**ANALYSIS OF THE RADIATION FLUX PROFILE ALONG A PV TROUGH CONCENTRATOR**

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ABSTRACT: The primary advantage of a PV concentrator is that concentrating light allows a significant reduction in the area of solar cell coverage, the main cost driver in a flat plate system. PV systems, whether flat plate or concentrating, normally have groups of solar cells connected in series in order to increase voltage and limit current. However, low illumination on a single cell proportionally reduces its current, and hence affects the performance of all other cells in series. Ideally, a reflective PV concentrator system will have high concentration, a uniform flux distribution, and low cost. However, it is difficult to obtain these three conditions simultaneously, as cost tends to increase with better mirror quality, improved tracking accuracy, and the use of secondary flux modifiers. Linear concentrators have the advantage of simpler and cheaper tracking and support structures than dishes; however, achieving a consistent flux profile on every cell along the focal line is challenging. The aim of this paper is to present results of direct measurements of the flux profile along the length of a single axis tracking trough, and to develop simulation techniques that allow the reasons for peaks and troughs in the flux profile to be better understood.
Keywords: Concentrators, Performance, Characterisation, Light uniformity

## 1 INTRODUCTION

The Combined Heat and Power Solar (CHAPS) collector, under development at the Australian National University, is a reflective trough concentrator that focuses light onto monocrystalline silicon solar cells to generate electricity (figure 1). Fluid flowing through a conduit at the back of the cells removes most of the remaining energy as heat, which can then be used for building heating and domestic hot water. The CHAPS system, and its electrical and thermal performance, has been described in some detail previously [1]. This paper examines the optical performance of the system, in particular concentrating on the reasons for non-uniformities in the focal beam at the receiver.

**Figure 1:** The CHAPS prototype system.

Photovoltaic systems normally have groups of solar cells connected in series in order to increase voltage and limit current. Low current means cable sizes for transmission can be reduced (and hence cost reduced) without significantly increasing voltage losses due to series resistance. Efficient dc-ac conversion is favoured by high voltage and low current. If solar cells are connected in series, as they are along the receiver of the CHAPS collector, the current passing through each cell is the same. 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. Therefore, it is important to try and achieve consistent flux uniformity along the entire length of the receiver.

The mirrors of the CHAPS system consist of a glass-on-metal laminate, spanning the whole width of the trough (with a 1.55 m wide aperture) and held in shape at the ends by small tabs stamped into sheet metal ribs. The 1.5 m long mirrors are butted up to one another end-to-end to form the trough. Ideally, the trough would be continuous along the entire length to prevent gaps in the illumination of the receiver, but in practice this is difficult to achieve. The EUCLIDES™ array in Tenerife [2] is the only other large scale PV concentrating parabolic trough collector. In this system the mirrors are supported from behind, and the gap is kept to an average 4 mm. However, for the CHAPS system, the stamped tab ribs are integral to the low cost and high optical accuracy of the mirrors. Due to the ribs the gap between mirrors is larger, on average 19 mm. Another unavoidable cause of flux non-uniformities in the CHAPS collector design is shading due to the receiver supports. The third reason for flux non-uniformity is due to perturbations in the mirrors. In this paper, results from measurements of the mirror shape are presented, and analysis is carried out on the combined effect of shape error, the gap between mirrors, and the shading from receiver supports. The results are found to be quite counter-intuitive.

Optical non-uniformity across the receiver is not discussed in this paper. However, a parabolic trough concentrator produces a flux distribution across the receiver that closely resembles a Gaussian curve. Such highly non-uniform flux within a single cell causes a reduction in efficiency of around 5-15%, depending on the distribution of light and the temperature of the cells [3, 4].

