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PHOTOGRAMMETRY: A POWERFUL TOOL FOR GEOMETRIC ANALYSIS OF SOLAR CONCENTRATORS AND THEIR COMPONENTS

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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 concentrators and their components. The combination of high quality mega-pixel digital still cameras, appropriate software 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 3-D coordinate measurements over almost any scale makes it particularly appropriate for the measurement of solar concentrator systems. It can also provide information for the analysis of curved shapes and surfaces, which can be very difficult to achieve with conventional measurement instruments. The paper gives an overview of quality indicators for photogrammetric networks, which have to be considered during the data evaluation to augment the measurement precision. A selection of measurements done on whole solar concentrators and their components are presented. The potential of photogrammetry is demonstrated by presenting measured effects arising from thermal expansion and gravitational forces on selected components. The measured surface data can be used to calculate slope errors and undertake ray-trace studies to compute intercept factors and assess concentrator qualities.

Keywords: Photogrammetry, Quality Control, Concentrator Analysis, Parabolic Trough Collector, Ray-Tracing

INTRODUCTION

The optical performance of solar concentrating collectors is very sensitive to inaccuracies of components and assembly. Because of a finite sun-shape and extant imprecisions of the collector system (e.g. tracking, receiver alignment, mirror alignment, mirror shape and mirror specularly) the interception of light at the focal receiver is reduced. High precision photogrammetry is an appropriate tool to measure 3D-coordinates of concentrator support points and mirror surfaces, especially for the analysis of large concentrators [1,2,3]. In contrast to measurement tools for monitoring solar flux in the focal region [4,5], the photogrammetric method directly delivers coordinates of selected test points and thus allows performance assessments of the concentrator to be made. Whereas other surface evaluation methods are limited to special shapes, e. g. to point focusing devices [6] (such as the (V)SHOT-method [7,8] or the SCCAN-method [9]), or to linear parabolic concentrators (indoor [10,11] or outdoor laser ray trace [12]), photogrammetry is a universal method for testing almost any type of concentrator or structure.

Overview of the photogrammetric system

Previous work [1,2] has described the application of photogrammetry to the characterization of solar collectors. Briefly, close-range photogrammetry involves the use of a network of multiple photographs of a targeted object (in the present case, a solar collector component) taken from a range of viewing positions, to obtain high-accuracy, 3-dimensional coordinate data

for the object being measured. A significant advantage of photogrammetry as a measurement tool is that it is a rapid non-contact technique that can readily be adapted to a range of object sizes. Further, photogrammetry is self-contained and requires little external information if only the shape and size of the object is of interest. However, most importantly, photogrammetric network computations automatically incorporate internal estimates of quality. These estimates reflect the level of internal consistency within a network made up of multiple images of targets on multiple photographs. The accuracy of the estimates of quality is dependent on a number of factors; however the most significant are the geometric strength of the network and the level of redundant measurements in the network.

Any photogrammetric network that has both geometric strength and high levels of redundancy will also exhibit optimal precision and reliability for the target coordinates. Optimization of the design of photogrammetric networks is well established [13] and is primarily aimed at improving the precision and reliability of target coordinates; however it has the collateral benefit of accurate quality estimates. Whilst interpretation of the results from a photogrammetric network computation is always a mixture of science and experience, the fundamental quantity that sets the baseline expectation for internal quality estimates is the pixel size of the image elements in the photographs that make up the network. A further requirement of the design of photogrammetric networks is to achieve target images of 5-10 pixels in diameter to optimise the precision of centroid locations of the target images [14]. The expected precision of the measurement of such target image centroids is typically in the range of 1/10 to 1/40 of a pixel, depending on many factors such as the quality of the sensor, quality of the camera, quality of the target images, the level of image noise [15], and the selected algorithms for the threshold and centroid computations [16]. Because of these many factors, an expectation for the typical image measurement precision for a particular camera can only be established from experience with a range of operational scenarios and image qualities.

