Full Moon Flux Mapping the 400m^2 "Big Dish" at the Australian National University

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Abstract

Videographic flux mapping of a lunar image has been used to characterize the focal flux distribution of the ANU 400m^2 "Big Dish" solar collector. This technique was undertaken by using a CCD video camera to capture the image of the moon focal flux projected onto a planar target. The advantage of this technique is that the moon has a very similar angular width to the solar image and the high heat flux associated with the solar insolation that would require a complex cooling system with complicated target structure is avoided. Conventional flux mapping was used to characterize the optical performance of the dish when it was first built. The aim of this investigation was to see if the optical performance had changed in the intervening years. In this experiment a light weight target was placed in front of the monotube boiler receiver that is currently fitted to the dish for the display of the flux image. Comparison of ray trace predictions and the measured flux indicated that the dish surface has a mean surface error of 7.5 $\pm$ 0.3 milliradian.

1. INTRODUCTION

Measurement of flux distribution in the focal regions of solar concentrating devices using the videographic flux mapping technique, has become a standard technique in many solar energy research institutes. At the Australian National University (ANU) this technique was developed to measure the characteristics of the 400^2 and 20m^2 dishes and then has been adapted to be used with paraolic trough concentrators. The technique is conducted by using a CCD image camera to capture an image of the focal flux projected onto a planar target. These electronic images are then analyzed and presented digitally to extract information such as flux profile, peak concentration, and integrated power, etc. A sequence of images taken of focal regions on a target as it is traversed through a focal region can also be used to quantify the focal point of a concentrator (Johnston, 1998).
The ANU 400m^2 "Big Dish" solar collector was characterized using the conventional solar image flux mapping technique when the dish was first built (Johnston, 1995). Johnston's result showed that the dish collector hada 6.0 milliradian surface slope error (deviation of the actual surface normal vector from the ideal normal vector) at that tie. However, a number of broken and corroded mirrors have been replaced recently and there is also a strong possibility that the surface shape of the original mirror panels may have changed over time. Duplicating Johnston's measurements is not simple since the water-cooled flux mapping target and its control apparatus are no longer available and in any case, using them would require an expensive and lengthy process to remove and then replace the current monotube boiler receiver. Thus, measurement using the lunar image has been introduced. The advantage of the lunar image experiment is that the moon has a very similar angular width to the solar image and the high heat flux associated with the solar insolation that would require a complex cooling system with complicated target structure is avoided.
This paper presents a current surface assessment of the ANU 400m^2 "Big Dish" collector using a videographic flux mapping technique of a full moon image. The Interactive Data Language (IDL) version 5.6 was used to analyze the focal flux image of the lunar beam and the measured focal flux was then compared to the predicted flux generated by ray trace modelling.

2. PREVIOUS STUDIES

There are a few reports associated with the lunar flux mapping experiments. Hisada reported the techniques of using the moon image to determine the optical accuracy of the mirror surface in a solar furnace (Hisada T. et al, 1957). The experiments attempted to measure the lunar radiation by focusing the lunar image on the focal plane to which bromide paper have been affixed. Experiments with the lunar image were also reported by Holmes (Holmes, 1982). Holmes used the lunar image to simply align heliostat facets and investigate the spatial extent of the focal radiant field. But there is no flux density distributions were reported in this study. At the ANU Thomas and Whelan (1981) described measurements attempted using photographic imaging of a full moon projected onto a flat target placed at the focal point of the ANU 20m^2 tiled dish.

3. THE ANU 400M^2 "BIG DISH" COLLECTOR

The ANU 400m^2 Paraboloidal dish solar concentrator, shown in figure 1, informally named "the Big Dish" by the virtue of the fact that the dish has an equivalent aperture diameter of 22.6 m which is significantly larger than existing collector worldwide. The ANU 400m^2 dish is a hexagonal aperture concentrator, having a nominal focal length of 13.1 m, and is comprised of 54 triangular mirror panels mounted on a space-frame sub-structure. The mirrors panels are of a glass-foam-sheet metal sandwich construction, with the mirrors comprised of 30 or 60 cm square, back-silvered 2 mm thick "green" glass tiles and have a nominal reflectivity of 86%. The tiles have been elastically deformed to approximate the paraboloidal curvature required according to their position on the dish surface (Johnston, 1995). Altitude and azimuth tracking is employed, 2-axis sun tracking, and the actuation is provided in both altitude and azimuth directions by a novel "walking ram" concept. These operate through a series of alternate extensions and retractions of appropriately mounted hydraulic rams. In this experiment tracking was achieved under manual control with an approximate error of 4 or 5 milliradian.

