SolarPACES 2024, 30th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

Measurement Systems, Devices, and Procedures

https://doi.org/10.52825/solarpaces.v3i.2282

Published: 20 Nov. 2025

3D-Shape Measurement of Parabolic Trough Mirror Panels:

First Results of the SFERA-III Round Robin

M. Montecchi[1,*], A. Benedetti[1], G. Cara[1], F. Torres[2], G. Bern[2], M. Röger[3], K. Blume[3], T. Schlichting[3], E. Lüpfert[3], D. Kesseli[4], G. Zhu[4], B. Smith[5], and R. Brost[5]

[1]ENEA - Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Italy

[2]F-ISE - Fraunhofer Institute for Solar Energy Systems ISE, Germany

[3]DLR Institute of Solar Research, Köln Germany / Almería Spain

[4]NREL - The National Renewable Energy, USA

[5]SNL - Sandia National Laboratories, USA

*Correspondence: Marco Montecchi, marco.montecchi@enea.it

Abstract. The 3D-shape round-robin initiative aims to compare the main geometric parameters of 3D shape measurements for parabolic-trough mirror panels, assessed using equipment developed and employed by each participating institution: ENEA, F-ISE, DLR, NREL, and SNL. Except ENEA equipment, all the other are based on deflectometry, also call fringe-reflection method. The round-robin is based on circulating 6 trough mirror panels (3 inner and 3 outer) of RP3 dimensions, with a focal length of 1710 mm, between participating laboratories; a simple and rugged supporting fixture together with precise instruction on how to use it have been provided to make the comparison more reliable. ENEA wrote a custom evaluation software for comparing the results. We observe a reasonable agreement among the mean values of the deviations of height and slopes from the ideal parabola: standard deviation better than 0.1 mm, 0.5 mrad and 0.3 mrad for z, slopeX and slopeY, respectively. The agreement is improved when a software realignment procedure for setting the height values on the support points to the expected ideal values is applied. The absolute difference between pairs of evaluators is sometimes greater than the declared experimental uncertainty; investigation into these deviations is still ongoing.

Keywords: Mirror Panel, Parabolic-Trough, Solar Collector, 3D Shape, Deflectometry

Acronyms:

3D: three dimensions

PT: Parabolic Trough

RMS: Root Mean Square

RP3: one of the standard size of PT solar collectors

RR: Round Robin

1. Introduction

In the context of the European Union (EU) project SFERA-III [1], within WP10 Task3, ENEA has coordinated the 3D-shape round-robin (RR) initiative. The aim is to compare the main geometric parameters of 3D shape measurements for parabolic-trough (PT) mirror panels, assessed using equipment developed and employed by each participating institution: ENEA, F-ISE, DLR, NREL, and SNL. Although the latter two institutions are located outside the EU, they have benefited from the Transnational Access program to visit various European laboratories, including the ENEA Casaccia research centre.

Approximately a decade ago, a similar round-robin exercise was undertaken within the SolarPACES Task III framework [2]. However, it did not yield satisfactory results because the deviations among the findings obtained by participants exceeded the experimental uncertainty. Consequently, despite the preliminary draft produced during the previous attempt, a finalized guideline on the subject is still lacking to this day.

Presently, the results obtained from this new RR initiative appear much more promising, while data analysis is continued, well beyond the conclusion of the EU project SFERA-III.

2. Methodology

The round robin is based on the inter-laboratory circulation of three inner and three outer parabolic-trough mirror panels of RP3 dimensions (width 1700 mm; chord 1641 mm and 1501 mm for inner and outer panels, respectively) with focal length 1710 mm (collectors LS3, EuroTrough etc.). The mirrors are thick glass mirrors (3.8 mm) with backside silver and coatings. For mounting on the supporting structure, each panel has four ceramic pads with a threaded metal nut inserted; these pads are glued on the mirror backside in well-defined positions.