Internal quality measures

The most important measure of internal quality is the Root Mean Square (RMS) error of the measured image coordinates from all photographs in the network, more often known simply as the RMS image error. This value represents the internal consistency of the network as a whole and should be commensurate with the expected image measurement precision. Any result that is atypical of the camera and network should be questioned, but can often be attributed to unusual circumstances such as low contrast target images or non-optimal network geometry. Any result that is outside the range of 1/10 to 1/40 of a pixel implies significant systematic or gross errors in the measurements and most often results from camera calibration or target stability problems.

External quality measures

A measure of the external quality of a network is often also required to ensure that the position, orientation and scale (size) of the network are correct. Internal quality measures are adequate if only the shape of the object, as described by the target array, is of interest, but it is often the case that the position,

orientation and scale of the target array are all important. Whilst the internal quality of a network may be optimal, a very high level of internal consistency does not guarantee that the network has, for example, the correct scale with respect to an external reference. One method to establish the position, orientation and scale of the network is to include reference targets that have had object space coordinates determined by an independent measurement process. Dependent on the size of the object, reference target coordinates can be established by a number of techniques, such as survey measurements or coordinate measuring machines [17].

However in many cases of photogrammetric measurement for industrial metrology, and particularly for solar collector measurement, only the shape and the size of the object is of interest. Because position and orientation is not important, provision of accurate reference targets is not warranted, as it is often difficult or costly to provide an independent, external frame. The quality of the shape of the target array is indicated by the internal quality measures; however the size of the object must also be subject to quality assurance. The common solution to this problem is to use multiple check distances. A single distance between two targets is required to establish the size of the object, whilst additional distances provide redundancy. The RMS error of the differences between the measured distances and the comparable distances computed from the target coordinates is an external quality measure that indicates the precision of the size of the object. The RMS deviations should be commensurate with the precision of the distance measurements and the target coordinates as determined from the network.

MEASUREMENT OF CONCENTRATOR GEOMETRY

Photogrammetry is an excellent tool to measure the structural shape accuracy of large-scale solar concentrators. With appropriate retro-reflective targets and flashlight it can be performed during the day, even under bright sun. After installation of the targets, actual measurement time is short, often limited to half an hour. Depending on the size of the project, the time taken from the start of target placement to final extraction of target coordinates is usually of the order of ½ to 1 day.

To illustrate the coordinate data that can be obtained using photogrammetry, the measurement of a EuroTrough collector module is presented. Figure 1 shows the space frame of the module in its zenithal orientation, the position in which all presented EuroTrough measurements were undertaken.



Figure 1: Space frame of a EuroTrough module with measurement targets on the mirror support points

Retro-reflective measurement targets were placed on all 112 of the mirror support points. This measurement was undertaken to check the assembly accuracy of these kinds of modules. The photogrammetric measurement included 92 photos. This high number of photos was necessary because of the special shape of the module, to compensate for less favorable photo conditions. However, using Vision Measurement System (VMS) [18] photogrammetry software, a high object space precision of about 0.2 mm was achieved. Figure 2 illustrates some results of this measurement. Please note that for all following colored contour plots only the values next to the marked points are of significance. Colors between them show interpolated values without underlying measured data.

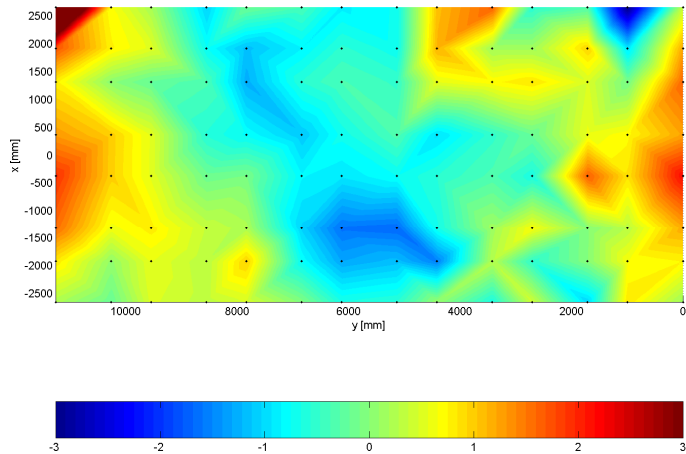


Figure 2: Deviations of EuroTrough mirror support points from design heights in mm

The maximal deviations from the design heights (top left and right edges of the image) indicate two 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 center part of the module as compared to the ends. Similar bending was found on all measured modules. After measuring the space frame, special retro-reflective targets were applied to the concentrator mirrors and the mirrors mounted onto the frame. The complete concentrator element is shown in Figure 3.



