Photogrammetry for dish concentrator construction

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ABSTRACT

Photogrammetry has been used to control the assembly of a convex paraboloidal jig, used in the construction of a 500 m² dish concentrator. The photogrammetric measurement precision was ~ 1:175,000, corresponding to an accuracy of better than 1 mm at the jig reference points. Equipment (camera, flash and retro-reflective film) and software are discussed. Photogrammetry was also used to characterise the dish mirror panels: the rear surface of the panels was mapped, as it made possible a denser target array and quicker image capture than if the reflective surface was used. The targets were produced with a digital projector, and the measurement precision attained was ~ 1:150,000.

INTRODUCTION

A prototype of a new design of solar concentrating dish, called SG4, has been constructed at the Australian National University (ANU) during 2008-09. The design philosophy for the 'Generation II Big Dish' is that at a given site a single or small number of very accurate jigs will be constructed, on each of which a large number of dishes can be assembled (Lovegrove et al, 2009). Any error in the jig reference points will result in pointing errors in the mirror panels; a design goal was set of an RMS pointing error of 1 mrad or less. This corresponds to a local height error in the jig, relative to the paraboloid, of approximately 0.5 mm. In a global xyz coordinate system, where z is a central axis of the paraboloid, this offset gives maximum allowable xyz errors of 1.0, 1.0, and 0.5 mm respectively, for a dish with a 50° rim angle.

Close-range photogrammetry involves the use of a network of multiple photographs of a targeted object taken from a range of viewing positions, to obtain 3D coordinate data for the target coordinates. A major advantage of photogrammetry as a measurement tool is that it is a rapid, non-contact technique that can readily be adapted to a range of object sizes. Further, photogrammetry is self-contained and requires little external information if only the shape and size of the object is of interest. Photogrammetric network computations automatically incorporate estimates of precision that reflect the level of internal consistency within a network of multiple images of targets on multiple photographs. Accuracy is most commonly assessed by including some precisely known lengths, also known as "scale bars", within the field of view. The accuracy and precision of the photogrammetric measurement is dependent on a number of factors, however the most significant are the resolution of the sensor, the geometric strength of the network and the level of redundant measurements in the network.

Photogrammetry has been used both for dish construction and mirror panel manufacture. The use of photogrammetry for geometric analysis of solar concentrators was previously described by Pottler *et al.* (2005), and Shortis and Johnston (1996, 1997). The current paper updates information on equipment and materials, describes features specific to the SG4 project, and compares photogrammetry to other measurement techniques.

SG4 JIG PHOTOGRAMMETRY

The SG4 dish is 25 m in diameter and 3 m deep, at which scale the measurement precision required for setting up the mounting points to 0.5 mm accuracy is 1:50,000 or better. Surveying equipment was considered for the task but a review showed that only robotic 'industrial' total stations have the required accuracy and efficiency, at a cost of the order of $100,000. By contrast, photogrammetry can provide measurement precision of 1:100,000 or better with consumer grade photographic equipment costing less than $5,000.

A set of at least 4 spatial reference points ('control points') is required in each photogrammetric image as a means of scaling the image and determining the camera location and orientation. Coded targets can be used at the control points; these targets are automatically identified by the photogrammetry software, and used to determine the camera location and to scale the image[1]. If approximate locations of the remainder of the targets are known (in the SG4 case, their design positions), then they can also be identified automatically, so that there is minimal manual effort required during the processing.

