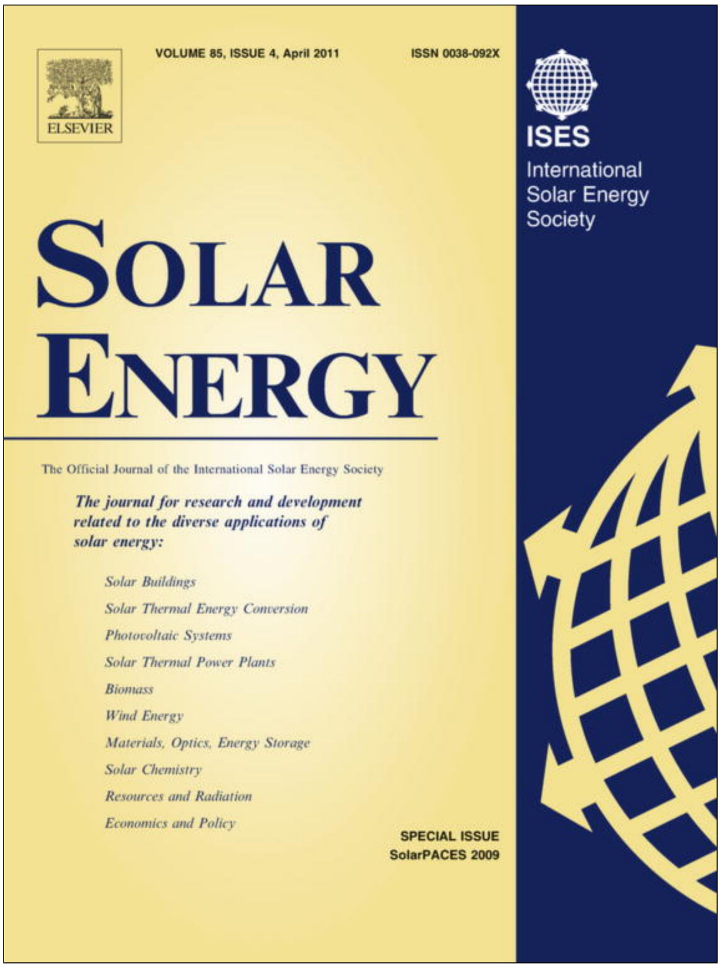
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A new 500 m^2 paraboloidal dish solar concentrator

K. Lovegrove *, G. Burgess, J. Pye

Department of Engineering, Australian National University, Canberra, ACT 0200, Australia

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Abstract

The Australian National University (ANU) has worked for many years on paraboloidal dish solar concentrators and demonstrated a 400 m^2 system in 1994. The commercialization of this technology has involved a re-design of the Big Dish concept for mass production. The new design is a 500 m^2 concentrator with 13.4 m focal length and altitude–azimuth tracking. It uses 380 identical spherical 1.17 m × 1.17 m mirror panels, which incorporate the Glass-on-Metal Laminate mirrors. Construction of a first prototype on the ANU campus began in the first quarter of 2008. The first on sun test was carried out on 29 June 2009.

Keywords: Big Dish; Paraboloidal dish; Mirror panels; Flux mapping

1. Introduction

Paraboloidal dish concentrators offer the highest thermal and optical efficiencies of all the concentrator options demonstrated to date. This must be set against a higher cost of construction per unit area, compared to linear systems. The Australian National University (ANU) has worked on dish systems for many years and the team remains confident that the overall economics favour dishes in many applications. The ANU 400 m^2 prototype (SG3, see Fig. 1) was completed in 1994 and successfully proved the technical viability of a concentrator that is approximately three times bigger than any other produced (CADDET, 1999). A subsequent similar system provided to the Ben Gurion University in Israel (Biryukov, 2004). In 2005, ANU dish technology was licenced exclusively to the Canberra-based company Wizard Power Pty Ltd. In collaboration with ANU, Wizard Power secured support under the Australian Government Renewable Energy Development Initiative (REDI) program, for a project that included the design and demonstration of a second generation Big Dish, suitable for commercial production.

This paper describes the new dish design and the experience with the construction of the first prototype on the ANU campus.