Figure 3: EuroTrough collector element with measurement targets on the concentrator mirrors

This module was measured again with photogrammetry. 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 can not be positioned exactly on their desired places and their distances may be variable. Data of the actual collector axes is difficult to measure because of poor accessibility of the axes in some cases or even non-existence of axes in other cases. Therefore the photogrammetric results had to be pre-processed to transform the measured target coordinates to an established reference system. Figure 4 illustrates the shape deviations of 364 surface-points over the whole concentrator module mirror surface after mirror assembly and correction of the support clamp at the top left corner of Figure 2.

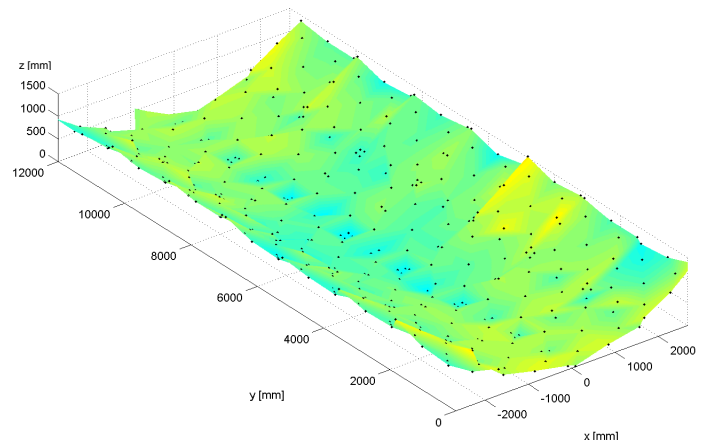


Figure 4: EuroTrough mirror surface. Deviations from the design heights (expanded scale)

The optical performance of a trough concentrator depends on the slope errors, which tend to deviate the reflected rays away from the ideal focal line. Figure 5 shows results for the slope errors in the x-direction (perpendicular to the absorber axis). The slope errors were approximated by the slope deviation from the ideal parabolic section line of neighboring points on 35 slices in y-direction.

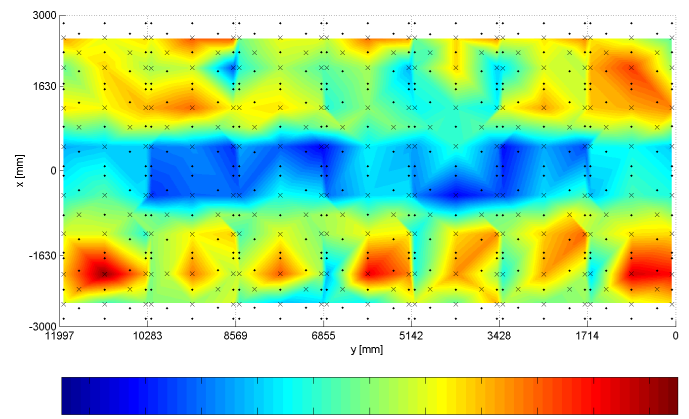


Figure 5: Transversal slope errors (marked as crosses) of neighboring points (marked as dots) in milliradian. Positive values indicate the areas where the reflected rays tend to pass over the focal line.

Inspection of the figure indicates that the overall precision of the EuroTrough collector module assembly with mirror facets has maximal slope errors in the transversal direction of about 5.2 milliradian with a standard deviation of 1.8 milliradian. 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, as will be done below for a single mirror facet; many more mirror points would have to be measured with high accuracy.

MEASUREMENT OF THERMAL EXPANSION

The assembly of EuroTrough space frames needs a precise jig with very small 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 at the Plataforma Solar de Almería (PSA) with the first prototype.