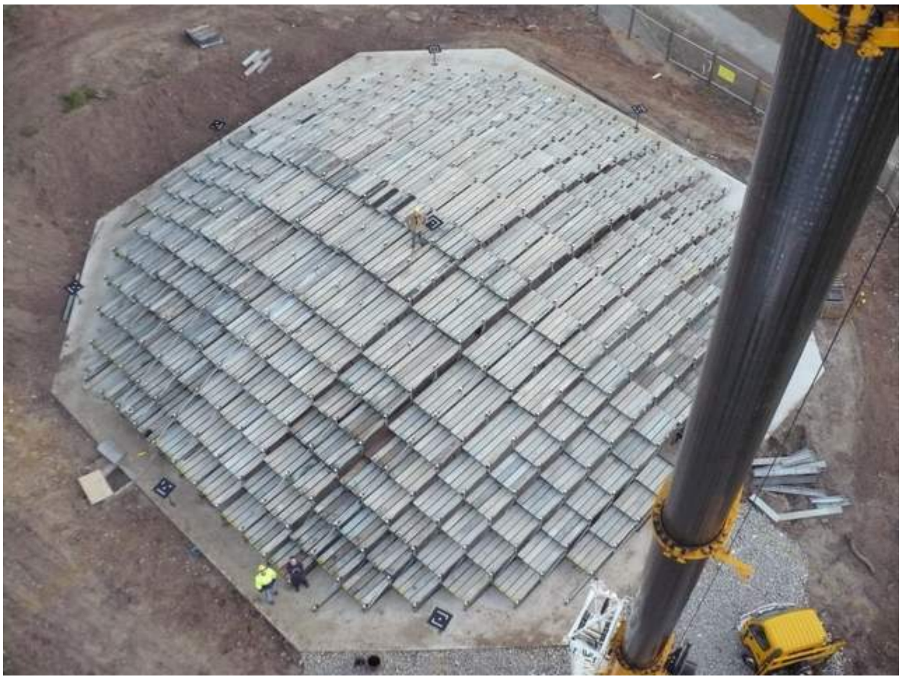

Fig. 1: Day time image of the jig, taken from a crane basket at a height of ~ 30 m.

Retro-reflective photogrammetry can generally be carried out in daylight, as a powerful flash will give good contrast between the targets and their surrounds. However in the

[1] The coded target locations must be measured using some independent technique; a +/-3 mm accuracy total station was used for the SG4 jig. A lesser degree of accuracy is required for these measurements as the control point locations will be updated during the process.

case of the SG4 jig the large amount of galvanised metal in the structure prevented reliable target identification, even in overcast conditions, so that all measurements were done at night.