2. Establishing the fundamentals

The new dish design, has been developed by a joint ANU/Wizard Power team starting from first principles. The mission was to design a large-area solar dish to produce energy at minimum levelised energy cost, when mass produced on a large scale. Additional customer requirements including minimising technical risk and maximising reliability, being attractive to investors, ease of operator training and applicability to a range of energy conversion options, were considered.

An analysis of normalised dish cost per unit aperture area as a function of dish radius has been presented previously (Lovegrove et al., 2003) and supports a choice of most cost-effective size between 400 and 1000 m^2.

For an ideal paraboloid, with a cavity receiver, theoretical analysis shows that a "rim angle" of 45° delivers the

* Corresponding author.
E-mail address: keith.lovegrove@anu.edu.au (K. Lovegrove).

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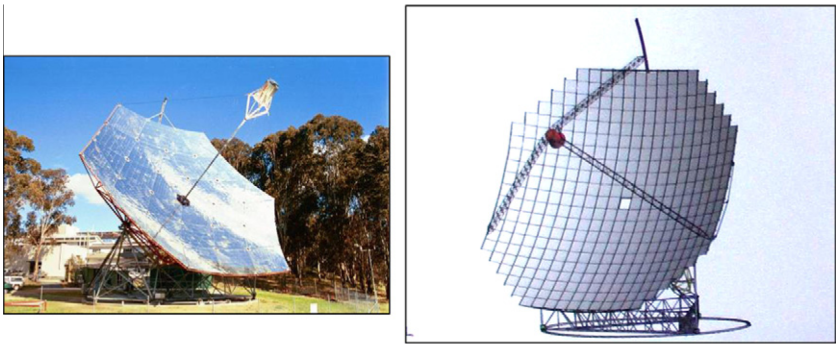

Fig. 1. The existing SG3 400 m^2 dish (left) and a CAD image of the new 500 m^2 SG4 dish at approximately the same scale.

highest concentration ratio and hence the highest thermal performance. For a real dish, optical and structural arguments favour a bigger one.

A range of basic geometries for the dish tracking structure were considered, including, polar–equatorial, altitude–azimuth with high pivots, SG3-type geometry, pedestal-mounted altitude–azimuth and a range of novel approaches. These were assessed against cost and other selection criteria according to their impact on structure, actuation systems and overall performance. Whilst a number of options were rejected outright, the remaining options were found to have comparable cost performance to the SG3 geometry, so the overall geometry of this earlier design has been kept.

3. Design development

The design process followed rigorous systems-design principles and carefully considered the interactions between the key subsystems of structure, mirrors, receiver, foundation and actuation, as each was developed in parallel.

With the exception of the size and overall altitude–azimuth tracking geometry, virtually every aspect of the design has been changed over the SG3 dish.

The original SG3 dish used a commercially-available space-frame system based on accurate cone-ended members screwed to solid ball nodes. This generated a precise one-off structure but does not give the best long-term economics under mass production. The new design instead incorporates a very accurate re-useable jig, to provide the accuracy of the frame supporting the optical surface. Novel fabrication techniques have been employed to form the space-frame on this jig in a manner that is rapid and cost-effective. The emphasis is to establish a ‘Factory-in-the-Field’ concept for manufacture of large dish arrays. A key element of this is the on-site production of roll-formed structural sections from steel coil stock.

‘Microstran’ software was used to analyse forces in frame elements, ‘Strand’ was employed for analysis of stresses in key elements, and ‘SolidWorks’ was used to visualize overall construction and to produce working drawings.

Mirrors were identified as a key driver for the design. The Glass-on-Metal Laminate approach using thin low iron back silvered glass mirrors had previously shown to be a durable and effective approach. For dish mirrors, forming into multilayered cored panels has proved to be an effective way of producing shapes with good optical quality. Previous studies (Johnston et al., 2003) indicated that a dish could be built with good optical performance using standard spherical element mirror panels which would suit mass production. Materials, optical and structural constraints were reviewed to choose a square rather than triangular unit and to determine an optimum unit size. It was identified that the stiff panel design needed for optical quality meant that there was an opportunity to leverage this to a contribution to the overall dish structure. Such an integrated approach is key to a cost optimized outcome.