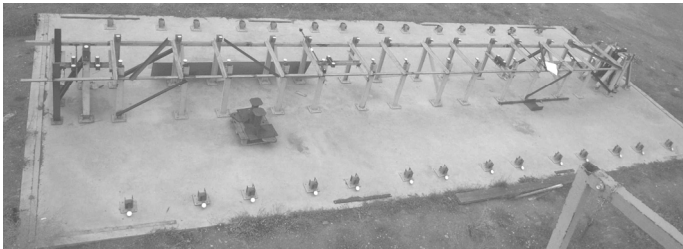


Figure 6: Site jig at the Plataforma Solar de Almería for the assembly of EuroTrough space frames

The jig was measured in the morning and again in the evening with precisions of about 0.1 mm (resulting from about 110 photos in each session). During this time the concrete foundations increased in temperature by about 10 K, 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 can only originate from temperature differences. The 3-dimensional photogrammetric results revealed primarily the linear thermal expansion coefficient of the foundations of $14 \cdot 10^{-6} \text{ K}^{-1}$ in both longitudinal and transversal directions. But in addition they revealed an effect that had been suspected before the study: Height of the reference support points varies in the order of 0.7 mm, which is not only caused by linear expansion, but by bending of the foundations under sun exposure. Figure 7 shows the result of this effect in the prototype jig at PSA.

The demonstrated shape-changes of the jig are higher than tolerated by the collector design. As a result of these outdoor-measurements the assembly in shaded working areas is recommended for such collectors.

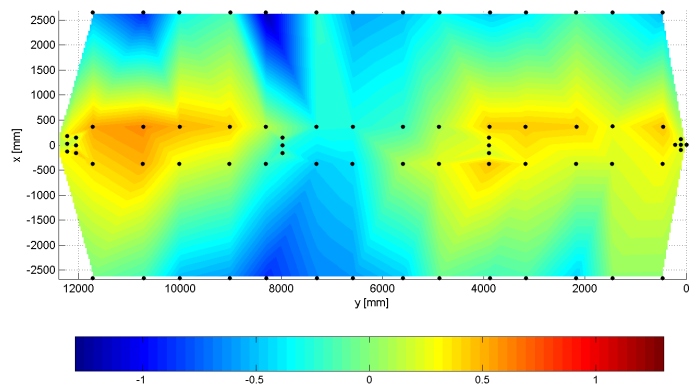


Figure 7: Thermally induced displacements in height (mm) of a EuroTrough construction jig as a function of ambient temperature changes

LARGE FACETS AND GRAVITATIONAL BENDING

Mirror facets used on the EuroTrough collector were analyzed in detail to measure shape deviations and to get an extended data basis for ray-tracing studies in order to calculate intercept factors. Figure 8 shows two facets with apertures 1.2 m x 1.7 m and 1.6 m x 1.7 m (same as LS-3 design) with about 7,000 targets on the facets. Target spacing is 30 mm.

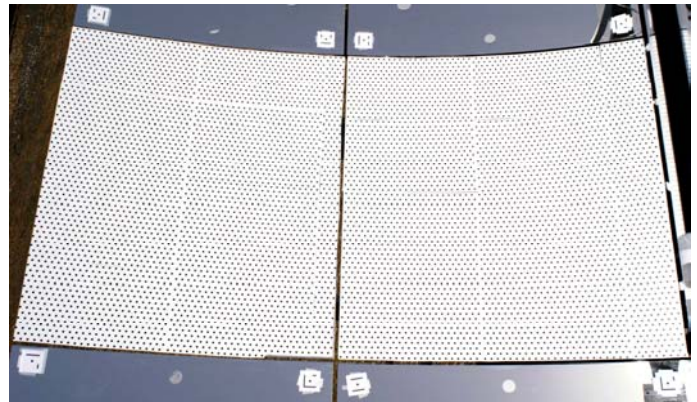


Figure 8: Two adjacent EuroTrough facets with 7,000 measurement targets as used for the study of the sag

Because the glass mirrors bend under gravitational forces, the mirror shapes were measured using photogrammetry for several different angular positions. Figure 9 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.