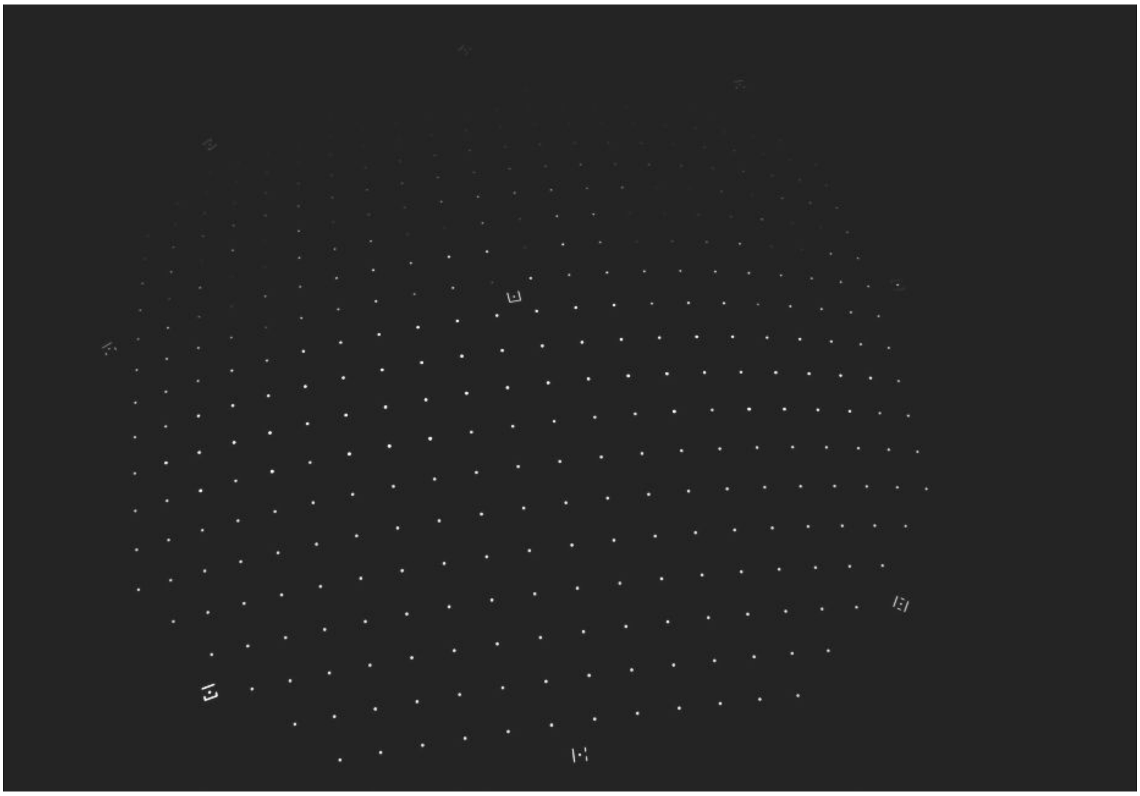

Fig. 2: Night time image of the jig with retro-reflective point location and coded targets. The top of the image represents the centre of the jig. The image has been contrast stretched to improve the visibility of the targets.

Night-time photogrammetry is not without disadvantages; including more difficult working conditions and increased costs for crane hire (a crane with work basket was required to reach the desired camera locations). Each session required 2 – 3 hours to capture the images, largely taken up with the time needed to set up and move the crane.

On one occasion dew started to form on the retro-reflective targets midway through the evening. The images taken thereafter had an annular appearance (figure 3), and the session had to be abandoned.

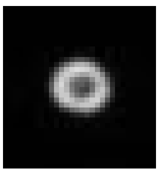

Fig. 3: Retro-reflective target with an annular reflectance pattern cause by surface dew.

Principal point stability and measurement accuracy

The principal point location is the intersection of the optical axis of the camera lens with the image sensor, and defines the origin of the internal coordinate system for image measurements. The location of the principal point is dependent on the stability of the sensor (Shortis *et al*., 1998) and orientation of the camera lens with respect to the plane of the image sensor, which has been shown to be a cause of instability in consumer digital cameras (Shortis *et al.*, 2006; Rieke-Zapp *et al.*, 2009). For the jig photogrammetry the ring flash was fixed to the end of the lens using the standard mount. There was evidence that the weight of the flash caused movement of the optical axis when the camera was held at different angles. As seen in figure 4, there is some systematic dependence of the principal point on the camera roll angle; whereas ideally there should be a random scatter. Although this effect was partially modelled by allowing the position of the principal point to be a free parameter in the network solution, a better result would be obtained by mounting the flash on the base of the camera (Rieke-Zapp *et al*., 2009).