Wind loads were a major driver in determining the structural design. The appropriate structural design code for Australia (Standards Australia, 2002) identifies ultimate limit state wind speeds based on location, height and other factors. The actuation geometry taken from the SG3 design, has the dish parked horizontally for maximum storm survivability. For the parked dish height chosen, a 162 km h^{-1} limiting wind speed was indicated.

The assumption that some form of space frame would be needed was made early in the process. Based on this a review of the cost effectiveness of various material approaches to supporting an indicative load over a 3 m span was carried out. Interestingly, wood or reinforced concrete were shown to be most cost effective but deemed impractical. Aluminium or galvanised steel tube sections were shown to be almost identical in cost effectiveness. Steel was chosen based on the wider applicability of fabrication techniques for large structures.

The SG3 dish employs a tetrahedral element space frame as this is the most structurally efficient modular unit. The potential to use mirror panels structurally; however, converts the entire front surface of the dish into a membrane. This being so, either a tetrahedral or square pyramid space frame unit performs equally well for the rest of the structure. Square pyramid was chosen for easier coupling to a mesh of square mirror panels.

The specifications of the new dish are:

Total panel aperture area	494 m^2
Total mirror aperture area	489 m^2
Focal length	13.4 m
Average diameter	25 m
Average rim angle	50.2°
Mirror reflectivity	93.5%
Number of mirrors	380
Mirror glass size	1165 mm × 1165 mm
Total mass of dish	19.1 t
Total mass of base and supports	7.3 t

4. Steps in construction

Construction of a first prototype (designated *SG4*), by ANU personnel, on a site immediately adjacent to the existing SG3 dish on the ANU campus, began in the first quarter of 2008.

4.1. Forming the frame

Site works began with the preparation of a concrete slab slightly bigger than the 500 m^2 aperture of the dish. This slab was designed to provide a stable surface for the assembly of the dish frame jig. For the SG4 prototype, the slab was subsequently re-used as the foundation for the dish itself. The intention for the construction of a commercial dish array, is that a single slab would be established for the jig, in the middle of the intended array, with dish frames then produced in sequence and transported short distances to their individual locations.

The jig is formed of a series of parabolic trusses as shown in Fig. 2. These were screwed to the concrete slab and linked together to form a paraboloidal dome. A series of adjustable supports were attached to the truss tops, forming a square pattern in plan view that roughly correlates with the mirror vertices. Photogrammetric measurements based on photographs taken from a box suspended from a crane and positioned at locations around and above the jig, allowed accurate determination of support positions. Iterative measurement and adjustment brought the supports to an RMS error of ±0.6 mm from the true paraboloid.

The dish frame was formed in two stages. Initially a front surface made up of "top hat" cross section steel members running in two directions to form an approximately square mesh, was positioned on the jig supports and riveted together using a self piecing riveting system. These top hat section members were themselves formed on site using a custom built section rolling machine that rolled them continuously from sheet metal coil stock. This rolling process also imparted a curvature equal to the average radius of curvature of the dish, so that elastic conformance to the jig was obtained with modest hold down forces. The advantage of on site forming using a containerized plant, is that it is not necessary to transport cumbersome long shaped structural members long distances.

The second stage of the process involved the attachment of a series of pyramid forms made from Circular Hollow Section galvanised steel. These pyramids were themselves pre-fabricated using a process of squashing their ends to a structurally optimized taper and welding to plate nodes. Pyramids were attached to span 3 × 3 cells across the surface structure. Once fixed, extra members were used to tie the pyramid vertices together and so form a complete space frame. Fig. 3 shows the completed dish frame being lifted off the jig. In this lifting process it was turned over and rested on the ground pending the construction of the base-frame.

With the dish frame complete, the jig was removed for re-use by Wizard Power at another location. A steel Azimuth tracking ring was installed to the slab, a pre-fabricated base-frame installed and the dish frame lifted in and installed to pivots and actuators as shown in Fig. 4. The base-frame is formed from three trusses joined to form a triangle. A wheel block at each vertex of the base-frame

Fig. 2. Construction of the dish frame forming jig from a series of trusses.

Fig. 3. Removal of the completed dish frame from the jig.

triangle supports the dish and allows Azimuth movement. The wheel blocks both support the dish and also incorporate engagement with the beam to resist overturning moments in strong winds.