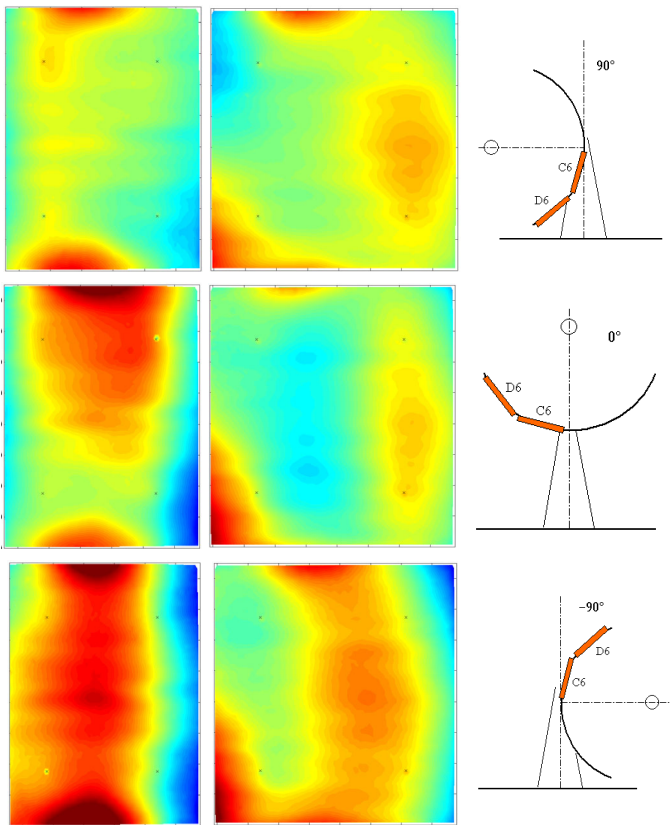


Figure 9: Shape change caused by gravitational forces for two facets. All pictures scaled uniformly.

SMALL FACET AND RAY-TRACE-STUDY

As noted, an attractive feature of close-range photogrammetry is its scale independence. In addition to the studies discussed thus far of the EuroTrough and its mirror elements having dimensions of meters, photogrammetry can also be applied to smaller components. As an illustrative case, a paraboloidal mirror facet having a square aperture dimension of 38 cm was investigated. Analysis of this device encompassed optical and ray-trace studies to assess its performance. Figure 10 shows the facet used for this study.

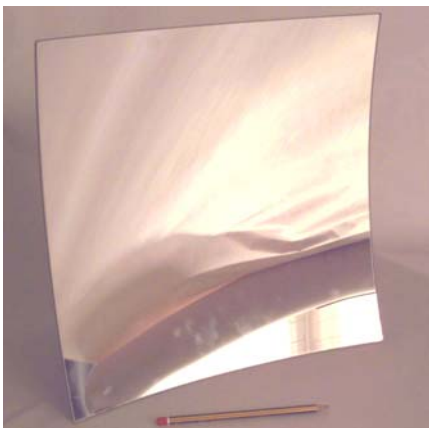


Figure 10: Curved, 38 cm square aperture mirror facet

A surface study was required for this device, and an array of 2,150 target points were applied to the facet surface. A set of 24 photographs was taken from 12 viewing stations. The photographs were processed using Vision Measurement System (VMS) photogrammetry software. Average relative precision obtained for the photogrammetric network solution was 1:47,000, which produced an average object space precision of 11 microns. Figure 11 shows the surface extracted from the ensuing photogrammetric coordinate data.

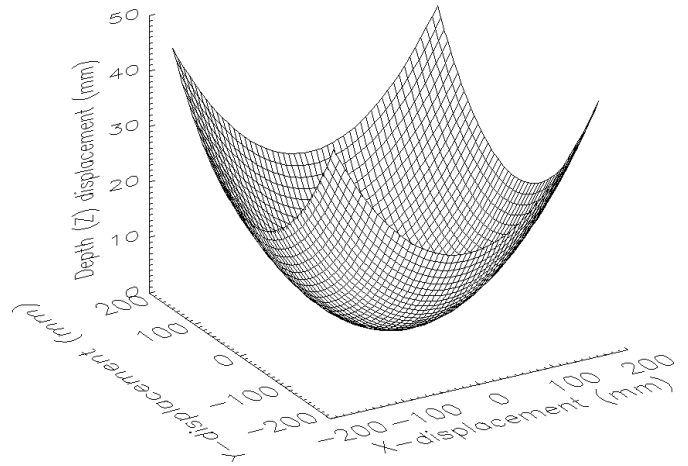


Figure 11: Curved shape of the mirror facet as calculated from photogrammetric data

Shape assessment

Assessment of the shape characteristics was conducted by optimization (least-squares adjustment) of the measured coordinate data according to both paraboloidal and spherical models. Figure 12 shows the optimized depth deviations of the target points on the facet from an optimal paraboloid having a best-fit focal length of 370.4 mm, as a function of radial distance from the center of the facet.