## 2 MEASUREMENT OF THE LONGITUDINAL RADIATION FLUX PROFILE

Measurement of radiation flux at the focus of collectors is often carried out using videographic flux mapping techniques, whereby a charge coupled device (CCD) video camera takes images of the focal flux projected onto a target [5]. Another technique for measurement of the flux profile of a parabolic trough was developed by Riffelmann et al. [6] using an array of photodiodes. The radiation flux distributions presented in this paper have been measured using a custom built device, known as the 'Skywalker' module, which consists of a calibrated concentrator solar cell mounted on a cooled aluminium block. The short circuit current of the solar cell is measured, and using results from the solar cell calibration, the radiation flux intensity at the cell can be calculated. The block is mounted on a trolley that is moved along the focal line of the collector by a motor and pulley system. As the cell is the same size as the cells used in the final CHAPS receiver, this technique gives a realistic measurement of the current expected for all positions along the focal beam.

## 3. RESULTS FROM THE SKYWALKER MODULE

In the case where radiation is incident upon the mirror at an angle away from the surface normal, the effect of the gap between mirrors and the receiver support arms becomes significant. This has been investigated for a range of incidence angles using the 'skywalker' device. The results are shown in summary in figure 2.

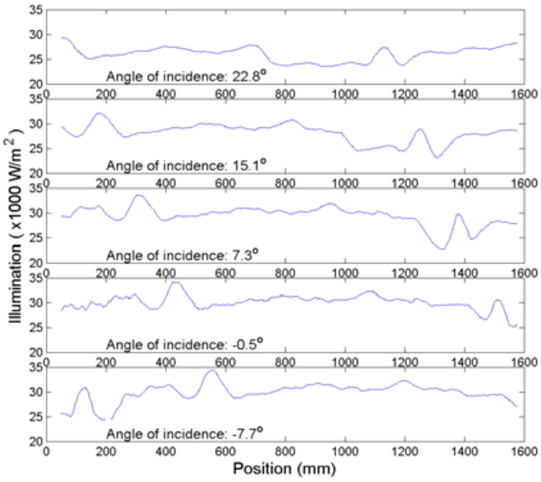


**Figure 2:** Flux profile at the focal line for a range of angles of incidence

The most prominent peaks and troughs in the flux profile are seen to move along the focal line as the angle of incidence changes. One of the most difficult aspects of the design of single-axis tracking linear PV concentrators is that it is not possible to isolate the problem areas and treat them specially. For example, if the region of low illumination were always at the end of a receiver, then it is likely that overall efficiency would be improved by the absence of solar cells in this region. However, while the deepest dips in the flux profile occur near the ends of the receiver when the sun is near perpendicular, at other times the dips are near the middle of the receiver, and solar cells at the ends do contribute significantly, as can be seen in figure 2. The deepest dip in the measured data occurs at an incidence angle of 4.7°, where the minimum flux intensity is 27% lower than the median. At larger angles the impact of the gap between mirrors and the receiver supports is reduced; however, typically the minimum illumination intensity is between 10-20% lower than the median, depending on the incidence angle of light. Given that thee regions of lowest illumination affect the entire receiver performance, it is clear that further investigation is required to understand the precise cause.

## 4. ANALYSIS USING OPTICAD

Geometric ray tracing can be used to simulate an optical system such as a parabolic trough collector. OptiCAD has been used to simulate the flux profile at the focus of two GOML mirrors.

The sun source is modeled in OptiCAD as a 'pillbox' shape, with half-angle set to 4.65 mrad. This means that all radiation coming from within solar disc is assumed to be of equal intensity, and that no radiation originates from outside the solar disc.

To simulate the measured mirror shape, a multifaceted mirror (called a polynet in OptiCAD) has been defined. The polynet is made up of continuous groupings of individual triangular polygon facets. The number of facets is determined by a tradeoff between the desired optical accuracy and the processing time and software limitations of the program. It was found that at least 150-200 facets across the width of the mirror are required to achieve similar optical accuracy to a smooth surface.

The shapes of two mirror panels were measured by the authors using the photogrammetric method developed by Johnston [5], with accuracy estimated to be 20-40 microns. Figure 3 shows the shape error of one of the troughs, which is the difference between the measured z-coordinates and those calculated for a parabolic trough fitted to the data using a least squares technique.

