PHOTOGRAMMETRIC ANALYSIS OF SOLAR COLLECTORS

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ABSTRACT:

Digital close range photogrammetry has proven to be a precise and efficient measurement technique for the assessment of shape accuracies of solar collectors and their components. The combination of high quality megapixel digital still cameras, appropriate software, suitable targeting and calibrated reference scales in general is sufficient to provide coordinate measurements with precisions of 1:50,000 or better. The extreme flexibility of photogrammetry to provide high accuracy three dimensional coordinate measurements over almost any scale makes it particularly appropriate for the measurement of solar collector systems. Photogrammetry can also provide information for the analysis of curved shapes and surfaces, which can be very difficult to achieve with conventional measurement techniques. A selection of measurement projects carried out on assembly jigs, component parts and whole solar collectors will be presented. The potential of photogrammetry will be demonstrated by presenting measured effects arising from thermal expansion and gravitational forces on selected components.

1. INTRODUCTION

Solar thermal electric power plants based on parabolic trough technology represents one of the major renewable energy success stories of the last two decades. Parabolic troughs are highly efficient, light weight and low cost to manufacture. This type of concentrating collector is one of the lowest cost solar electric power options available today and has significant potential for further cost reduction. Accordingly, adoption of solar thermal plants as a renewable energy generation technology is under consideration throughout the world.

Figure 1: Existing solar thermal power plants in California, USA

Solar power plants are currently in the planning, design, construction or test phases in many places (Spain, USA, Africa), generally located in high altitude desert regions to maximise exploitation of the solar resource. For example, a consortium of Spanish and German companies has commenced construction of two 50 MWatt solar power plants, known as AndaSol, in the high altitude desert of southern Spain. These trough plants of 500,000 m^2 mirrors will generate steam to operate turbines and, using molten salt, store heat for hours to support daily periods of peak load.

The construction of solar thermal power plants requires quality control measures for components, subsystems, and the entire collector rows. Quality control and performance measurements are required in all phases of the manufacture and construction. However the greatest improvement in efficiency of power generation can be achieved from the quality assurance of the individual collectors.

The optical performance of solar concentrating collectors is very sensitive to inaccuracies of components and assembly. Because of a finite sun shape and small imperfections in the collector system such as component alignments, the interception of light at the focal receiver is reduced. High precision photogrammetry is an efficient and effective tool to measure 3D coordinates of collector support points and mirror surfaces, especially for the analysis of large collectors [Shortis and Johnston, 1996, 1997; Lüpfert et al., 2003].

In contrast to measurement tools for monitoring solar flux in the focal region [Ulmer et al., 2004], the photogrammetric method directly delivers coordinates of selected test points and thus allows performance assessments of the collector to be made. Whereas other surface evaluation methods are limited to special shapes such as point focusing devices [Wendelin and Grossman, 1995] or limited to linear parabolic collectors indoors [Butler and Pettit, 1977] or outdoor laser ray tracing [Hansche, 1978], photogrammetry is a universal method for testing almost any type of collector or structure.

2. EUROTROUGH MEASUREMENT

2.1 Collector Geometry

To illustrate the coordinate data that can be obtained using photogrammetry, the measurement of a EuroTrough collector module (figure 2) is presented. Figure 3 shows the space frame of the module in its zenith orientation, the position in which all presented EuroTrough measurements were undertaken.

Retro-reflective targets were placed on all 112 of the mirror support points. In common with the other projects described in this paper, coded targets were also placed to provide scale and a recoverable reference for the coordinate system. This measurement was undertaken to check the assembly accuracy of these kinds of modules. The photogrammetric measurement included 92 exposures. This high number of photos was necessary because of the elongated rectangular shape of the module, to compensate for less favourable network geometry. Digital images were captured with a Rollei RD7 metric camera, which has a 7.5mm lens and a CCD sensor with 2552 by 1920 pixels at a spacing of 3.5 micrometres. For the module, an object space precision of ±0.2 mm was achieved from the photogrammetric network.

Figure 2: EuroTrough line focussing collector module

Figure 3: Space frame of a EuroTrough module with measurement targets on the mirror support points

Figure 4 illustrates the result of this measurement, based on interpolation between the measured data points. The maximum deviations from the design heights (top left and right edges of the image) indicate incorrectly mounted mirror support clamps. The standard deviation of the height variations for all measured points is ±1 mm. The bending of the structure, which was supported at central points on the left and right ends of the module, can be observed by the characteristic lower points in the centre part of the module as compared to the ends. Similar bending was found on all measured modules.