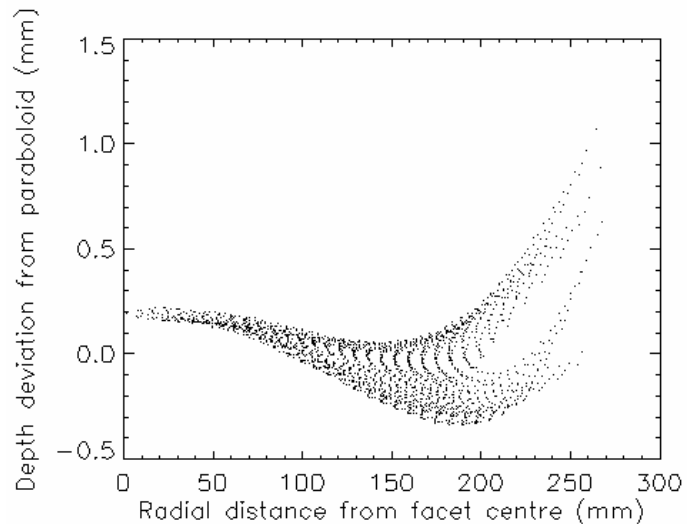


Figure 12: Depth deviation data optimized to a paraboloid having a focal length of 370.4 mm

Figure 13 shows a similar depth deviation plot for the target coordinates, optimized 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 lower for the data fitted to a spherical surface, rather than to a paraboloidal surface. Discussions with the manufacturer confirmed that the facet had been constructed on a spherical mould, rather than a paraboloidal one.

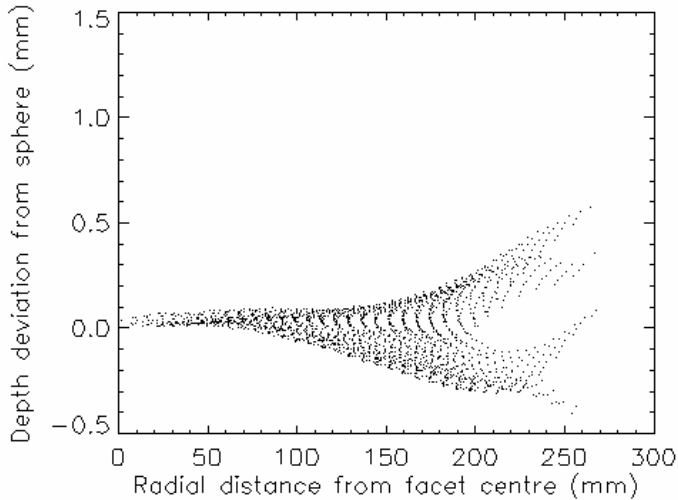


Figure 13: Depth deviation data optimized to a sphere having a radius of curvature of 759.3 mm

Visualization of the surface deviations of the facet coordinates from a spherical surface is shown in Figure 14.

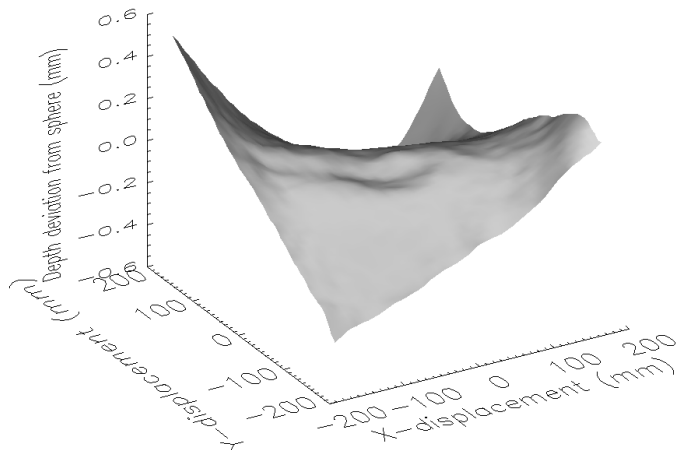


Figure 14: Spatial distribution of facet depth deviations from a spherical surface, radius: 759.3 mm