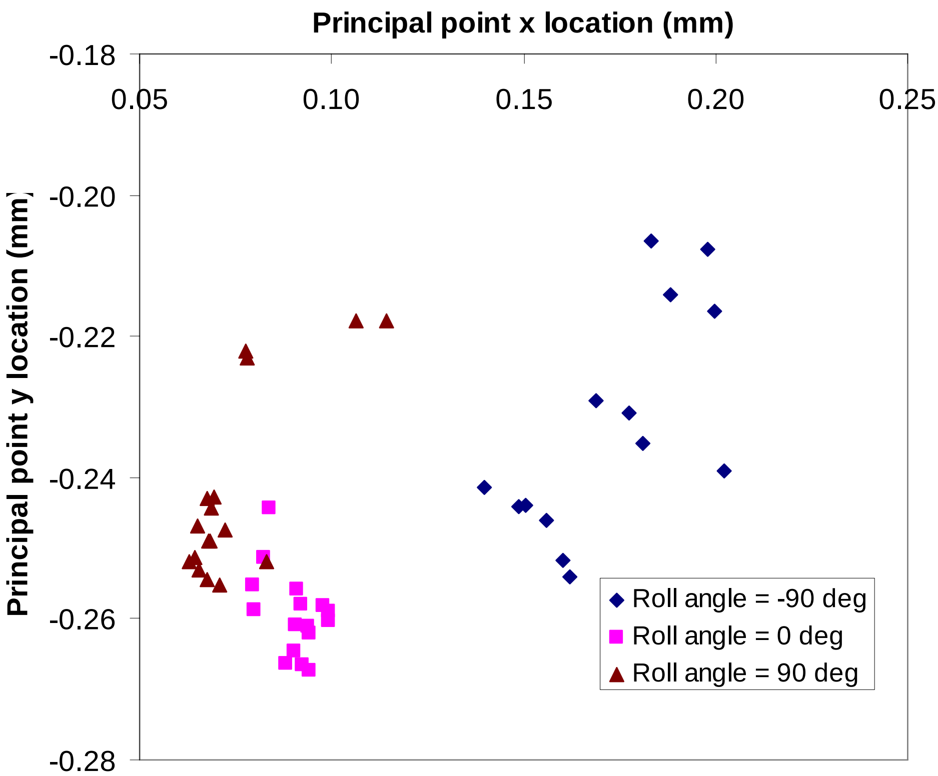

Fig. 4: Principal point variation with camera roll angle

Acceptable results were nonetheless obtained, with typical RMS image residual of 0.35 µm, corresponding to approximately 1/15 of the sensor pixel size. The typical measurement precision estimated by the photogrammetric network solution was approximately 1:175,000, corresponding to positional accuracy of the order of 0.2-0.3 mm. The precisions for the three usable sessions are given in Table 1.

Tab.1: Measurement precisions and numbers of usable images for the three valid sessions of jig photogrammetry (session 3 was abandoned due to dew forming on the targets). Z is the symmetry axis of the paraboloid.

		Measurement precision		
Session	Images	sx (mm)	sy (mm)	sz (mm)
1	28	0.20	0.20	0.33
2	47	0.14	0.14	0.22
4	48	0.14	0.14	0.20

The measurement precision does not take into account some types of systematic errors in the process, such as principal point instability (Shortis *et al.*, 1998), which can cause a significant reduction in the measurement accuracy. A check was made of the accuracy by analysing 127 reference points which were not adjusted between sessions 2 and 4 as their positions were already sufficiently close to their design value. The RMS xyz shifts in the measured positions of these points were calculated. These would ideally equal the combined precisions of the two sessions. The agreement was good for the z component, but the x and y shifts were of the order of 3 times the combined precisions. These shifts could not be accounted for by thermal expansion alone; however rather than being due to systematic errors it is suggested that they may have been due to real movements in jig. The residual shifts are less than 1 mm, and could have been due to construction activity on the jig, or possibly to movement in the underlying concrete slab (which was laid three months prior to the first session).

Camera station geometry

There is extensive literature relating to the photogrammetric measurement of dish surfaces (Fraser, 1986; Shortis and Johnston, 1996; 1997; Wiktowy *et al.*, 2003; Fraser *et al.*, 2005; Pottler *et al.*, 2005). Fraser (1986) shows that for a concave dish the optimal location of the camera stations, in terms of an optimisation of the precision of the target coordinates, is given when the convergence angle of a ring of cameras stations around the edge of the dish is in the range 70-100 degrees at the centre of the dish. However this does not necessarily hold true for a convex paraboloid, as the targets which are at the greatest distance from the camera also have the highest retro-reflective entrance angle (assuming that the targets are tangent to the surface). These two factors combine to produce a sharp decrease in intensity, so that targets on the far side of the jig cannot in general be located (see figure 2).