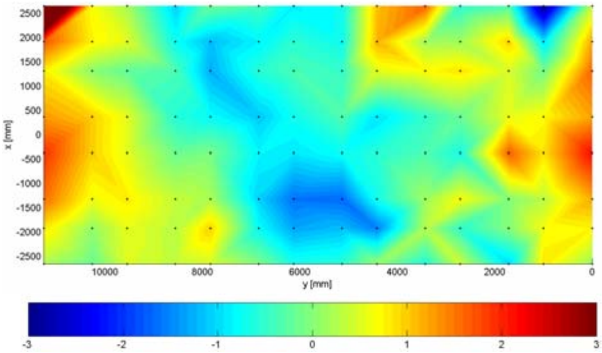


Figure 4: Deviations of EuroTrough mirror support points from design heights in mm

After measuring the space frame, special retro-reflective targets were applied to the collector mirrors and the mirrors mounted onto the frame. The complete collector element is shown in Figure 5.

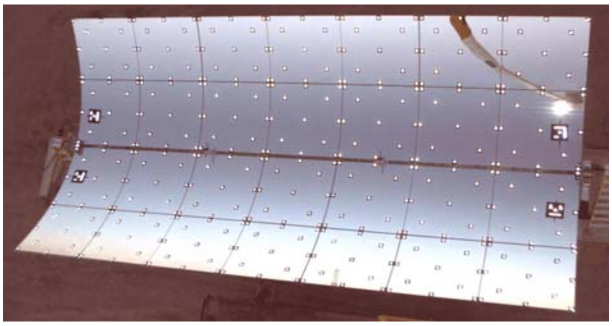


Figure 5: EuroTrough collector element with measurement targets on the mirrors

The module was measured with photogrammetry, again achieving an object space precision of 0.2mm, in this case from a network of 116 exposures. The targets were fixed on the glass surface which, due to the thickness of the glass, placed them about 4 mm above the reflective surfaces of the mirrors. As for all measurements with targets on mirror surfaces, the targets cannot be positioned exactly on the desired surface and the separation distances may be variable. Further, the alignment of the actual collector axes is difficult to measure because of poor definition of the axes in some cases or complete lack of signalisation of the axes in other cases. Therefore the photogrammetric results had to be post-processed to transform the measured target coordinates to an established reference system. Figure 6 illustrates the shape deviations of 364 surface points over the whole collector module mirror surface after mirror assembly and correction of the support clamp at the top left corner of Figure 4.

The optical performance of a trough collector depends on the slope errors, which tend to deviate the reflected rays away from the ideal focal line. Figure 7 shows results for the slope errors in the x-direction (perpendicular to the absorber axis). The slope errors were approximated by the slope deviations from the ideal parabolic section line of neighbouring points on 35 sections in the y-direction.

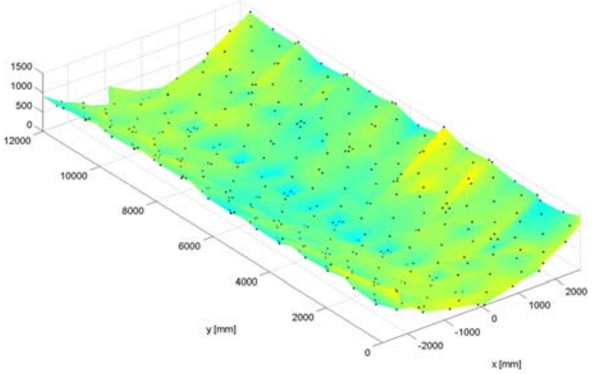


Figure 6: Deviations from the design heights (exaggerated) for the EuroTrough mirror surface.

Inspection of the figure indicates that the overall precision of the EuroTrough collector module assembly with mirror facets has maximum slope errors in the transverse direction of about 1.1 seconds of arc (5.2 milliradians) with a standard deviation of ±0.4 seconds. It should be noted that this analysis investigated the quality of the EuroTrough space frame and mirror assembly. In order to calculate the optical intercept factor and conduct ray trace analysis, many more mirror points would have to be measured with high accuracy.

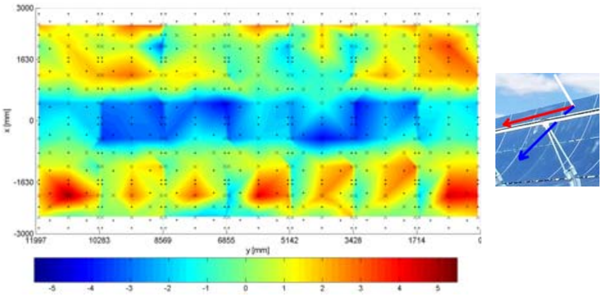


Figure 7: Transverse slope errors of neighbouring points in milliradian.