Further characterization was undertaken by fitting a surface through the measured photogrammetric data for the facet, and calculating the surface normal deviations (surface slope error) across the facet surface. Figure 15 shows the frequency distribution plot of surface slope errors for the data points across the facet. The frequency distribution takes the form of a Rayleigh distribution, and it can be shown that the mode of the distribution equals the standard deviation of a circular, bivariate Gaussian distribution of slope errors [19]. This standard deviation

becomes a figure of merit for a measured surface. As noted in Figure 15, the mode is approximately 1.7 milliradian. It should be observed, however, that the actual frequency distribution (solid line) deviates noticeably from the best-fit distribution (dashed line) shown in Figure 15 for slope error above approximately 5 milliradian. This indicates that the actual distribution of slope errors deviates somewhat from the ideal model of a circular, bivariate Gaussian distribution of errors.

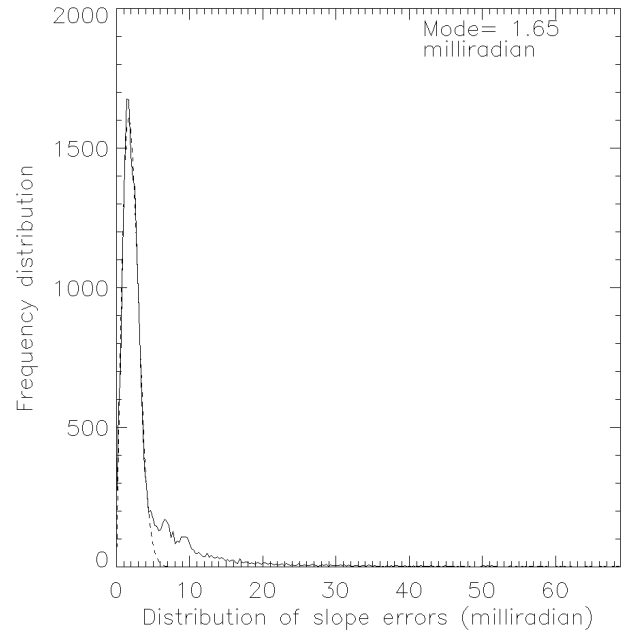


Figure 15: Frequency distribution of surface normal deviations (slope errors) for the target coordinates across the mirror facet. Solid line shows actual frequency distribution, dashed line shows the best-fit Rayleigh distribution to the data.

Optical modeling of the mirror facet

The high level of coordinate precision that can be obtained from photogrammetry also allows modeling of the measured surface to extract quasi-optical information. This further processing allows ray tracing studies and focal region performance prediction to be undertaken. Experience to date indicates focal region capture fractions predicted from photogrammetric data generally shows compatibilities with flux mapping data of between 2% to 5%. Ongoing studies are investigating methods of getting the predicted flux performance assessments to have an even lower level of deviation from measured data.

Surface normal data was calculated for the small facet surface, and used to supply input to a ray-trace program written by the author (Johnston). A 50 mm diameter disk target was modeled at a focal position of 370 mm from the facet vertex. An insolation level of 1000 W m^{-2} was used, and the mirror was modeled with a reflectivity of 100%. Figure 16 shows an image of the predicted focal light distribution on the disk target (no target shading is taken into account in the ray-trace program), while Figure 17 shows a surface plot of the light distribution on the target.



