad

Table 1 shows the statistical values of the different measurements and of their comparisons. For the comparisons the data of the local differences was used to determine the given statistical values. Following effects can be seen:

- The mean values of DF and PG are very similar, LRf is slightly too negative
- The standard deviation of PG is very low because the local deviations are not measured
- The standard deviation and RMS of LRf is in between PG and DF, because it measures more local deviations compared to PG but less than DF
- As the quality of the module is very good, the SDx values are low and the RMS values of the difference matrices are comparably high (mainly due to the different resolutions)

Table 1: Statistical data of different measurements and of their comparisons

	Mean [mrad]	Std. Dev. [mrad]	RMS [mrad]
Deflectometry (DF)	-0.56	1.82	1.91
Photogrammetry (PG)	-0.54	1.29	1.40
Laser radar filtered (LRf)	-0.74	1.50	1.67
Difference PG-DF	0.04	1.43	1.43
Difference LRf-PG	-0.20	0.94	0.96
Difference LRf-DF	-0.17	1.24	1.25

3.3. Measurement of Reference Water Surface

A water surface at the floor under the target screen was used as a flat reference surface. The size of the water surface, 12m length and 3m width, was chosen close to the size of the current parabolic trough module. The deflectometry system was calibrated independently, thus measured deviations from the ideal flat surface are attributed to measurement errors (Figure 17 and Figure 18, please note that deviations are shown in a reduced scale of ± 2.5 mrad). The measured slope deviations have a RMS value of <0.4 mrad in both directions.

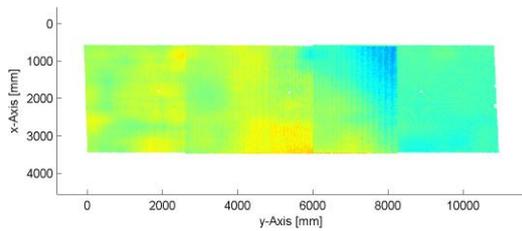


Figure 17: Difference of DF result to an ideal flat water surface in x-direction, in mrad

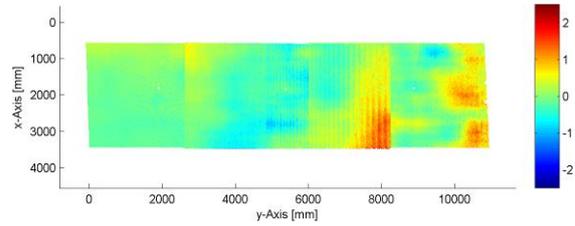


Figure 18: Difference of DF result to an ideal flat water surface in y-direction, in mrad

3.4. Repeatability and Sensitivity Study

A repeatability and sensitivity study has been performed to determine the influence of the module positioning on the measurement results. Based on these studies requirements for the accuracy of the module positioning can be defined.

Repeatability study:

To determine the sensitivity of the measurement results on the measurement of the module's position by the total station, the same module has been measured five times. In between each measurement the module has been repositioned arbitrarily between the pylons to simulate a new positioning of the module. Table 2 gives the results of the repeatability study. The results show a high repeatability for measurements with an individual measurement of the modules position with the total station (differences in SDx and SDy are in the range of ± 0.03 mrad). As an example the local slope deviations between two measurements (Reference to Measurement 1) are shown in Figure 19 and Figure 20. The RMS values of the local differences are in the range of 0.3 mrad.

