Quality control facilities for large optical reflectors at ENEA-Casaccia for physics application

S. Baccaro [a,c], C. Bosio [c], A. Maccari [b], M. Montecchi [a,c]

[a] FIS-ION, ENEA-Casaccia, Via Anguillarese 301, 00060 S. Maria di Galeria (Roma), Italy

[b] SOLTERM, ENEA-Casaccia, Via Anguillarese 301, 00060 S. Maria di Galeria (Roma), Italy

[c] INFN- Sezione di Roma1, P.le A. Moro 2, 00185 Roma, Italy

The paper describes the quality control facilities for large optical reflectors available at ENEA-Casaccia. Commercial and custom spectrophotometers allow to measure the reflectance; specular and diffused for flat samples, and specular for the full-size reflector. In the case of spherical shape, the 2*f* and the *pin-hole* optical tests give a quick evaluation of the focusing effectiveness and the curvature uniformity, respectively. An optical profilometer allows to accurately measure the reflector profile and its deviations from the project specifications.

1. INTRODUCTION

Large optical reflectors have different applications ranging from astronomy, in telescopes whose imaging capability is very relevant, to solar energy, like sun-power collectors, where the optical requirements are much less severe. At mid way in this range is the application of mirrors in RICH detectors for High Energy Physics experiments, where they are used to focus the Cherenkov radiation on optical sensors, according to a quasi-imaging usage, due to the finite resolution of these sensors. Many applications need reflectors so large that they are composed by several panels, each one being some meters large.

Despite the deep differences about structure, composition, shape and features dictated by the specific application, always the large reflectors, or each one of its sub-panels, have to be qualified to verify the correspondence with the project specifications. The optical qualification concerns basically the reflectance (specular and diffused), and the geometrical shape of the reflecting surface. The first is mainly due to the surface quality and its treatment, often enhanced with a suitable optical coating; the latter dominates the focusing feature of the reflector.

The optical qualification of large reflectors requires dedicated instrumentations and good skill to solve the problems related to the specific application. Aim of this paper is to describe some optical facilities actually available in ENEA-Casaccia that allow a quite complete qualification of large reflectors. In particular an optical profilometer has been developed in the framework of the *Concentrating Solar Power Project*, of which Italian government has charged ENEA [1]; the other facilities have been prepared to qualify the mock-ups of the reflectors for the LHCb RICH [2].

2. REFLECTANCE

The reflectance is one of the most important features of the reflector; it is mainly due to the surface quality and its treatment, that often includes a suitable optical coating. Generally the reflectance should be uniform along all the reflector surface and higher than a threshold value in a wavelength-range given by the actual application.

During the R&D phase, the reflectance can be measured by means of spectrophotometers for reduced-scale plane samples, representative of the reflector surface. Two spectrophotometers, one commercial, the other one custom, allow to measure the specular component of the reflectance in the UV-VIS-NIR range. The double-beam optical-scheme adopted in both the instruments allows to reach 1% accuracy. Both the instruments allow to measure the hemispherical reflectance when equipped with an integrating sphere (diameter 15 cm). The diffused component of the reflectance is then obtained by subtracting the specular to the hemispherical spectrum; for a good reflector the diffused component should be less than 1%.

After R&D, the reflectance of the full scale reflector can be qualified by means a spectrometer similar to those used in the ENEA-INFN Casaccia Regional Centre where the electro-magnetic calorimeter (ECAL) of the CMS experiment is assembled [3]; this spectrometer is mainly composed by a well collimated white light beam and an Ocean Optics spectrometer. Because this instrument adopts a single-beam optical scheme, the error is about 1%.

3. SHAPE

The focusing capability of a mirror is driven by the geometrical shape of the reflector surface. In the case of spherical shape, the 2*f* and the *Pin-hole* tests allow a quick qualification of the reflector, giving the focal length, the image spot dimension and the homogeneity of the surface curvature. A more accurate measurement of the curvature is provided by an optical profilometer that works for any surface-shape, although it is actually developed for one-dimensional curvature, like the parabolic trough solar collectors.