In the first session of jig photogrammetry eight camera stations were used, spaced equally around the jig and positioned at a convergence angle of 80° where possible (subject to limitations on crane access). Three camera roll angles were used at each station, giving a total of 24 images. In subsequent sessions eight stations closer to the axis of the paraboloid (convergence angle of 60°) were added. Although these additional stations would, if processed in isolation, give poor z precision, they strengthened the overall solution by tying together data sets from different parts of the jig, as they suffered less from the target intensity decrease than the 80° positions.

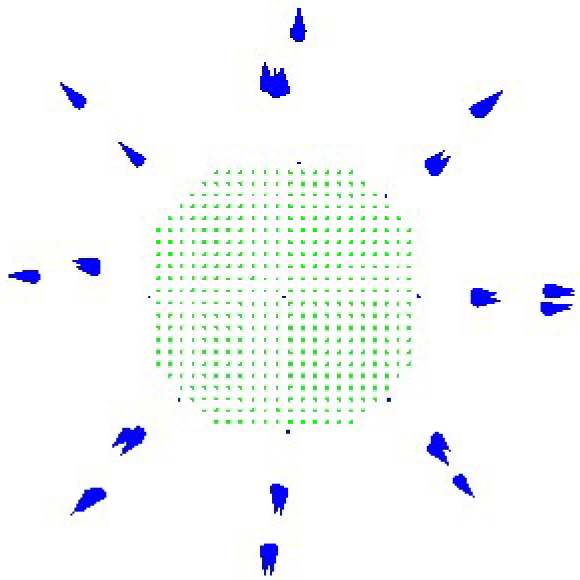

Fig. 5: Plan view of the camera station geometry (cone markers) and targets (dots) for the second session, with additional inner stations. Three images with different roll angles were taken at each station; in some cases they appear as only one or two markers due to co-location.

Future production of Generation II dishes will take place inside a covered shed with an on-site gantry crane, which would avoid the need for expensive crane hire. There will however be height and consequently convergence angle restrictions, which will require re-evaluation of the camera station geometry.

PHOTOGRAMMETRY EQUIPMENT

A Nikon D300 camera was used with a Nikkor AF 20mm f/2.8D lens and a Sigma EM-140 DG ring flash, with total cost of $2,600. A ring flash is preferred because the illumination is distributed evenly with respect to the lens of the camera. A side flash can cause bias and the effect may be exacerbated for targets near the angular limit of retro-reflectivity.

The software used for processing the images was VMS (Vision Measurement System), developed by Mark Shortis and Stuart Robson (University College London). VMS provides a rigorous least squares estimation solution for close-range photogrammetric networks including the self-calibration of the camera or cameras using a variety of additional parameter sets. The principal point location can be included as block-invariant or photo-invariant parameters. VMS uses a coded target system (Shortis *et al.*, 2003) and processes distance measurements as rigorous constraints within the network. There are similar close-range network adjustment applications available from vendors such as AICON, Geodetic Services, Leica and Rollei. The cost of the software varies depending on available features and licence arrangements.

Retro-reflective film

Although specialised high-gain reflective films are available for the targets, commercial quality retro-reflective films for signage applications can be adequate for photogrammetry. Desirable characteristics are relatively flat response versus incident angle, up to an angle of at least 40°, and uniform appearance. The angular transfer functions of two 3M and one Avery reflective film were measured, and are shown in figure 6.