Table 2: Results of the repeatability study

	SDx [mrad]	SDy [mrad]	FDx [mm]	FDy [mm]	Area [%]	SDx local [mrad]	SDy local [mrad]
Ref.	2.28	3.31	9.03	11.33	96.0	-	-
Diff 1	-0.02	-0.02	-0.10	-0.09	-0.06	0.24	0.27
Diff 2	-0.03	0.00	-0.14	0.00	-0.01	0.29	0.43
Diff 3	-0.03	0.00	-0.14	-0.02	0.04	0.26	0.27
Diff 4	-0.03	0.00	-0.15	-0.01	0.07	0.31	0.31
RMS	0.03	0.01	0.13	0.05	0.05	0.28	0.33

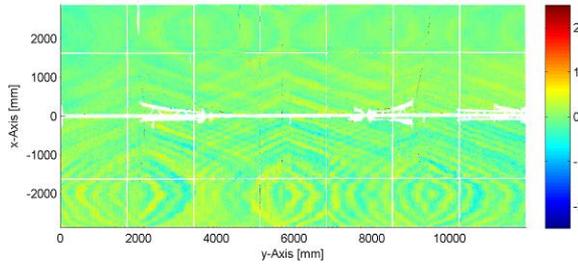


Figure 19: Slope deviation in x-direction between two measurements of the same module, in mrad

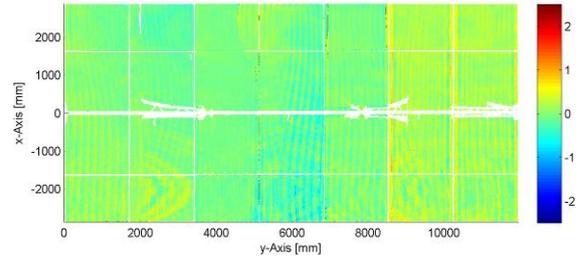


Figure 20: Slope deviation in y-direction between two measurements of the same module, in mrad

Sensitivity of the measurement results on the orientation of the module:

For the purpose of this study the same module has been measured in different orientations. For each measurement it has been rotated by a defined angle along its axis. Each evaluation was done with the measurement pictures of the rotated module and the measured position of the initial measurement.

Table 3: Results of the sensitivity study on the module orientation

Rotation [mrad]	SDx [mrad]	SDy [mrad]	FDx [mm]	FDy [mm]	Area [%]	SDx local [mrad]	SDy local [mrad]
0	2.28	3.31	9.03	11.33	96.0	-	-
1.0	0.02	0.01	0.09	0.04	0.01	0.12	0.19
2.0	0.04	0.02	0.17	0.08	0.05	0.22	0.36
3.0	0.05	0.03	0.24	0.10	0.09	0.31	0.54
3.8	0.05	-0.01	0.22	-0.03	0.04	0.39	0.59
7.7	0.07	0.02	0.31	0.07	0.11	0.61	0.7
16.1	-0.09	-0.25	-0.19	-0.85	0.02	0.97	1.43
24.1	-0.27	-0.22	-0.98	-0.76	0.06	1.45	1.74

Sensitivity of the measurement results on the position of the module:

For the purpose of this study the same module has been evaluated various times with the same measurement pictures but a virtually modified position in the measurement system. Its position has been modified in 2 mm steps along its curved direction (x-dir.) or non-curved direction (y-dir.).

Table 4: Results of the sensitivity study on the module position in curved direction

Displacement [mm]	SDx [mrad]	SDy [mrad]	FDx [mm]	FDy [mm]	Area [%]	SDx local [mrad]	SDy local [mrad]
Ref	2.28	3.31	9.03	11.33	96.0	-	-
2 (x-dir)	0.01	0.01	0.04	0.03	0.01	0.06	0.09
4 (x-dir)	0.01	0.01	0.07	0.04	0.01	0.11	0.16
6 (x-dir)	0.02	0.02	0.10	0.06	0.01	0.16	0.23
8 (x-dir)	0.03	0.02	0.12	0.07	0.02	0.2	0.31
10 (x-dir)	0.03	0.03	0.14	0.09	0.04	0.25	0.38
2 (y-dir)	0.00	0.02	0.01	0.05	0.00	0.04	0.15
4 (y-dir)	0.01	0.03	0.01	0.08	0.01	0.08	0.28
6 (y-dir)	0.01	0.03	0.03	0.09	0.02	0.11	0.39
8 (y-dir)	0.01	0.03	0.04	0.10	0.03	0.12	0.47
10 (y-dir)	0.01	0.03	0.04	0.10	0.04	0.15	0.55

