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A novel procedure for the optical characterization of solar concentrators

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Abstract

A novel procedure for the optical characterization of solar concentrators is presented. The method is based on recording at night the light of a star reflected by the mirror. Images of the mirror taken from its focal region allow the reconstruction of the slope map. The application of this technique for the in situ characterization of heliostats is particularly simple and at very low cost. Results on first tests carried out with a heliostat of the CESA-I field at the Plataforma Solar de Almeria have shown the feasibility of this technique. Uncertainties in the reconstructed slopes of about 1.0 mrad have been estimated.

1. Introduction

A reliable qualification of solar concentrators is crucial for the prediction of the capabilities of a solar thermal plant. Several procedures have been developed which allow to determine the optical properties of large mirrors. The VSHOT method (Jones et al., 1997) and his predecessor SHOT (Wendelin et al., 1991) measure the slope of the surface at many points of the mirror by directing a laser beam to the mirror and recording the reflected back beam on a screen. Both the laser and screen are located at a distance of about twice the focal length f of the mirror. This procedure can be used for solar dishes from 2.0 to 15.0 m in diameter D over a focal length-to-diameter f/D in the range 0.5–3.0. On the other hand, in the so-called $2f$ test (Grossman, 1994) a camera views a target of concentric rings located at the radius of curvature of the mirror by looking back the reflected image from the center of the screen. This method seems to be applicable for f/D greater than 3.0.

A useful technique which allows a full characterization of the mirror surface is the photogrammetric method developed by Shortis and Johnston (1996, 1997). In this method several cameras record, from different view points, a number of targets fastened over the surface to be measured. This technique has been successfully applied in a large range of mirror sizes (up to 400 m^2) with focal lengths up to about 13 m.

The above methods are not practical for the qualification of mirrors with a very large focal length, e.g. heliostats of a central tower system with a typical focal length of 100 m or larger. The usual procedure for the characterization of heliostats relies in the analysis of the Sun image on a lambertian screen (Thalhammer and Phipps, 1979; King, 1982; Kiera and Schiel, 1989). This technique has also been applied for solar dishes (Grossman et al., 1992) and compared with SHOT and $2f$ methods by Wendelin and Grossman (1995). The image which is recorded by a CCD camera, allows to measure in a direct way the spatial distribution of energy flux at the focus. Unfortunately the measure of the flux distribution is not sufficient for the full optical characterization of the mirror.

In most of the above methods the orientation of the heliostat is constrained to the experimental needs. For

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instance in (V)SHOT and $2f$ methods the heliostat has to be vertical while in the photogrammetric technique it has to be horizontal. It is well known that the optical properties of a solar concentrator are strongly dependent on the orientation because the mechanical strains deform the mirror surface in a non-negligible way.

In this paper a novel procedure for the optical qualification of a solar concentrator is presented. In spite of its simplicity this method may provide very accurate results. We will describe the basis of the method which in principle could be applied to any large mirror. Its application is particularly simple for heliostats of a central tower system. First results of this technique for a heliostat of the CESA-I field at the Plataforma Solar de Almeria PSA will be shown.

The historical origin of this method comes from the GRAAL experiment (Arqueros et al., 2002; Arqueros, 2003) which used the heliostat field CESA-I for the search of cosmic gamma-rays. In GRAAL the heliostats were used as a primary collector for the air-Cherenkov light generated by cosmic gamma-rays in the atmosphere (Danaher et al., 1982). In order to check the alignment of the mirrors, a visible star was focused onto the detectors located up in the central tower. A visual observation of the heliostats from the tower showed bright spots in the mirror surface due to the reflected light of the star. It could be checked that the position of the bright spots changed with the view point of the observer. This effect can be easily explained from elementary geometrical optics. As will be shown in the next section by measuring the position of these bright spots with a CCD camera located at the tower, the slope of the mirror in these points can be determined in a similar way to the (V)SHOT method. In our method, however, a star provides an unidirectional light beam which cover the whole mirror surface. The method has been named SCCAN which stands for "Solar Concentrator Characterization At Night". A patent for this technique has been submitted to the Spanish Patent Agency (P200201771) on July 2002.