The mirror panel is not very rigid, therefore the 3D shape of its reflecting surface depends on how the sample is supported at the pads. On the other hand, for the sake of the success of the round robin, the good reproducibility of the panel-mounting is important, even if obtained by unusual manner, not representative of the normal usage in the solar collector.

As described in detail in [3] and shown in Fig 1, four identical steel balls are screwed in the ceramic pads; four supports are arranged in the Lab so that the ball centres lie on the same horizontal plane. Measurement position of the mirror panels is horizontal facing up. Along the RR, the hardware for such a simple and rugged supporting fixture was shipped together with the specimens; precise instruction on how to use it have been provided to make the comparison more reliable

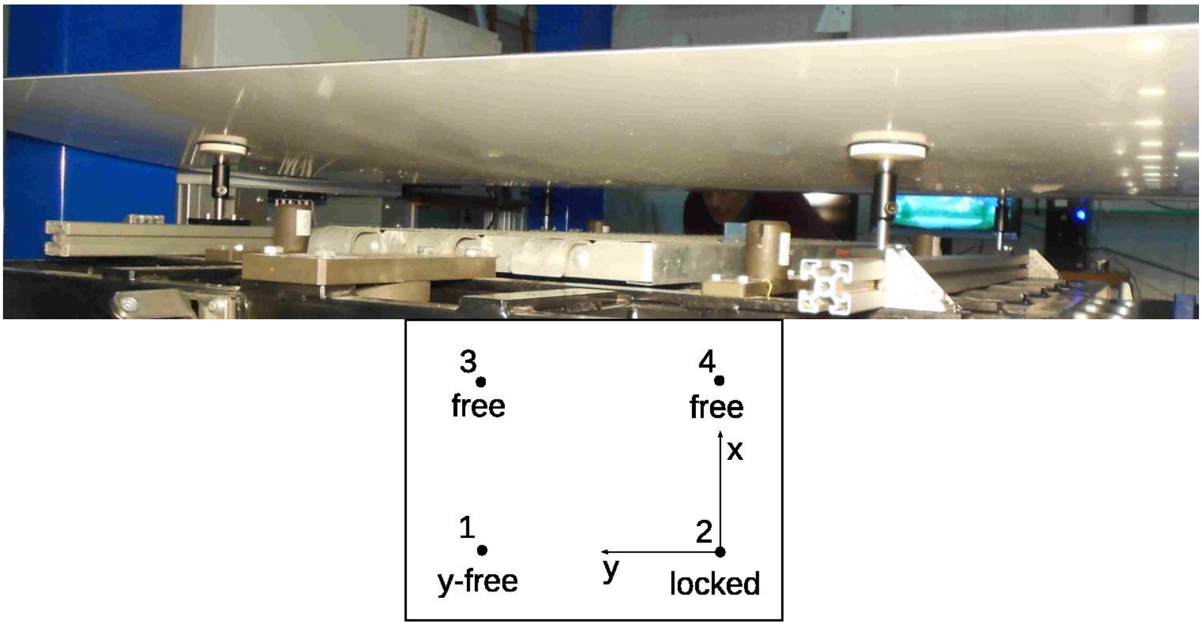

Figure 1. *View of the supporting system (above). Four support points and strategy to set their precise positioning in the XY plane of the Lab reference frame (below) – x along the curved direction of panel and y as longitudinal parallel to the receiver tube in the trough (straight direction of panel)*

The participants aligned the specimens according to the above procedure and then run the measurement with their own experimental set-up described elsewhere: ENEA [4], F-ISE [5,6], DLR [7,8], NREL [9] and SNL [10]. In brief, ENEA instrument is based on VIS method; those of F-ISE, DLR and SNL belong to the deflectometry class, while NREL system is based on a mix of photogrametry and deflectometry.

To be comparable, at the end of the measurements each participant shares results expressed in the Lab reference frame with the origin in the centre of the steel ball at the support point P2 and Y axis crossing P1, while the *z*-axis is vertical. Because each experimental set-up adopts a different Lab reference frame, the results must be transformed to be comparable.

