ANALYSIS OF THE RADIATION FLUX PROFILE OF THE 100 SUN PROMOTEO FACETTED DISH CONCENTRATOR

J.S. Coventry[2], M. Stefancich[1], A. Antonini[1], A. Ronzoni[1],
M. Armani[1], P. Zurru[1] and G. Martinelli[1]

[1]Department of Physics, University of Ferrara,Via Saragat 1, 44100 Ferrara, ITALY, email: stefancich@fe.infn.it
[2]Centre for Sustainable Energy Systems, Australian National University, Canberra ACT 0200 AUSTRALIA,
email: Joe.Coventry@anu.edu.au

ABSTRACT: All PV systems have cells or groups of cells connected in series in order to build up voltage and minimise current. Because current is almost linearly dependent on the incident light, the current in a string of identical solar cells will be limited by the cell with the least illumination. It is therefore important to achieve a flux profile as uniform as possible. Typically for dish concentrators this is achieved through the use of secondary flux modifiers which disperse light at the centre of the receiver more evenly. However, for a facetted dish such as the Prometeo, in theory the flux profile at the focus should be uniform. In practice it is costly to achieve highly accurate optics for a dish system, due to the need for both a tightly toleranced mirror support structure and a precise solar tracking system. The aim for the Prometeo system is to lower costs by using simple materials that can be manufactured without the need for precision tooling, and at the same time, to achieve a consistent flux profile on the whole PV receiver. In this paper the measured and simulated flux profiles are compared, and the results are discussed.
Keywords: Concentrators, Performance, Characterisation, Light uniformity

1 INTRODUCTION

The Sensors and Semiconductor Laboratory is a research centre based in the Department of Physics at the University of Ferrara. The group specialises in concentrator photovoltaics (CPV) using dish based reflective systems, and in particular, has developed a novel faceted dish concentrator called Prometeo (figure 1). The dish is square in shape, with overall dimensions 1.75 m x 1.75 m, and consists of 120 individual flat aluminised polycarbonate mirrors, each 0.14 m x 0.14 m, mounted on a parabolic-shaped moulded fibreglass substructure. Each mirror is approximately the same size as the receiver, and therefore the system is essentially 'non-imaging'. In other words, light is not concentrated by each individual flat mirror (as it is for smooth parabolic shaped mirrors). However, because there are multiple flat mirrors, there is an overall geometric concentration ratio of 120x at the focus. The dish structure is currently mounted on a commercially available satellite dish tracking actuation system, although a more cost effective tracking system is under development. The receiver consists of high efficiency monocrystalline silicon solar cells from BP Solar. A secondary reflector is being trialed to collect light that misses the receiver, and to improve the uniformity of the flux profile.

The University of Ferrara is collaborating with the Centre for Sustainable Energy Systems (CSES) at the Australian National University (ANU) on both the development of a new receiver using a tiled arrangement of ANU concentrator cells, and on the present study of optical uniformity of the flux profile of the concentrator. CSES has been involved in CPV technology since the mid-1990s, mostly with PV troughs such as the 20kW two-axis tracking array at Rockingham, Western Australia [1] and the 40kW single-axis tracking combined heat and power solar (CHAPS) array at the Bruce Hall, a residential building on campus at ANU [2].

Figure 1: The Prometeo dish at the University of Ferrara (left), and the receiver on sun (right).

Concentrator photovoltaics is a promising solar technology that has the potential to lower photovoltaic electricity costs well below those predicted for standard flat plate photovoltaic systems. The primary advantage of the concentrator systems is that concentrating light allows a significant reduction in the area of solar cell coverage, the main cost driver in a flat plate system.