2. The Basis of SCCAN

The SCCAN technique relies in simple principles of geometrical optics. The image of an ideal paraboloidal mirror for a point source (object at infinity) on the optical axis is a geometrical point at the focus. Therefore an observer located at the focus would see the whole mirror surface "bright" (i.e. light comes from all mirror points). Because a realistic mirror is far from ideal, the image of a point source has a finite size. In fact the image of a point source out of the optical axis has a finite size even for an ideal mirror.

In the following a realistic mirror focusing an out-of-axis point source will be assumed. The volume where the light gets the maximum density will be called the "concentration region" CR. The intersection of the CR with the plane located at the CR center and perpendicular to the straight line joining the CR with the mirror, will be called the "light spot" LS (see Fig. 1). In the abovementioned procedure of on-Sun testing for both solar dishes and heliostats, a lambertian target is placed in the center of the CR and the spatial distribution of light intensity in the LS is measured. In a solar concentrator the longitudinal size of the LS ranges from a few centimeters up to more than 1 m (e.g. in heliostats of a central tower system) and its shape is roughly circular although elliptical LS are not unusual.

An observer located at the CR would see certain regions of the mirror surface "bright", in fact those points of the mirror surface for which the observer location fulfills the reflection law. If the observer moves around the whole LS, in general inside the CR, every mirror point will be seen "bright" for some observer position. This effect can be easily observed in a heliostat from the central tower. Fig. 2 shows two typical images of a heliostat showing the abovementioned bright spots.

If the diameter d of the entrance window (e.g. diaphragm of a camera, iris of a human eye, ...) is much smaller that the focal length and assuming ideal specular reflection, the position of the "bright" regions allows a precise measurement of the unit vector normal to the mirror surface by a simple application of the law of reflection. Assuming a perfect knowledge of the location and orientation of the mirror, the angular position of the star and the location of the camera, the theoretical limit for the uncertainty of the slope measurement is of d/f radians.

For a practical and fast data taking, the images can be recorded with a CCD camera. In order to characterize the whole mirror surface, the camera has to take images at many positions by scanning the whole LS.

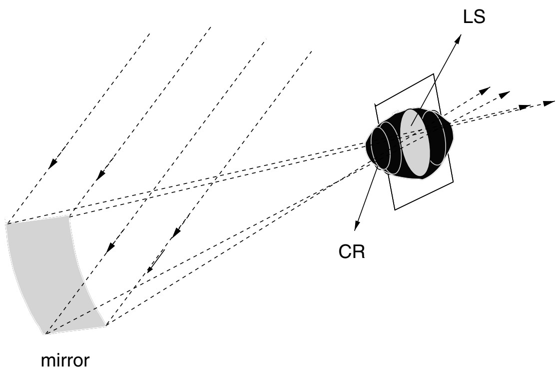

Fig. 1. The light from a point source is focused by the mirror in the concentration region CR. The intersection of this region with a plane perpendicular to the line joining the CR and the mirror defines the light spot LS.