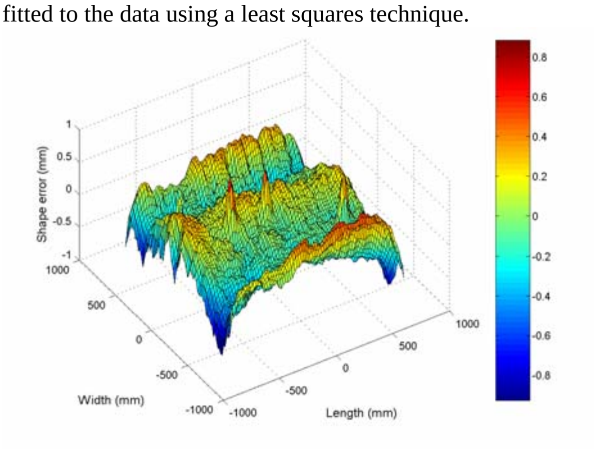


**Figure 3**: Deviation from a perfect parabolic trough.

Maximum deviation from the ideal shape is in the order of 1 mm, and the majority of the mirror surface is within 0.4 mm. Due to constraints in the photogrammetry process, the definition of the points measured was limited to around 70 points across the width and 60 points along the length, and therefore the data is interpolated. Another constraint in the photogrammetry process meant that it was not possible to measure a row of points right at the very end of the mirror. Unfortunately, the ends of the mirror have the largest slope error, and it was found that the last 50mm at either end of the mirror has a significant effect on the flux profile in the critical area of lowest flux. Data points were extrapolated using a linear scheme right to the ends of the trough. Raw shape data was available for a limited number of intermittent points which allowed the extrapolation scheme to be verified. A cell target 40mm wide is placed at the focal point, and a further sheet simulating the receiver cover is placed slightly above the focal point. The gap between the mirrors in the model is set to 19mm as per the measured gap. The receiver support arms are made from 10 x 25 steel bar, supported from outside the mirror.

### 4.2. Validation of the ray tracing

A comparison is made between the flux profile predicted by ray tracing and the measured flux profile for a GOML mirror, as shown in figure 4. Also plotted in figure 3 is the flux profile resulting from a 'perfect' parabolic mirror shape.

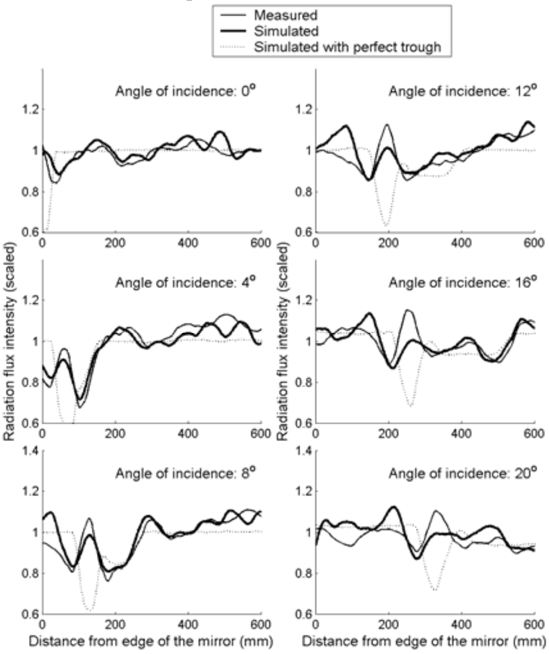


**Figure 4:** Comparison between the measured and predicted radiation flux profiles

The flux profile created by ray tracing using the 'real' mirrors shows good agreement with the measured profile. The magnitudes of the peaks are not perfectly matched. However, given the sensitivity of this area to the mirror shape at the ends of the mirror, the error is to be expected. Importantly, the peaks and dips coincide in position for the simulated and measured data, and the magnitude of the deepest dip is reasonably well predicted. It can be concluded that the ray tracing is a useful tool for predicting flux profile if the measured mirror shape is used, and that the observed variations in the flux profiles are indeed a result of mirror shape imperfections.