Figure 1: The ANU 400 m^2 paraboloidal dish.

This dish was built to implement the SG3 50kW$_e$ solar thermal power system which became operational in 1994 at the ANU. During 1996-2000 the system was mothballed and under control of ANUTECH Pty Ltd. In late 2002, the system was re-commissioned by the ANU Solar Thermal Group and a new program of system improvements commenced. This program included the collector surface refurbishment resulting in replacement of 47m^2 of corroded and broken mirrors by covering them with new 1mm. thick low iron mirrors (96% reflectivity).

In addition to the potential effect of the replacement mirrors, qualitative assessment of the original foam supported mirrors, suggests that some shape changes have occurred since manufacture. Accurate knowledge of focal region characteristics and hence the thermal input to receiver, is an essential pre-requisite to understanding and modeling thermal performance. This was the motivation for the current study.

4. THE LUNAR FLUX MAPPING SYSTEM

A schematic layout of the arrangement of the lunar flux mapping system is shown in figure 2. The dish collector tracks the moon and concentrates the moon light which is focused on to a light weight target. The flux image displayed on the target is captured by the CCD VDO camera.

A light weight target was fabricated from 2 sheets of Polystyrene foam bonded with silicone glue to form a 1.8 m square shape and mounted in the front of the cavity receiver (approximately 465 mm away from the focal point) which is currently fitted to the dish. The front surface of the target is white and smooth so as to offer an approximately Lambertian reflecting surface. RedLED lights were

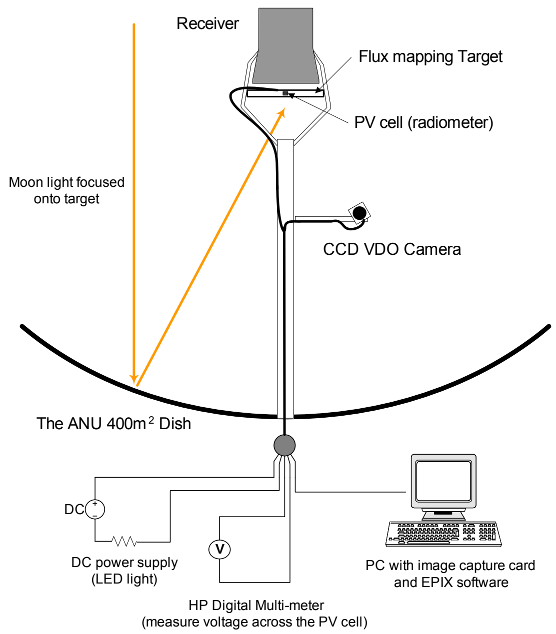

Figure 2: Arrangement of the flux mapping equipment on the ANU 400 m^2 dish collector.

attached at each corner of the target as a reference for the image processing program.
A BP Saturn photovoltaic (PV) cell, having dimensions 1.25 x 2.0 cm was mounted in the center of the target such that absolute intensity could be measured and used to calibrate the pixel intensities recorded by the CCD VDO camera. The scaling was performed by choosing 4 pixels surrounding and adjacent to (but excluding to) the black PV cell image in the flux images. An average value was taken of these pixels values with the PV cell voltage reading at the time of the measurement.
A CCD VDO (Kodak MEGAPLUS ES1.0) camera with TAMRON 28mm. lense was mounted approximately 4 m below the target, on the extension bar which was clamped to the center pole, and focused on the target. Using the extension bar provided a better view of flux images as the receiver quadrapod leg and its support structure would be obscured if the camera was directly mounted onto the center pole. A maximum of 32.372 msec camera exposure time was set to ensure the ability of the camera to capture the low intensity light such as the moonlight. The cable of the PV cell and LED lights were mounted together along the center pole to the ground in the same way as the camera cable was conveyed. On the ground, the 9V DC power supply with 100Ω resistor was connected in a series with the LED light cable and the HP digital multimeter (DMM) was connected with the PV cell cable. The camera cable was connected via the image capture card which was installed on to a PC with the EPIX software to provide the real time flux image display.