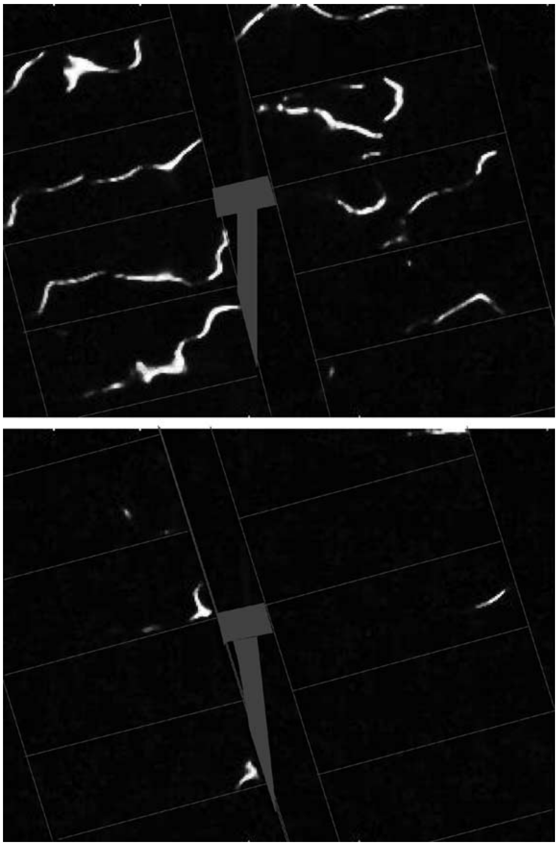

Fig. 2. Two typical pictures of a heliostat recorded by a CCD camera from the central tower. A star has been focused onto the camera. The bright spots correspond to those mirror regions for which the reflected light gets the camera. A draw of the facet profiles and the heliostat support has been overlapped.

Note that the slope can also be reconstructed by an observer outside the maximum concentration region as far as it is crossed by the ray paths. However the CR is the most efficient location for these measurements.

3. Application to heliostats in a central tower system

The application of the SCCAN technique is particularly simple for the in situ characterization of heliostats in the field. The experimental set-up consists of the following elements (see Fig. 3): (1) the heliostat under regular working conditions, (2) a set of CCD cameras (one or more) attached up in the central tower and aiming at the heliostat and (3) the computing system for the camera(s) control and image acquisition. The heliostat is assumed to operate under a control system which provides full information of its orientation. The field of view of the set camera-lens determines the mirror surface to be studied. A fraction of the mirror, the whole heliostat or even several heliostats at the time can be characterized.

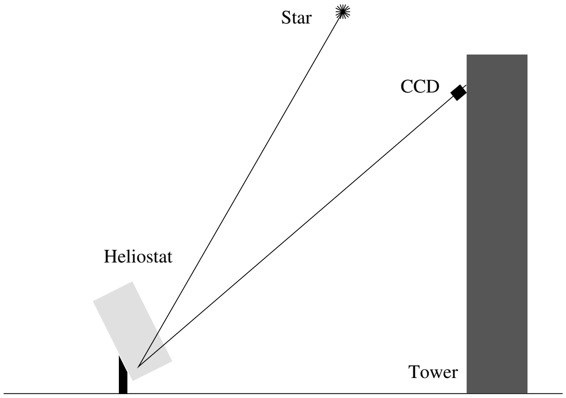

Fig. 3. Scheme of the SCCAN technique for the optical characterization of heliostats in a central tower system.

The procedure is the following. First an isolated star is chosen. Then the heliostat is oriented in order to focus the star light onto the camera location while it takes images of the heliostat from many different positions of the LS. This can be achieved by using several procedures: (a) the heliostat follows the star with the tracking system. This can be easily achieved by using the tracking program for the Sun by modifying the star coordinates. With the star on focus, the CCD camera(s) is shifted around the whole LS while it takes heliostat images. This procedure can be very efficient, however, a system for the precise movement of the cameras are needed, increasing the cost of the set-up; (b) alternatively, the orientation of the heliostat can be shifted under the control system producing a similar effect, i.e. scanning the LS over the CCD camera entrance which remains fixed. This procedure is simple with no additional cost since the heliostat control system already exists. (c) Finally it is possible to use the apparent movement of the star to get a very fine scan with an even more simple scheme. The heliostat is fixed to an orientation for which the star LS crosses the camera, due to the earth rotation, while the camera(s) takes pictures of the heliostat. Techniques (b) and (c) can be combined in such a way that several scans of the star at fixed orientation are carried out, but the heliostat orientation is different for each one, that is, the LS crosses the camera at different heights.

Since the direction of the star is needed for the reconstruction, the image time has to be known accurately with a maximum uncertainty of about 5 s. This can be achieved by synchronizing the computer which control the CCD camera with a UTC server.