The results show a significant difference between ray tracing from a perfect parabolic mirror and from a 'real' mirror. Figure 4 shows that where there is a dip in the 'perfect' trough profile, there is a peak in the 'real' trough profile. The dip in the 'perfect' trough profile corresponds to the position where you would expect a dip based on the position of the sun and the gap between mirrors. However, as both the measured data and the modeled data using the 'real' trough shape show, there is a peak. The reason for the peak is that the significant slope error at the ends of the troughs (which can be seen in figure 3) creates a kind of 'pseudo concentrator', as shown diagrammatically in figure 5.

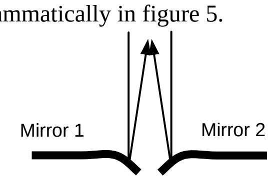


**Figure 5:** Pseudo-focus between adjacent mirrors

Figures 6a-d show the results of comparisons between a perfect parabolic trough (the dotted lines) and the simulated 'real' trough for all combinations of receiver supports and gaps between mirrors.

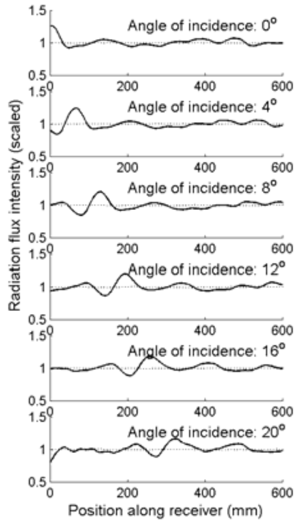


**Figure 6a**: The flux profile <u>without</u> a gap between mirrors and <u>without</u> receiver supports.

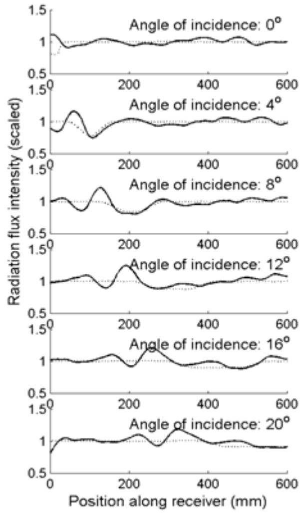


**Figure 6b:** The flux profile <u>without</u> a gap between mirrors and <u>with</u> a receiver support

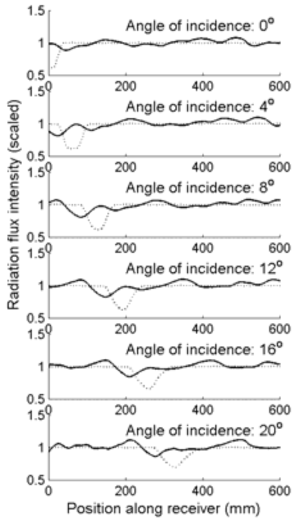


**Figure 6c:** The flux profile <u>with</u> a 19mm gap between mirrors and <u>without</u> receiver supports

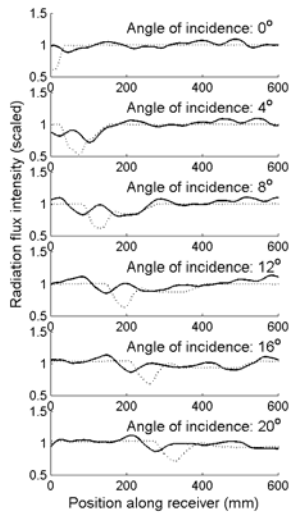


**Figure 6d:** The flux profile <u>with</u> a 19mm gap between mirrors and <u>with</u> a receiver support

Figure 6a shows the flux profile that could be expected if there was no gap between the mirrors and no receiver support. For all angles, a pronounced hump can be seen in the flux profile for the position corresponding to the end of the mirror (i.e. for 0°, 4°, 8°, 12°, 16°, 20° the positions are 0, 59, 119, 180, 242 and 308 mm from the end of the receiver respectively), further demonstrating the effect of the pseudo-focus due to the slope error at the ends of the mirror. However, an interesting corollary can be drawn by direct comparison of figure 6a and 6c, as shown in figure 7. In all cases the illumination at the point corresponding to the gap between the mirrors is not the minimum. Moving the mirrors apart has the effect of reducing the peak at this point. Eventually, of course, if the gap is large enough then there will be a corresponding gap in the flux profile.