To make the comparison replicable to everyone, ENEA wrote in C++ the dedicated software *RRcomparator*, available as open source from [11] together with the MS Windows executable, and the full set of experimental results provided by each participant. There, both the placing procedure document [3] and the conclusive SFERA-III report [12] are available; the latter also describes the RRcomparator software in some detail.

To discover possible inconsistency, the results must pass the acceptance check-point consisting of the comparison of the values at the support points with the ones expected for the ideal parabola (according to Section 3 of [3]). This check can be accomplished by means of the “Tab parameter” of the RRcomparator software.

This preliminary check has been very useful to identify some inconsistency generally affecting the first release of the data provided by all participants: this indicates that the transformation of the coordinate system, although it follows well-known rules, is not easy to apply. After some initial hurdles, all participants have been able to deliver valid data-sets. Typically, height and slope values at the support points deviate from the ideal values by less than 0.5 mm and 0.3 mrad.

3. Results

All results reported here have been obtained by RRcomparator from the data provided by each participant available at [11] by August 2024; in the future, software and data could be improved and updated, with slightly modified results, but recognizable by looking at the release version of each file.

3.1 Deviations from the ideal parabola

The more the shape conforms to the ideal parabola, the higher the optical-geometric efficiency in terms of intercept factor of the mirror panel.

Evaluators provided both absolute shape as well as its deviation from the ideal parabola in the reference frame with origin in the centre of the steel ball at the master support point #2 (the locked one), z-axis aligned along the vertical, and y-axis crossing the centre of the steel ball at the support point #1.

The RRcomparator computes the mean values on the entire data-set, or on the limited XY region common to all the evaluators. As very interesting further option, each data set can be realigned on the expected height (z) values on the support points [11]; the purpose of such realignment is to reduce the residual effects due to imperfections in the horizontal alignment of the four support points.

The values of the RMS deviation from the ideal parabola of height (z) and the slopes along the curved (x) and straight/linear (y) directions of the mirror panels represent a robust indication about the specimen shape quality. Tables 1, 2 and 3 show the mean and standard deviations among the RMS deviations obtained from the data-sets provided by each participant. These values have been achieved with the RRcomparator under different conditions:

i) as it is;

ii) limiting the analysis to the common XY region for all the evaluators;

iii) like ii) but after the software realignment.

The agreement among the different evaluations increases when the RMS deviation computing is limited to the XY common area (case ii) as well as the 3D shape is realigned over the support points (case iii): the standard deviation of RMS *z*-value and slope deviations is less than 0.1 mm and 0.5 mrad, respectively.

Table 1. *Mean and standard deviation of the RMS z-deviations from the ideal parabola as it is, limited to the common XY area, and applying the software realignment. (*) NREL data not available.*

	As it is (mm)	**XY common (mm)**	**XY common and SW re-alignment (mm)**
Inner#60	0.47 ± 0.11	0.43 ± 0.10	0.40 ± 0.10
Inner#61*	0.57 ± 0.08	0.55 ± 0.10	0.48 ± 0.08
Inner#62	0.39 ± 0.10	0.35 ± 0.10	0.31 ± 0.06
Outer#93	0.38 ± 0.14	0.37 ± 0.13	0.33 ± 0.08
Outer#97	0.37 ± 0.12	0.35 ± 0.11	0.29 ± 0.08
Outer#99*	0.44 ± 0.16	0.41 ± 0.14	0.30 ± 0.09

Table 2. *Mean and standard deviation of the RMS slopeX-deviations from the ideal parabola as it is, limited to the common XY area, and applying the software realignment*

	As it is (mrad)	**XY common (mrad)**	**XY common and SW re-alignment (mrad)**
Inner#60	2.66 ± 0.35	2.42 ± 0.37	2.42 ± 0.44
Inner#61*	3.23 ± 0.49	3.00 ± 0.49	3.01 ± 0.53
Inner#62	2.27 ± 0.25	2.07 ± 0.22	2.02 ± 0.18
Outer#93	1.61 ± 0.22	1.56 ± 0.22	1.52 ± 0.14
Outer#97	1.55 ± 0.20	1.53 ± 0.19	1.45 ± 0.11
Outer#99*	1.73 ± 0.24	1.69 ± 0.23	1.56 ± 0.07