The first step in the image analysis is the reconstruction of the position of the bright spots in the heliostat reference frame. This can be carried out by using standard geometrical techniques for the change of coordinate system (camera/heliostat). Then the slope of the mirror in every bright point can be easily determined by the application of the reflection law. If a sufficient number of pictures covering the whole LS are taken, a dense map of slopes can be obtained providing a detailed optical characterization of the mirrored surface.

The field of view of the heliostat defined by the LS is only of about 0.5° (let us assume 1.5° in case of very large slope errors) and therefore many isolated stars can be chosen. In case of a weaker star in the field of view its contribution can be easily removed by an intensity cut in data analysis. In regard with the intensity of the star the choice depends on the spectral type of the star and the spectral response of the camera-lens set. Digital CCD cameras provide enough sensitivity even for not very bright stars. In principle a planet could also be used although in this case the maximum accuracy of the slope reconstruction is limited by the angular size of the source. Taking into account the above considerations many stars all around the sky can be used in this technique and therefore the characterization of the heliostat can be carried out for any orientation of interest.

4. Results and discussion

An experimental test of the SCCAN method has been carried out at the Plataforma Solar de Almeria (Spain; 37°.09 N, 2°.36 W). The heliostat 402 of the CESA-I field has been used for these tests. This heliostat is located at 76.17 m from the tower basis. It consists of 12 facets with a total mirrored area of 39.7 m^2. A single camera has been installed in the hole at the 70 m level of the tower. The camera has been a cooled digital CCD 320×240 pixels (10 square microns each). A lens of 50 mm focal length attached to the camera allowed taking images of a significant fraction of the mirrored surface of the heliostat.

For these tests the star Aldebaran (68.98 ra., 29.09 dec.) was used. Several fixed orientations of the heliostat were calculated to perform scans of the reflected light through the camera. By modifying properly the focus height in the control system software, the expected LS center crossed the camera at vertical distances h ranging from +0.8 to −0.8 m in steps of 0.2 m. Each scan was 8 min long. The exposure time was 1.5 s at a rate of one image every 6 s. Data acquisition was divided into two series. Series 1 consisted of nine scans (azimuth range of 159–140° and elevation 51–62°) covering the whole h range (from +0.8 to −0.8 m). Series 2 consisted of seven scans (azimuth 135–110° and elevation 63–68°) with h ranging from +0.8 to −0.2 m. A total of 1239 images were taken over a period of about 2 h.

In the image analysis a cut was applied to removed hot pixels and those with an intensity below a certain threshold. Fig. 4 shows the heliostat points which were observed bright at least in one of the recorded images. A fraction of the heliostat could not be characterized because of the restricted field of view of the CCD-lens set. This problem can be easily solved either by using a lens with a shorter focal length or a camera with a larger CCD chip. The figure also shows a lack of data in some regions of the heliostat surface viewed by the optical field of the CCD. Increasing both the scan number and the h range would allow to cover the whole surface. But, even with this lack of data, very significant information of the optical properties of this heliostat could be obtained as will be shown below.

Following the procedure described above, the vector normal to the surface $\vec{n}_r$ has been obtained in all bright points and compared with the expected one from an ideal mirror $\vec{n}_t$. The heliostat 402 was designed and canted to get an average spherical shape of 194 m curvature radius. For such a large f/D value (about 16), the spherical shape is equivalent to a circular paraboloid.

Very interesting results can be obtained from a simple analysis of the slope map. Let us assume a standard 3-D Cartesian coordinate system (x, y, z) on the mirror. The general equation of an elliptical paraboloid is

$$z = \frac{x^2}{2R_x} + \frac{y^2}{2R_y} + Cxy + g_{x0}x + g_{y0}y \tag{1}$$

where z is the surface height from the x–y plane. The gradient of z in the x (horizontal) and y (vertical) directions are very nearly given by the partial derivatives of z, that is

$$g_x = g_{x0} + \frac{x}{R_x} + Cy \tag{2}$$

$$g_y = g_{y0} + \frac{y}{R_y} + Cx \tag{3}$$

If $C = 0$ the axis of the elliptical cross section coincide with the x and y axis and R_x and R_y represent the curvature radii of the paraboloid in the horizontal and vertical directions respectively. In addition, in this case the heliostat center is aiming at the direction $(g_{x0}, g_{y0}, 0)$. In the ideal case g_{x0} and g_{y0} should be 0 since the plane xy is tangent to the heliostat at its center. However the orientation of a realistic heliostat is very often slightly shifted due to the so-called offset errors arising from mechanical defects. This offset which gives rise to a shift of the LS with respect to the expected focus is usually compensated via the control system software.