However, there are significant technical challenges for the successful design of PV concentrator systems, and perhaps the largest is ensuring an even radiation flux profile for all solar cells on the collector. Because electrical current is almost linearly dependent on the incident light, the current in a string of identical solar cells will be limited by the cell with the least illumination. For a dish concentrator with parabolic mirrors, the illumination profile at the focus is highly non-uniform (and approximately Gaussian in shape). For the Prometeo dish, which consists of many flat mirrors each having a similar size to the receiver, the flux profile at the focus should in theory be quite consistent (figure 2). However in reality it is difficult to achieve such a uniform flux profile: the mirrors are not perfectly specular and more significantly, the mirror substrate is not precisely fabricated as per the design. As a result, it is quite likely that a single cell at the focus will have lower illumination than other cells in the string, and hence limit the current and performance of all cells in the series, bringing down overall system output.

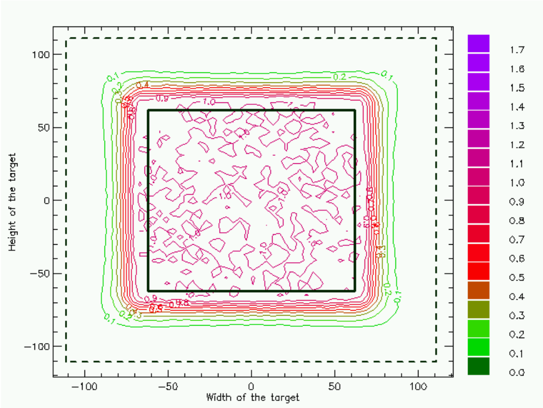

Figure 2: Flux intensity predicted by ray tracing if the mirror had the ideal shape. Units are normalised against the median.

This research report examines the sources of radiation flux non-uniformities for the Prometeo collector, and the magnitude of the problem of illumination mismatch between cells. The precise shape of the dish, both before and after the application of mirrors, was examined in detail using photogrammetry techniques. To study the effect of the measured non-uniformities in the dish shape, ray tracing studies were carried out using the measured data, and the results of the analysis are presented in this paper. The effectiveness of a simple planar secondary reflector is also discussed.

2 BACKGROUND

Concentrating optics for most existing CPV systems tend to be either Fresnel lens refractors or parabolic reflectors. Point focus lens systems are currently the most prevalent type of concentrator photovoltaic system. Groups working on such systems include: Amonix, with over 600 kWp of concentrator modules installed in Arizona [3]; Fraunhofer ISE in conjunction with the Ioffe Institute with the FLATCON™ collector [4, 5]; and Daido Metal / Daido Steel, who have achieved the highest system efficiency to date at 28% with injection-moulded dome shaped lenses and multi-junction cells from SHARP Corporation [6]. ENTECH uses linear concentrating Fresnel lenses for its fourth-generation concentrator module, but is currently looking at point focus lenses for use with multijunction cells [7]. Sunpower and Ciudad University are developing a 300x CPV module that uses a non-imaging optical design based on a lens that uses the principle of total internal reflection [8]. Each of these aforementioned systems consists of a module made up of many individual lenses, each focusing light onto a single cell. Because there are not multiple cells in each focal spot, the problems associated with series connection of cells with different average light intensities are avoided. However, lenses tend to be more costly than mirrors, due both to the cost of the lens material, and the need for accurate fabrication of the lens.

In recent years there has been renewed interest in the use of reflective optics for photovoltaic concentrators. In addition to the work at the ANU mentioned previously, the Melbourne based company Solar Systems has been working on dish systems for some years. Their 220 kWp system serving a mini-grid on the Anangu Pitjantjatjara lands in central Australia [9] will soon be joined by a further three systems in central Australia of a similar size. At the University of Nevada, Las Vegas, the SAIC dish concentrator (formerly used with a Stirling engine) has recently been retrofitted with a PV receiver [10]. Similar to the Prometeo dish, the SAIC concentrator consists of a number of flat faceted mirror tiles, designed to give uniform illumination (with a secondary reflector) of around 250 suns. The University of Lleida is working on a combined PV/T concentrator using a linear Fresnel reflector: prototypes have been developed to operate with a concentration of 11x and 20x [11]. The EUCLIDES trough concentrator [12], which has been operating for many years, will shortly have some new test systems installed in Italy and Germany as part of the EU funded IDEOCONTE project. A 400 m^2 dish installed at the Ben-Gurion University in Israel is proposed for testing with a photovoltaic receiver, but is still under development [13]. There are also a number of low concentration (<5x) CPV systems under investigation, driven by the advantage of using production line one sun cells with little or no modification, such as the LGBG cell in production by BP Solar [14]. Some recent projects include the MaReCo collector, which uses CPCs [15], the ARCHIMEDES V-trough system [16] and the PV Venetian Store [17], however there are many more such low concentration PV projects based on similar optical systems.