Table 3. *Mean and standard deviation of the RMS slopeY-deviations from the ideal parabola as it is, limited to the common XY area, and applying the software realignment*

	As it is (mrad)	**XY common (mrad)**	**XY common and SW re-alignment (mrad)**
Inner#60	2.60 ± 0.32	1.61 ± 0.07	1.60 ± 0.05
Inner#61*	2.75 ± 0.34	2.32 ± 0.09	2.30 ± 0.08
Inner#62	2.56 ± 0.32	1.61 ± 0.14	1.59 ± 0.13
Outer#93	2.17 ± 0.33	1.85 ± 0.21	1.83 ± 0.20
Outer#97	1.90 ± 0.42	1.61 ± 0.26	1.59 ± 0.25
Outer#99*	2.10 ± 0.38	1.87 ± 0.24	1.84 ± 0.26

The narrow distribution of the RMS deviations as well as the similarity of contour maps and shape profiles shown in Fig. 2 (for brevity only the slopeX deviation of the specimen inner#60 is reported here) prove the reasonable agreement among the evaluations provided by the participants. This represents an important improvement with respect to the previous round-robin.

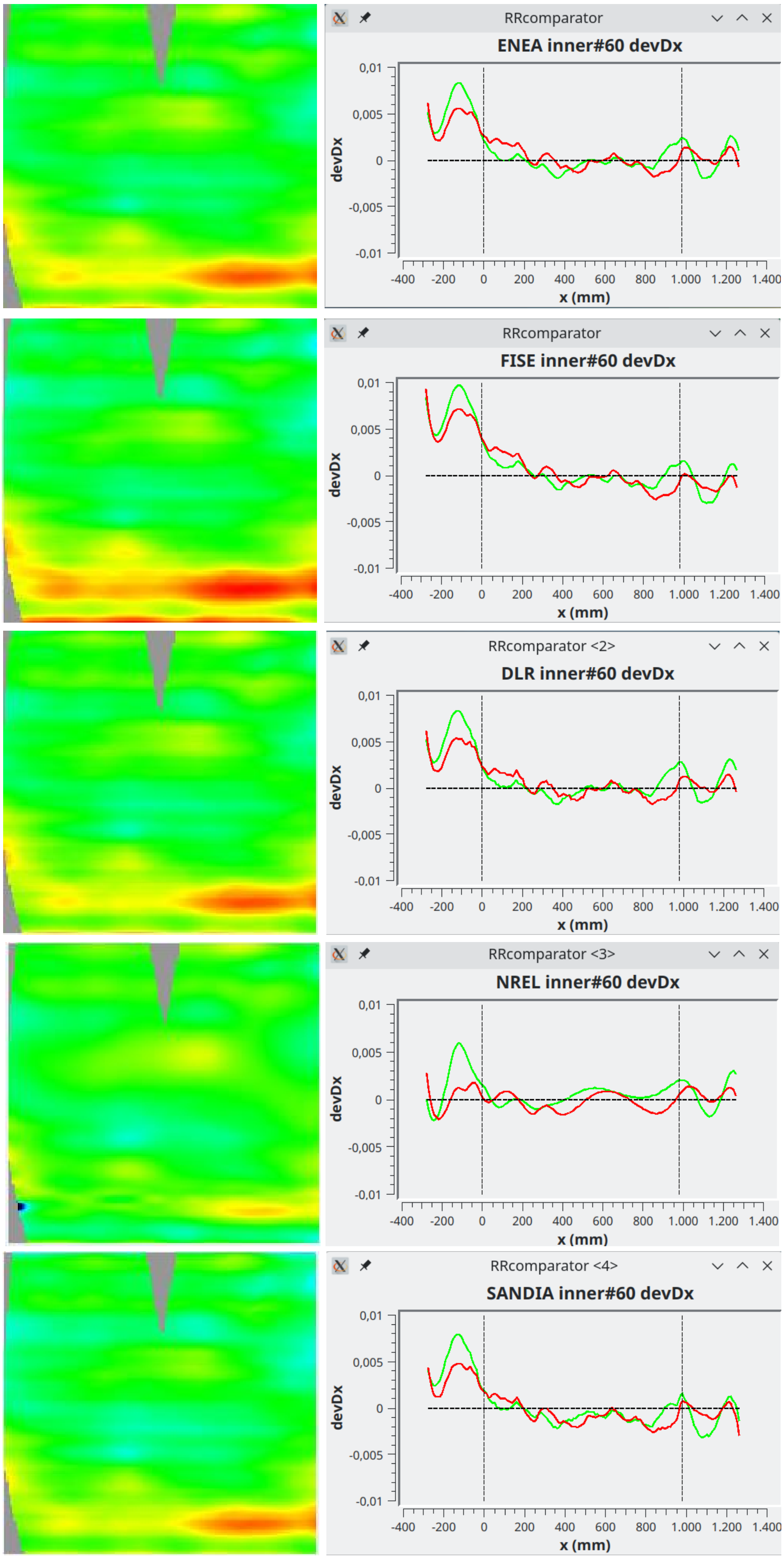

Figure 2. *Evaluations of the slope deviation (in curved x direction) from the ideal parabola for the specimen inner#60; on the left the 2D contour map, on the right the two profiles across the pair of support points 1-3 (red) and 2-4 (green). The scale is from -0.01 (blue) to 0.01 (red) rad*

3.2 Agreement between pairs of evaluators

On the other hand, considering the absolute measurement uncertainty (1 sigma) declared by the participants (Tab. 4), and analysing the difference of height and slope values normalized to the mean uncertainty (3 sigma) between pairs of participants, the result is less encouraging. For example, Tab. 5, 6 and 7 show the results for the specimen inner#60: while for the height (z) the difference remains