4.2. Fabricating and installing mirrors

For the prototype, all the mirror panels were fabricated by hand in the ANU workshop. Fig. 5 shows the mirror panel installation process underway. A system of wooden decking across the dish surface allowed personnel to work across the surface safely. Mirror panels were positioned and bonded along two edges to the top hat front surface sections forming the upper most layer of the front surface structure. As each panel was laid, the decking piece under it was subsequently withdrawn for use at another location. Panels were covered with plastic sheets to protect against unwanted reflections during the installation proves.

Fig. 5. Early stages of mirror installation on the dish surface.

Installation proceeded from the centre outwards to ensure close packing. Small wedge shaped gaps appear between adjacent panels along a row as the square panels are packed to conform with the paraboloid.

Fig. 4. Dish frame assembled on base-frame, with actuation systems in place.

4.3. Balance of system

Electric drive was chosen over the hydraulic system used on the SG3 dish after a review of costs. AC motors coupled to reduction gearboxes are used. Elevation is achieved with a motor gearbox unit driving a pinion on a machined rack attached to curved back-beam fixed to the back of the dish frame. Azimuth drive uses an identical motor gearbox unit directly driving one of the wheels. The reduction of 400:1 in the gearboxes is insufficient for continuous tracking so intermittent operation is used.

A tetrahedral receiver support system was fabricated and installed in parallel with the mirror installation. The three legs are light weight trusses optimized to minimise shading. They have been designed to support a receiver unit up to 2000 kg in weight. The three legs terminate at a large cylindrical structure that is designed as a "plug in" port for a range of different receivers that are likely to be used into the future.

Initially a water cooled approximately lambertian flux mapping target was installed to the front of the receiver mount.

Fig. 6 shows the first on sun operation of the dish on 29 June 2009. It can be seen that the wooden decking remains in place where mirror panels are not yet installed around the periphery of the dish.

Fig. 7 shows the completed dish under operation during the first test with all the mirror panels uncovered.

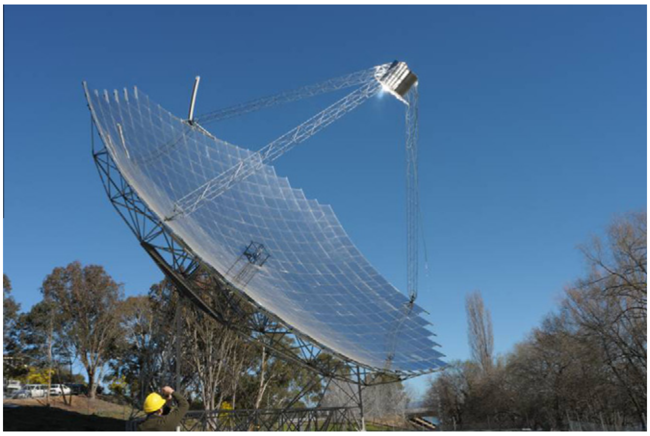

Fig. 7. First on sun tests with all mirrors uncovered.

5. Assessing optical performance

The camera target flux mapping method (see, for example Ulmer et al. (2002)) has been chosen as the primary method for assessing optical performance. A Prosilica GC1290 12-bit monochromatic machine-vision camera has been employed.

Representative mirror panels have been flux mapped during the manufacturing process. Fig. 8 shows the results of flux mapping a single representative mirror panel. The distribution suggests an average surface slope error for the panel of 1.3 mrad.

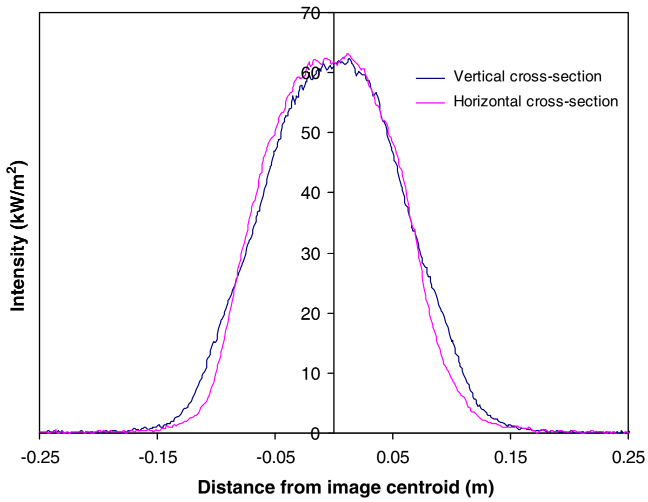

Fig. 8. Flux mapping results for a single mirror panel.