Figure 16: Image of the expected light distribution at the 370 mm focal point of the mirror facet

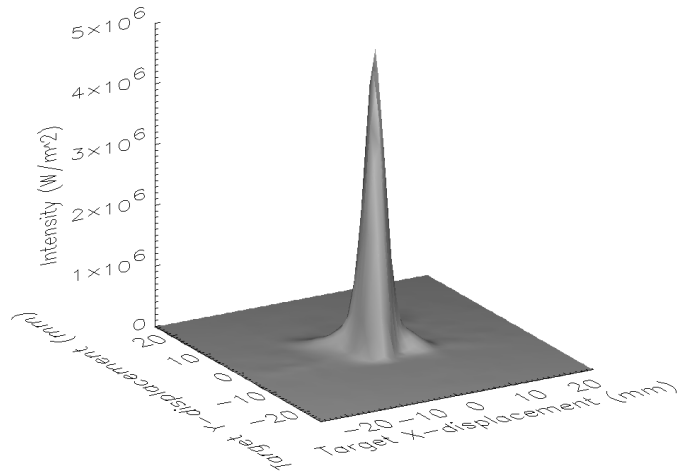


Figure 17: Surface plot of the focal light distribution shown in Figure 16

As can be seen in Figure 17, the peak flux predicted is approximately $5 \cdot 10^6 \text{ W m}^{-2}$, or some 5000 suns. This will also vary with actual mirror reflectivity. Focal region performance is also assessed by analyzing the percentage of the total power contained in a varying radius from the centroid of the flux distribution.

Figure 18 shows the percent-power-in-radius plot for the flux distribution. Approximately 98% of the predicted focal power is contained in a radius of approximately 15 mm from the flux centroid. Unfortunately no flux map data was available for comparison with the predicted focal region performance for this facet.

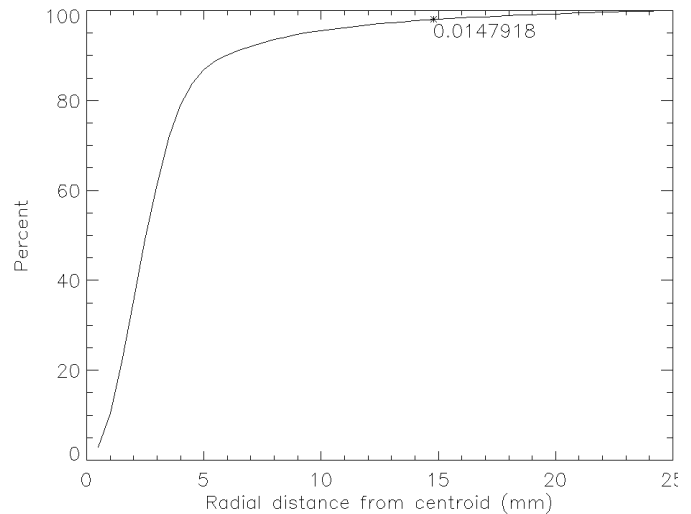


Figure 18: Percent-power-in-radius plot for the flux distribution shown in Figure 16

CONCLUSIONS

The present paper has provided descriptions of the photogrammetric process, and issues that affect the accuracy and precision of the results so obtained. Results presented have described the use of close-range photogrammetry to measure a range of solar concentrator components, from EuroTrough fabrication jigs, to concentrator 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 the subsequent processing of the photogrammetric data to provide optical and ray-trace analysis of the facet performance. In addition to both the internal and external measures used to ensure photogrammetric accuracy, the authors are pleased to present the results of these studies as being consistent and justifiable within the bounds of expectation of measurement for the different systems studied. 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 concentrating systems. This further contributes to enhancing the thermal output of solar power plants while maintaining minimum mirror usage.

The results presented in this paper have been achieved using manual photography of the objects being measured. Work has been conducted for a variety of applications that utilise dedicated arrays of cameras to undertake multiple, instantaneous photographs of an object. Examples of applications for measurement of dynamic objects are flow velocimetry [20] and tracking of aerospace models in wind tunnels [21], and for rapid measurement of static objects are the characterizations of tube sections for the automotive industry [22] and production line control [23]. Similar techniques can be applied in the field of solar collector shape characterization for deformation studies or quality control in manufacturing. Many of the aspects of quality measures for photogrammetric networks discussed previously in the paper can also be applied to rapid measurement techniques.

Future work is anticipated that utilises similar multi-station arrays, together with specialist software that will enable high-

speed quality assessment and control of individual solar concentrator elements as they are fabricated. Further ray-trace studies on the basis of collector surface geometry results are ongoing to quantify performance variations of real collectors over their annual operating range.

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