2.2 Thermal Expansion

The assembly of EuroTrough space frames needs a precise jig with very stringent tolerance limits for the reference mounting points. Aside from checking the adjustment accuracy at a particular time, long term stability under varying ambient temperature regimes is also of interest. The following example shows the photogrammetric assessment of jig shape changes caused by thermal expansion as experienced with the first prototype.

The jig was measured using the Rollei RD7 in the morning and again in the evening with precisions of the order of 0.1 mm (resulting from networks of 110 exposures and 124 targets for each network). During this time the concrete foundation increased in temperature by about 10 Kelvin, while the steel structure warmed by only 3 K, due to constant air temperature and little wind. Because the structure was not under mechanical load between the measurements, shape changes could only originate from temperature differences.

The three dimensional photogrammetric results revealed primarily a linear thermal expansion coefficient of the foundations of 14 parts per million per K in both longitudinal and transverse directions. In addition, the measurements revealed an effect that had been suspected before the study. The heights of the reference support points varied in the order of 0.7 mm, which is not only caused by linear expansion, but instead by bending of the foundation under sun exposure.

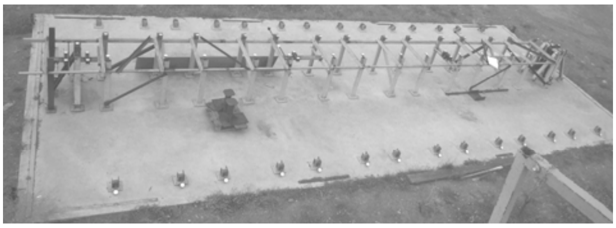


Figure 8: Site jig for the assembly of EuroTrough space frames

Figure 9 shows the result of this effect in the prototype jig. The demonstrated shape changes of the jig are higher than the tolerance allowed by the collector design. As a result of these outdoor measurements, assembly in shaded working areas is recommended for such collectors.

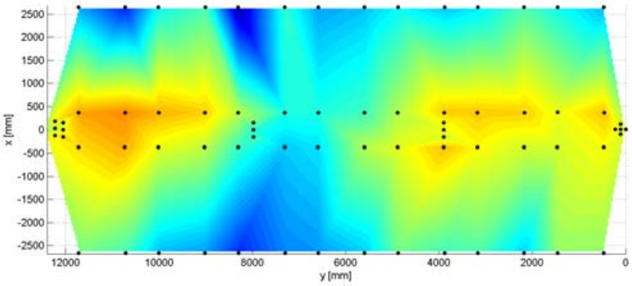


Figure 9: Thermally induced displacements in height (mm) of a EuroTrough construction jig.

3. FACET SHAPE

3.1 Large Facets and Gravitational Bending

Mirror facets used on the EuroTrough collector were analysed in detail to measure shape deviations and to get an extended database for ray tracing studies in order to calculate intercept factors. Figure 10 shows two facets with apertures 1.2 m x 1.7 m and 1.6 m x 1.7 m with approximately 7,000 targets on the mirror surfaces. The target spacing is 30 mm. Each facet was measured with the RD7 to an object space precision of ±0.03mm using a network of 24 exposures.

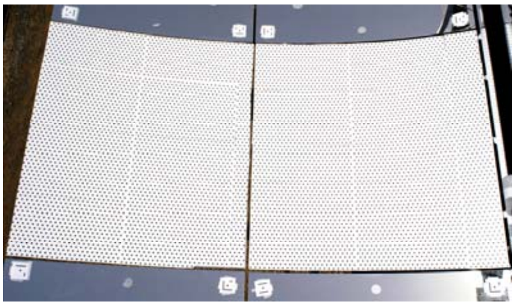


Figure 10: Two adjacent EuroTrough facets with 7,000 measurement targets as used for the study of the sag

Because the glass mirrors bend under gravitational forces, the mirror shapes were measured using photogrammetry for several different angular positions. Figure 11 shows the shape of two adjacent mirror facets for three collector positions (sunrise, zenith, sunset), as seen from the position of the sun. The shapes of the mirrors change with orientation and thus influence flux distribution in the focus. The magnitude of this effect on the daily or annual performance characteristics of a collector can be computed by ray trace studies.