Conclusion for positioning of the module:

Based on the results of the repeatability and sensitivity study it can be concluded that an individual measurement of the module position with the total station is not always necessary for each measurement. Requirements to maintain the system's high reproducibility without an individual measurement of the position of each module are a tolerance on the position of ± 3 mm in curved and non-curved direction and a rotation of less than 2 mrad around the module's axes. Within these positioning tolerances the differences in

the results are in the range of the general repeatability. If they can be fulfilled the module's position does not need to be measured for each measurement with the total station. Preliminary tests showed that these positioning tolerances can be fulfilled with relatively simple measures in regular production conditions. For systems with different layouts these requirements might change.

3.5. Uncertainty Analysis

A previously developed tool to estimate the uncertainty on the slope deviation for parabolic through panel measurements [see 2] was used to perform an uncertainty analysis for the deflectometry measurement of the entire parabolic through module. The calculation of the slope deviation is based on the determination of the reflection of the target in the mirror seen by the camera. Therefore the uncertainty analysis takes all relevant parameters into account which have an influence on the determination of the incoming light ray (target to reflector) and outgoing light ray (reflector to camera). Such parameters are the precision of the measurement of the component's positions in space, image processing, correction of lens distortion, influence of background light, non-linearity of cameras and projectors and image noise. By using the Gaussian law of error propagation to combine the different influences the uncertainty on the slope deviation for each pixel is determined.

Figure 21 and Figure 22 display the results of the uncertainty analysis, which are maps of the uncertainty on the local slope deviations on the reflector surface in milliradians. In overlapping areas where local results are obtained by more than one reflector camera the local uncertainty on the slope deviation is smaller, because the final local slope deviation is an average of both local measurements. In non-curved direction of the reflector surface the uncertainty is higher due to the increased influence of the distortion of the target pictures. Table 5 gives the expected uncertainty of the slope deviation in each direction as a RMS value for the parabolic trough module and for the water surface.

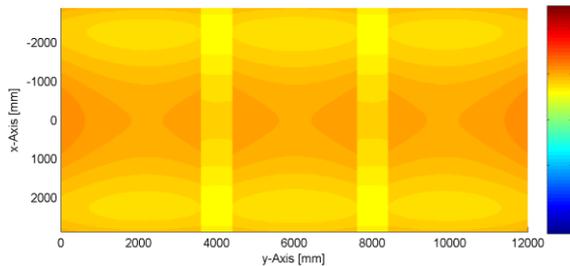


Figure 21: Uncertainty on slope deviation in x-direction for parabolic through module, in mrad

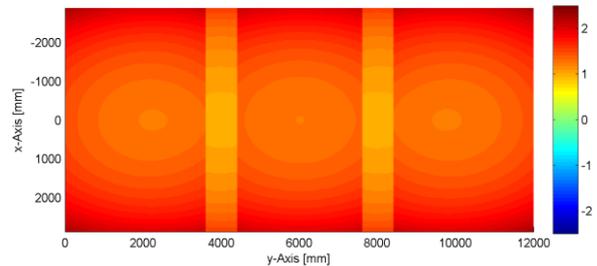


Figure 22: Uncertainty on slope deviation in y-direction for parabolic through module, in mrad

Table 5: Results of the uncertainty analysis

	RMS SD _x [mrad]	RMS SD _y [mrad]
Parabolic Through	0.88	1.50
Water Surface	0.83	0.83

The comparison of the results of the uncertainty analysis to the differences between PG, DF and the laser radar shows that the measured deviations are generally in the range or smaller than the estimated uncertainty. Also, the measured uncertainties of the water surface are with a RMS value of 0.4 mrad by a factor of 2 lower than the expected values from uncertainty analysis. The estimated RMS values of the uncertainty on the slope deviations are too high, because they are calculated from the maximum deviation in each pixel. In reality not all measurement points exhibit this maximum deviation. Additionally it can be stated that the uncertainty analysis overestimates the uncertainty in y-direction, because the use of two projectors cannot be considered yet correctly in the uncertainty model. To achieve an improved result for the uncertainty estimation the implementation of the angle of view of the cameras, the use of multiple projectors and the picture distortion in the uncertainty model has to be improved.