5. FLUX MAPPING RESULTS

The lunar flux experiment was conducted on the night of full moon on Tuesday 5 May 2004. Five images of flux distribution, viewed by the camera, were recorded on a high resolution 16 bit TIFF image file format. The images were digitized and analyzed using Interactive Data Language (IDL) version 5.6. Johnston (1998) developed an algorithm in the IDL language, named “dish flux processor”, to analyze the flux images produced by the dish collector. This was used to convert the original 16 bit image file (pixel values range from 0-65535) into a 10 bit image file (pixel values range from 0-1023) to which the absolute intensity scale (W/m^2, calibrated from the PV cell voltage signal) were then be applied.
Figure 3 and 4 show a mesh surface plot and a contour plot of the flux distribution measured on the target positioned at 12.635 m from the dish vertex (465 mm away from the focal point). At the time the image was taken the dish was pointing 4.54 milliradian off the moon under manually controlled tracking. Figure 3 shows that the flux field exhibits an approximately Gaussian type distribution with the peak intensity of 352 mW/m^2. Figure 3 and 4 have had the image of the (Red) LED lights removed from the corner of the target. The bright spot at the center of the region, shown in figure 4, is the image of the PV cell used for calibration. In addition, there is an image of the receiver quadrapod legs and its structure obstructing the flux image on the left of the figure. Therefore the overall intercepted power is difficult to estimate precisely and such that the average dish reflectivity cannot be derived (Johnston, 1995). However, the interested in this study is the collector surface slope error which can be derived from the flux distribution image. Figure 5 depicts a cross-section plot of the flux distribution measured on the target. The cross-sectional flux distribution was taken at the centroid point of the flux image which is approximately 57 mm. away from the center of the target. This helps to minimum the risk of obscured flux image from the quadrapod leg and its structure. The deterioration of the Gaussian distribution shape near the top in figure 5a and at the base in figure 5b is caused by the PV cell and the receiver quadrapod legs respectively.

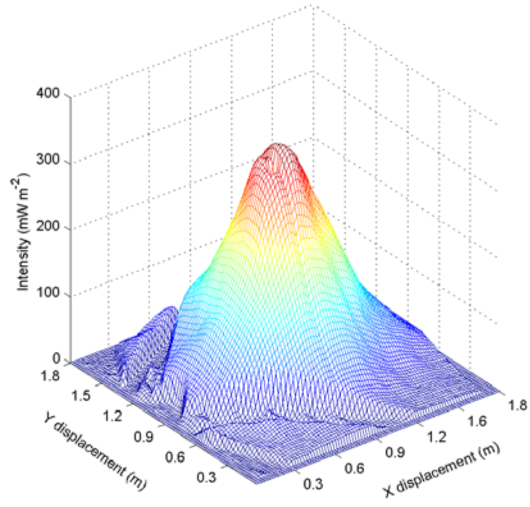

Figure 3: Surface plot of the flux distribution measured at the target of the ANU 400m² dish.

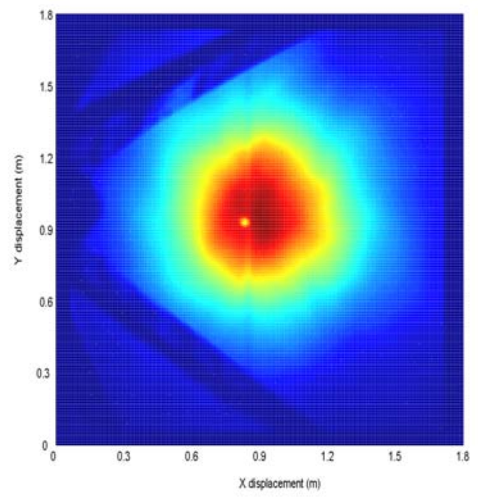

Figure 4: Contour plot of the flux distribution measured at the target of the ANU 400 m² dish.

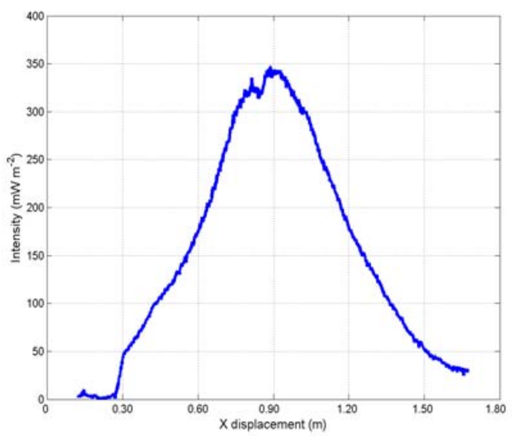

Figure 5a: Flux cross section at the image centroid point along the target X-axis