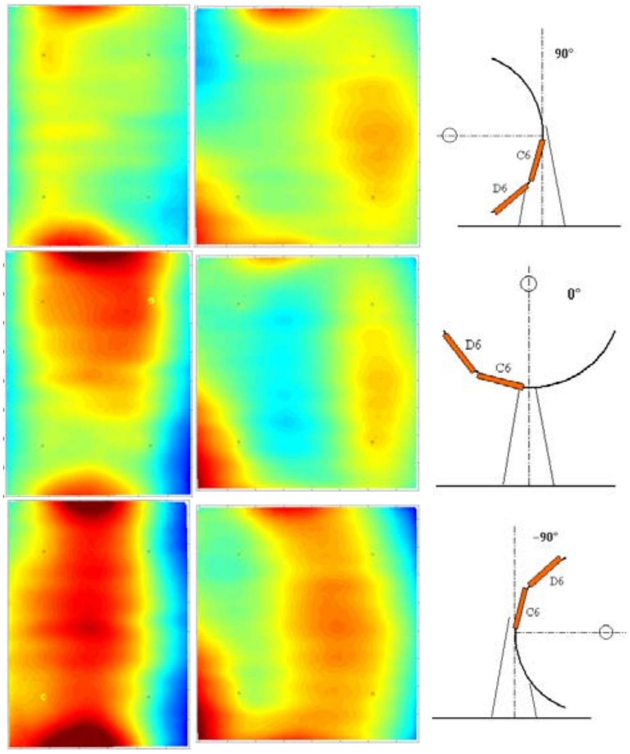


Figure 11: Shape change caused by gravitational forces for two facets.

3.2 Small Facet Shape Assessment

In addition to the studies of the EuroTrough and its mirror elements having dimensions of metres, photogrammetric measurement can also be applied to smaller components. As an illustrative case, a concentrating mirror facet having a square aperture dimension of 38 cm was investigated. Figure 12 shows the facet used for this study.

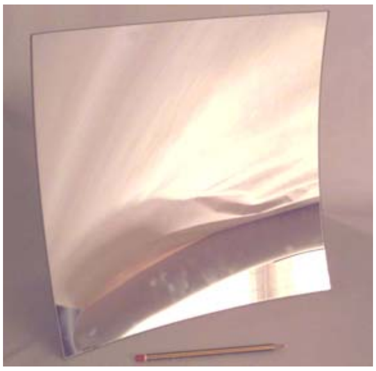


Figure 12: Curved, 38 cm square aperture mirror facet

The surface study was based on an array of 2,150 target points applied to the facet surface. A set of 24 exposures from 12 camera stations was taken with a 6-megapixel Nikon D70 camera. Average relative precision obtained for the photogrammetric network solution was 1:47,000, which produced an average object space precision of ±11 microns. Figure 13 shows the surface extracted from the ensuing photogrammetric coordinate data.

Assessment of the shape characteristics was conducted by optimisation (least squares adjustment) of the measured coordinate data according to both paraboloid and spherical models.

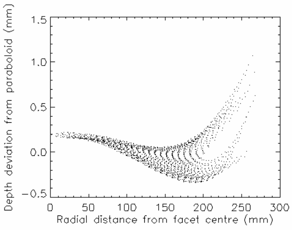


Figure 13: Depth deviation data optimised to a paraboloid

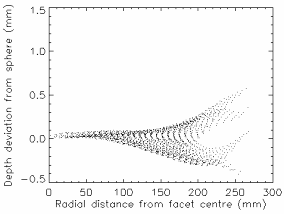


Figure 14: Depth deviation data optimised to a sphere

Figure 13 shows the optimised depth deviations of the target points on the facet from an optimal paraboloid with a best fit focal length of 370.4 mm, as a function of radial distance from the centre of the facet. Figure 14 shows a similar depth deviation plot for the target coordinates, optimised to a spherical surface having a best fit radius of curvature of 759.3 mm.

Comparison of the two plots shows that the range of deviation is reduced for the data fitted to a spherical surface, as compared to a paraboloid surface. Discussions with the manufacturer confirmed that the facet had been constructed on a spherical mould. Visualization of the surface deviations of the facet coordinates from a spherical surface is shown in Figure 15.