3 METHODOLOGY

Measurement of the intensity of light at the focus of the dish was carried out by taking images of a white lambertian target using a Hamamatsu CCD video camera. As the camera was mounted on an angle relative to the target, the flux profile was corrected for geometrical perspective and light intensity using the method described by Paretta et al. [18]

The precise shape of the fibreglass mirror substrate, before and after the application of mirrors, was measured using the photogrammetric method developed by Johnston [19], with accuracy in displacement estimated to be 70 microns. The photogrammetric method involves taking a series of photographs of target points on a mirror from different positions, establishment of reference coordinate system with known target points on the mirror, and complex trigonometric calculations using custom developed software called VMS to create 3-dimensional coordinates for the target points.

The methodology followed here for ray tracing follows the technique developed by the first author for parabolic troughs, also presented at this conference [20]. Ray tracing was carried out using the simulation software TracePro. A multi-faceted dish was defined using the data from the photogrammetry. Measured points contained within the boundary of each mirror of the collector were triangulated so that a surface plot of the shape error could be obtained. Then a new grid of 5 x 5 regularly spaced points (28 mm between each point) was superimposed on the surface with the z-coordinates (the shape error) calculated by a smooth interpolation and extrapolation scheme (based on quintic polynomials). The number of facets and number of rays (9 million) were determined by a trade-off between the desired optical accuracy and the processing time and software limitations of the program.

4 RESULTS OF THE FLUX MEASUREMENT

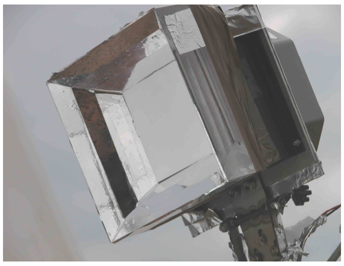

Figure 3: Secondary reflector mounted on the lambertian target.

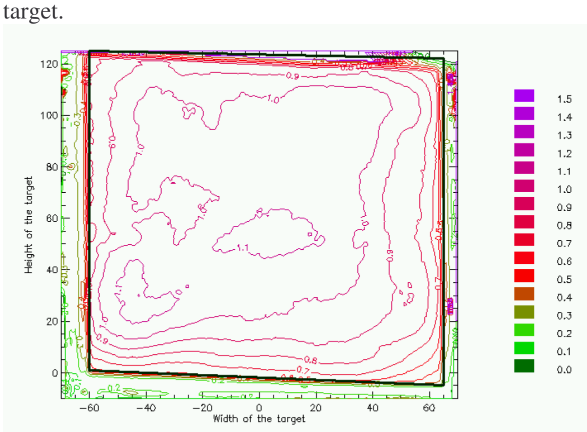

Figure 4: Measured radiation flux intensity at the focus <u>without</u> the secondary reflector. Units are normalised against the median.