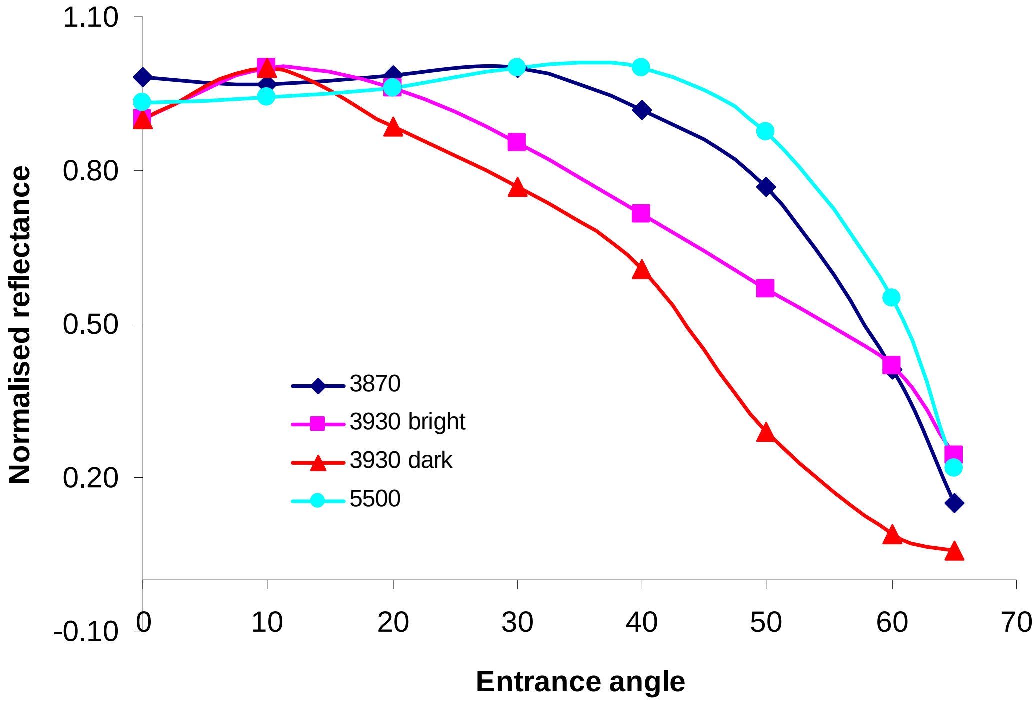

Fig. 6: Retro-reflective film angular transfer functions. The entrance angle is the angle between the incident light and the normal to the plane of the reflective film. The results have been normalised such that the maximum reflectance for each film is 1.0

Both Avery T5500 and 3M 3870 are suitable for photogrammetry; however 3870 has recently been discontinued. 3930 is listed by 3M as the replacement for 3870, but its pattern of alternating bands with different reflective properties makes it unsuitable for accurate centroid location.

MIRROR PANEL CHARACTERIZATION

The SG4 dish has 380 square mirror panels (1.2x1.2 m) which ideally have a uniform spherical radius of curvature (r.o.c.). The panels were manufactured in-house at ANU, and it was decided to measure the surface profile of the panels as a quality assurance measure. A standard photogrammetric technique for detailed surface measurement is to project an array of target images onto the surface; however this method is not suitable for mirrored or highly reflective surfaces. To provide a non-reflective surface for target projection, the glass surface can be temporarily coated with a washable acrylic paint, but this is quite time consuming. Another approach is to place retro-reflective targets on the glass surface (Pottler *et al.*, 2005), but this implies the use of a relatively small number of targets.

The mirror panels were instead characterized using their rear surface. A NEC LT280 digital projector was used to project 1830 targets onto the panel, as well as a set of six coded control points, and some extra points used to give depth to the target array (figure 5). The additional targets prevent correlations between camera calibration and photo orientation parameters that can have an impact on the stability of the photogrammetric network and introduce significant systematic errors. The potential for such correlations increases dramatically if the target array is planar, so a small number of additional targets are an effective prevention strategy. Mirror panel photogrammetry required 15 - 20 minutes to capture, download and process the 27 images for each panel (a shorter time could be achieved with automated camera positioning and image capture).