3.1 2*f* test

In case of spherical reflectors, the focal length can be quickly evaluated by means of the 2*f* optical test [4], sketched in Fig.1: the punctual light source is kept on the same plane of the screen and both are moved along the optical axis of the reflector in order to optimise the focusing of the source image. The optimal distance from the reflector vertex gives the curvature radius, that is twice the focal length. Typical error is 1 cm for focal length of about 1 m.

In the case of reflector-size of about 1 m, a LED can be considered as a punctual light source; for smaller mirror, the punctual light source can be achieved by focusing the light of a lamp on a pin-hole. When the diameter of the pin-hole has to be much smaller than 1 mm, higher intensity can be achieved by focusing a previously expanded laser beam on the pin-hole.

Finally, the 2*f* test gives also an easy evaluation of the focusing effectiveness of the reflector: in the case of a perfect mirror, light source and its image have the same dimension; conversely in the practical case, any deviation of the curvature from the spherical shape causes the spreading of the image. For some applications this feature can be used as qualification criterion.

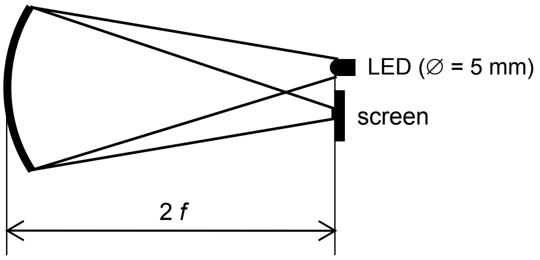

Figure 1: optical scheme of the 2*f* test.

3.2 Pin-hole test

The 2*f* test allows to evaluate the overall focusing effectiveness of the reflector, but is unable to localise the regions of the reflector surface deviating from the spherical profile. Such information is very useful to improve the manufacturing process, and can be achieved by few modifications of the experimental set-up of the 2*f* test: as shown in Fig.2, the screen is moved away from the reflector and replaced by a pin-hole having the same dimension of the light source; a lens is suitably positioned in between pin-hole and screen to focus the image of the reflector surface on the screen.

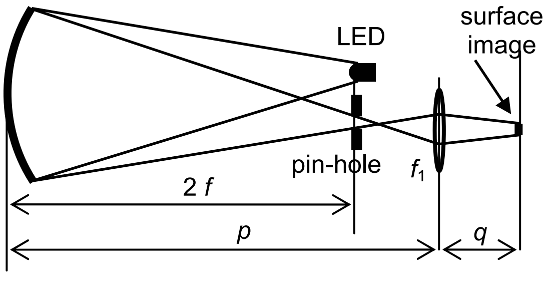

Figure 2: optical scheme of the pin-hole test.

In the ideal case, the surface appears uniformly luminous; conversely, the surface regions deviating from the spherical profile reflect the light rays outside the pin-hole entrance and result as dark regions.

This test, we named *pin-hole* test, at our knowledge is quite original and belongs to the same category of the Foucault and Wire tests [4].