4. Summary and Outlook

A new measurement system able to measure the shape accuracy of complete mirrored parabolic trough modules in series production has been successfully developed. Key features of the measurement system called QDec-M are its high spatial resolution of about 1 million points per module, its low local and global measurement uncertainty of less than 0.9 mrad and 0.2 mrad respectively and its total measurement time of less than 9 minutes. The system was validated by comparison to photogrammetry and laser radar measurements, by measuring a flat reference surface and by a repeatability and sensitivity study. The determined measurement uncertainties are within the expected range from theoretical uncertainty analysis and the measurement repeatability is high. This makes the new measurement system suitable for final geometric quality control of parabolic trough concentrators in series production and for continuous optimization of concentrator optical quality and prototype development. At Abengoa's test and production site in Seville, Spain, the measurement system is in continuous operation and a valuable tool for these purposes.

Further development steps are the implementation of the measurement of the absorber tube support positions with the automated total station, the extension of the model for theoretical uncertainty analysis and based on this a further reduction of the measurement uncertainties.

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References

- [1] S. Ulmer, T. März, C. Prah, W. Reinalter, B. Belhomme: Automated High Resolution Measurement of Heliostat Slope Errors Solar Energy 85 (2011), pp. 681–687, doi:10.1016/j.solener.2010.01.010.
- [2] T. März, C. Prah, S. Ulmer, S. Wilbert, C. Weber, Validation of two Optical Measurement Methods for the Qualification of the Shape Accuracy of Mirror Panels for Concentrating Solar Systems, Journal of Solar Energy Engineering, August 2011, Volume 133, Issue 3, 031022 (7 pages), doi:10.1115/1.4004240, 2011.
- [3] A. Heimsath, W. Platzer, T. Bothe, L. Wansong: Characterization of Optical Components for Linear Fresnel Collectors by Fringe Reflection Method, Proceedings of Solar Paces Conference, 2008, Las Vegas, NV.
- [4] C. Andracka, S. Sadlon, B. Myer, K. Trapeznikov, C. Liebner: Rapid Reflective Facet Characterization Using Fringe Reflection Techniques. Proceedings of the Energy Sustainability 2009, July 19-23, 2009, San Francisco, California, USA.
- [5] Luhmann, T., Robson, S., Kyle, S., and Harley, I., Close Range Photogrammetry: Principles, Techniques and Applications, Wiley 2007. ISBN-13: 978-0470106334.
- [6] K. Pottler, E. Lüpfert, G. Johnston, M. Shortis, Photogrammetry: A Powerful Tool for Geometric Analysis of Solar Concentrators and Their Components, Journal of Solar Energy Engineering, February 2005, Volume 127, Issue 1, pp. 94-101.
- [7] K. Pottler, M. Mützel, J. Engelke, C. Prah, M. Röger: QFOTO: Automatic Inline Measurement System for Parabolic Trough Structures: Experiences and Developments, Concentrating Solar Power and Chemical Energy Systems, SolarPACES Conference, Paper 24589, 20-23 Sept. 2011, Granada, Spain
- [8] Nikon MV330 User Manual and Training Documentation, 2011.
- [9] R. E. Keller, W. Banzhaf, J. Mehnen, K. Weinert: CAD Surface Reconstruction from 3D Point Data with a Genetic Programming/Evolution Strategy Hybrid, Advances in Genetic Programming, MIT Press, MA, USA, 1999, Volume 3, pp. 41-65
- [10] D. E. Goldberg: Genetic Algorithms in Search, Optimization, and Machine Learning. Reading, Addison-Wesley, 1989. ISBN-10: 0201157675
- [11] L. Piegl, W. Tiller: The NURBS Book, 2nd ed. New York: Springer, 1997