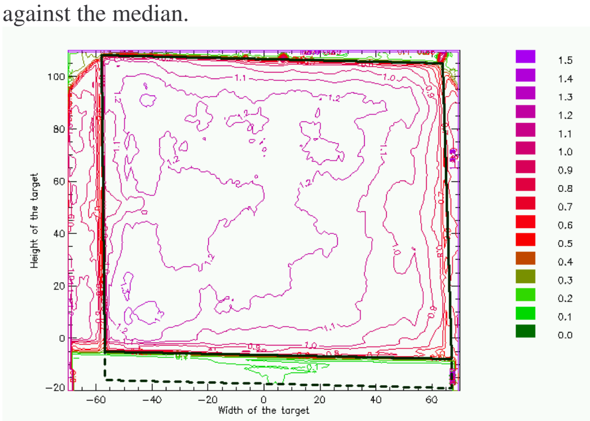

Figure 5: Measured radiation flux intensity at the focus <u>with</u> the secondary reflector. Units are normalised again using the median of the data in figure 4.

Figures 4 and 5 show the measured flux profile, both with and without the secondary reflector. The images are slightly skewed as the camera was not exactly positioned in the plane orthogonal to the receiver. It is also shown in figure 5 that part of the target was not visible as it was obscured by the secondary reflector. Both figures are normalized against the median intensity of figure 4. The uniformity at the focus improves with the addition of the secondary reflector. In figure 5, the average light intensity is higher than in figure 4, as a result of the collection of light by the secondary that would otherwise miss the target. In figure 4, the intensity falls away at the fringes of the target by as much as 30% compared to the median intensity, however in figure 5 the uniformity is generally within 20% of the median. However, these regions of lower illumination will dictate the operating current of the receiver.

5 RESULTS OF THE PHOTOGRAMMETRY

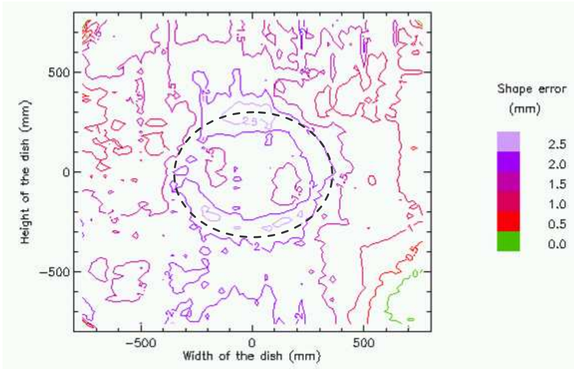

Figure 6: Shape error of the dish <u>before</u> mirrors were applied. The dashed line indicates the clear impression left by the support ring mounted on the back of the dish.

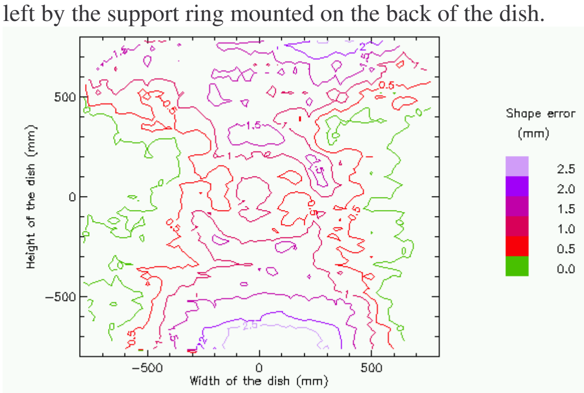

Figure 7: Shape error of the dish <u>after</u> mirrors were applied.

Figures 6 and 7 show the measured shape error before and after mirrors were applied to the fibreglass substrate. In general, the result confirms that the mirror supporting substrate is manufactured with reasonably good accuracy. In figure 6 the deviation from the ideal shape is less than 1 mm for most of the dish, with some localised regions of higher error in the order of 2 mm. However, once mirrors were applied, the shape error actually worsened, as can be seen in figure 7. Possibly the increased deformation is due to the additional weight of the mirrors flexing the fibreglass structure. A saddle shape is apparent, with deviation from the ideal shape in the order of 2 mm.