During the first on sun test, the plastic covers remained on most of the mirrors and the radiation was focused from the exposed mirror edges only. In this configuration the total area of mirror in operation was only approximately 82 m^2 of the ultimate total of 489 m^2. Fig. 9 shows a close up of the target viewed through neutral density filters. The square target is 1.5 m on a side and the image size suggests a geometric concentration ratio of approximately 1600. It should be noted though that the target was 200 mm behind the nominal focal position and there was fluctuating cloud at the time, both factors would limit the concentration achieved.

Fig. 6. First test of the dish on sun, 29 June 2009.

Several attempts were made to flux map SG4 'on-sun' using water-cooled targets made of aluminium; however in each case the target was damaged by higher than expected peak flux levels before good data could be obtained. The flux also melted a ceramic blanket (put in place to protect the receiver structure) which was rated at 1200 °C.

Efforts were then transferred to night time flux mapping using Jupiter and the full moon. This is an established technique for measuring the optics of high concentration collectors (Biryukov, 2004): the full moon image size is

Fig. 9. Zoomed in view of the flux mapping target through neutral density filters.

close to that which would be obtained with the sun, as the solar and lunar angular diameters agree to within 7%. A successful full moon flux map was carried out on 4 September 2009, a 2d plot of the analysed image is shown in Fig. 10.

The target position could be adjusted from the ground by means of an electrically driven screw jack. This was done in order to determine the actual focal length.

Graphs of peak and geometric concentration ratios (adjusted to allow for the solar to lunar size difference) are shown in Figs. 11 and 12 as functions of the target position. The most notable feature is the very high concentration levels, with a peak of 14,100, and a geometric concentration ratio for 95% capture of 2240. (These can be compared to be original SG3 dish built at ANU, which has values of ~1000 and 500, respectively.)

Based on the measurements, the focal plane is in the region 13.40–13.45 m from the dish vertex, which agrees well with the design value of 13.4 m. Significant parameters are listed in Table 1 for the best fit focal length.

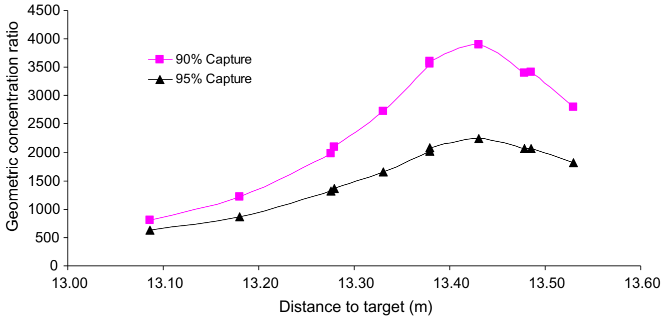

Fig. 11. Geometric concentration ratio vs target position.

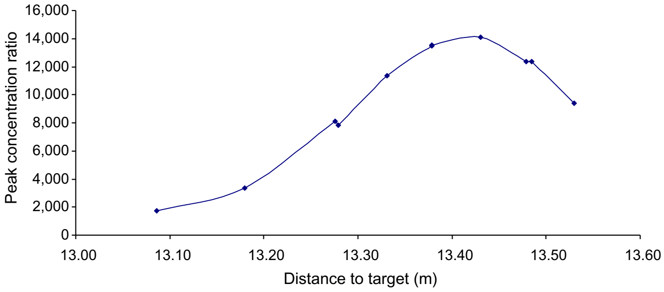

Fig. 12. Peak concentration ratio vs target position.

Table 1
Measured parameters for the SG4 dish. The aperture diameters would need to be increased to allow for tracking error, to achieve the stated percent captures.