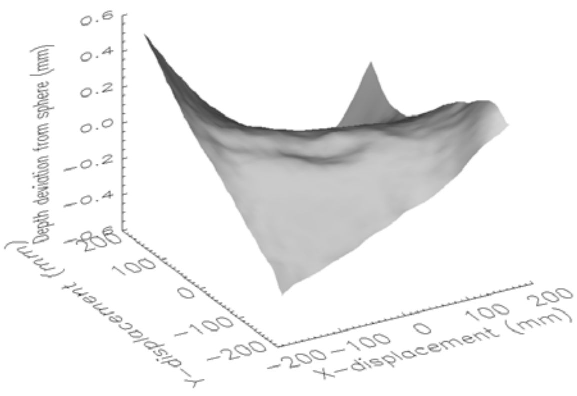


Figure 15: Spatial distribution of facet depth deviations from a spherical surface.

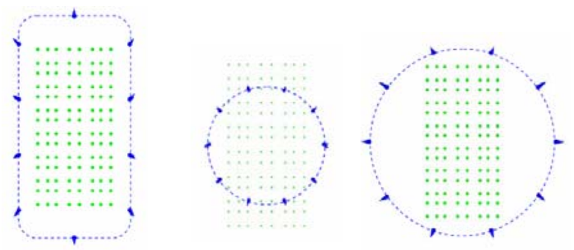
4. AUTOMATIC MEASUREMENT SYSTEM

The construction of solar thermal power plants will require multi-station photogrammetry and specialist software that will enable high-speed quality assessment and control of individual solar collector elements as they are fabricated. In particular, close range photogrammetry will be used to measure the geometry of collector structures. The measurement system will consist of a digital camera, moved around the structure automatically while shooting photos of the collector structure from various positions. The photos will be evaluated with photogrammetric software to check the assembly quality. The measurement and evaluation procedure must be computer-controlled and fast enough to be integrated into the production line for the manufacture of the solar collectors.

4.1 Simulation Studies

There are a number of factors to be considered when designing an automated quality assessment system. First, the geometry of the network must enable the design precision to be achieved across the entire structure. Experience with the EuroTrough suggested that the most favourable network geometry would be camera stations around the entire periphery of the structure. Accordingly, a single mobile camera was favoured over a network of fixed cameras, simply because of the number of cameras that would be required for a fixed network and the potential for equipment failure to result in an unacceptable degradation of precision. The motion component for a single mobile camera could be readily provided by a pan-tilt head on either a rail system or a rotating arm. The elongated rectangular shape of the EuroTrough structure would be expected to reduce the uniformity of the precision attainable with a rotating arm, but nevertheless two arm lengths were chosen as possible options.

The simulation results, shown in figure 17, confirm the expectations predicted by experience and geometric considerations. Because the rail system provides the camera always with the best viewing angle of the structure, this configuration has the optimal and most uniform precision. The short rotating arm shows good precisions in the middle of the structure while the measurements of the edge-points suffer from poor viewing angles. The large rotation arm delivers more or less constant precisions with higher values, since the distance of the camera from the structure often is too large. The results give an estimate of the obtainable measurement uncertainties, which must be proven experimentally. As the simulation does not include non-random errors in the image observations, the measurement uncertainties will inevitably be larger than the predicted precision values.



rail: 8m wide, 14m long

rotating arm: 4m long

rotating arm: 7m long

Figure 16: Camera movement tracks and target array used for the measurement uncertainty simulation study.

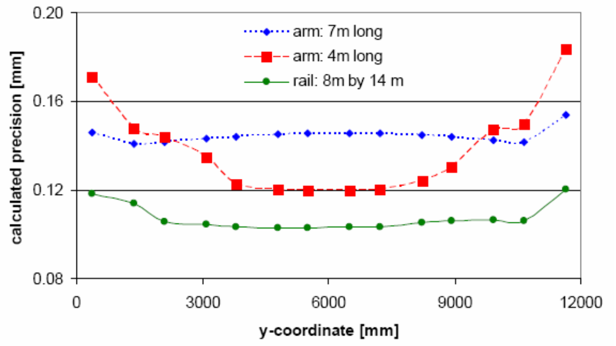


Figure 17: Measurement precision simulation results for different camera tracking systems.

4.2 Prototype System

For the quality control of a collector assembly line, an automatic measurement system accurate enough to find assembly errors and fast enough to not disturb the regular assembling procedure is needed. This has been achieved with the rail-based automatic photogrammetry system “Q-Foto”. Q-Foto has been developed to automatically verify the correct assembly of the 12-m long parabolic trough steel structure. In the current version, Q-Foto uses a 12-megapixel Nikon D2X camera and a motorized positioning system on a curved track with pan-tilt head and camera rotating unit. It includes the automatic camera control and positioning, photo evaluation and data post-processing. Figure 18 illustrates the system.