The heliostat surface has been divided into 5 × 5 cm^2 square cells. For each cell the gradient components g_x, g_y have been reconstructed. A chi-square fit to Eqs. (2) and (3) has provided the values of C, g_{x0}, g_{y0}, R_x and R_y. A result for C of 3.5×10^{-5} m^{-1} has been found which corresponds to a negligible rotation of the ellipse with

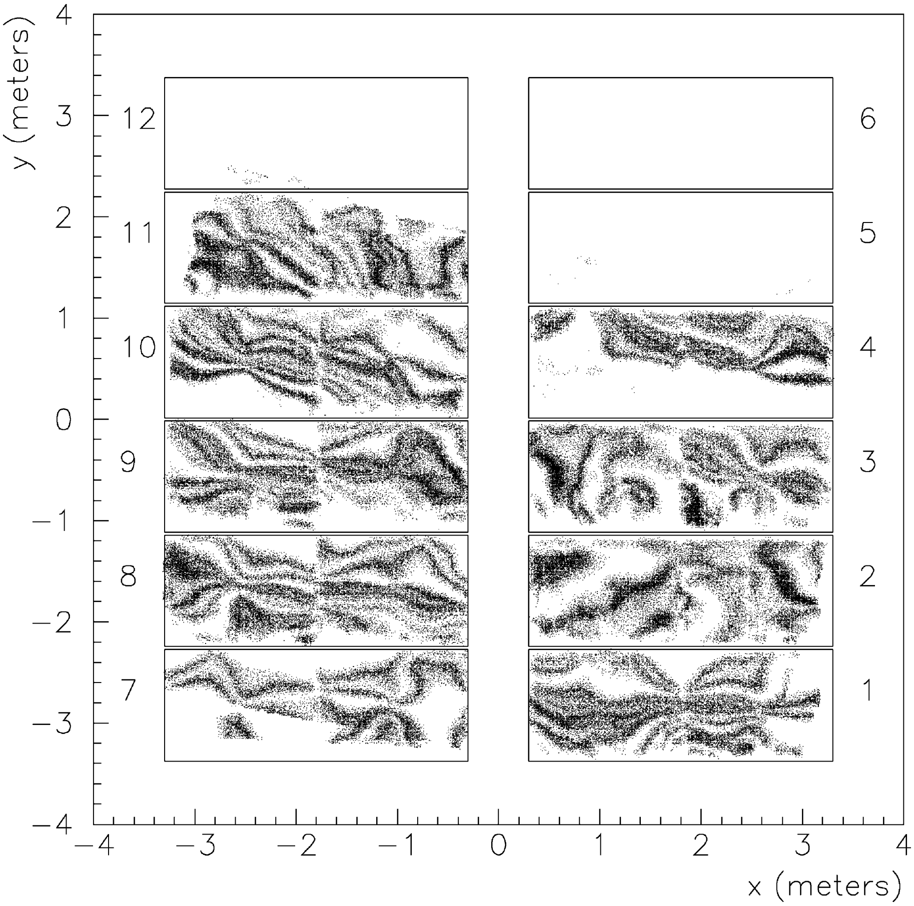

Fig. 4. Points of the heliostat surface which were observed bright in, at least, one recorded image. Facet numbers are indicated.

respect to the heliostat reference system smaller than 0.3°. In the following this small rotation will be neglected. Fitted values of R_x and R_y have been 200.0 and 193.8 m respectively. The average curvature radius of 196.9 m can be compared with the optimal value of 194 m. The heliostat center is aiming at the direction $g_{x0} = -1.8$ mrad and $g_{y0} = 3.4$ mrad revealing non-corrected offset errors.