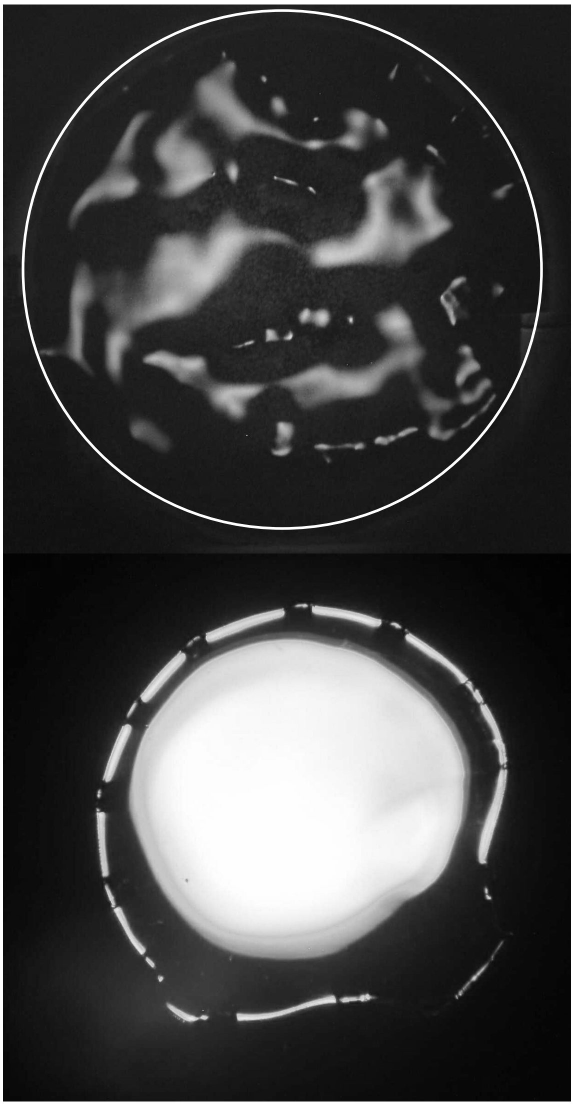

Figure 3: image of the surface reflector obtained with the Pin-hole test for two imperfect mock-ups.

Figure 3 shows the results observed for two imperfect mock-ups for the LHCb RICH; they have similar focal length (about 115 cm) and diameter (about 40 cm). The first (top, in the figure) was obtained by hot-bending a polymethylmethacrylate (PMMA) sheet on a spherical master and gluing it to a honeycomb structure to freeze the achieved curvature. The second (bottom, in figure) was obtained by pouring PMMA liquid on the master. According to the images, the surface of the former has many peaks and valley; the latter one is uniform in the centre, and deviates only at the specimen border.

3.2 Optical profilometer

The optical profilometer of ENEA-Casaccia has been developed to characterise the parabolic trough reflectors of the *Concentrating Solar Power Project*; which are composed by a sequence of panels being 6 m high, and 1 m wide. The scansion of these panels is obtained by the rotation and the translation of a HeNe laser head. As shown in Fig. 4, the HeNe laser is mounted on a high precision rotation stage (20 µrad repeatability). The reflected beam intersects the screen in a point whose position (x_S) is deduced processing the image acquired by a high resolution digital camera (Nikon D1X). The laser with the rotation stage, the screen and the camera are all mounted on a translational stage to accomplish several scansions along the panel width. The whole measurement is totally automatic.

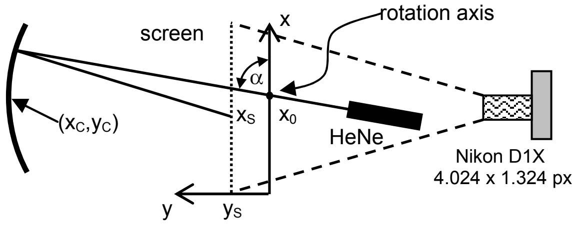

Figure 4: scheme of the ENEA optical profilometer.

The data-set of each scansion is processed with two different methods, both based on the geometric optics and considering the Lab-reference drawn in Fig. 4.

In the first method, the reflector-shape is approximated by a suitable analytical function depending on some parameters, among them the focal length. In order to reduce the unknown parameters, the coordinate of the central point of the reflector (x_c,y_c) are directly measured. Given a parameter-set, x_S is predicted and compared with the experimental datum measured by the corresponding laser orientation. Then the best-fitting parameters are obtained by minimising the least squares of the whole data set with the Levenberg-Marquardt algorithm [5].