below the threshold value of 1 (i.e. the difference is not greater than the experimental uncertainty), for the slope the mean value and/or the standard deviation exceed the threshold value of 1 (i.e. the difference is greater than the experimental uncertainty set to 3 sigma) in many cases.

Table 4. *Experimental uncertainty declared by the participants (1 sigma)*

	Height(z) (mm)	**slopeX** (mrad)	**slopeY** (mrad)
ENEA	0.30	0.09	0.09
F-ISE	0.13	0.30	0.18
DLR	0.20	0.20	0.20
NREL	0.26	0.12	0.12
SNL	0.20	0.08	0.08

Table 5. *Inner#60 - difference normalized to 3 sigma of height (z) between pairs of evaluators*

	F-ISE	**DLR**	**NREL**	**SNL**
ENEA	0.05 ± 0.22	-0.04 ± 0.08	0.00 ± 0.26	0.13 ± 0.36
F-ISE		-0.14 ± 0.37	-0.09 ± 0.50	0.11 ± 0.51
DLR			0.05 ± 0.33	0.21 ± 0.50
NREL				0.13 ± 0.45

Table 6. *Inner#60 - difference normalized to 3 sigma of slope in x-direction (curved) between pairs of evaluators*

	F-ISE	**DLR**	**NREL**	**SNL**
ENEA	0.01 ± 0.65	0.09 ± 0.31	-1.38 ± 4.16	-2.32 ± 2.86
F-ISE		0.02 ± 0.52	-0.65 ± 1.75	-0.89 ± 1.31
DLR			-0.95 ± 2.62	-1.41 ± 1.77
NREL				-0.51 ± 4.75

Table 7. *Inner#60 - difference normalized to 3 sigma of slope in y-direction (straight) between pairs of evaluators*

	F-ISE	**DLR**	**NREL**	**SNL**
ENEA	-0.06 ± 1.22	-0.20 ± 0.89	-0.64 ± 1.71	-0.76 ± 1.33
F-ISE		-0.08 ± 1.42	-0.27 ± 1.46	-0.45 ± 1.43
DLR			-0.25 ± 1.08	-0.23 ± 0.95
NREL				0.07 ± 1.82

As general rule, ENEA and DLR are the pair of participants in closer agreement, while NREL and SNL deviate the most with respect to the others. In the case of NREL, probably the disagreement could arise from the spatial uncertainty of the data-points in the plane XY.