Peak concentration ratio	Geometric concentration		Aperture diameter (mm)	
	90% capture	95% capture	90% capture	95% capture
14,100	3900	2240	400	530

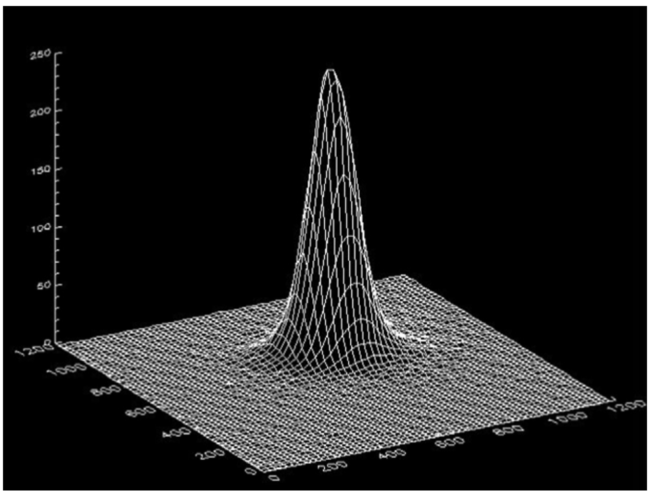

Fig. 10. Surface plot of the full moon image (4/9/09, vertex to target distance of 13.43 m), generated by the flux map image processing software written in IDL. Horizontal scales in mm, vertical scale is relative.

These values indicate an optical performance that is higher than expected. They are slightly better than the results reported for the Israel dish by Biryukov (2004) and an order of magnitude higher than obtained for the SG3 dish (Johnston, 1995). It should be emphasized that they are still preliminary. Uncertainties are estimated to be approximately 5%. Two obvious sources of error have been considered in depth. The angular response of the diffuse white target has been measured and incorporated in a ray trace analysis to test sensitivity and thus shows an over prediction of concentrations by about 1.0–2.5%. The level of back ground intensity can only be measured within the camera limitations at the aperture chosen, this could be significant; however the error can only be in the direction of an underestimate of background level with a consequent underestimate of concentration. Ultimately direct measurement of solar flux with a radiometer instrument is desirable.

6. Moving forward

From here, the dish will be used as a research tool to investigate energy conversion via direct steam generation, thermochemical processes for fuels and energy storage and small (Brayton) turbine cycles among others.

In parallel with this, Wizard Power has commenced construction of a pilot system of four such dishes in Whyalla in South Australia. Once this system has operated successfully, the hope is to proceed to full commercial power stations in the near future.

7. Conclusion

The large dish approach to solar concentrator systems offers the highest possible conversion efficiencies and justifies the higher capital cost per unit area. ANU has worked for many years in this field and has now finished construction of a new 500 m^2 unit that is a prototype of a design optimized for manufacture. The construction of the prototype has successfully proven a range of novel design features including the use of the mirror panels to form part of the structure itself. This paves the way for construction of commercial arrays. Initial optical analysis shows that operation of receivers with geometric concentration ratios of at least 2000 times should be possible.

Acknowledgement

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References

Biryukov, S., 2004. Determining the optical properties of PETAL, the 400 m^2 parabolic dish at Sede Boqer. Journal of Solar Energy Engineering 126, 827–832.

CADDET, 1999. Solar thermal demonstration system with a large paraboloidal dish concentrator. Technical Brochure No. 105, <www.caddet-re.org>.

Johnston, G., 1995. Flux mapping the 400 m^2 "Big-Dish" at the Australian National University. ASME Journal of Solar Energy Engineering 117, 290–292.

Johnston, G., Lovegrove, K., Luzzi, A., 2003. Optical performance of spherical reflecting elements for use with paraboloidal dish concentrators. Solar Energy 74, 133–140.

Lovegrove, K. et al., 2003. Paraboloidal dish solar concentrators for multi-megawatt power generation. ISES Solar World Congress, Göteborg, Sweden, 16–19 June 2003.

Standards Australia, 2002. Australian Standard for structural design, AS1170.

Ulmer, Steffen, Reinalter, Wolfgang, Heller, Peter, Lüpfert, Eckhard, 2002. Beam characterization and improvement with a flux mapping system for dish concentrators. Journal of Solar Energy Engineering 124 (2002), 182–188.