The second method allows to draw a realistic profile of the reflector-surface by the iterative application of a criterion about the intersection between the tangents of adjacent points (see Fig. 5). The iterative procedure starts from the central point of the surface

((x_c,y_c) in Fig. 4 and P_1 in Fig. 5, where the tangent in P_1 is assumed to be parallel to x-axis) which tangent can be univocally determined thanks to the simultaneous knowledge of its coordinates and x_S, Then the adjacent point P_2, illuminated by tilting the laser of a small angular step ($\Delta\alpha$), is considered; this step should be small enough to assume monotonic the variation of the tangent between these two points. By definition, P_2 is a point belonging to the incident straight-line, and in P_2 the tangent has to agree with x_S. Let be C the intersection between the tangents in P_1 and P_2; its position strongly depends on where the position of P_2 is placed along the incident straight-line. On the other hand, as described in Fig. 6, if the behaviour of the profile was regular, these three points have to satisfy a relationship. The basic idea of this second processing method is to assume known such a relationship, although locally the profile may deviate from the ideal behaviour. Once position and tangent in P_2 are known, the procedure is repeated for P_2 and the next adjacent point P_3, and so on. As a result, the profile of the surface is obtained with an iterative procedure starting from the central point of the reflector.

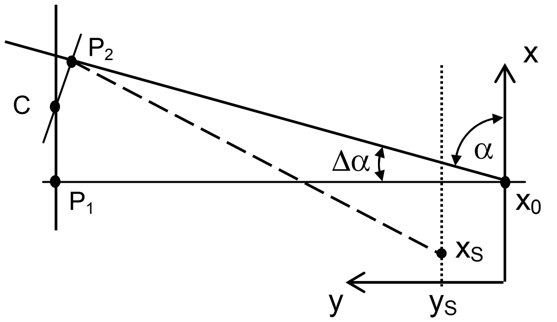

Figure 5: determination of position and tangent in P_2 when P_1 is known and a relationship between the tangents in the two points is assumed.

Resuming, the fit processing method allows us to evaluate the parameters of the analytical profile just best fitting the experimental data; they can be compared with the project specifications to establish the confidence level of the manufacturing process.
The iterative method allows to draw a realistic profile and consequently a map of the deviations from the project profile, important to improve the manufacturing technology.

Figure 7 shows the profilometer measurements of a 1:10 scaled-reduced solar-concentrator together with the best-fit curve. Due to the rough manufacturing process, close to the edges, the curvature of this very preliminary sample is sensibly deviating; on the other hand these defects are very useful to validate the proposed methodology. To achieve a good fit, the most scattered data were neglected and a profile mixture of circle (68%) and parabola (32%) was considered; the focal length was $185.5 \leq 0.5$ mm and the parabola vertex did not correspond to the central point of the reflector. More precisely the parabola axis is $11.3 \leq 0.8$ deg tilted.

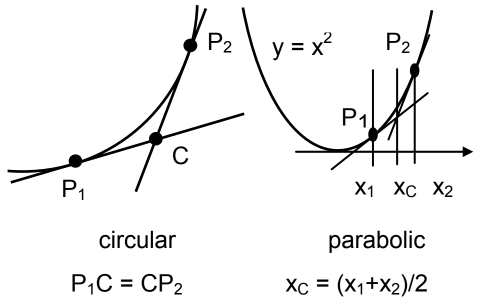

Figure 6: relationship between the tangents in P_1 and P_2 for circular and parabolic profiles.

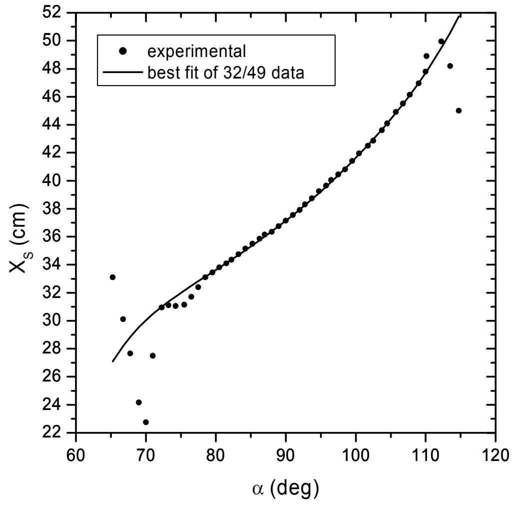

Figure 7: Fit processing of the data-set measured for a scaled-reduced solar-concentrator.