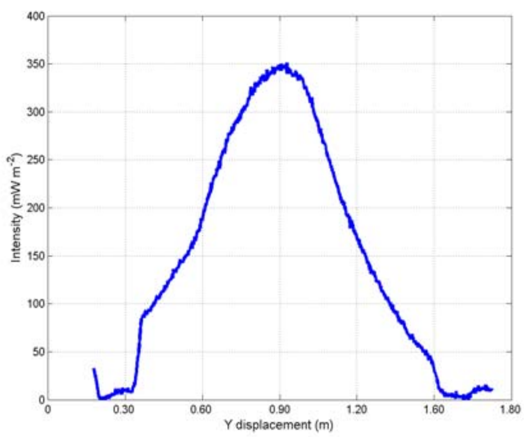

Figure 5b: Flux cross section at the image centroid point along the target Y-axis.

6. FLUX MODEL USING CONTRACE

A ray trace algorithm CONTRACE (acronym for CONcentrator ray TRACE) was used in this study. This ray trace code is the latest version of COMPREC was developed by Johnston during his flux mapping project (Johnston, 1995). The algorithm is implemented in Visual Pascal language and can model the flux distributions expected on the receivers, having planar rectangular, disk or annular shapes, as well as cylindrical, conical and partial spherical geometries. Concentrator pointing errors, surface error, and collector reflectance can also be included. In addition, concentrator configurations, namely paraboloidal and sperical shape, can be implemented in the model. The solar disk can be modelled with Kuiper's empirical sunshape or pillbox sunshape (Johnston, 1998). For simplification a simple "pillbox" sunshape was used to represent the moon disk in the present investigation. The details of the CONTRACE parameters used in this investigation are summarized in table 1.

Table 1. Parameters used in CONTRACE for predicting lunar flux on the ANU 400m² dish

Configuration	Value	Comments
Dish mirror reflectivity	73.4 $\pm$ 3.9 %	Taken on 5 panels (including the new mirror panel) a day prior to the experiment
Dish effective aperture area	380 $\pm$ 1.5 m^2	Excluding the gaps, holes and all degraded tiles
Dish surface slope error	6.5 – 12.5 mr	For a comparison purpose (original of 6.0 mr)
Moon intensity	1mW m^{-2}	Estimated using L. Gallouët (1964) formula

In addition, the other dish parameters implemented in CONTRACE, such as the shape, focal length, average diameter, etc, use the original design specifications (mentioned in section 3). Figure 6 shows the result of the predicted flux cross-section generated by CONTRACE for different levels of surface slope error.

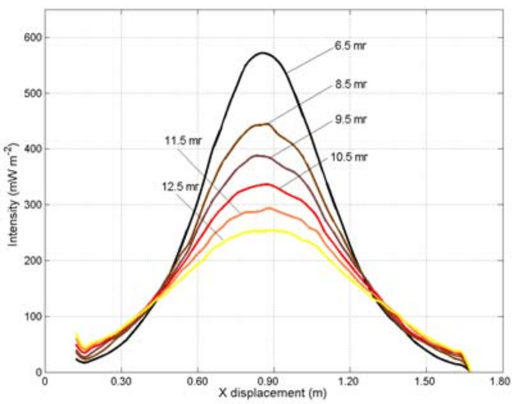

Figure 6a: Flux cross section along the Y-axis on the target.

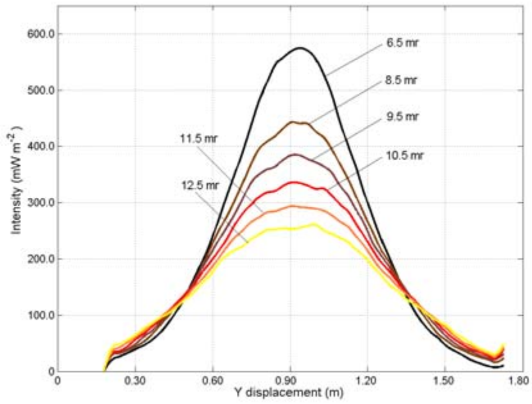

Figure 6b: Flux cross section along the Y-axis on the target.

7. COMPARISON OF EXPERIMENT AND MODEL

Conventional technique of flux mapping for determining the collector surface slope error is adjusting the surface normal error in the CONTRACE simulation until the predicted and measured flux distributions showed equal peak intensity. However in this study, the moon intensity was not measured.