Using a single high-definition camera and camera self-calibration, the system can achieve a high level of measurement precision, even under changing ambient temperature. This is a significant advantage over systems with stationary cameras that have to be calibrated individually. With the collector space frame located into the measurement area, retro-reflecting targets are placed on the mirror attachment points, receiver supports and reference points and a number of photos are exposed. The evaluation results are stored and deviations from the specifications can be identified for adjustment. The required measurement time for analysis, display and storage of the data is about five minutes. Overall cycle time, including target mounting, is less than 30 minutes.

Figure 18: Camera shuttle in different measuring positions (top), and space frame with targets on cantilever arms and receiver supports (bottom).

4.3 System Accuracy Validation

The quality and the measurement uncertainties of the Q-Foto measurement system have been certified according to the German technical rule VDI/VDE 2634 for optical point measuring devices. The qualification test was performed with measurement targets, whose distances are much more precisely known than the photogrammetric system is able to measure. The targets were fixed on carbon-fibre-reinforced polymer rods with very low expansion coefficient (approximately -5x10^{-7}/K) and lengths up to 12 m. With these rods, a network was built up that filled the measurement volume of 12 x 6 x 1.5 m³ (figure 19). A Laser Doppler displacement meter was used for gauging the distances between the targets on these rods with an uncertainty of less than ±0.05 mm. To account for temperature changes inside the rods, the rod temperatures were measured with thermocouples and corrections for thermal expansion were calculated.

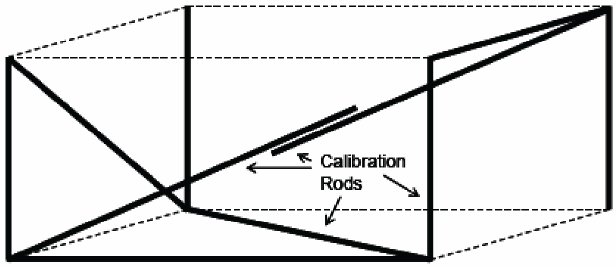


Figure 19: Schematic view of the certification network of carbon-fibre-reinforced calibration rods according to technical rule VDI/VDE 2634

Differences between the rod lengths measured by the distance meter and the photogrammetry system are used to determine the uncertainty of the photogrammetry system (figure 20). The largest uncertainty of all single distance measurements is below ±0.4 mm while the standard deviation is ±0.1 mm. Based on these experimental results, further simulation studies were performed to investigate possible improvements due to optimized camera viewing angles and paths. According to these simulations, a further reduction of 28% of the maximum deviation would be possible, so that a maximum uncertainty of well below ±0.3 mm can be reached for the final system.

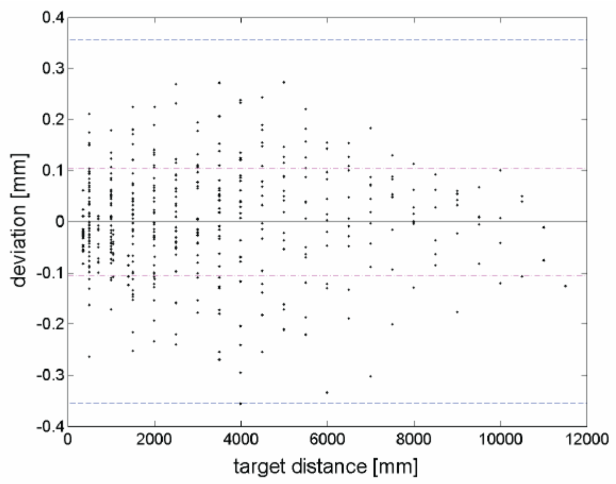


Figure 20: Results of the certification measurements. The graph shows the deviations of the photogrammetric distance measurements from the reference values in mm

5. CONCLUSIONS

This paper has described the use of close-range photogrammetry to measure a range of solar collector components, from EuroTrough fabrication jigs, to collector sub-frames, to trough mirror facet surface deviations under varying gravitation loads, to structural distortions arising from differential thermal expansions in the structure, to small scale mirror facets and quality control for the construction of solar thermal power plants. The body of evidence arising from these studies provides considerable justification for the application of close-range photogrammetry as an appropriate tool that aids both the design and quality control of the construction of solar collector systems. This further contributes to enhancing the thermal output of solar power plants while maintaining minimum mirror usage.

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