A similar analysis has been carried out for those individual facets for which enough information was recorded (all facets except 5, 6 and 12). Average values for the corresponding horizontal and vertical curvature radii of 268 ± 20 and 220 ± 11 m have been found. These uncertainties are due to both large errors in the fitting of individual facets because of their the small size and large fluctuations between different facets.

Fig. 5 shows g_x and g_y against x and y, respectively. In this plot all data from both series have been included. The straight lines represent the result of the fit to Eqs. (2) and (3). These plots reveal some interesting features. For instance, Fig. 5(a) shows some asymmetry between the left ($x < 0$) and right ($x > 0$) sides of the heliostat both in the slope (i.e. the curvature radius) and the offset error which is very likely due to some structural problem and/or a canting defect. On the other hand Fig. 5(b) shows point clusters each one due to a pair of facets. Vertical canting seems to be reasonably accurate since no cluster deviates significantly from the fit. It has been checked that all the irregularities in these plots appear in individual scans. Similar diagrams can be obtained for each facet, therefore, getting information on the contribution of each facet to the heliostat defects.

Fig. 6(a) shows the module of the vector difference $|\vec{g}_m - \vec{g}_f|$ between the measured gradient $\vec{g}_m$ and that obtained from the fit for all heliostat cells with some bright spot. The figure shows that these deviations are usually smaller than 3 mrad. The optimal procedure for checking the reliability and accuracy of this method would be by studying a previously characterized mirror with an slope accuracy much better than the expected accuracy of our method. Unfortunately no such reference mirror was available. Nevertheless the repetitivity

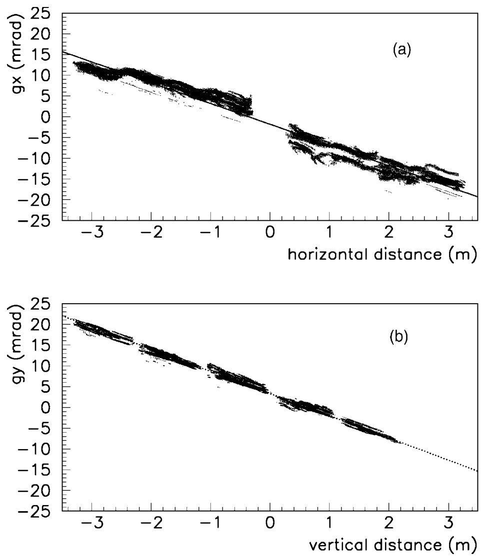

Fig. 5. x and y components of the unit vector normal to the surface versus the horizontal and vertical distance of the heliostat point. The straight lines represent the fit to Eqs. (2) and (3).

of the results over different series provides useful information. In the first place the results of R_x and R_y have been compared for both series (see Table 1). The table shows that the repetitivity between these two independent series is worse than expected from the pure statistical uncertainties. From this comparison, realistic uncertainties in the curvature radii of about 1 and 3 m for R_x and R_y, respectively can be estimated. These large values are due to the fact that both series do not cover the same mirror surface. They could be significantly lowered by increasing the heliostat coverage.

On the other hand, the slope maps from series 1 and 2 have been compared. The root mean square of the x and y component of the vector difference $\vec{g}_2 - \vec{g}_1$ and that of its module have been calculated:

$$\sigma_x = \sqrt{\sum_i \frac{(g_{2x} - g_{1x})_i^2}{N}} \tag{4}$$

Table 1
Horizontal and vertical curvature radii of the heliostat as measured from the data series

	R_x (m)	R_y (m)
Series 1	200.3 ± 0.4	190.1 ± 0.2
Series 2	202.6 ± 0.6	196.7 ± 0.3
Series 1 and 2	200.0 ± 0.4	193.8 ± 0.2

Statistical uncertainties are shown.