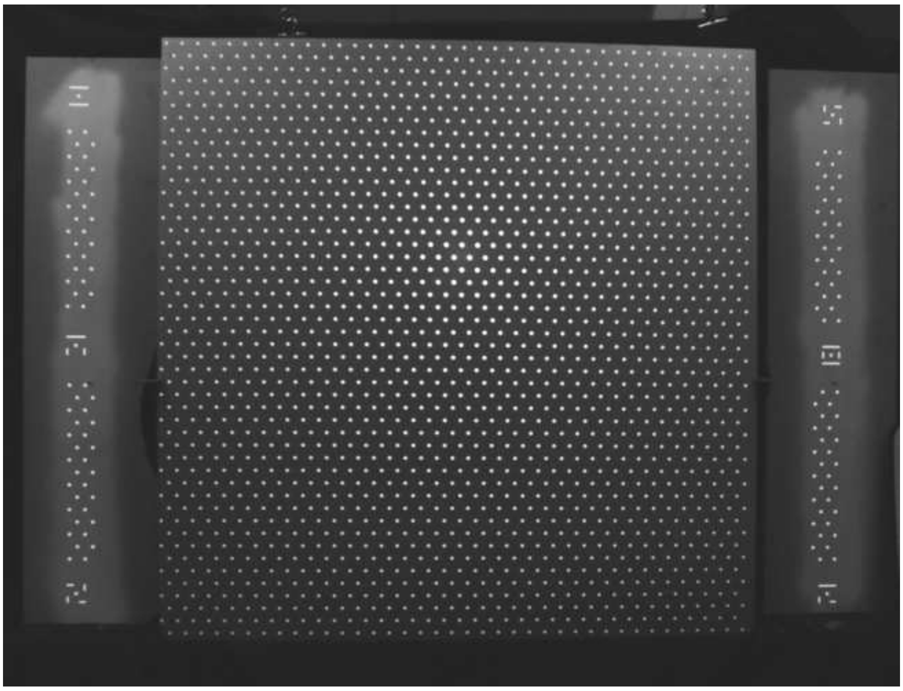

Fig. 5: Mirror panel rear surface with projected targets. The targets on the left and right columns are projected onto a surface which is offset from the plane of the panel, in order to give depth to the image. The image has been contrast stretched to improve the visibility of the targets.

The target images had a diameter of only 4 projected pixels, and were consequently noticeably non-circular when viewed close-up. The target quality is limited by the projector resolution (1024x768 pixels in the case of the LT280), and the desired density of targets on the panel. A slide projector could give better quality images, however the LCD arrays in digital projectors tend to be more stable than slide film once the heat distribution reaches equilibrium.

The results obtained using the digitally projected targets were acceptable, with relative measurement precision of ~ 1:150,000, and accuracy of 15-20 μm in the axis normal to the plane of the panel. The RMS image residual was typically ~ 0.40 μm, a value slightly degraded compared to the dish images, most probably due to the irregular shapes of the projected targets.

Validity of back surface measurements

Three randomly chosen panels had both their front and back surfaces mapped (the mirror sides being coated with paint as described above). The panels were measured with greater than usual accuracy, with 54 images taken of each side, the resulting relative precision being ~ 1:200,000. An elliptic paraboloid was fitted to the data, giving a pair of radii of curvature for each surface. The front and back r.o.c. showed a small systematic variation, which is explainable in terms of the panel construction (details cannot be given here for commercial reasons). The difference is within the desired error band of the r.o.c. measurements; but a correction could be applied to the rear surface values for the remainder of the panels, in order to get a result closer to the true mirror r.o.c.

CONCLUSION

Photogrammetry has been a valuable tool throughout the construction of the SG4 dish. At a moderate cost it provided a means of efficiently assembling the dish structure to high accuracy (better than 1 mm). The optimal camera station geometry for a convex paraboloid is a possible area of further research.

Photogrammetry was also used to measure the mirror panel radii of curvature. The projection of targets onto the rear surface of a reflective panel can be an efficient alternative to the standard techniques. Work is continuing on whether the mirror slope error can be reliably estimated from the rear surface data.

ACKNOWLEDGEMENTS

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BRIEF BIOGRAPHY OF PRESENTER

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