One unexpected result from the measurements was the noticeable circular ridge at the centre of the dish (shown by the dashed line in figure 6). The position of the ridge corresponds to a steel support ring attached to the back of the dish, which is used to attach the dish to the tracking actuation system. The ring was attached to the fibreglass structure in the same processing step that the dish structure itself was formed. The results indicate that the ring leaves a clear impression, possibly due to its self-weight causing stresses during the fibreglass curing stage. The manufacturing technique can be simply modified to avoid this unnecessary shape error.

6 RESULTS OF THE RAY TRACING

Ray tracing using TracePro is carried out to compare the flux profile expected from a geometrically perfect dish with that expected from the ‘real’ dish. Figure 8 shows the entire focal plane, with the position of the receiver shown by the bold line, and the position where the secondary reflector would be shown by the dashed line. Figure 9 shows the simulated flux profile if the secondary is utilised.

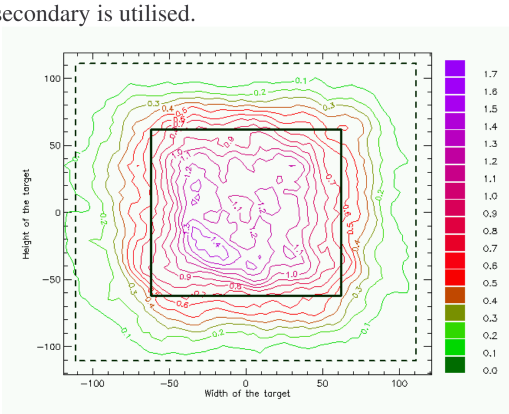

Figure 8: Simulated flux intensity <u>without</u> the secondary reflector. Units are normalised to the median of the area corresponding to receiver (shown in bold).

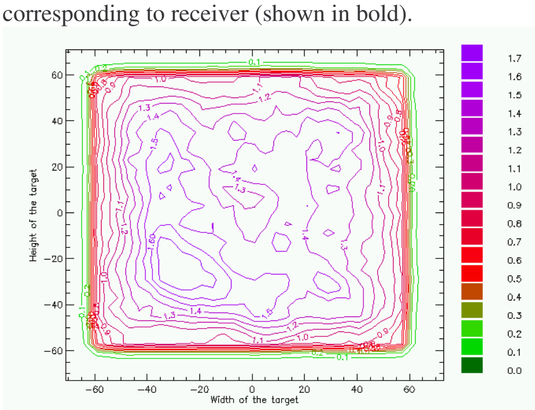

Figure 9: Simulated flux intensity <u>with</u> the secondary reflector. Units are normalised to the median of the receiver area shown in figure 8.

The results in figures 8 and 9 show that a small degree of shape error in the mirror substantially reduces the 'squareness' of the flux profile (compare figure 8 to figure 2), and hence the uniformity of light on the solar cells. They also show that in a 'real' system, a secondary reflector helps catch most of the stray light.

However, in comparison to the measured profile, the simulated flux profile is a little too pessimistic in its prediction of uniformity. The simulated curves are more 'rounded' in the region of the focus than in reality. Random error is unavoidable in fitting the small mirror facets to the measured data, in particular in the extrapolation of data to the edge of each mirror. Random error in mirror shape (whether real, due to effects such as non-specular reflection and errors in mirror shape, or due factors in the simulation technique, as described here) causes the flux profile to tend towards a Gaussian shape. It can be concluded that this technique of simulating the focal region demonstrates the trend away from the ideal - a uniform and 'square' flux profile – but for the Prometeo style faceted dish, does not accurately simulate the detail of the measured profile.

7 CONCLUSIONS

It is shown that reasonably good light uniformity can be achieved at the focus of a facetted dish concentrator over most of the focal region. However, it is also shown that the shape accuracy of the mirror is crucial to flux uniformity. Small errors in manufacturing tolerance have a large affect on uniformity. Further improvement of mirror accuracy will allow a larger area of the receiver to be covered in solar cells, and hence improve the system performance.

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