In order to evaluate the amount of these deviations, the data-set had to be processed also with the iterative method to obtain a realistic profile. Figure 8 shows the difference between analytical (fit processing) and realistic (iterative processing) profiles; the difference is calculated along the radius originating from the focal point. In the central part the deviations are very small.

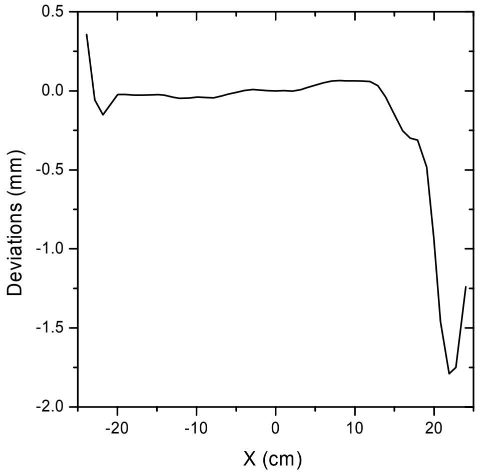

Figure 8: deviations of the profile from the analytical shape obtained with the fit processing.

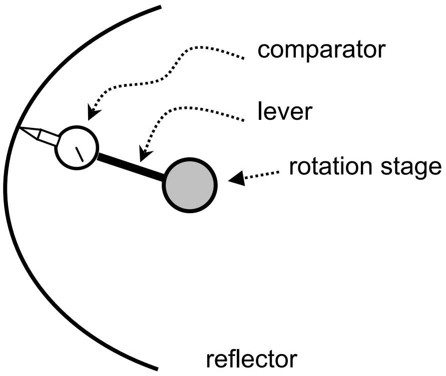

Figure 9: experimental set-up for the validation of the profile deduced with the iterative processing.

The dimensions of this reduced concentrator make possible the validation of the profile obtained with the iterative processing by comparison with the experimental measurements achieved with a comparator mounted with a lever on the rotation stage, as depicted in Fig. 9. The agreement, shown in Fig. 10, is quite good.

4. CONCLUSIONS

The facilities available in ENEA-Casaccia allow the quite complete qualification of large reflectors. In particular, several spectrophotometers allow to measure both specular and diffused reflectance. In the case of spherical shape, the 2*f* and the *Pin-hole* tests allow a quick qualification of the reflector, giving the focal length, the image spot dimension and the homogeneity of the surface curvature. An optical profilometer allows to accurately measure the reflector profile and its deviations from the project specifications by means of two separate data processing methods based on a best fit and iterative procedures, respectively. Actually the instrument is suitable for reflector curved only in one dimension, but a more versatile version of the set-up will be imminently available.

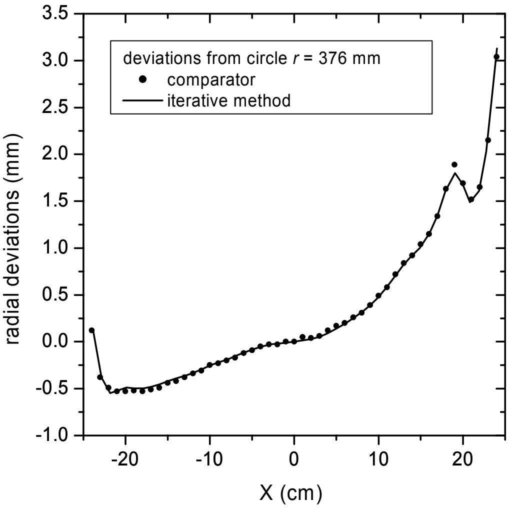

Figure 10: comparison of the profile deduced by the iterative method with the measurements of the set-up depicted in Fig.9.

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