Since the flux field at the target exhibits Gaussian distribution type the standard deviation of the distribution can be used, instead of peak intensity, for a comparison. With this method, the problem of large scale error in calibration of the moon intensity is avoided and the scaling factor of the Gaussian distribution curve can be found. Figure 7 shows the superposition of the measured flux image (figure 5) and the predicted flux image produced by CONTRACE. The predicted flux distribution along the X and Y axis matched the measured one for a surface normal error of 7.6 and 7.2 milliradian with the scaling factor of 69.4% and 65.5% respectively. The scaling factor compensates for the error associated with the receiver quadrapod legs structure and the over estimation of the moon intensity, plus the dish mirror reflectance error caused by the dew that was spread all over the mirror tiles when the experiment was conducted. The offset of the curve between the measured and predicted flux is due to the concentrator pointing error.

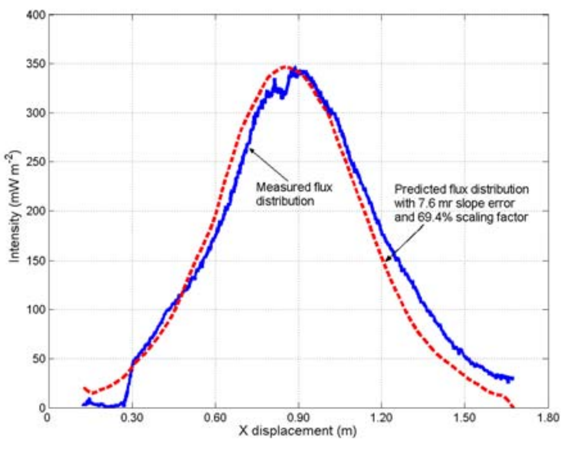

Figure 7a: Superposition of measured and predicted flux distribution along the X-axis on the target.

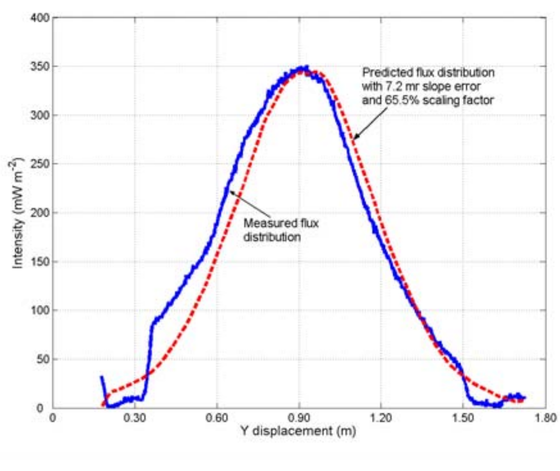

Figure 7b: Superposition of measured and predicted flux distribution along the Y-axis on the target.

The investigation shows the successful operation of the lunar flux mapping experiment at the ANU. The advantage of this moon experiment is that the flux mapping target was easily made and there is no requirement for a complicated water cooling apparatus. However the moon is only full for a few nights a month and can be obscured by cloud during these brief availabilities.
Five focal flux images were recorded and analyzed in this study which gave the average surface normal error of 7.5 ± 0.3 milliradian with the average scaling factor of 67.45%. Conventionally, the scaling factor can be used to determine the dish mirror reflectivity if the light source intensity is accurately measured. However in this study the moon intensity was not measured accurately enough.

8. CONCLUSION

Measurement of the lunar flux distribution produced by the ANU 400m^2 paraboloidal dish solar concentrator in July 2004 showed an essentially Gaussian distribution curve. A peak flux of 352 mW/m^2, and an integrated power of 200 ±12 W were measured at the focal point. The distribution of the flux in the focal plane was analyzed and compared with the predicted flux, produced by CONTRACE, to derive the dish collector surface error. As a result it can be concluded that the ANU 400m^2 'Big Dish' has a mean surface error standard deviation of 7.5 ± 0.3 milliradian. This figure showed that the dish surface has increased in its mean surface slope error about 1.5 milliradian over the last ten year. This increase is consistent with qualitative observations of changes in the mirror surface over that period.
The known focal region characteristics are a valuable input to investigation and modeling of thermal performance of the dish system.
The investigation confirms the usefulness and convenience of flux mapping using lunar images.

9. ACKNOWLEDGMENTS

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