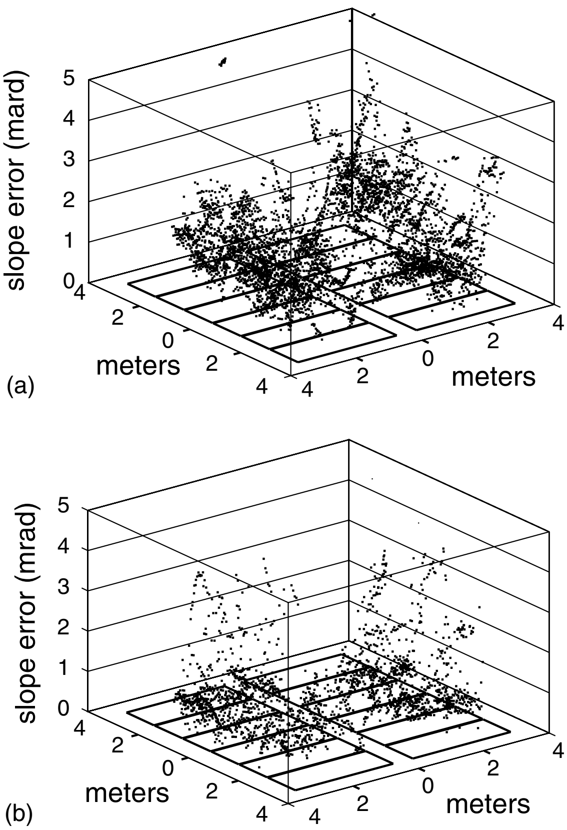

Fig. 6. (a) 3-D plot representing the module of the vector difference between the measured gradient and that expected from the fit to Eqs. (2) and (3) versus the heliostat position. An average slope error of about 4 mrad is found. (b) The same representation for the vector difference between the measured gradient in series 1 and 2. A repetitivity of about 1 mrad is found from this comparison.

$$\sigma_y = \sqrt{\sum_i \frac{(g_{2y} - g_{1y})_i^2}{N}} \tag{5}$$

$$\langle|\vec{g}_2 - \vec{g}_1|\rangle = \sum_i \frac{|\vec{g}_2 - \vec{g}_1|_i}{N} \tag{6}$$

where $\vec{g}_1$ and $\vec{g}_2$ represent the reconstructed unit vectors from series 1 and 2 respectively. Only N cells were used, those for which the slope could be determined in both series. Fig. 6(b) shows the module of the vector difference $|\vec{g}_2 - \vec{g}_1|$ for these cells. Table 2 shows the results of this comparison which has been carried out for the whole heliostat (last row on the table) as well as for several individual facets. For the whole heliostat, uncertainties in the horizontal (vertical) component of the slopes of 0.90 mrad (0.60 mrad) have been found leading to an uncertainty in the module of the difference vector of 1.10 mrad. Similar accuracies have been found for

Table 2
Statistical parameters from the comparison of slopes in series 1 and 2

Mirror	σ_x (mrad)	σ_y (mrad)	$\langle\lvert\vec{g}_2 - \vec{g}_1\rvert\rangle$ (mrad)
Facet 2	1.02	0.46	1.12
Facet 8	0.95	0.82	1.25
Facet 10	0.51	0.68	0.85
Heliostat	0.90	0.63	1.10

σ_x, σ_y and $\langle\lvert\vec{g}_2 - \vec{g}_1\rvert\rangle$ are the standard deviation of the x and y component and module of the difference between gradients of both data series 1 and 2.

individual facets except facet 10 with a somehow smaller uncertainty of 0.85 mrad.

The above statistical parameters have been also used to study the average deviations of the reconstructed slopes from the theoretical ones. The slope map obtained from all data (series 1 plus series 2) has been compared with both a circular paraboloid of radius 194 m (optimal shape) and that of Eqs. (2) and (3) with the fitted values. From the comparison with Eq. (1), a result of 1.61, 0.60 and 1.73 mrad for σ_x, σ_y and $\langle\lvert\vec{g}_2 - \vec{g}_1\rvert\rangle$ have been obtained (see also Fig. 6(a)) while the comparison with the ideal circular paraboloid gave values of 2.49, 3.66 and 4.42 mrad respectively. The above results indicate that the uncertainty of the method is significantly smaller than the measured slope deviations from the theoretical shape and thus the characterization of the mirror is reliable up to the 1 mrad level.