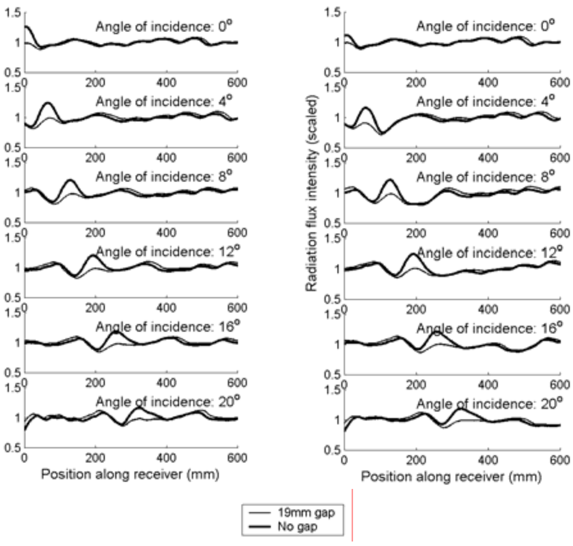


**Figure 7:** Comparison between flux profiles <u>with</u> and <u>without</u> a gap both without shading from the receiver support (left) and with the receiver support (right).

Modeling indicates that for the mirrors measured, a further 10mm gap would be possible before the concentrating effect of the pseudo-focus due to the sloped mirror ends is negated. However, while the general shape of the curve on either side of the hump in figure 7 is similar for the gap and no gap cases, there is a slight decrease in the magnitude of the lowest dip when there is a gap. Therefore there remains some advantage in further minimising the gap.

The effect of the receiver support can be seen in figures 6b and 6d, but is a little obscured by the interference due to the mirror end effects. Unlike for a 'perfect' mirror, the shading due to the support for 'real' mirrors is significant, particularly for incidence angles around 4° to 8°. An unavoidable consequence of the 'pseudo-focus' at the mirror ends is that there will be a region on either side of the hump that has lower illumination than average. The radiation has to be taken from somewhere, and in effect, light that is incident on this curved section at the end of the mirror is spread out along a greater length of the receiver, and hence the concentration ratio is reduced where there is no superposition of light from the adjacent mirror. The precise position of the minima in the profile depends on the angle, and the co-incidence of shading and mirror shape effects. For larger angles, the impact of the receiver support shading 'smears' along the focus and becomes less significant.

## 8. CONCLUSION

Analysis of the radiation flux profile has been carried out with a new custom built measurement device. Significant variation in the profile along the focal beam is observed. By measuring the precise shape of two adjacent mirrors (using photogrammetry techniques) and carrying out ray tracing analysis, it is found that the measured flux along the focal beam can be accurately simulated. While the shape of the mirror seems quite accurate (mostly within 0.4 mm from the ideal shape), it is revealed that a small shape error in each mirror can have a significant impact on the system performance of a PV concentrator. In particular, a pronounced convexity near the ends of the mirrors causes a peak in illumination in the region where a dip might be expected because of the gap between the mirrors. This is advantageous, as it masks the effect of the 19 mm gap between mirrors. However, adjacent to the peak, dips in the flux profile occur. One of these dips is always the minimum point in the radiation flux profile for the receiver, and hence limits the current of the entire receiver. The technique demonstrated here for both measuring the flux profile and carrying out ray tracing simulations can be used to fine-tune the system design to minimise the lowest dip in the illumination profile. The technique may also be useful for other PV concentrator systems, such as the Prometeo dish system at the University of Ferrara, also presented at this conference [7].

## 8. REFERENCES


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