Understanding the root causes of this disagreement demands a rigorous examination of each instrument, including potential recalibration and iterative measurement and comparison. This is a complex and costly endeavor, requiring dedicated financial resources for each institution involved. Regrettably, no funding is currently available or anticipated.

Data availability statement

Data-sets from all participants, as well as RRcomparator software are available from the GitHub repository https://github.com/mmonty1960/RRcomparator

Underlying and related material

At the same GitHub repository, the document describing the recommended procedure for positioning the specimen in any experimental set-up is available, as well as the final report on the round robin released at the end of the EU project SFERA-III.

Author contributions

Montecchi: investigation, methodology, software, supervision, original draft

All the other: investigation, review & editing

Competing interests

The authors declare that they have no competing interests.

Funding

The round robin activity was partially funded by the EU project SFERA-III, Solar Facility for the European Research Area, grant agreement no. 832802.

References

[1] Solar Facility for the European Research Area. https://sfera3.sollab.eu/ (August 2024)
[2] TASK III: Solar Technology and Advanced Applications. https://www.solarpaces.org/solarpaces-tasks/task-iii-solar-technology-and-advanced-applications/ (last accessed August 2024)
[3] M. Montecchi, G. Cara, A. Benedetti, “Procedure for placing PT-panels in SFERA-III WP10 Task3 3D shape measurement round-robin”, https://github.com/mmonty1960/RRcomparator (last accessed August 2024)
[4] M. Montecchi, G. Cara, A. Benedetti, “VISproPT: a high precision instrument for 3D shape analysis of parabolic trough panels”, Open Research Europe, https://doi.org/10.12688/openreseurope.15967.2
[5] A. Heimsath, W. J. Platzer, T. Bothe, and W. Li, "Characterization of optical components for linear Fresnell collectors by fringe reflection method," in SolarPACES 2008, 14th Solar Power And Chemical Energy Systems International Symposium, Las Vegas, USA, 2008.
[6] A. Heimsath, "Optical efficiency of concentrating solar collectors - Investigation of loss mechanism of solar reflectors," Dissertation, Fraunhofer IRB-Verlag, 2023.
[7] T. März, C. Prahl, S. Ulmer, S. Wilbert, C. Weber, Validation of Two Optical Measurement Methods for the Qualification of the Shape Accuracy of Mirror Panels for Concentrating Solar Systems, Journal of Solar Energy Engineering 133, 2011, 031022, https://doi.org/10.1115/1.4004240
[8] S. Meiser, E. Lüpfert, B. Schiricke, R. Pitz-Paal, Conversion of parabolic trough mirror shape results measured in different laboratory setups, Solar Energy 111, p.396-406, 2015, https://doi.org/10.1016/j.solener.2014.09.021
[9] Kesseli, D., Keshiro, M., Mitchell, R., & Zhu, G. (2022). A New Reflected Target Optical Assessment System: Stage 1 Development Results. In SolarPACES Conference Proceedings (Vol. 1). https://doi.org/10.52825/solarpaces.v1i.618

[10] C. Andraka, et al. Rapid Reflective Facet Characterization Using Fringe Reflection Techniques. *Journal of Solar Energy Engineering* **136**, February 2014
[11] M. Montecchi, RRcomparator, https://github.com/mmonty1960/RRcomparator
[12] M. Montecchi, A. Benedetti, G. Cara, F. Torres, G. Bern, M. Röger, E. Lüpfert, D. Kesseli, G. Zhu, B. Smith, R. Brost, “Preliminary Result of the Shape Round-Robin”, SFERA-III report (2024) available at [11]