As mentioned above the theoretical limit of accuracy in the slope reconstruction is given by the ratio d/f. In our tests a focal length of about 100 m and a lens diaphragm of 0.3 cm was used and thus a theoretical limit of about 0.03 mrad would be expected. Uncertainties in the various geometrical parameters restrict the final accuracy of this technique. A small systematic error in the installed location of both the heliostat and the CCD camera induces a systematic error similar to that of an offset error but without any practical effect on the optical characterization of the mirror. A cross check with diurnal offset measurements by analysing the Sun images can be very useful. A serious limitation to the accuracy of the optical characterization of the mirrored surface comes from random errors in the heliostat pointing direction, for instance due to the wind or mechanical defects. However, these effects are intrinsic to a realistic heliostat and therefore the statistical uncertainties in the measured slope map is an interesting feature of the heliostat at normal working conditions. The measurements presented here were carried out with a wind speed below 15 km/h. Other uncertainty source comes from the fact that in a realistic mirror the reflected ray behaves like a cone instead of beam and thus many spots are observed at a “wrong place”. This effect can be easily reduced by applying an intensity cut to the usable pixels before the analysis. We have checked a significant increase in our repetitivity tests after appropriate intensity cuts.

On the other hand the pixel size imposes a theoretical limit to the spatial resolution and thus to the slope accuracy. In our case a pixel sees about 2×2 cm^2 heliostat surface. For the analysis 5×5 cm^2 cells have been used with an accuracy limit in the slope ($R \approx 200$ m) of about 0.2 mrad. In practice the spatial resolution may be worsened by errors in the reconstruction of the position of the bright points in the heliostat reference system from their position in the 2-D CCD image particularly for long acquisition periods for which the orientation of the heliostat changes significantly.

An interesting test which has been carried out to check the repetitivity of the measurements is the comparison of the slope results in mirror cells with multiple hits within the same data series. This comparison has shown a repetitivity in the module of the gradient difference (Eq. (6)) of about 0.2 mrad for cells with more than 3 hits (about 1520 cells in the first series and 743 in the second one). However a much worse repetitivity is found (around 1 mrad) when comparing slope measurements from both series. This can be due either to some error in the position reconstruction or to a variation in the conditions between both series (wind, mechanics, ...).

5. Conclusions

A novel procedure for the optical qualification of solar concentrators has been presented. The method can be easily applied to heliostats of a central tower system. The results of a first test carried out using a single CCD camera has been reported. A heliostat has been characterized with a data taking period of about 2 h. The analysis of the slope map has allowed to determine relevant properties of the heliostat like offset errors, canting accuracy and possible structural defects.

The estimated errors in the slope reconstructions inferred from the comparison of two data series were of about 1 mrad. This accuracy may be sufficient for checking the quality of heliostats in a central tower system. However it is significantly worse than that of those procedures for solar concentrators of smaller focal length. For instance Jones et al. (1997) reports VSHOT slope errors of the order of 0.1 mrad. The theoretical limit of SCCAN is also much below 1 mrad. Presently, more tests are being carried out to determine the real accuracy of this technique for heliostats. In principle our technique could also be applied to other solar concentrators. The feasibility for solar dishes and parabolic troughs will be studied.

The SCCAN technique has several advantages as compared with others. In the first place, data are taken overnight with no need of interrupting energy production in the solar plant. On the other hand, both mirror orientation and data acquisition can be done in an automatic way. In fact the data used in this paper were carried out in this way. On the other hand, the heliostat is characterized in situ at usual working conditions. Besides, since many stars are available, the characterization can be performed for any mirror orientation of interest. Finally the cost is extremely low.

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